THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

BRIEFING

MAY 2018

# Fuel consumption testing of tractor-trailers in the European Union and the United States

This paper summarizes the results of a pioneering vehicle testing program aimed at comparing the fuel efficiency of selected tractor-trailers in Europe and the United States. The ICCT commissioned the Institute for Internal Combustion Engines and Thermodynamics of the Graz University of Technology (TU Graz) and the Center for Alternative Fuels, Engines, and Emissions at West Virginia University (WVU) to conduct track testing and chassis dynamometer testing to determine the aerodynamic drag and fuel consumption of tractor-trailers in the European Union (EU) and the United States under comparable conditions. Three trucks were tested: a typical EU tractor-trailer, a best-in-class EU tractor-trailer, and a best-in-class U.S. tractor-trailer. The vehicles were tested using the drive cycles and payloads stipulated by the EU $CO_2$ certification regulation and by the U.S. fuel consumption standards for heavy-duty vehicles.

When tested over the same long-haul driving cycle and payload, the best-in-class EU tractor-trailer had a fuel consumption of 29.9 liters per 100 km. The best-in-class U.S. tractor-trailer consumed a similar amount of fuel at 30.1 liters per 100 km. At 32.6 liters per 100 km, the average EU tractor-trailer consumed the highest amount of fuel over the test cycle, exhibiting 9% higher fuel consumption than the EU best-in-class.

## BACKGROUND

$CO_2$ emissions from on-road freight transport, particularly those from tractor-trailers operating on long-haul routes, represent a substantial and growing share of global carbon emissions. Five countries around the world—Japan, the United States, Canada,

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**Acknowledgements:** This work was generously supported by the European Climate Foundation and by Environment and Climate Change Canada.

China, and India—now have $CO_2$ or efficiency standards for heavy-duty vehicles (HDVs). The EU plans to release a regulatory proposal setting $CO_2$ limits for HDVs in early 2018.[1]

Available data[2] suggest that the average fuel efficiency of tractor-trailers in Europe has remained relatively constant over the past decade in the absence of regulatory targets. Before the introduction of HDV fuel efficiency standards in the United States, the U.S. fleet also showed stagnating average fuel consumption improvements.[3] The U.S. HDV fuel efficiency standards, first introduced in 2011[4] and updated in 2016,[5] set mandatory targets for improving the fuel consumption of the HDV fleet and created incentives for research and development of fuel-saving technologies and their deployment into the vehicle fleet. The U.S. HDV fuel efficiency standards aim for new tractor-trailers in 2027 to offer fuel consumption reductions of approximately 50%, relative to a 2010 baseline.

Publicly available literature on tractor-trailer fuel consumption in the EU is scarce. The data available in regulatory documents in the United States are constrained to the U.S. test cycles and payloads; thus, they do not allow a direct comparison to other regions. The vehicle testing commissioned by the ICCT allows such a direct comparison by testing tractor-trailers over the same set of driving cycles and payloads in a controlled laboratory environment, following strict test procedures.

To analyze the fuel consumption of tractor-trailers and understand the differences between regions, it is useful to consider fuel consumption as the product of the powertrain efficiency (i.e., combined efficiency of engine, transmission, and axles) and the road-load energy demand (i.e., combined effect of aerodynamic drag, rolling resistance, inertial forces, and road grade). The powertrain efficiency can be expressed as the fuel consumption, in grams, necessary to provide a unit of work at the wheel hub, in kilowatt-hours, as measured on the chassis dynamometer. This metric is called the powertrain *brake specific fuel consumption* (BSFC). This approach is shown in the equation below.

$$\text{Fuel consumption [g]} = \text{Powertrain BSFC}\left[\frac{\text{g}}{\text{kWh}_{\text{wheel}}}\right] \times \text{Road-load energy }[\text{kWh}_{\text{wheel}}]$$

The key component dictating the powertrain BSFC is the engine. Likewise, the engine efficiency can be quantified as the required fuel mass to be burned to provide a unit of engine work. The mechanical efficiencies of the transmission and drive axle also play an important role in the powertrain efficiency. The relation between these metrics is shown in the expression below.

$$\text{Powertrain BSFC}\left[\frac{\text{g}}{\text{kWh}_{\text{wheel}}}\right] = \frac{\text{Engine BSFC}\left[\frac{\text{g}}{\text{kWh}_{\text{engine}}}\right]}{\text{Transmission eff. [\%]} \times \text{Axle eff [\%]}}$$

1 European Commission, "Europe on the Move: An Agenda for a Socially Fair Transition Towards Clean, Competitive and Connected Mobility for All" (Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, May 31, 2017); http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52017DC0283.

2 Rachel Muncrief, "Shell Game? Debating Real-World Fuel Consumption Trends for Heavy-Duty Vehicles in Europe" (ICCT Staff Blog, April 24, 2017); www.theicct.org/blogs/staff/debating-EU-HDV-real-world-fuel-consumption-trends.

3 Stacy C. Davis, Susan E. Williams, and Robert G. Boundy, "Transportation Energy Data Book—Edition 36" (Oak Ridge National Laboratory, December 1, 2017); http://cta.ornl.gov/data/download36.shtml.

4 U.S. Environmental Protection Agency (EPA) and U.S. Department of Transportation (DOT), "Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles; Final Rule" (Federal Register, Vol. 76, No. 179, September 15, 2011); www.gpo.gov/fdsys/pkg/FR-2011-09-15/pdf/2011-20740.pdf.

