THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

Trailer CO_2 Certification in the European Union

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Date: September 2018
Keywords: Trailers, VECTO, HDV CO_2 certification, HDV CO_2 standards, trailer technologies

Introduction

On May 17, 2018, the European Commission released a regulatory proposal (European Commission, 2018) for setting mandatory CO_2 standards for heavy-duty vehicles (HDVs). The regulation would set fleet average limits for the years 2025 and 2030 for rigid and tractor trucks with a gross vehicle weight (GVW) exceeding 16 tonnes, in either 4×2 or 6×2 axle configurations. A revision of the future standards is planned for the year 2022 to assess, among other topics, the inclusion of trailers as a regulated category in the CO_2 standards.

The European Union (EU) would not be the first region in the world to introduce CO_2 standards for trailers: The United States, Canada, and California have all adopted trailer standards.

- In 2016, the United States finalized the second phase of its greenhouse gas (GHG) standards for HDVs (U.S. EPA & DOT, 2016b) and included trailers as one of the regulatory categories. The U.S. Phase 2 GHG standards for trailers would mandate CO_2 reductions of up to 9% by 2027 from a 2017 baseline.[1]
- In May 2018, Canada introduced limits on GHG emissions that result from the operation of trailers, in full alignment with the limits established by the U.S. standards. However, the Canadian trailer standard will be applied starting in 2020,[2] whereas the U.S. Phase 2 GHG regulation is intended to go into effect during 2018 (Environment and Climate Change Canada, 2018).
- In 2008, California became the first market to put forward a regulation targeting GHG emissions from the operation of trailers (California Air Resources Board, 2009). Beginning in 2010, new trailers belonging to the regulated categories were not allowed to travel on California's highways unless the trailers were certified by the U.S. EPA SmartWay program[3] or were equipped with similar technology. Currently, the state administration is finalizing the California Phase 2 trailer standards. California is aligning with the federal U.S. GHG Phase 2 trailer standards in structure and stringency. However, because the proposed rule would apply to trailers with model years from 2020 onward, it includes interim procedures for 2018 and 2019 model year trailers (California Air Resources Board, 2018).

Although trailers do not directly emit CO_2, their designs affect the tractive force exerted by the pulling vehicle and therefore contribute substantially to the CO_2 emissions and fuel consumption of HDVs. The European Commission's intention to include trailers in the regulatory measures for curbing CO_2 emissions from on-road freight is a step forward to overcome the market barriers that prevent the adoption of cost-effective trailer technologies (Sharpe, 2017). Trailer CO_2 standards would incentivize the development and deployment of known cost-effective technologies that would result in CO_2 reductions of as much as 12% for long-haul tractor-trailers (Sharpe & Rodríguez, 2018).

The starting point of any policy measure designed to incentivize the development and deployment of technologies for reducing the trailer road-load (e.g., aerodynamic devices, low-rolling-resistance tires, lightweighting) is to develop a certification methodology that captures their CO_2 and fuel consumption benefits. In December 2017, the EU adopted a regulation for the certification of the fuel consumption and CO_2 emissions of HDVs (European Union, 2017). The certification procedure,

1 The U.S. Phase 2 GHG standards for trailers establish limits for the years 2018, 2021, 2024, and 2027. However, the implementation of the U.S. Phase 2 GHG standards for trailers has been provisionally placed on hold by a U.S. federal court while U.S. EPA revisits the Phase 2 trailer provisions.

2 The Canadian trailer standard establishes limits for the years 2020, 2021, 2024, and 2027.

3 EPA's SmartWay program verifies and certifies vehicles and trailers with installed fuel-saving technologies.

Acknowledgments: This project was supported by the European Climate Foundation. I thank Oscar Delgado, Ben Sharpe, and Rachel Muncrief for their contributions and critical feedback.

which is based on a combination of component testing and full vehicle simulation, addresses the HDV groups with the highest contribution to CO_2 emissions from the sector. HDVs are certified using predefined standard trailers. Therefore, the certification does not consider any benefits from the available trailer road-load technologies.

This paper provides an overview of these technologies, assesses the possible policy pathways for extending the scope of the CO_2 certification framework to include trailers, examines the elements of existing trailer regulations, and provides policy recommendations for the EU.

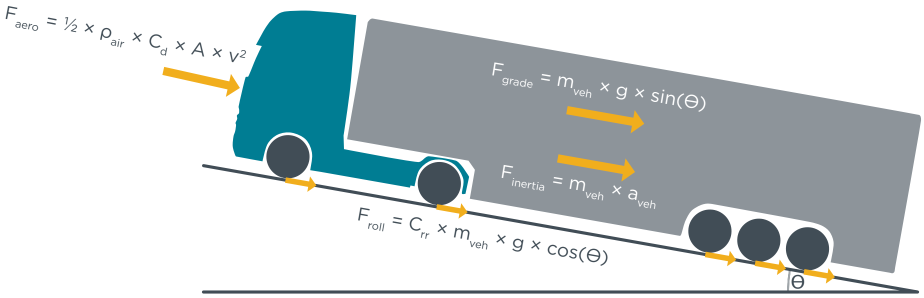


Figure 1. Road-load forces acting on a tractor-trailer.

