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BRIEFING

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Comparison of Aerodynamic Drag Determination Procedures for HDV CO_2 Certification

INTRODUCTION

The European Union (EU) and the United States (U.S.) have established regulations to certify the fuel consumption and CO_2 emissions from heavy-duty vehicles (HDVs). HDVs exhibit a wide range of vehicle configurations and usage characteristics, which prevents the determination of their fuel consumption and CO_2 emissions through conventional laboratory procedures, such as chassis dynamometer testing. To circumvent this, the certification procedures developed by the United States Environmental Protection Agency (EPA)[1] and the European Commission (EC)[2] use a combination of component testing and vehicle simulation. The simulation tools, GEM in the United States and VECTO in the EU, rely on standardized component testing to determine the inputs used in simulation. The key component tests determine the engine fuel consumption map, transmission and axle efficiency maps, tire rolling-resistance, and vehicle aerodynamic drag. Using the component data, the tools simulate the vehicle operation over region-specific drive cycles and payloads. The tools' outputs are the fuel consumption and CO_2 emissions. These are used in vehicle certification.

This briefing paper focuses on the aerodynamic drag determination procedures used for CO_2 certification in both regions. In particular, the paper seeks to:

1 Final Rule: Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles–Phase 2, 81 Fed. Reg. 206, (October 25, 2016), https://www.gpo.gov/fdsys/pkg/FR-2016-10-25/pdf/2016-21203.pdf.

2 Regulation (EU) 2017/2400 of 12 December 2017 Implementing Regulation (EC) No 595/2009 of the European Parliament and of the Council as Regards the Determination of the CO_2 Emissions and Fuel Consumption of Heavy-Duty Vehicles and Amending Directive 2007/46/EC of the European Parliament and of the Council and Commission Regulation (EU) No 582/2011, Official Journal of the European Union L 349 (December 12, 2017), http://data.europa.eu/eli/reg/2017/2400/oj.

Prepared by Oscar Delgado, Felipe Rodriguez, and Nikiforos Zacharof

- » Describe the tests, data preparation, and calculations used to estimate the aerodynamic drag in the format required by the simulation tools in both regions.
- » Compare the relative advantages and opportunities for improvement of both procedures.
- » Provide recommendations to other countries and regions planning to implement such procedures in their CO_2 or fuel consumption certification process.

AERODYNAMIC DRAG DETERMINATION PROCEDURES

In the context of CO_2 certification, the aerodynamic characteristics of a vehicle are captured by a parameter called the aerodynamic drag area (C_DA). The C_DA, measured in m^2, is the product of the dimensionless aerodynamic drag coefficient (C_D) with the vehicle's frontal area (A). The C_DA defines the relationship between the dynamic pressure[3], which is proportional to the square of the vehicle's velocity, to the aerodynamic drag force exerted by the air flowing around the vehicle. Due to the complexities of air flow phenomena, the C_DA value is dependent on the test procedure used to develop it and on the weather conditions during testing. The aerodynamic drag area of a vehicle is usually determined using one of the following four methods.

- » **Coastdown testing**. On-road test in which the vehicle is allowed to decelerate, or coast down, from a fixed high speed to a lower one. The engine is decoupled from the driveline during coast down. The measured vehicle and wind speeds are used to estimate the aerodynamic drag. Coastdown testing is the primary method used in the Phase 2 GHG regulation in the United States.[4]
- » **Constant-speed testing**. On-road test in which the vehicle is constantly operated at two or more different speeds. The measurement of the driving torque and of the wind speed allow the estimation of the aerodynamic drag. Constant-speed testing is the only accepted method in the CO_2 certification procedure in the European Union.[5]
- » **Wind Tunnel Testing**. This method uses a test chamber in which a stationary vehicle, in most cases a scale model, is exposed to a controlled air flow. The measurement of the horizontal force experienced by the vehicle is used to estimate the aerodynamic drag. The method allows testing at different yaw angles[6] and wind speeds.
- » **Computational fluid dynamics (CFD)**. This method uses a numerical simulation tool to model the air flow around a virtual model of the vehicle and estimate aerodynamic drag. The method allows estimation of aerodynamic drag at different yaw angles and wind speeds.

This study's focus is on the coastdown and constant-speed procedures, as they are the primary method used for certification in the United States, and the only accepted certification method in the EU, respectively. The following sections describe the procedures in more detail.

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3 Dynamic pressure is the kinetic energy per unit volume of a fluid particle, defined as rv2/2, where r is air density, and v is flow speed.

4 Final Rule: Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles–Phase 2, 81 Fed. Reg. 206.

5 Regulation (EU) 2017/2400, Official Journal of the European Union L 349.

6 Yaw angle is the wind angle observed by the vehicle with respect to the direction of motion. Zero yaw represents wind flow parallel to the vehicle.

US PHASE 2 COASTDOWN TEST

The coastdown provisions are outlined in the U.S. greenhouse gas Phase 2 standards[7] and in the SAE standards J1263[8] and J2263[9]. In the coastdown test, the vehicle is accelerated to a fixed high speed, and then allowed to decelerate, mainly due to aerodynamic forces[10], while the transmission is set in neutral. Although coastdown testing is the primary tractor[11] aerodynamic drag determination procedure in the United States, the regulation allows alternate test methods such as constant-speed testing, wind tunnel measurements, and computational fluid dynamics, as long as their results are correlated to the coastdown procedure[12]. Nevertheless, according to the U.S. regulation,[13] an alternate testing method is required to normalize the coastdown results to appropriate yaw angle conditions, as explained below.