5 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" (Federal Register, Vol. 81, No. 206, October 25, 2016); www.gpo.gov/fdsys/pkg/FR-2016-10-25/pdf/2016-21203.pdf.

The road-load energy is the sum of the forces opposing the movement of the vehicle multiplied by the distance traveled. It can be divided into four main categories according to origin: aerodynamic drag, rolling resistance, road grade, and inertial forces. The aerodynamic drag force is mainly a function of the vehicle geometry and the square of the vehicle speed. The rolling resistance force depends mainly on the vehicle mass and the rolling resistance coefficient of the vehicle's tires. The road grade force is a function of the road inclination and the vehicle mass. Lastly, the inertial forces depend on the vehicle mass and the acceleration imposed by the driving cycle. These forces are illustrated in Figure 1.

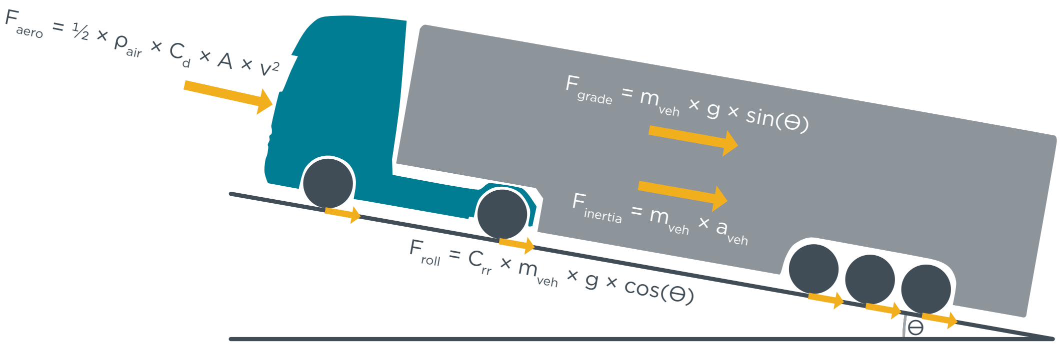


**Figure 1.** Road-load forces acting on a tractor-trailer.

The testing program was designed to evaluate the fuel consumption performance of the complete vehicles, as well as to understand the differences in road-load energy demand and powertrain efficiency between the tested tractor-trailers. Special emphasis was placed on the aerodynamic drag and engine efficiency determinations. The fuel efficiency results summarized in the following sections refer to the EU Long Haul cycle, the corresponding regulatory payload, and the air drag testing procedure as defined in the EU regulations.[6] The complete set of results—including the aerodynamic drag determination (based on the U.S. regulation) and fuel consumption measurements over a wider set of regulatory boundary conditions for the EU and the United States—can be found in the Annex to this document and in the corresponding technical reports of TU Graz[7] (for the EU trucks) and WVU[8] (for the U.S. tractor-trailer).

Because the market characteristics and regulatory boundary conditions can have a direct impact on the powertrain efficiency and road-load energy demand, Table 1 summarizes the impact of the regional differences on tractor-trailer fuel consumption. The testing program was designed to minimize the impact of these differences on the comparison, thereby allowing us to study the impact of vehicle technology on fuel consumption.

6 European Commission, "Commission 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 29, 2017); http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L:2017:349:TOC.

7 Martin Rexeis, Martin Röck, and Stefan Hausberger, "Comparison of Fuel Consumption and Emissions for Representative Heavy-Duty Vehicles in Europe" (Technische Universität Graz, March 2018); www.theicct.org/publications/HDV-EU-fuel-consumption-and-emissions-comparison.

8 Thiruvengadam, Arvind, Marc Besch, Berk Demirgok, Dan Carder, and Cem Baki. "Fuel Consumption and Emissions Testing of a Best-in-Class Tractor-Trailer in the US." (West Virginia University, May 2018); www.theicct.org/publications/HDV-US-best-in-class-fuel-consumption-testing