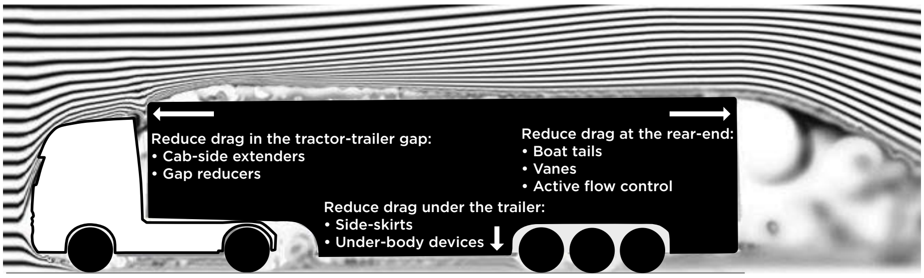


Figure 2. Key energy loss areas during typical operation of a trailer, and technologies to reduce these losses.

Trailer road-load technologies

The road-load is the sum of the forces opposing the movement of the vehicle. These forces can be divided into four main categories based on their origin: aerodynamic drag, rolling resistance, road grade, and inertial forces. The aerodynamic drag force is mostly 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, or gravitational force, is a function of the road inclination and the vehicle mass. Lastly, the inertial forces depend on vehicle mass and acceleration. 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 during the braking events required to follow the speed trace imposed by the road conditions or the driving cycle. These forces are illustrated in Figure 1.

For tractor-trailers, which account for more than 70% of the fuel consumption of on-road freight in the EU (Delgado, Rodríguez, & Muncrief, 2017), the road-load is the result of the forces acting on the tractor truck and on the semi-trailer. The following sections provide a brief overview of the available technologies to reduce a trailer's aerodynamic drag, rolling resistance, and mass.

AERODYNAMIC TECHNOLOGIES

Three key energy loss areas can be targeted to improve a trailer's air drag performance. These are illustrated in Figure 2.

Gap fairings reduce the cross-flow of air in the gap between the tractor and the trailer and smooth the airflow transition in the tractor-trailer articulation. Side skirts limit the flow of air underneath the trailer to reduce the generation of turbulence caused by the irregular geometries present in the trailer's underbody. Lastly, rear-end devices, most commonly in the form of boat tails, reduce the size of the turbulent wake formed in the rear of the trailer; this wake results in a low-pressure zone that creates a resistive force.

During the development of the U.S. Phase 2 GHG standards for HDVs, the regulatory agencies in the United States examined the aerodynamic impact of these trailer technologies and of their combinations. Through wind tunnel tests, they quantified the reduction achieved in the air drag area (C_dA)[4] at two different crosswind conditions (i.e., different yaw angles). Their findings, summarized in Figure 3, show that the simultaneous application of all three trailer technologies

4 The air drag area, C_dA, is measured in square meters and is defined as the product of the air drag coefficient C_d and the frontal area A.

can reduce the air drag area by as much as 1.4 m². This corresponds to approximately 25%[5] of the air drag area of a typical EU tractor-trailer, which has an air drag area of 5.5 to 6 m².

ROLLING RESISTANCE TECHNOLOGIES

The rolling resistance coefficient is a parameter relating the force countering a tire's rotation to the normal force applied to the tire. This dimensionless coefficient is typically expressed in units of N/kN. In 2009, the EU introduced a labeling system (European Commission, 2009) that segments HDV tires into several efficiency classes. The most efficient class is A, with a rolling resistance coefficient lower than 4 N/kN; the least efficient is class F, with a rolling resistance coefficient higher than 8 N/kN.

The rolling resistance distribution for the EU HDV tire market and the industry's projections for 2030 are shown in Figure 4. Although the available data does not differentiate trailer tires from other HDV applications, it exemplifies the rolling resistance improvements that are possible as the distribution of the HDV tire market shifts toward class A tires.

Additionally, improvements in tires' in-use rolling resistance are possible by ensuring that they are always inflated to the optimal pressure. Tire pressure monitoring systems (TPMS) can provide real-time feedback on the inflation condition of the tires. Automatic tire inflation systems (ATIS) add inflation capabilities and enable the automatic compensation of pressure changes resulting from air leakage, temperature differences, and vehicle loading conditions.