TEST DESCRIPTION

The testing procedure requires a setup that includes a vehicle speed measurement system, an onboard anemometer to measure the air speed and direction from the vehicle's perspective, and a stationary weather station to measure wind speed, wind direction, ambient air temperature, relative humidity, and atmospheric pressure.

Prior to testing, the vehicle must warm-up for 30 minutes by running at an average speed of 80 km/h (50 mph) and then start the test immediately. During the coastdown test, the parameters described above are measured and recorded. The test has two phases. In the high-speed phase, the vehicle coasts from 113 km/h (70 mph) down to 97 km/h (60 mph), In the low-speed phase, the coast down takes place from 32 km/h (20 mph) to 16 km/h (10 mph). The coastdown can be performed continuously from the highest to the lowest speed or can be done as a split test in which braking is allowed between the high-speed and low-speed ranges. Test runs must be performed in both directions of travel and using the same method for transitioning from the high-speed to the low-speed range. Figure 1 presents the high/low-speed test sequence.

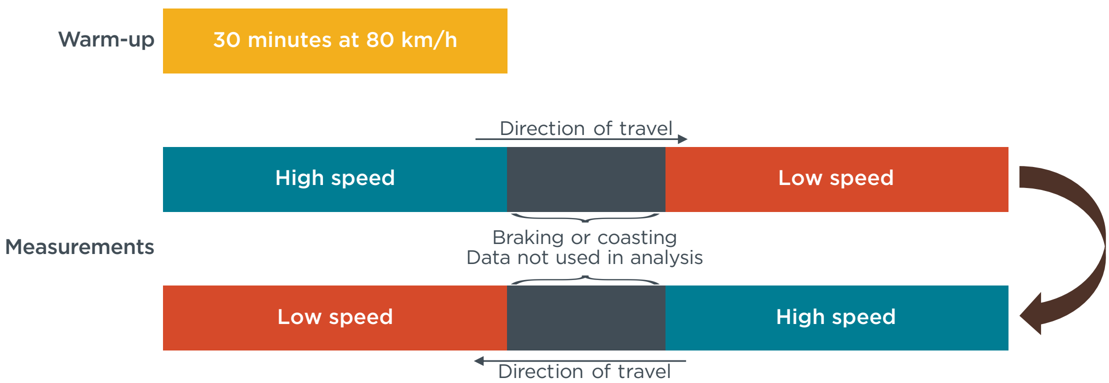

Figure 1: Run sequence of coastdown test.

7 Final Rule: Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles–Phase 2, §1037.528.

8 "Road load measurement and dynamometer simulation using coastdown techniques," Standard J1263-201003, Society of Automotive Engineers, 2010, https://saemobilus.sae.org/content/j1263_201003/

9 "Road load measurement using onboard anemometry and coastdown techniques," Standard J2263-200812, Society of Automotive Engineers, 2008, http://saemobilus.sae.org/content/j2263_200812

10 Tire rolling resistance, as well as driveline frictional forces are also present. The aerodynamic force is the dominant one at high speeds. At lower speeds, the non-aerodynamic forces become more dominant.

11 The U.S. has a separate trailer standard. The primary method for trailers is wind tunnel testing but the program allows for trailer manufacturers to use coastdown or CFD methods, after approval from the agencies.

12 Test procedures are described in §1037.530 for wind-tunnel, §1037.532 for CFD, and §1037.534 for constant-speed.

13 Final Rule: Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles–Phase 2, §1037.525.

DATA ANALYSIS

The data post-processing can be divided into three general phases: data validation, C_DA estimation for observed test conditions, and C_DA adjustment to the wind-averaged conditions used by the simulation tool, GEM. Figure 2 presents an overview of the data analysis process.

The data validation phase consists of two main steps. First, the vehicle speed, air speed, yaw angle, wind speed, and wind direction are filtered and outliers are removed. Second, the recorded air flow data, which is measured at 1.5 meters above the top surface of the truck, is corrected to estimate the flow conditions observed at truck height. The correction approach uses a regression model that uses the wind speed and direction measured by a stationary anemometer located at a height corresponding to the centerline of the vehicle.