**Table 1.** Impact of regional differences between the EU and the United States on tractor-trailer fuel consumption.

| | | General remarks | EU | United States |
|---|---|---|---|---|
| Powertrain efficiency | **Engine** | The pollution control systems necessary to comply with emissions standards have an impact on the engine's fuel consumption | • Typical configuration: 6-cylinder, 13-liter engine<br>• The $NO_X$ limit under the Euro VI regulation is 0.4 g/kWh | • Typical configuration: 6-cylinder, 15-liter engine<br>• The $NO_X$ limit under the U.S. 2010 regulation is 0.27 g/kWh<br>• Engine efficiency standards are in place |
| Powertrain efficiency | **Transmission** | The shifting strategy and mechanical efficiency of the gear sets directly affects fuel consumption | • Typical configuration: Automated manual transmission with 12 gears in geometric progression, and direct drive in the 12th gear | • Typical configuration: Manual transmission with 10 gears, and direct drive in the 9th gear |
| Powertrain efficiency | **Axles** | Fuel efficiency is affected by the number of driven axles and by the mechanical efficiency of the differentials | • Typical tractor configuration: Two axles, one driven (i.e., 4x2)<br>• Typical trailer configuration: Three axles | • Typical tractor configuration: Three axles, two driven (i.e., 6x4)<br>• Typical trailer configuration: Two axles |
| Road-load energy demand | **Air drag** | Aerodynamic drag force is the product of the air drag coefficient, the frontal area, and the square of vehicle speed | • The regulatory Long Haul cycle has a maximum speed of 85 km/hour<br>• Length limitations apply from the front of the tractor to the rear of the trailer; to maximize cargo volume, tractor length is minimized, resulting in cab-over-engine designs. (See Figure 2)<br>• Air drag is measured using EU's constant-speed test | • The regulatory constant speed cycles with grade are run at 88.5 km/hour (55 mph) and 105 km/hour (65 mph)<br>• Length limitations only apply to trailers, allowing elongated tractor designs. (See Figure 2)<br>• Air drag is measured using the U.S. coast-down procedure<br>• Trailer side skirts have a high market adoption |
| Road-load energy demand | **Rolling resistance** | Rolling resistance force is the product of rolling resistance coefficient and vehicle weight | • See below for vehicle mass<br>• Typical tire dimension: 315/70 R22.5 | • See below for vehicle mass<br>• Typical tire dimension: 295/75 R22.5 |
| Road-load energy demand | **Inertial forces** | Product of vehicle mass and vehicle acceleration | • Maximum GVW (gross vehicle weight) of 40 tonnes, with a 13.6-m trailer and 92.5 $m^3$ of volume<br>• Typical cargo is volume-limited, resulting in actual GVWs significantly lower than the maximum<br>• Regulatory payload over the long-haul cycle is 19.3 tonnes | • Maximum GVW of 36.3 tonnes, with a 16-m trailer and 112 $m^3$ of volume<br>• Typical cargo is volume-limited; however, larger trailers result in typical payloads higher than in the EU, despite lower maximum GVW<br>• Regulatory payload over the long-haul cycle is 17.2 tonnes |
| Road-load energy demand | **Road grade** | Dependent on vehicle mass and road inclination | • See above for vehicle mass<br>• Maximum road grade of 6.6% over the Long Haul cycle | • See above for vehicle mass<br>• Maximum road grade of 5% over the 55- and 65-mph constant-speed cycles |

## VEHICLES TESTED

Three tractor-trailers were tested, corresponding to a pair of best-in-class (BIC) vehicles, one from each market, and a typical European tractor-trailer. The BIC tractor-trailers were specified with the support of an original equipment manufacturer (OEM) with substantial market presence in both the EU and U.S. markets; this OEM also helped to procure the vehicles for testing. The typical EU tractor-trailer (AVG-EU) was specified using vehicle registration and technology adoption data[9] in an attempt to match, to the extent possible, the average specifications found in the available data. The vehicle specifications are shown in Table 2.

The BIC vehicle selection in the United States (BIC-US) was constrained by the model year of the BIC truck in the EU, which was selected and tested first. To achieve a fair and direct comparison, it was decided that the selected U.S. tractor-trailer should represent the best-available technology in the year 2015, and not the best technology of the manufacturer for model year 2018 (MY2018). The fuel consumption of a 2015 BIC-US is expected to be higher than its MY2018 counterpart because of the engine and vehicle efficiency improvements mandated by the U.S. greenhouse gas (GHG) Phase 1 standards for 2017. For the particular OEM used in this testing project, the 2017 upgrades include improvements in engine efficiency, cabin design, aerodynamics, transmission and axle efficiency, and powertrain management. The difference between the 2015 BIC-US truck tested and the current best effort of the OEM is approximately 8% in fuel efficiency.[10]

**Figure 2.** Examples of tractor-trailers in the EU (left) and United States (right). The images are for illustration purposes only and do not correspond to the actual vehicles tested.

9 Vehicle registration data for 2016 supplied by IHS Global SA. HDV technology adoption data for 2015 provided by Knibb, Gormezano & Partners.

10 Internal communication with the OEM.

**Table 2.** Specifications of the tractor-trailers tested.

| | BIC-US | BIC-EU | AVG-EU |
|---|---|---|---|
| **Axle configuration** | 6x4 | 4x2 | 4x2 |
| **Cabin type** | High roof, sleeper cabin | | |
| **Registration year** | 2015 | 2015 | 2014 |
| **Trailer type** | • 2 axles, compliant with U.S. GHG Phase 2 regulation for aerodynamic testing; trailer with side skirts | • 3 axles, compliant with EU $CO_2$ certification regulation for aerodynamic testing; trailer without side skirts | • 3 axles, compliant with EU $CO_2$ certification regulation for aerodynamic testing; trailer without side skirts |
| **Engine rated power** | 300 to 330 kW | 300 to 330 kW | 300 to 330 kW |
| **Engine rated torque** | 2100 to 2400 Nm | 2100 to 2400 Nm | 2100 to 2400 Nm |
| **Number of cylinders** | 6 cylinders, inline | 6 cylinders, inline | 6 cylinders, inline |
| **Engine capacity** | 14 to 15 liters | 12 to 13 liters | 12 to 13 liters |
| **Engine technology features** | • Common-rail injection with up to 2600 bar injection pressure, and injection rate shaping<br>• 18.5:1 compression ratio<br>• Single-stage, fixed-geometry, asymmetric turbocharger<br>• Direct-charge air cooling | • Common-rail injection with up to 2700 bar injection pressure, and injection rate shaping<br>• 18.3:1 compression ratio<br>• Single-stage, fixed-geometry, asymmetric turbocharger<br>• Direct-charge air cooling<br>• Top torque: Higher torque at low engine speeds on 12th gear<br>• Reduced EGR rates | • Common-rail injection with 1800 bar injection pressure<br>• 18:1 compression ratio<br>• 2-stage turbocharging<br>• Indirect-charge air cooling<br>• High EGR rates for $NO_x$ control |
| **Emission standard** | U.S. 2010 | EURO VI | EURO VI |
| **Emissions control** | EGR, DOC, DPF, SCR | | |
| **Transmission type** | Automated manual transmission (AMT) | | |
| **Number of gears** | 12 | | |
| **Direct drive gear** | 12th | | |
| **Axle ratio** | 2.41 | 2.53 | 2.53 |
| **Aerodynamics** | • Aero package (roof spoiler, side flaps, side panels) | • Aero package (roof spoiler, side flaps, side panels) | • Aero package (roof spoiler, side flaps) |
| **Engine cooling** | • Belt-driven clutched fan<br>• Variable-speed water pump | • Belt-driven fan, electronically controlled visco-clutch | • Transmission-driven fan, electronically controlled visco-clutch |
| **Steering system** | • Fixed displacement | • Variable displacement, mechanically controlled | • Fixed displacement |
| **Pneumatic system** | • Medium-supply single-stage | • Clutched, medium-supply two-stage with energy-saving system and air management system | • Medium-supply single-stage |