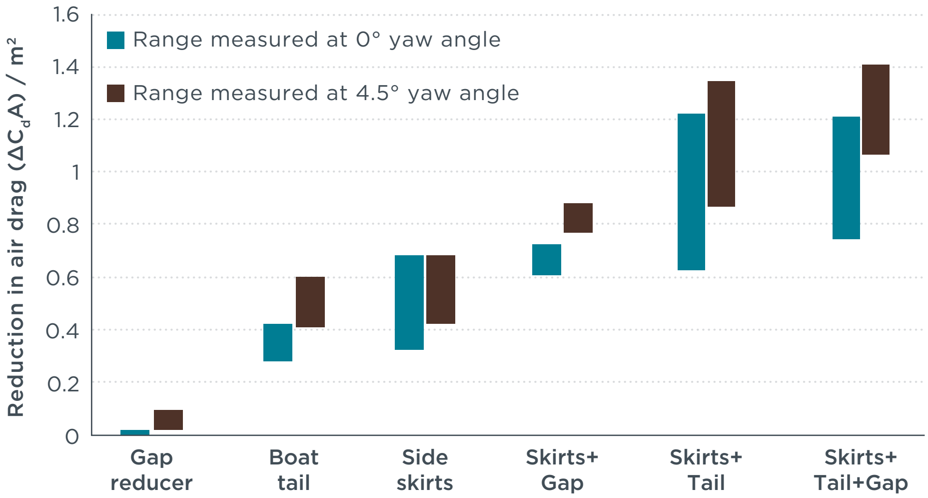


Figure 3. Air drag reduction ranges for various trailer technologies, as measured by wind tunnel tests of several tractor-trailer combinations (U.S. EPA & DOT, 2016c).

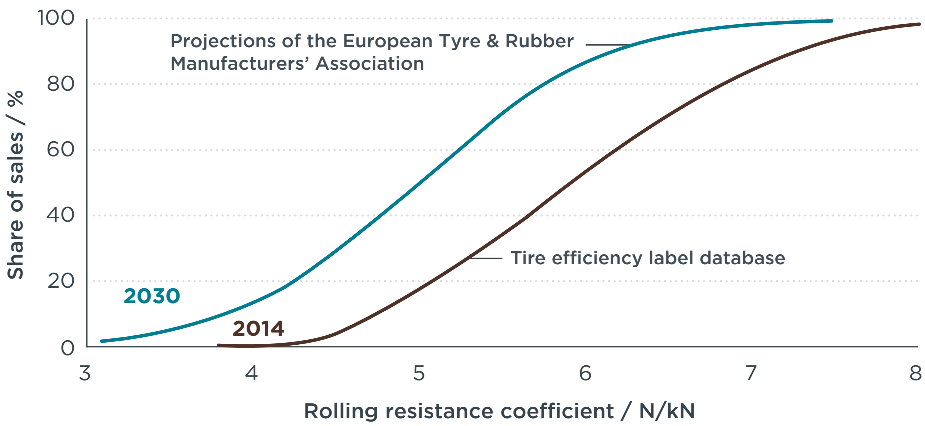


Figure 4. Cumulative distribution function for the rolling resistance coefficient of HDV tires for 2014 and projections for 2030 (ETRMA, 2016)

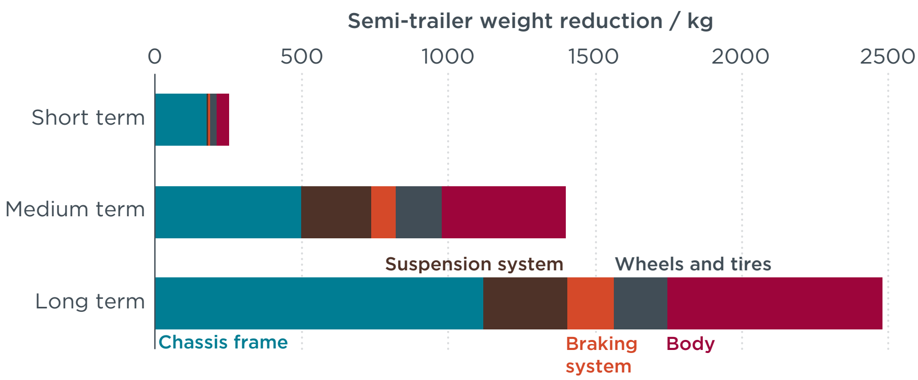


Figure 5. Estimated mass reduction potential by system for a 7-tonne semi-trailer (Hill et al., 2015).

LIGHTWEIGHTING TECHNOLOGIES

Typical curtainsider trailers in the EU have curb weights between 6 and 7 tonnes (Sharpe & Rodríguez, 2018). Several lightweighting technologies can be applied to trailer construction. Ricardo Energy & Environment carried out an assessment (Hill et al.,

5 Typically, the tractor-trailer gap in the United States is larger than in the EU. Thus, the opportunities for air drag reduction using gap reducers are more limited in the EU.

2015) of the lightweighting potential of HDVs, including trailers. Their findings are summarized in Figure 5.

Weight reductions of around 200 kg, 1400 kg, and 2500 kg are possible in the short term (by 2020), medium term (by 2030), and long term (by 2050), respectively. The largest gains can be achieved through material substitution (e.g., use of aluminum or high-strength steel) in the chassis frame and in the body structure. These advanced lightweighting levels can already be found in the market, albeit at low market penetration (Sharpe & Rodríguez, 2018).