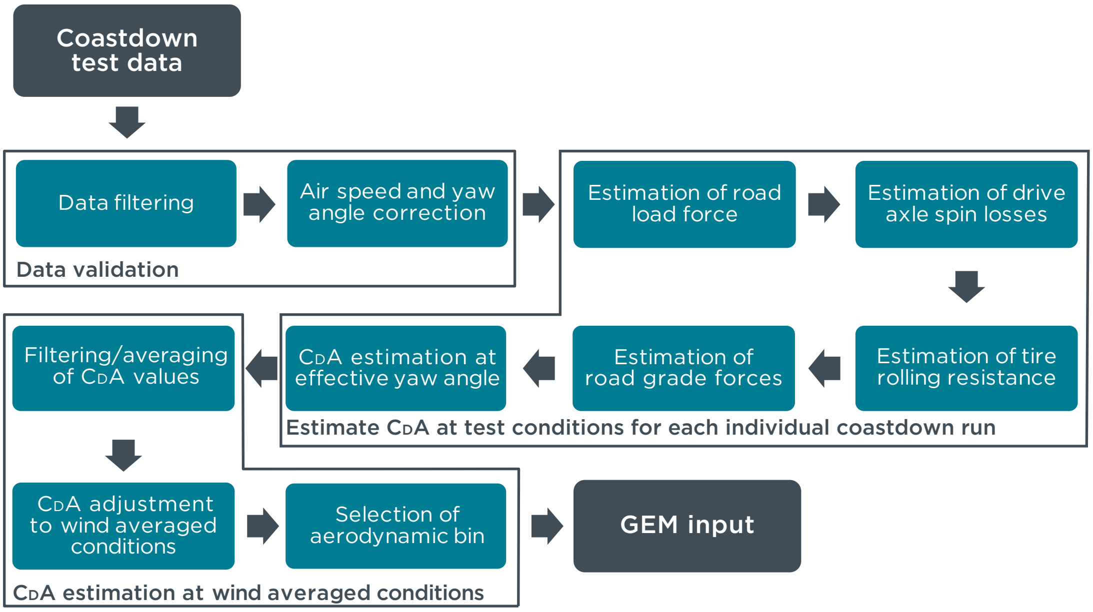

Figure 2: Flowchart of estimating the C_DA value with the coastdown procedure.

In the next phase, the C_DA is estimated at the wind conditions observed during testing. This is done in five main steps. First, the total road-load force is calculated from the deceleration measured during coast down. The road load includes aerodynamic drag, rolling resistance, axle spin losses, and road grade forces. To isolate the aerodynamic contribution, the speed dependence of the drive axle losses and the tires' rolling resistance losses are quantified in the next two steps. In a fourth step, the road grade forces are estimated using the test track inclination. In a final step, the C_DA is estimated at the observed yaw angle during each individual coastdown run.

In a final phase, the C_DA and respective yaw angle results from repeated runs are filtered to eliminate outliers and invalid measurements, and then averaged to obtain the final C_DA of the vehicle at the effective average yaw angle. At least 24 valid runs have to be conducted to determine a mean drag area and yaw angle. The average C_DA is then adjusted to a yaw angle of 4.5°, a surrogate angle representing the wind-averaged conditions, using an alternate method (e.g., CFD or wind-tunnel). In a final step, the wind-averaged C_DA is allocated to one of the aerodynamic bins determined in the regulation. Each bin has a predefined value, which is used as input to GEM.

EU CONSTANT-SPEED TEST

In the European Union, the only aerodynamic drag determination procedure permitted by the regulation[14] is the constant-speed test. The procedure is based on the measurement of the driving torque during steady-state operation at two different vehicle speeds. The torque data, in combination with the vehicle speed, air speed, and yaw angle, are used to estimate the aerodynamic drag. The measured data are used as input in a post-processing tool, called VECTO Air Drag, which calculates the C_DA value required by the simulation tool, VECTO.

TEST DESCRIPTION

The test sequence begins with a warm-up phase in which the vehicle is operated at the target high speed for over 90 minutes, the torque meters are zeroed to account for the drift associated with temperature variations, and the vehicle is operated for another 10 minutes. The warm-up phase is followed by a low-speed run between 10 and 15 km/h, a 5 minute warm-up, a high-speed run between 85 and 95 km/h, and a second low-speed run. At least 10 valid[15] high-speed runs must be recorded in each direction. As a final step, the torque meter drift is controlled and the misalignment calibration test is performed. The latter is used to calculate the misalignment error and perform the corresponding correction, and can also be performed independently from the rest of the test. Figure 3 presents the test sequence for the constant-speed procedure.

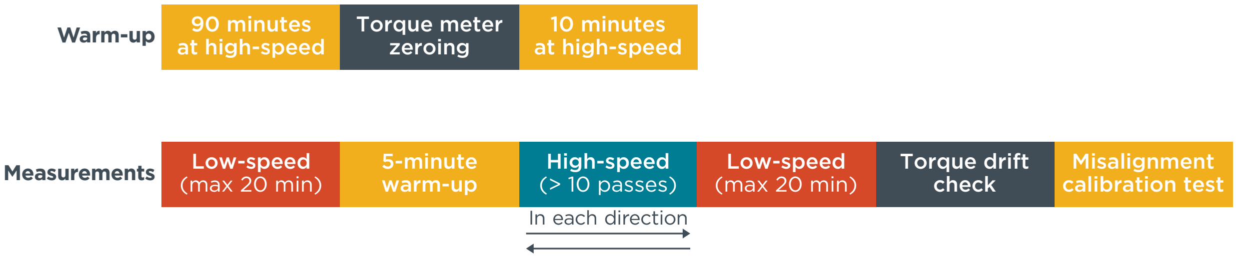

Figure 3: Test sequence for the EU constant-speed measurements Each low/ high-speed test requires 10 valid passes per heading.

The procedure requires a data acquisition system to simultaneously log the data from the vehicle and the instruments installed. The vehicle speed is measured by the vehicle's own sensors and read from the Controller Area Network (CAN bus). To achieve the accuracy required, the CAN-bus data is calibrated using either a Differential Global Positioning System (DGPS) or two optoelectronic barriers placed at a known distance from each other. The road surface temperature is measured by an infrared sensor mounted on the vehicle. Torque is measured at all driven axles with the use of either wheel torque meters or half shaft torque meters.

An onboard anemometer, placed 1.5 meters above the top surface, measures the air speed and yaw angle. To correct the anemometer to the flow conditions observed at truck height, the EU constant-speed provisions do not require a stationary anemometer. The height dependence of the wind speed is approximated by a generic model using the wind profile power law, and the possible flow artifacts caused by the vehicle shape at the measurement position are estimated by driving the vehicle in two opposite directions during the calibration run. The stationary weather station measurements are limited to the ambient air temperature, relative humidity and atmospheric pressure.