EGR: exhaust gas recirculation, DOC: diesel oxidation catalyst, DPF: diesel particulate filter, SCR: selective catalytic reduction

## TESTING METHODOLOGY

The fuel consumption of the vehicles was measured via chassis dynamometer testing. To emulate vehicle operation conditions on the chassis dynamometer, it is necessary to determine the road-load forces that must be applied to the wheel over the driving cycle. As already mentioned, the road-load energy demand is the combined effect of aerodynamic drag, rolling resistance, inertial forces, and road grade.

The air drag was measured through the EU constant-speed procedure. During the constant-speed test, the driving torque at the traction wheels, vehicle speed, air flow velocity, and yaw angle are measured at two vehicle speeds under defined conditions on a test track. Although the rolling resistance can be estimated by the constant-speed procedure, the test focus is the aerodynamic drag determination and requires low-rolling-resistance tires to be fitted on the vehicle. As a result, the tires used during constant-speed testing, and the consequent rolling resistance value, were not representative of the market. To eliminate the uncertainties associated with tire selection, estimates of the rolling resistance used for setting the resistive forces in the chassis dynamometer were based on available data for the European market,[11] and were kept the same for all three vehicles. Tires with the rolling resistance used in the chassis dynamometer are available in both markets.

Lastly, the inertial and road grade forces are a function of the vehicle mass and the driving cycle. The combined vehicle curb mass used for the dynamometer settings was adjusted to include 500 liters of diesel fuel and the empty weight of the standard trailer for each market. During testing, the total vehicle mass was increased to include the payload defined by the regulations. Thus, the differences in total test weight between the vehicles are only a consequence of the differences in vehicle curb weight.

There are inherent uncertainties in the testing results associated with variabilities in weather and test track conditions during air drag testing, and with differences in measurement equipment and operators during chassis dynamometer testing. To minimize these uncertainties, we scrutinized the testing results in detail with the aid of redundant measuring systems and vehicle simulation.

Further details of the testing methodology, measurement equipment, and chassis dynamometer settings can be found in the corresponding technical reports of TU Graz[12] (for the EU tractor-trailer) and WVU[13] (for the U.S. tractor-trailer).

## DRIVING CYCLES AND PAYLOADS

The three tractors were tested on the chassis dynamometers over the same driving cycle and payload combinations. The driving cycles tested include the relevant regulatory mission profiles for the EU, Regional Delivery and Long Haul, and the regulatory cycles in the United States, 55-mph constant speed[14] (with and without road grade) and ARB transient. The payloads used for each cycle are in line with the regulations for HDV $CO_2$ certification in each region.

11 European Tyre & Rubber Manufacturers' Association, "Low Emission Mobility with a Focus on Freight Transport" (December 14, 2016); www.etrma.org/newsroom/70/75/Low-emission-mobility-with-a-focus-on-freight-transport/.

12 Rexeis et al., 2018.

13 Thiruvengadam et al., 2018.

14 The vehicles were not tested over the U.S. 65-mph constant-speed cycle, because that speed is outside the operational range of the EU vehicles.

This summary paper focuses on the results for the EU Long Haul cycle, shown in Figure 3. The EU regulatory payload for tractor-trailers over the Long Haul cycle is 19.3 tonnes. The results for the complete set of drive cycles and payloads tested can be found in the Annex and in the reports of TU Graz[15] and WVU[16] for the EU and U.S. trucks, respectively.