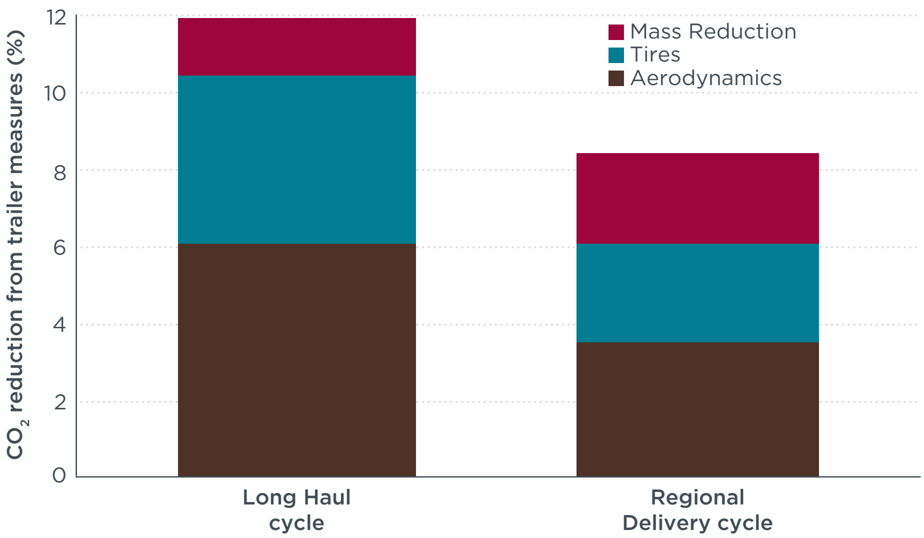


Figure 6. Fuel consumption reduction potential of trailer road-load technologies over the regulatory VECTO Regional Delivery and Long Haul cycles.

TRAILER ROAD-LOAD TECHNOLOGIES SUMMARY

Considering the combined impacts of aerodynamic, tire, and weight reduction interventions, the ICCT's research shows that by 2030 the fuel consumption reduction potential stemming from trailer road-load technologies can be close to 12% in long-haul operation and more than 8% in regional delivery operation, as assessed by the EU's Vehicle Energy Consumption Calculation Tool (VECTO) (Sharpe & Rodríguez, 2018). The relative contributions of the different technology areas are shown in Figure 6. Aerodynamic technologies provide the most benefit over the long-haul and regional delivery cycles analyzed, followed by low-rolling-resistance tires. Although lightweighting has a marginal benefit in long-haul operation, it can provide important gains in more transient operation, such as in regional delivery.

Policy options for trailers

The recently adopted certification regulation in the EU (European Union, 2017) does not take into account the impact of trailer road-load technologies on the certified CO_2 emissions and fuel consumption of tractor-trailers. Instead, tractor trucks are certified in combination with standard trailers that have been tightly specified in terms of their geometry, tire rolling resistance, and mass.

The inclusion of trailer road-load technologies in the CO_2 certification procedure does not require major modifications in VECTO, as the model can already simulate changes in the road-load parameters of the whole vehicle (i.e., drag area, rolling resistance, curb weight) and the trailer-specific contributions need not be specified separately. Nonetheless, the extension of the CO_2 certification procedure to include trailer road-load technologies does create some challenges that will need to be overcome by the regulatory design, for example:

- Tractors and trailers are produced by different manufacturers.
- Tractors and trailers are sold separately.
- Trailers are interchangeable and do not remain with a given tractor for their lifetime.
- EU trailer manufacturers have not been regulated for direct emissions in the past.
- The trailer industry has limited experience performing aerodynamic drag determination and vehicle simulation.
- There are many small manufacturers and a few large manufacturers. This results in a large number of regulated entities and in differences among manufacturers with respect to the impact of the associated compliance costs.
- Trailer configurations are very diverse (e.g., box, tank, container, flatbed, tipper).

Tractors[6] and trailers operate as a system for the movement of freight. The aerodynamic performance of the vehicle combination is the result of the cross-interactions of the air flow around the tractor and the trailer (Sharpe, Clark, & Lowell, 2013). Because aerodynamic losses have a dominant role in the fuel consumption of tractor-trailers operating in long-haul cycles, measurements of the air drag of the complete vehicle would ideally take into consideration the interactions between the

6 Unless otherwise specified, the terms *tractor* and *tractor truck* are generically used to include tractor units that are used to tow semi-trailers, as well as rigid trucks that are used to tow trailers. Similarly, the term *trailer* is used to include both drawbar trailers and semi-trailers.

Table 1. Summary of options for establishing a trailer CO_2 certification procedure and comparison to the trailer certification approach for the U.S. GHG Phase 2 standard.