14 Regulation (EU) 2017/2400, Official Journal of the European Union L 349.

15 The validity criteria include anemometer misalignment, torque stability, vehicle speed stability, engine speed stability, and road temperature. The validity checks are done by VECTO Air Drag tool.

DATA ANALYSIS

The European Commission developed an official pre- and post-processing tool, called VECTO Air Drag, to analyze the constant-speed measurement data. The tool was developed to reduce the possibility of ambiguous interpretation of the regulatory provisions and to ensure that the data analysis is performed uniformly. As with the coastdown case, the data analysis is divided in three general phases: data validation, C_DA estimation for specific test conditions, and C_DA adjustment to conditions used by the VECTO simulation tool. Figure 4 presents an overview of the process.

In the data validation and calibration phase, VECTO Air Drag filters the data by removing tests that do not comply with ambient conditions criteria and then checks the validity of the torque, vehicle speed and engine speed measurements. It then applies a correction to the air speed and the yaw angle measurements, based on the parameters found using the data from the misalignment calibration test.

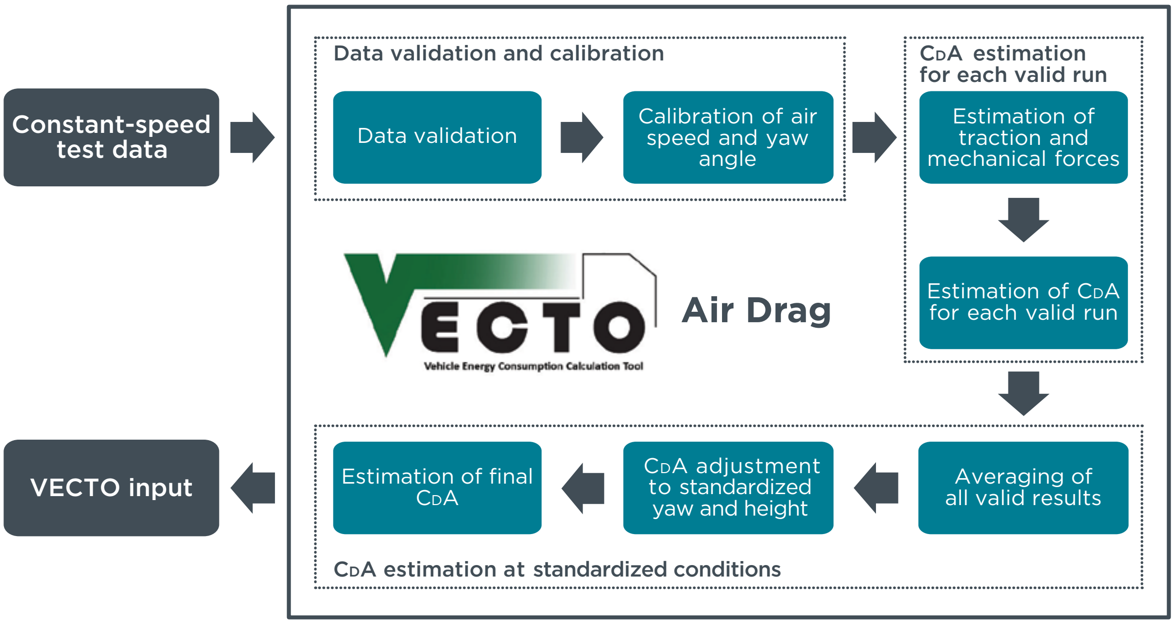

Figure 4: Flowchart for estimating the C_DA value with the constant-speed procedure.

In the next phase, VECTO Air Drag estimates the C_DA for each valid run at the wind conditions observed during testing (i.e., test-specific yaw angle) in two steps. The tool estimates the traction force for the high- and low-speed tests along with other mechanical forces, namely rolling resistance, gradient force and vehicle inertia. The rolling resistance estimation assumes it to be independent of speed. In this way, the aerodynamic forces that are exerted on the vehicle are isolated by subtracting the low-speed test's traction force from the respective value of the high-speed test. The C_DA is then estimated directly from the resulting aerodynamic force.

In the last series of steps, the tool averages the C_DA and the measured yaw angle of all valid runs. The resulting value is adjusted to represent the C_DA at zero yaw angle, to account for the height of the standard bodies used in certification, and to account for the air drag induced by the onboard anemometer. The calculation of the zero-yaw angle correction is realized with a third-degree polynomial, whose coefficients are specific to the vehicle type and its respective standard vehicle body. The reference height adjustment is a linear correction. The anemometer drag correction is a constant value equal to 0.15 m^2. This is the final C_DA value output from VECTO Air Drag, and the input to be used for VECTO.[16]

16 VECTO applies internally an additional crosswind correction, which is a function of vehicle speed, to account for real wind conditions.

PROCEDURE COMPARISON DISCUSSION

To identify relative advantages and improvement opportunities for the two aerodynamic drag procedures, this section compares the various aspects related to the instrumentation, test-track, testing effort, data analysis, and precision of the results.

INSTRUMENTATION REQUIREMENTS

Equipment requirements and their cost, as well as the availability of a test-track that satisfies the requirements are important considerations for countries and regions that are looking to implement an aerodynamic drag testing procedure within their HDV efficiency or CO_2 regulations. Table 1 presents the required measurement equipment for each procedure, as well as accuracy and measurement frequency requirements stipulated in the EU constant-speed and in the U.S. coastdown regulations.