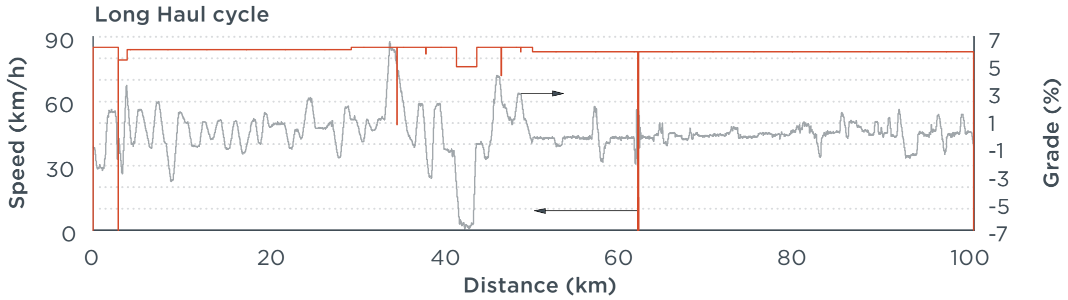


**Figure 3.** Vehicle speed target and road grade as a function of distance for the EU Long Haul cycle.

## FUEL CONSUMPTION COMPARISON

The fuel consumption over the EU Long Haul cycle for each of the trucks tested is shown in Figure 4. The measured fuel consumption of the BIC-US and BIC-EU trucks was 30.1 and 29.9 liters per 100 km, respectively. This allows us to conclude that there are not significant fuel consumption differences between the best-in-class trucks of both regions. Nonetheless, the small difference in fuel consumption between the U.S. and EU best-in-class trucks falls within the experimental uncertainty[17] of the chassis dynamometer testing and does not allow us to establish a clear ranking between the trucks. At 32.6 liters per 100 km, the AVG-EU truck exhibited a fuel consumption 9% higher than the BIC-EU truck.

As previously mentioned, it is useful to consider the fuel consumption as the product of the powertrain efficiency and the road-load energy demand. The sections below analyze these two areas in detail, attempting to gain further insight into the differences in measured fuel consumption.

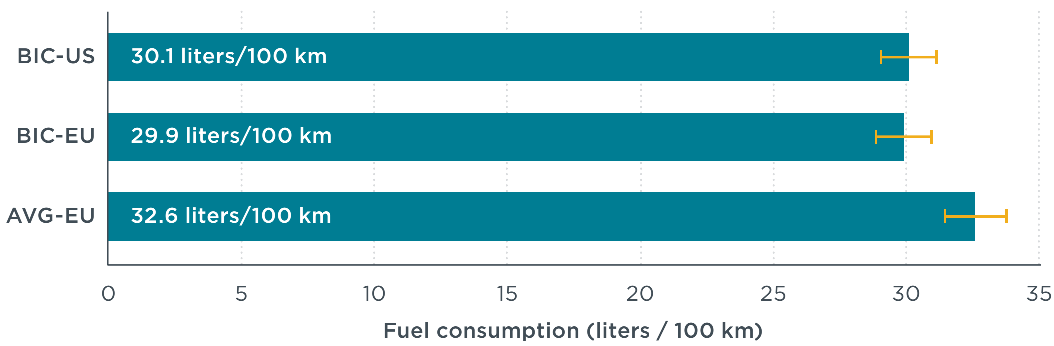


**Figure 4.** Measured fuel consumption on the chassis dynamometer over the EU Long Haul cycle. Error bars represent a 3% uncertainty associated with chassis dynamometer testing.

15 Rexeis et al., 2018.

16 Thiruvengadam et al., 2018.

17 TU Graz estimated an uncertainty of 3% in the fuel consumption measurements on the chassis dynamometer.

## POWERTRAIN EFFICIENCY

The powertrain efficiency of the tested vehicles is shown in Figure 5, using the powertrain BSFC as a metric. The BIC-US and BIC-EU trucks showed similar powertrain efficiencies at 205 $g/kWh_{wheel}$ and 202 $g/kWh_{wheel}$, respectively. The AVG-EU truck had a BSFC of 227 $g/kWh_{wheel}$, 11% higher than that of the BIC-EU truck.

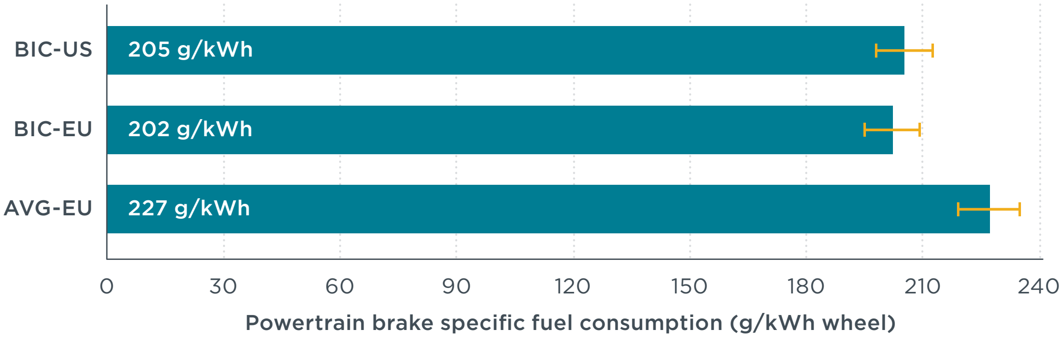


**Figure 5.** Powertrain efficiency, quantified as the measured fuel consumption per unit of work at the wheel. Error bars represent a 3% uncertainty associated with chassis dynamometer testing.

Quantifying the engine efficiency, or its BSFC, would provide additional information to understand the differences in powertrain efficiency. This would require the measurement of the engine output work at the crankshaft, which cannot be done with the engine mounted on the vehicle and requires an engine dynamometer. However, the engine work can be approximated using the engine torque and speed signals that are broadcast within the information network of the vehicle, called CAN bus. These signals are estimates used for the vehicle and powertrain control. Engine torque from the CAN bus has a lower accuracy than when measured on an engine dynamometer. From provisions in emission legislation, the engine torque values in the CAN bus data can have a maximum 5% inaccuracy.