Trailer CO_2 certification modality	Regulatory design options	U.S. Phase 2 GHG standard
CO_2 metric	• Use of gCO_2/km, gCO_2/t-km, or gCO_2/m³-km, based on the result of the VECTO simulation with the standard tractor • Use of relative metrics capturing the change in CO_2 emissions versus the standard trailer	Relative metric in CO_2 grams per ton-mile and gallons per 1,000 ton-miles
Definition of standard tractor truck	• Use of currently available data resulting from the development of VECTO for the definition of the standard tractor • Use of future data resulting from the proposed Monitoring and Reporting regulation (European Commission, 2017)	The standard tractor used in trailer CO_2 certification is tightly defined and hard-coded in the regulatory vehicle simulation tool, GEM The standard tractor used in air drag determination of trailers must only meet minimum aerodynamic, cabin type, and axle configuration requirements
Trailer types covered by the certification regulation	• All trailers • Trailer types with sales volumes or annual kilometers traveled above a threshold • Trailers for which at least one road-load technology is applicable • Trailers for which aerodynamic technologies are applicable	Box vans (all aero devices are suitable) Partial-aero box vans (not all aero devices are suitable) Non-box designs (no aero devices are suitable, but low-rolling-resistance tires are suitable); examples: tankers, flatbeds, and container chassis
Aerodynamic drag	**Air drag metric** • Absolute air drag area (C_dA) • Change in air drag area (ΔC_dA) relative to a baseline **Air drag determination** • Constant-speed test, mirroring the air drag determination for tractor trucks • Coastdown testing • Wind tunnel testing • Computational fluid dynamics (CFD) simulation • Pre-approved aerodynamic devices data	Determination of air drag requires a pair of tests: (1) a standard tractor pulling a standard trailer; (2) a standard tractor pulling the trailer to be certified Only the change in air drag area (ΔC_dA) is quantified, with respect to a standard trailer Depending on the measured ΔC_dA, the trailer is assigned to an aerodynamic bin to account for testing variability and to provide consistency in the values used for compliance ΔC_dA is adjusted to a yaw angle of 4.5° to reflect real-world conditions Manufacturers are allowed to choose an appropriate test method (i.e., wind tunnel, CFD, or coastdown) Improvement data from pre-approved aero devices can be used instead of air drag testing; the pre-approval is based on testing done using the Phase 2 procedures
Weight reduction	**Weight reduction metric** • Absolute curb weight • Reduction of curb weight in comparison to standard trailers • Reduction of curb weight in comparison to a given manufacturer's own baseline **Weight reduction determination** • Direct measurement • Use of prespecified lightweight components	There is no weight baseline Compliance through the substitution of predetermined lighter-weight components Off-cycle credits for significant weight reductions; bilateral agreement with U.S. EPA is required
Determination of CO_2 performance	• VECTO simulation • Standardized equation depending on only the key parameters (i.e., mass, air drag, and rolling resistance)	Generic equation determined by EPA based on GEM (regulatory simulation tool); inputs are (1) change in air drag with respect to the standard trailer, (2) mean rolling resistance, and (3) change in trailer curb mass

tractor and trailer designs. However, given that tractors and trailers are produced by different manufacturers, are marketed as individual units, and are paired in different tractor-trailer combinations during their lifetime, a CO_2 certification regulation targeting tractor-trailers as a unit would be prohibitively complex. Considering tractors and trailers as separate regulated entities greatly simplifies the regulatory design (Sharpe, 2014).

The current CO_2 certification regulation for HDVs in the EU determines the CO_2 emissions of each individual tractor truck in combination with a predefined standard trailer.[7] This method could be extended to the CO_2 certification of trailers by reversing the approach—that is, by determining the CO_2 emissions of a predefined standard tractor truck in combination with each individual trailer.

Establishing such a regulatory approach will require consideration of the appropriate CO_2 metric, the trailer types affected by the regulation, the specifications for the standard tractor truck, and the aerodynamic drag determination procedure for trailers.

Table 1 summarizes the different regulatory options for the aforementioned aspects of extending the CO_2 certification procedure to trailers, and also presents the approach used in the U.S. Phase 2 GHG regulation[8] for trailer certification.

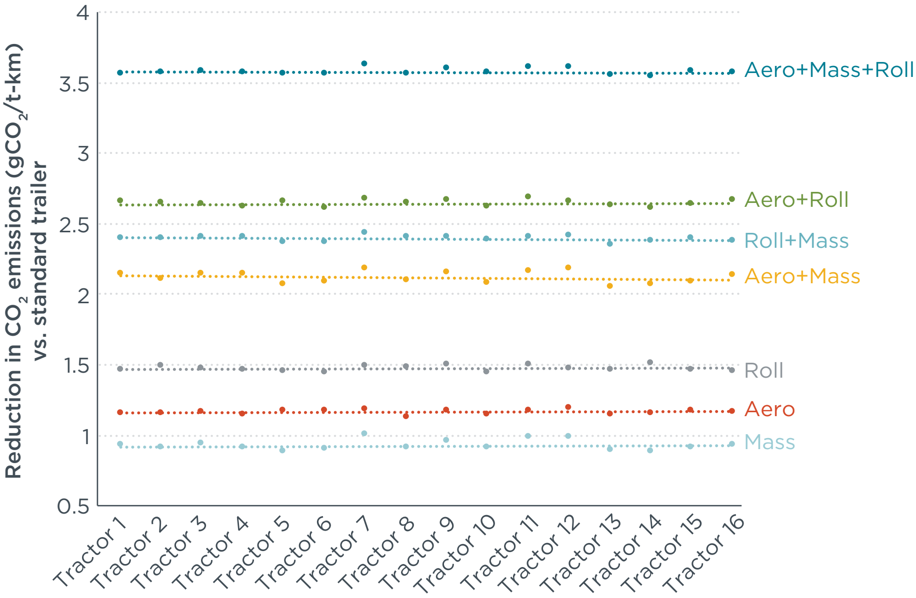


Figure 7. Relative CO_2 reduction resulting from trailer improvements, separately or in combination, for 16 different tractors over the Long Haul cycle. The relative CO_2 reduction is fairly insensitive to the tractor selection.