Table 1: Comparison of required equipment by test.

Instrument	Requirement	EU constant-speed test	U.S. coastdown test
Hub, rim or half shaft torque meter	Accuracy	Linearity and repeatability: < ± 6 Nm Crosstalk: < ± 1% of full scale	Not required
	Frequency	≥ 20 Hz	
On-board anemometer	Accuracy	Air speed: < ± 3.5% of full scale Yaw angle: < ± 1°	Air speed: < ± 1 km/h Yaw angle: < ± 0.5°
	Frequency	≥ 4 Hz	≥ 10 Hz
On-board thermometers	Accuracy	Air temperature: < ± 1°C Road temperature: < ± 2.5°C	Air temperature: < ± 1°C Road temperature: Not required on-board, only at beginning of test.
	Frequency	≥ 1 Hz	≥ 10 Hz
Stationary anemometer	Accuracy	Not required	Air speed longitudinal: < ± 1.6 km/h Air speed crosswind: < ± 1.6 km/h Yaw angle: No requirement
	Frequency		≥ 10 Hz
Stationary weather station	Accuracy	Temperature: < ± 1°C Relative humidity: < ± 5 % RH Pressure: < ± 1 mbar	Temperature: < ± 1°C Relative humidity: Not required Pressure: < ± 7 mbar
	Frequency	At least once every 6 minutes	≥ 10 Hz
Vehicle and engine speed	Accuracy	Vehicle: Defined by calibration Engine: CAN-bus accuracy	Vehicle: < ± 0.2 km/h Engine: Not required
	Frequency	≥ 20 Hz	≥ 10 Hz
DGPS (optional)	Accuracy	DGPS: < 3 m, 95 % Circular Error Probable	Not required
	Frequency	≥ 100 Hz	
GPS with optic barriers (optional)	Accuracy	GPS: < 0.15 m, 95 % Circular Error Probable	Not required
	Frequency	GPS: ≥ 4 Hz Barriers trigger: ≥ 100 Hz	

Both procedures require similar instrumentation for the measurement of wind and ambient conditions, namely anemometers, data loggers, and ambient data measurement devices. However, there are a few differences between the equipment requirements. The coastdown procedure requires a stationary anemometer to record the wind speed and angle at the test track; this is not a requirement for the constant-speed procedure. Conversely, the constant-speed procedure requires the measurement of the air relative humidity and the continuous measurement of the road surface temperature. Furthermore, while the coastdown provisions only set requirements on the accuracy of the vehicle speed measurement, the constant-speed procedure sets specific provisions for its measurement and calibration.[17]

The most notable difference between the methodologies is the requirement of a torque meter in the constant-speed test. The procurement and installation of this instrument cause a significant difference in the instrumentation cost. Rim and hub torque meters are not widely available and only a handful of manufacturers[18] offer them for heavy-duty vehicles. The price of a pair of wheel torque meters, suitable for a single drive axle, is around 100,000 USD.[19] The use of half-shaft torque meters would reduce the instrumentation cost by approximately an order of magnitude.[20] However, half-shafts of the test vehicle need to be modified to allow the installation of such an instrument. In comparison to the torque meters, the cost of the other instruments is lower. For example, the on-board and stationary anemometers have a list price of approximately 1,000 USD.[21] In summary, the cost of the instrumentation for the constant-speed procedure is higher than that of the coastdown test.

TEST-TRACK REQUIREMENTS

Both procedures include requirements for the test track and set a series of limitations on the ambient conditions. The constant-speed procedure sets limitations on the wind conditions which include wind speed, gust speed, and yaw angle. The coastdown testing sets limitations on the wind speed, gust speed and the average components of the wind parallel and perpendicular to the road. Table 2 presents the comparison of the test conditions between the two procedures. The constant-speed procedure has tighter requirements on ambient conditions, as it has a narrower ambient temperature range and lower value for maximum road surface temperature.

In the constant-speed procedure, the portions of the test track used for data collection and speed stabilization are defined on the traveled distance. Although the minimum length of the test track is not explicitly defined, the test track must be long enough to include at least one measurement section of 250±3 m and a speed stabilization section of at least 25 m prior to entering the measurement section. In addition, the test track layout should allow the vehicle to reach the designated maximum test speed before entering the stabilization section.

In the coastdown procedure, the portions of the test track used for data collection do not have a fixed length but are defined by the vehicle speed trace. That is, each measurement section starts and ends when the vehicle reaches certain speeds. Although

17 The vehicle speed is read from the CAN-bus and calibrated with the aid of a DGPS or GPS in combination with optoelectronic barriers.

18 To the authors' knowledge only Michigan Scientific Corporation and MTS Systems Corporation in the United States, and Kistler Instruments in the European Union offer wheel torque meters suitable for heavy-duty applications.

19 Internal communication with instrument providers.

20 Internal communication with an instrument provider.

21 Internal communication with an instrument provider.

the minimum test-track length is not defined in the regulation, the vehicle must be able to reach the test speed and complete the test runs travelling in a straight line.

Table 2: Comparison of the test conditions between the EU constant-speed and U.S. coastdown procedures.