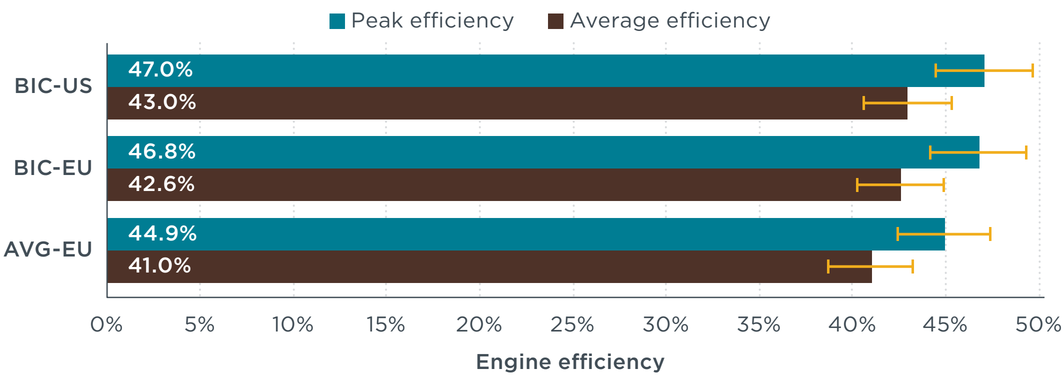


**Figure 6.** Average and peak efficiency estimated from the fuel consumption, as measured by the chassis dynamometer, and the work at the engine's crankshaft, as estimated from the CAN bus. Error bars represent a 5% uncertainty associated with the maximum inaccuracy expected from the CAN bus signals.

Figure 6 shows the engine's efficiency averaged over the EU Long Haul cycle, as well as the highest engine efficiency identified in the engine map in the typical range of engine speed during cruising. The BIC-US engine showed the highest cycle-average efficiency of 43% and a peak efficiency of 47.0%. The BIC-EU engine exhibited similar values, with a cycle-average efficiency of 42.6% and a peak efficiency of 46.8%. The AVG-EU vehicle was measured to have a 41% cycle-average efficiency and a 44.9% peak efficiency. However, the differences in efficiency fall within the uncertainty range resulting from the use of engine torque data from the CAN bus.

## ROAD-LOAD ENERGY DEMAND

For comparison of the road-load energy demand of the tested vehicles, it is useful to analyze the differences in performance for each of the road-load components: aerodynamic drag, rolling resistance, inertial forces, and road grade.

The energy consumption resulting from aerodynamic resistance is directly proportional to the drag coefficient. The dimensional limits imposed by the regulations in the EU and the United States have affected the overall tractor design in each region. Regulations in the EU set a length limit of 16.5 m for tractor-trailers, measured from the most forward point to the most rearward point of the whole vehicle. In the United States, the total overall length of the tractor-trailer is not restricted; only the trailer length is, ranging between 14.6 and 18 m, depending on the state. As a result, trucks in the EU are designed as cab-over-engine to minimize the tractor length and maximize the trailer's dimensions.

A recently adopted regulation in the EU, Directive (EU) 2015/719, amends the dimensions and weight limits for HDVs in the EU set by Directive 96/53/EC. The directive from 1996 had set a length limit of 16.5 m for tractor-trailers. Its 2015 amendment allows for HDVs to exceed this maximum length, provided that their cabs deliver improved aerodynamic performance, energy efficiency, and safety performance, and that they do not result in an increase in load capacity. However, it is not expected that truck manufacturers in the EU will move away from the cab-over-engine design.

In the United States, the cabins are designed with an elongated frontal engine compartment, resulting in greater freedom for aerodynamic design. However, the absence of overall length limits allows for a larger gap between the tractor and trailer, which increases the air drag.[18]

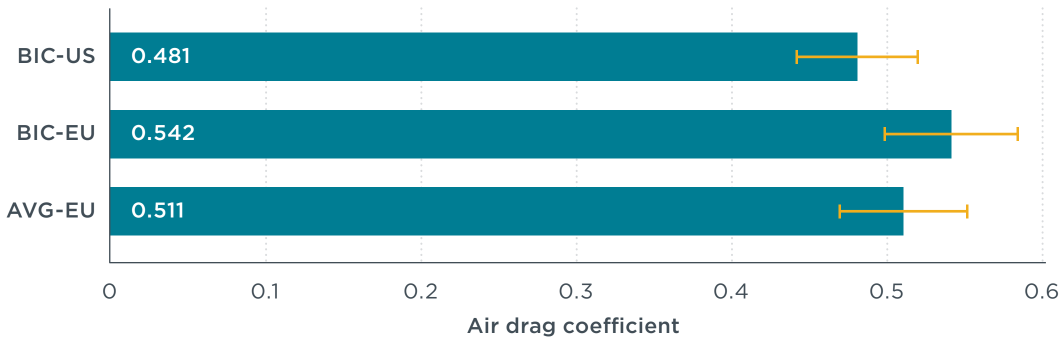


**Figure 7.** Air drag coefficient as measured by regulatory EU constant-speed test. Error bars are set to 7.5%, which is the tolerance allowed by the EU for the conformity of production testing of the air drag.

The air drag coefficient was determined experimentally by measuring the torque at the wheels under constant-speed operation, following the provisions established by the $CO_2$ certification regulation for EU HDVs. The experimental results for the three vehicles tested are shown in Figure 7. The BIC-US tractor-trailer was measured to have the lowest drag coefficient, at 0.48, followed by the AVG-EU at 0.51 and the BIC-EU at 0.54. It was an unexpected result that the AVG-EU tractor-trailer exhibited better aerodynamic performance than the BIC-EU. Because many aggregated design features contribute to the overall air drag, it was not possible to identify the source of the differences in aerodynamic performance.