REGULATORY CO_2 METRIC AND DEFINITION OF STANDARD TRACTOR TRUCKS

For the selection of the regulatory CO_2 metric, there are two possible options: an absolute metric (in gCO_2/km, gCO_2/t-km, or gCO_2/m^3-km), or a relative metric that measures the change in CO_2 emissions relative to a standard trailer (either in one of these three metrics, or as a percentage change). The use of absolute values is advantageous to harmonize the metrics across the different vehicle groups and facilitates the inclusion of trailers in the existing regulation framework as an additional vehicle group. Under this approach, the resulting CO_2 certification values for trailers correspond to those of the standard tractor, and consequently, a careful definition and characterization of the standard tractors used in VECTO simulation is required.

The use of a relative metric—that is, one that only measures the change in CO_2 emissions relative to a standard trailer—relaxes the constraints placed on the definition and characterization of the standard tractors used in VECTO simulations. The relative change in energy use stemming from improvements in the road-load technologies of trailers is highly dependent on the drive cycle and is mostly independent of the tractor truck definition. Figure 7 shows the VECTO results[9] of the relative reduction achieved by different combinations of trailer road-load technologies for 16 different tractors.[10] The trailer technologies considered are the seven unique combinations of the

7 The trailer specifications are established in Annex VI, appendix 4 of the CO_2 certification regulation (European Union, 2017).

8 Throughout the paper, for simplicity, we reference only the U.S. trailer standards, as the United States was the first jurisdiction in the world to finalize fuel efficiency requirements tied to trailer design, and Canada's provisions for trailers are largely identical to those in the United States.

9 VECTO version 3.2.1.1133 was used. Each point in Figure 7 represents a pair of VECTO simulations: one for the standard trailer, and one for the trailer with improved road-load parameters.

10 The 16 tractors investigated are variations from the default tractor included in VECTO, in four areas: air drag (–10%), rolling resistance (–10%), curb mass (–10%), and auxiliary technologies (–20%). The 16 tractors represent all 15 possible combinations of these four changes, plus one tractor with none of these changes.

following three trailer road-load improvements:[11]

1. Aero: Reduction in air drag area (C_dA) by 0.5 m^2
2. Roll: Reduction in trailer tire rolling resistance by 1 N/kN
3. Mass: Reduction of trailer curb mass by 1,000 kg

As shown in Figure 7, the relative CO_2 reductions of different trailer road-load technologies are relatively insensitive to the definition of the standard tractor. The results indicate that the use of a relative CO_2 metric for trailer certification relaxes the demands on the definition of the standard truck. Consequently, the data obtained during the development of VECTO can be used for the definition of the standard tractor without affecting the accuracy of the CO_2 certification of trailers. In this scenario, the use of future data resulting from the proposed Monitoring and Reporting regulation (European Commission, 2017) would not be necessary, as it would not result in additional advantages.

TRAILER TYPES COVERED BY THE CERTIFICATION REGULATION

A key point for the definition of a CO_2 certification procedure for trailers is the definition of the regulatory scope—that is, of the trailer types to be covered by the CO_2 certification. The trailer market is a diverse one that involves the participation of large and small manufacturers and a great variety of trailer designs tailored to specific applications. As a consequence, the CO_2 certification of all trailer types would require substantial resources for determining the base CO_2 performance of combinations of standard tractors and standard trailers. The regulatory efforts can be greatly reduced by focusing on the trailer types that have the greatest impact on the CO_2 emissions of on-road freight. Unfortunately, the fleet operational data needed to quantify the trailer-kilometers traveled are scarce, and a proxy indicator must be used. Trailer registrations data can be used for this purpose.

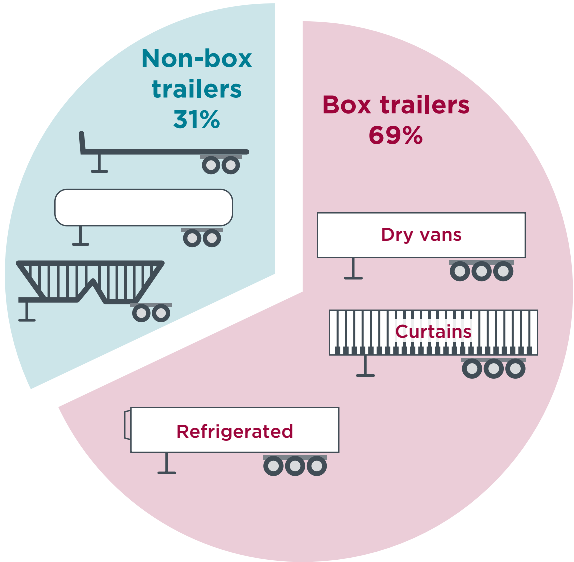


Figure 8. Box and non-box semi-trailer 2016 registrations (Sharpe & Rodríguez, 2018).