Parameter	EU constant-speed test	U.S. coastdown test
Measurement sections	Distance defined at 250 ± 3 m	High-speed: 116 km/h – 93 km/h Low-speed: 36 km/h – 12 km/h
Road grade	Maximum ± 1%	Maximum ± 0.5%
Ambient temperature	0 – 25°C	5°C – 35°C
Road temperature	≤ 40°C	≤ 50°C
Wind conditions	Average wind speed below 5 m/s with wind gusts below 8 m/s. Yaw angle below 3° for high-speed and 5° for misalignment calibration test.	Average wind speed below 4.4 m/s with wind gusts below 5.5 m/s The average component of the wind parallel and perpendicular to the road must be below 2.7 and 2.2 m/s, respectively.

TESTING EFFORT

The ICCT commissioned[22] studies comparing aerodynamic drag measurements on a U.S. tractor-trailer, an EU tractor-trailer, and an EU rigid truck using both the U.S. coastdown and the EU constant-speed procedures. One of the objectives of the testing campaign was to gain insight into the testing details that cannot be described by the regulation.

In the preparatory phase of the constant-speed test, the installation and calibration of the additional instruments, the requirement of a misalignment calibration test, as well as the stricter provisions for vehicle warm-up, implied an additional effort compared to the coastdown test. However, once the vehicle entered the first low-speed phase of the test, the data collection did not pose major challenges. The test duration, including warm-up, low-speed, high-speed, and torque meter checks, and misalignment calibration test, was approximately 4 hours. However, since the constant speed test requires additional complex equipment such as torque meters and DGPS, equipment issues are more likely and an engineering margin must be allowed, especially if the testing staff is not familiar with the torque meters. In ICCT's testing campaign, one of the wheel torque meters failed during testing and the test had to be aborted half-way through.

The preparatory phase of the coastdown testing was significantly simpler, and testing was initiated directly after the 30 minutes warm-up run. For the EU tractor-trailer a total of 64 coastdown runs were collected. The coastdown tests were performed as split tests, with a duration of approximately 4 minutes including acceleration to high-speed, high-speed range coast down, braking to low-speed, low-speed coast down, and direction switching when required. The test duration, including warm-up and 64 coastdown runs lasted approximately 4 hours. However, in data post-processing, it became apparent that only 11 runs were valid due to the crosswind conditions present during testing. Therefore, depending on the wind conditions, good engineering judgment is necessary to determine the target number of coastdown runs required to achieve the regulatory minimum of 24 valid runs. Since the validation criteria depends on the median of the

22 J. Felipe Rodriguez et al., "Heavy-Duty Aerodynamic Testing for CO2 Certification: A Methodology Comparison [Technical paper 2019-01-0649]," (Warrendale, PA: SAE International, 2019), https://doi.org/10.4271/2019-01-0649.

measurements, the validity of a coastdown run can only be known after testing during data post-processing.

The coastdown methodology requires an alternate testing method, such as CFD or wind-tunnel testing, to adjust the results to the regulatory yaw angle, and additional component tests of the tires and axle to correct for the speed dependency of the mechanical losses.

In summary, both testing methodologies present similar testing efforts. While the constant-test procedure requires additional effort in the preparatory phase, the coastdown test can require additional effort during the testing phase, as a large number of runs can be required to satisfy the requirements on the number of valid coastdown runs, and it requires additional component tests.

DATA ANALYSIS AND USE WITHIN SIMULATION TOOLS

The data analysis applies several steps to validate, filter, calibrate, and correct the different datasets and values. The main differences found are summarized in Table 5. The coastdown data post-processing filters and smoothens data for the air speed, yaw angle, wind speed, wind direction and vehicle speed measurements. The constant-speed procedure on the other hand applies a series of stability criteria on the vehicle speed, torque measurements and engine speed, which may discard a test run if they are not in accordance.

The data post-processing requirements of the U.S. coastdown test include a correction to account for the differences in mechanical forces, such as tire rolling resistance and axle spin losses, over the low- and high-speed ranges. The tires' rolling resistance is a consequence of the energy dissipated as the tire deforms as it touches the ground and then recovers behind the contact area. The vehicle speed affects the deformation time, temperature and pressure of the tire, and thus has an influence on the rolling resistance. To quantify the speed dependence of the tire rolling resistance, the U.S. coastdown test requires that the truck tires are measured in a simulated stepwise coastdown tire rolling resistance test, SAE J2452[23].

The drive axle spin losses are caused by the movement of the oil inside of the axle housing, and thus depend on the vehicle's speed. The speed dependence of the drive axle spin losses is estimated by performing a regression of the power-loss map of the equipped axle, under no load. This power-loss map is one of GEM's inputs.

Contrary to the U.S. coastdown method, the EU constant-speed procedure disregards the speed-dependency of the tire rolling resistance. The EU provisions assumes that the same rolling resistance takes place over the high- and low-speed portions of the test. Since the drive torque is measured at the wheel, that is downstream of the powertrain, it is not necessary to include any correction for the speed dependency of the axle losses in the EU constant-speed method.

The treatment of the correction of the C_DA as a function of yaw angle differs in both methodologies. The U.S. coastdown test requires the use of an alternate C_DA determination method, one where the yaw angle can be set freely (i.e., CFD and wind-tunnel testing), to correct the measured C_DA to the regulatory yaw angle. The EU constant-speed test, on the other hand, uses generic correction polynomials to perform this correction.