18 Thorsten Frank, "Aerodynamik von schweren Nutzfahrzeugen—Stand des Wissens" (Forschungsvereinigung Automobiltechnik e.V., Berlin, 2012); www.vda.de/de/services/Publikationen/fat-schriftenreihe-241.html.

To eliminate the uncertainties associated with tire selection, the rolling resistance coefficient used in the chassis dynamometer was estimated from available market data and was kept the same for all three vehicles. Therefore, the differences in total rolling resistance stem from differences in the curb vehicle mass. In the same way, because the vehicles are evaluated over the same driving cycle and payload, the differences in inertia and road grade forces are the result of the vehicle curb mass. The curb masses of the tractor-trailer combinations, corrected to account for the mass of 500 liters of diesel fuel, are shown in Figure 8.

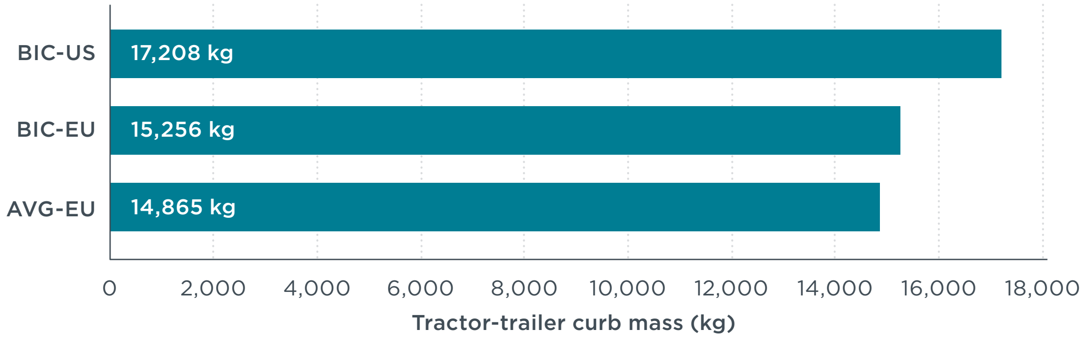


**Figure 8.** Curb mass of the tested tractors with 500 liters of fuel.

Although the inertial and road grade components of the road load are conservative forces (i.e., the energy input can be in principle recuperated), the energy is dissipated in the form of heat as a result of the braking required to follow the speed trace imposed by the driving cycle. The inertial and road-load forces are directly proportional to the total vehicle mass. Accounting for the 19.3 tonnes of payload over the EU Long Haul cycle, the differences in curb weight result in a 5.6% higher total mass for the BIC-US tractor-trailer with respect to the BIC-EU. The AVG-EU tractor-trailer had a 1.1% lower total mass. Nonetheless, these differences have a minor effect on the overall fuel consumption over the EU Long Haul cycle (see Figure 3) because the speed is relatively constant over the cycle.

The average road-load work applied by the chassis dynamometer at the drive wheels of the tested tractors is shown in Figure 9. At 1.17 kWh/km, the AVG-EU truck has the lowest road-load energy demand, due mainly to its lower air drag coefficient and lower curb mass. The road-load demand of the BIC-EU truck is approximately 3.5% higher than the AVG-EU truck, with 1.21 kWh/km. At 1.22 kWh/km, the BIC-US resulted in a road-load energy demand similar to that of the BIC-EU.

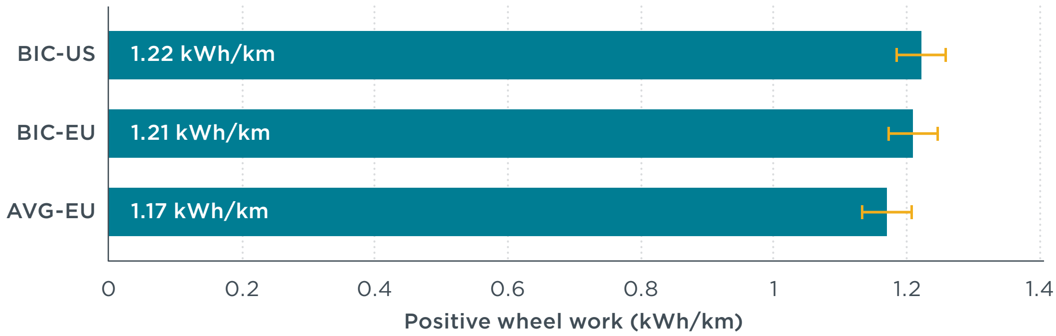


**Figure 9.** Distance-specific work applied by the chassis dynamometer on the wheels. Error bars are set to approximately 3%, representing only the impact of the uncertainties in aerodynamic testing. The uncertainty in the vehicle mass measurement is negligible. The same rolling resistance coefficient was used for all trucks.

Figure 10 shows the energy consumption of the individual road-load components (i.e., aerodynamic drag, rolling resistance, inertial forces, and road grade), averaged over the Long Haul cycle, for the BIC-EU and BIC-US tractor-trailers. The advantages in road-load energy demand from the better aerodynamic drag performance of the BIC-US, relative to the BIC-EU, are entirely offset by higher rolling resistance losses. Despite having used the same rolling resistance coefficient, the higher curb mass of the BIC-US increases the total rolling resistance force with respect to the BIC-EU truck. In the same way, the cycle-averaged inertial and road grade losses increase slightly in the BIC-US tractor-trailer when compared to its EU counterpart.