The accompanying ICCT analysis of the EU trailer market (Sharpe & Rodríguez, 2018) shows that curtainside semi-trailers are the most popular trailer type, with 43% of new registrations in 2016. Refrigerated and dry-box semi-trailers have market shares of 15% and 10%, respectively. Despite the differences in loading type and application, these three trailer types share a common geometry and can be categorized as box trailers. The rectangular shape of box trailers and their associated aerodynamic drag make them ideal candidates for the application of the aerodynamic technologies described above to reduce drag and improve fuel consumption. If a relative CO_2 metric were to be pursued, the standard box semi-trailer currently defined in the HDV CO_2 certification regulation could be used for the aerodynamic characterization of the reference case.

Trailer registrations corresponding to tippers, container/swap bodies, and tanker semi-trailers amounted to 31% of the EU trailer market in 2016 (see Figure 8). Depending on their missions, these trailer types exhibit more complex geometries and present a challenge for the definition of standard bodies and their respective aerodynamic characterization (Luz et al., 2014). Nonetheless, these trailer types can still be covered by the CO_2 certification regulation by considering only non-aero road-load technologies—that is, lightweighting and rolling resistance improvements.

AERODYNAMIC DRAG DETERMINATION

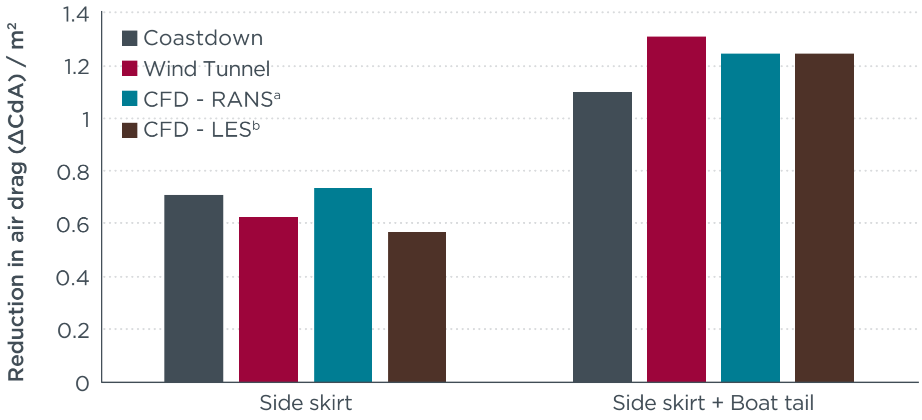
The characterization of the air drag contribution of trailers, and of their aerodynamic technologies, can be done on an absolute basis by measuring the air drag area (C_dA) of the combination of a standard tractor pulling the trailer being measured, or as the change in air drag area (ΔC_dA) relative to a baseline. The latter is the methodology adopted in the U.S. GHG Phase 2 trailer standards and has been named “A to B testing.”

11 The trailer improvements evaluated in the sensitivity analysis do not represent the maximum technology potential of trailer road-load technologies and were selected only to study the impact of the base tractor definition.

A to B testing comprises two tests: one test of a baseline trailer with no aerodynamic devices installed (A test), and one test that includes the aerodynamic improvements to be certified (B test). Because an A test characterizes the air drag of a standard tractor pulling a baseline trailer, the test can be used for the certification of several B test configurations. A to B testing also minimizes the impact of the tractor design on the $\Delta C_d A$ results, thereby relaxing the constraints imposed in the definition of the standard tractor and allowing different tractor models to be used in testing without affecting the determination of the relative air drag change (U.S. EPA & DOT, 2016b).

The definition of the standard tractor for aerodynamic testing is, in principle, independent from the standard tractor used in VECTO simulations for CO_2 certification. The standard tractor used in the VECTO-based CO_2 certification exists only in the simulation domain and can be unambiguously specified. The standard tractor used for air drag determination, on the other hand, must be specified in broader terms to ensure that a suitable vehicle is always available and to reduce the costs associated with the procurement of such vehicles.

The aerodynamic testing of HDVs can be done through a number of methods. The European Commission developed a constant-speed testing (CST) procedure for the measurement of the air drag area of HDVs, which is described in the CO_2 certification regulation. The CST measures the torque at the wheels during sustained operation of the vehicle at two different steady conditions, high and low speed. From the measured torque data, it is possible to estimate the aerodynamic drag of the vehicle. The CST minimizes the influences of other losses (e.g., drivetrain losses) on the measured data and offers good repeatability and reproducibility. However, the use of expensive wheel torque meters, the requirements on the test track, and the installation and logging of other measurement equipment make the CST a convoluted and expensive approach for small-volume trailer manufacturers.



a: Reynolds-Averaged Navier-Stokes
b: Large Eddy Simulation

Figure 9. Comparison of different methodologies for the determination of the change in air drag for two trailer technologies (U.S. EPA & DOT, 2016c).