23 "Stepwise coastdown methodology for measuring tire rolling resistance," Standard 2452-201707, Society of Automotive Engineers, 2017, https://saemobilus.sae.org/content/j2452_201707/

Table 3: Parameters that affect the C_DA used in simulation

Parameter	EU constant-speed test	U.S. coastdown test
Data pre-processing and validation	No pre-processing required Validity criteria checks: • Anemometer misalignment • Wheel torque stability • Vehicle speed stability • Engine speed stability	Pre-processing required for air speed, yaw angle, wind speed, wind direction and vehicle speed data: • Identify outliers with Hampel method • Replace outliers with median Correction of on-board air speed and direction using the wind speed and wind direction from weather station
Speed dependence of rolling resistance	No correction	Measured tire rolling resistance per SAE J2452. Estimated in the coastdown data post-processing
Speed dependence of spin axle losses	Torque measured at the wheel; powertrain losses are irrelevant	Measured axle power losses as a function of speed per 40 CFR 1037.560. Estimated in the coastdown data post-processing
Yaw angle correction	Based on generic formulas	Effective yaw angle used to normalize results from alternate measurement procedures

PRECISION AND ACCURACY

The EPA recently undertook an analysis to validate the coastdown procedure and investigate test uncertainties.[24] The study found that relative standard error[25] decreases below 1% when the number of coastdown runs exceeds 20. However, the author of the study highlights that wind conditions could have a significant impact on the measurements and that test boundary conditions must be respected. The regulatory impact analysis carried out for the Phase 2 of the GHG standards by EPA estimates relative standard errors between 0.5% and 0.8% for the constant-speed procedure.[26] As an effort to evaluate the repeatability[27] and reproducibility[28] of the coastdown test results, the National Research Council of Canada (NRCC) evaluated the U.S. coastdown procedures by testing the same vehicle used by EPA in its evaluation exercise. The NRCC study[29] tested the vehicle under the same configurations as EPA and found a difference no greater than 5%, with respect to EPA's coastdown results.

In the EU, the constant-speed procedure was evaluated and validated by the European Commission's Joint Research Centre (JRC).[30] The study tested two vehicles, a rigid truck and a tractor-trailer which were previously tested by the respective manufacturers.

24 Prashanth Gururaja, "Evaluation of Coastdown Analysis Techniques to Determine Aerodynamic Drag of Heavy-Duty Vehicles," 2016, https://doi.org/10.4271/2016-01-8151.

25 Standard error indicates the uncertainty around the estimate of the mean measurement, and it is estimated by dividing the standard deviation by the square root of the sample size. Standard error decreases as the sample size increases.

26 U.S. EPA and U.S. DOT, "Final Rule: Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles–Phase 2. Regulatory Impact Analysis" (Environmental Protection Agency and Department of Transportation, August 2016), https://nepis.epa.gov/Exe/ZyPDF.cgi/P100P7NS.PDF?Dockey=P100P7NS.PDF.

27 Repeatability is a measure of agreement between the results performed by the same observer with the same equipment and under the same procedure.

28 Reproducibility is a measure of agreement between the results performed by different observers with different equipment, but under the same procedure.

29 Brian R. McAuliffe and David Chuang, "Coast-down and Constant-Speed Testing of a Tractor-Trailer Combination in Support of Regulatory Developments for Greenhouse Gas Emissions" (National Research Council Canada, May 12, 2017), http://doi.org/10.4224/23001919.

30 Georgios Fontaras et al., "An Experimental Methodology for Measuring of Aerodynamic Resistances of Heavy Duty Vehicles in the Framework of European CO_2 Emissions Monitoring Scheme," *SAE International Journal of Commercial Vehicles* 7, no. 1 (April 1, 2014): 102–10, https://doi.org/10.4271/2014-01-0595.

Compared to the C_DA values estimated by the manufacturers, the testing resulted in a difference of 1.3% for the rigid truck and -0.3% for the tractor-trailer. The study found a repeatability standard deviation at 2.4% for the rigid truck and 1.8% for the tractor-trailer, with the respective reproducibility standard deviation at 2.9% and 2.2%.

The ICCT conducted[31] measurements on a U.S. tractor-trailer, an EU tractor-trailer, and an EU rigid truck in order to evaluate the two methodologies. In this study, all three vehicles were tested under the coastdown and constant procedures and their results were corrected to zero yaw angle to enable their comparison. The results are shown in Figure 5.

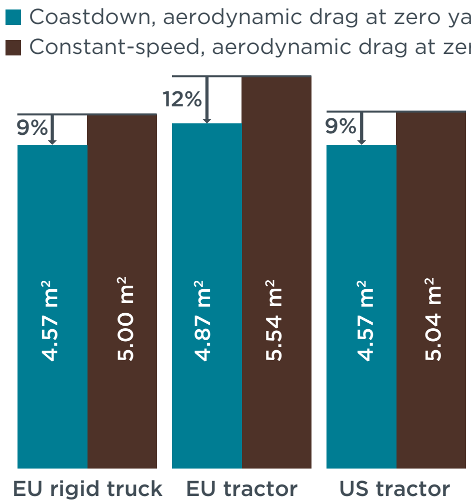

Figure 5: Aerodynamic drag measurement comparison by procedure and vehicle.

The study found a difference of 9.2% for the U.S. tractor-trailer between the coastdown and constant-speed procedure. For the EU vehicles, the difference was 8.6% for the rigid truck and 12.1% for the tractor-trailer. For reference, a 0.5 m^2 change in C_DA can result in approximately 0.3% fuel consumption change over low speed urban operation, and around 3% in high speed highway operation.[32]

The explanation of the divergence between the two procedures can be partly attributed[33] to the following factors:

» **Adjustment factors:** Each post-processing procedure applies several adjustment factors to the results in order to comply with the set regulatory boundary conditions. This includes the yaw angle adjustment (4.5° in the United States, 0° in the European Union), and the drag created by the onboard anemometer. The latter is not considered in the U.S. regulations. The EU regulations subtract 0.15 m^2 from the measured C_DA to account for this additional drag.