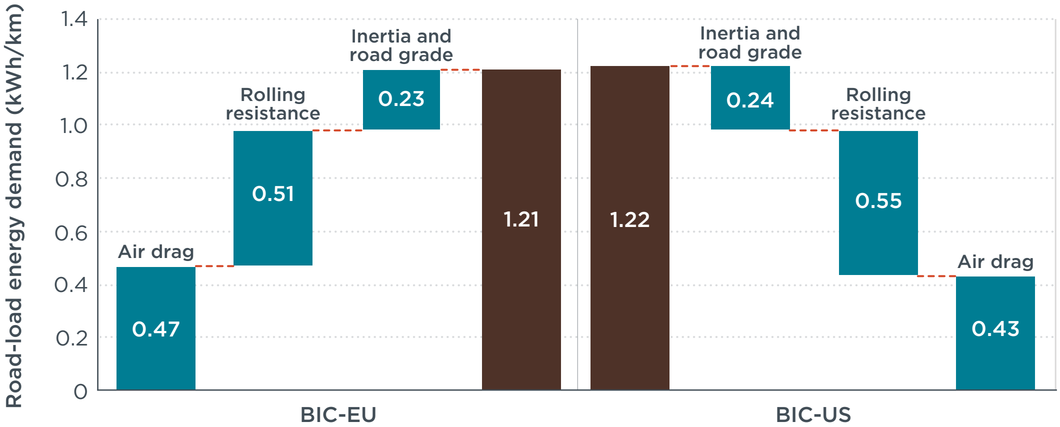


**Figure 10.** Individual contributions of components to the total road-load energy demand for the BIC-EU and BIC-US tractor-trailers over the EU Long Haul cycle.

# SUMMARY

The ICCT commissioned a testing project, carried out by Graz University of Technology and West Virginia University, to measure the fuel efficiency of three tractor-trailers: a typical EU tractor-trailer, a best-in-class EU tractor-trailer, and a best-in-class U.S. tractor-trailer. The results show a substantial fuel consumption difference between the best-in-class tractor-trailer and the typical tractor-trailer in the EU. Over the EU Long Haul cycle, the best-in-class truck consumed 29.9 liters per 100 km; the typical tractor-trailer, at 32.6 liters per 100 km, consumed 9% more fuel. The higher engine efficiency, lower auxiliary power consumption, and higher mechanical efficiency of the transmission and drive axle of the best-in-class truck more than compensate for its higher air drag coefficient and slightly greater curb mass relative to typical EU tractor-trailer.

For a direct comparison of the fuel efficiency of tractor-trailers in two different regions, it is necessary to test the vehicles over the exact same set of driving cycles and payloads in a controlled laboratory environment. Accordingly, the EU Long Haul cycle, with its respective payload, was used for vehicle testing. For determination of the chassis dynamometer settings to reproduce the resistive forces at the wheel, the air drag coefficient was measured using the EU constant-speed procedure. The same tire rolling resistance value was used for all tractor-trailers to eliminate the uncertainties associated with tire selection. The results from this direct comparison show that at 30.1 liters per 100 km, the fuel consumption of the best-in-class U.S. tractor-trailer is similar to the best-in-class EU truck, which consumed 29.9 liters per 100 km. The differences in fuel consumption are within the expected error margin.

Phase 1 of the GHG standards for HDVs in the United States mandated a tractor-trailer fuel consumption reduction of 23% by 2017 with respect to the 2010 baseline. The current Phase 2 of the standard mandates a further 27% reduction by 2027 with respect to the 2017 baseline. The results of this project, although representing a small sample of vehicles, indicate that the fuel consumption of best-in-class tractor-trailers in the United States and the EU is now at the same level, despite the substantially lower fuel prices in the United States. The fuel consumption reduction trend in the United States is expected to continue with the implementation of the Phase 2 GHG standards for HDVs.

## ANNEX: SUMMARY OF RESULTS OVER ALL CYCLES TESTED

**Table 3.** Fuel consumption over all regulatory cycles tested.

| | | BIC-US | | BIC-EU | | AVG-EU | |
|---|---|---|---|---|---|---|---|
| | Payload tonnes | liters/ 100 km | mpg | liters/ 100 km | mpg | liters/ 100 km | mpg |
| **Long Haul (EU)** | 19.3 | 30.1 | 7.82 | 29.9 | 7.87 | 32.6 | 7.22 |
| **Regional Delivery (EU)** | 12.9 | 31.7 | 7.43 | 31.6 | 7.44 | 34.3 | 6.86 |
| **55 mph with grade (U.S.)** | 17.2 | 28.5 | 8.26 | 28.6 | 8.22 | 30.7 | 7.66 |
| **55 mph flat (U.S.)** | 17.2 | 24.5 | 9.61 | 25.6 | 9.19 | 27.9 | 8.43 |
| **ARB Transient (U.S.)** | 17.2 | 64.4 | 3.65 | 56.4 | 4.17 | 60.3 | 3.90 |

**Table 4.** Air drag coefficient ($C_d$) measured over the EU constant-speed and U.S. coast-down procedures.

| | BIC-US | BIC-EU | AVG-EU |
|---|---|---|---|
| **EU constant-speed (zero yaw)** | 0.481 | 0.542 | 0.511 |
| **U.S. coast-down (zero yaw)** | 0.438 | 0.471 | Not measured |