» **Speed-dependency of tire rolling resistance:** The U.S. coastdown methodology considers the speed-dependency of tire rolling resistance based on component testing. The EU constant-speed test does not include a speed-dependency correction. The differing assumptions on tire rolling resistance dependency with speed was identified as the main source of bias.

31 Rodriguez et al., "Heavy-Duty Aerodynamic Testing for CO_2 Certification: A Methodology Comparison."

32 Oscar Delgado, Felipe Rodríguez, and Cristiano Façanha, *Technology Verification Tool for Green Freight Programs*, (ICCT: Washington, DC, 2019), https://www.theicct.org/publications/technology-verification-tool-green-freight-programs.

33 A detailed quantification of the impact of these factors can be found in a related paper by the authors: Rodriguez et al., "Heavy-Duty Aerodynamic Testing for CO_2 Certification: A Methodology Comparison."

- **Speed-dependency of axle spin losses:** Generic axle data was used for post-processing of U.S. coastdown data in the results shown in Figure 5, increasing the uncertainty of the coastdown results. In the EU constant-speed test, the drive torque is measured downstream of the axle and variations in the axle losses do not influence the C_DA results.
- **Post-processing approach:** The U.S. coastdown corrects the on-board air speed measurements with the help of a stationary anemometer located at a height corresponding to the centerline of the vehicle. The EU constant-speed provisions, on the other hand, uses a generic wind speed profile to correct the on-board air speed data.

These findings suggest that the U.S. coastdown test results in a lower estimation of the C_DA when compared to the EU constant-speed test, even when accounting for the quantifiable sources listed above. Other studies have found different trends to the ones identified in ICCT's study. Shoffner[34] reported the opposite trend, finding that coastdown test resulted in higher values than the constant-speed tests. McAuliffe and Chuang[35] reported no difference between the methods, finding that the results from constant-speed measurements, following the U.S. constant-speed provisions, agreed with the coastdown results within 1%. The testing of a larger sample of vehicles over both tests is recommended to reconcile these conflicting findings.

Regarding precision, the available evidence suggests that the constant-speed procedure has a higher repeatability and reproducibility than the coastdown procedure. However, increasing the number of coastdown tests reduces the measurement uncertainty. EPA choose the coastdown as their primary method because it produced results with acceptable repeatability and at a lower cost than the constant speed testing.[36]

SUMMARY AND RECOMMENDATIONS

This briefing summarized and compared the two main test methods for aerodynamic evaluations of heavy trucks in the United States and the European Union. Both methods have relative advantages and deficiencies and it is not the purpose of this paper to recommend the use of one methodology over the other. Countries and regions interested in developing policies to reduce fuel consumption and CO_2 emissions ideally would leverage the work already done by the United States and the European Union, adapting the existing simulation tools and component testing methodologies to their specific markets.

For markets with limited testing resources, where the acquisition cost of the torque meter required for the constant speed test is a barrier, the coastdown procedure is usually explored first, as it requires less costly and more simple equipment, and regulatory agencies are already familiarized with the methodology, which is applied for passenger vehicles' aerodynamic determination. The main challenge with the coastdown procedure is that it involves additional component tests to estimate the speed dependency of the drive axle spin losses, the speed dependency of the tire rolling resistance, and the yaw angle dependency of the drag area. These additional tests represent complexity and added cost. If these measurements are not available

34 Brent Shoffner, "Heavy Duty Class 8 Truck Coastdown and Constant Speed Testing" (Southwest Research Institute, April 22, 2015), https://www.regulations.gov/docketBrowser?rpp=50&po=0&s=0463&dct=SR&D=EPA-HQ-OAR-2014-0827.

35 McAuliffe and Chuang, "Coast-down and Constant-Speed Testing of a Tractor-Trailer Combination in Support of Regulatory Developments for Greenhouse Gas Emissions."

36 Final Rule: Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles–Phase 2. Regulatory Impact Analysis.

or the resources are limited, they could be replaced by engineering estimations based on generic physical models, at the expense of increasing the test uncertainty and reducing the test reproducibility. These models would simplify the process but must be well validated and proven to be appropriate for their intended purposes and must be regularly updated as technology evolves. As an example, the U.S. methodology requires the use of CFD or wind-tunnel testing to adjust the values to wind-average while the EU procedure offers a simpler alternative to evaluate the yaw angle dependency by offering generic polynomial functions for different vehicle types. As the polynomial coefficients are dependent on vehicle geometry, these functions are expected to be regularly updated as the European Union starts to see changes in vehicles' shape due to updates to its weights and dimensions regulation. A similar approach could be followed to simplify the coastdown test.

We recommend that regardless of the chosen methodology, the regulatory agencies develop a post-processing tool which takes as input the raw data and outputs the aerodynamic drag value to be used in simulation, as was done by the European Union. This would eliminate the room for misinterpretation of the regulatory provisions and guarantee consistency in the analysis. Based on the observed differences between the methodologies, we recommend that if both are going to be allowed for aerodynamic certification, that a conversion factor is used to guarantee comparability of results, as is done in the United States.