Another widely used procedure for air drag determination is coastdown testing (CDT). In the CDT, the measured parameter is the vehicle speed while it coasts down from a high speed to a lower one. From the recorded vehicle speed data, it is possible to calculate the air drag coefficient. In comparison to the CST, the absence of wheel torque meters reduces the costs associated with CDT. Nonetheless, the amount of testing and subsequent post-processing of the test data still requires substantial effort.

In the United States, where all aerodynamic testing methods are permitted for trailers, the trailer industry indicated in the comments submitted in response to the regulatory proposal (U.S. EPA & DOT, 2016a) that trailer manufacturers were unlikely to use the CDT procedure for air drag measurement, relying instead on wind tunnel testing and computational fluid dynamics (CFD). The use of physical or computational models to estimate the aerodynamic drag reduces the testing complexity and the associated compliance costs. U.S. EPA compared the different air drag determination methodologies for estimating the change in air drag area from several aero-devices. As shown in Figure 9, the different test methods produced similar results (U.S. EPA & DOT, 2016c).

Despite this finding, if wind tunnel testing or CFD are to be used for the air drag determination, their methodologies must be well defined for regulatory purposes, as the boundary conditions of the testing (e.g., model scale in wind tunnel testing, or mesh resolution and solving algorithm in CFD) can have a large impact on the air drag results (Frank, 2012; Peiró Frasquet & Indinger, 2014). The International Association of the Body and Trailer Building Industry (CLCCR) is currently working on the definition of a standardized CFD simulation tool for trailer aerodynamic certification (CLCCR, 2017). However, there is no publicly available information on the status of the CFD tool development.

Another option for the estimation of the aerodynamic characteristics of trailers, consistent with the A to B methodology described above, is the use of aerodynamic data from pre-approved aero-devices. Under this approach, trailer manufacturers would not be required to measure the change in air drag of their products with respect to the standard trailers. The change in air drag area would be estimated from predefined values for off-the-shelf technologies from device manufacturers, such as side skirts, underbody devices, aerodynamic mud flaps, or rear-end devices. Under this approach, the burden of determining the change in air drag is on the aerodynamic device manufacturers, who must certify their products and obtain an approval from the regulatory agencies. Once a given product is on a list of pre-approved aero-devices, it could be provided to any trailer manufacturers that wish to install the device. This approach is allowed under the GHG Phase 2 trailer standards.

Lastly, the air drag determination should take into account that the benefits of aerodynamic devices for trailers can be larger under crosswinds, like those observed in real-world operation, compared to zero-yaw conditions (see Figure 3). The determination of the $\Delta C_d A$ benefits of trailer aerodynamic devices at different yaw angles in wind tunnel testing and CFD simulation poses no difficulties. By contrast, quantifying the benefits at different yaw angles in on-road air drag testing would increase the testing effort, as the yaw angle cannot be adjusted freely. This must be considered when defining the yaw angle requirements for $\Delta C_d A$ determination and the corresponding testing methodology.

DETERMINATION OF THE ROLLING RESISTANCE AND WEIGHT REDUCTION

The determination of trailer rolling resistance does not present major difficulties and can follow the provisions already established in the HDV certification regulation (European Union, 2017). Because the determination of tire rolling resistance is the responsibility of tire manufacturers, no additional burden is placed on trailer manufacturers. The data resulting from the HDV tire labeling regulation (European Commission, 2009) can be used to establish a baseline for the rolling resistance coefficient of trailer tires, as was done for the specification of the current standard trailer in the HDV CO_2 certification regulation.[12]

The determination of trailer curb weight is a straightforward procedure. However, the determination of the associated weight reduction carries more difficulties. The determination of baselines against which lower-weight designs could be compared for regulatory purposes requires a careful segmentation of the different trailer types (e.g., curtainsiders, refrigerated boxes, dry-box trailers with or without insulation, container chassis, tippers). However, the data from the upcoming Monitoring and Reporting regulation (European Commission, 2017) could provide the information necessary for determining the baseline curb weights of the different trailer segments.

An alternative approach pursued in the U.S. GHG Phase 2 trailer standard, which does not require the definition of baselines for the determination of weight reduction measures, is to use predefined values to capture the benefits of material substitution in specific trailer areas (e.g., chassis, wheels, suspension, doors). This greatly simplifies the process, as there is no need to determine the baseline absolute weight of the trailer.

12 The standard trailer defined in the HDV CO_2 certification regulation features a tire rolling resistance of 5.5 N/kN.

DETERMINATION OF THE CO_2 PERFORMANCE

Once the CO_2 metric, standard tractors, and air drag assessment methodology have been defined, the CO_2 performance of trailers must be estimated. This can be achieved by performing vehicle simulations in VECTO, or by the use of a standardized equation determined with VECTO.

The use of a standardized equation reduces the compliance burden on trailer manufacturers, as they would not be required to devote resources to installing and running VECTO for the determination of the CO_2 performance of the trailer. This is the approach followed in the U.S. Phase 2 GHG standards for trailers.

The development of the equation must be based on VECTO to ensure consistency between the CO_2 emissions (or relative CO_2 reductions) estimated with the simulation tool and those estimated with the simplified equation. The existence of such an equation is made possible by the linear dependence of the CO_2 emissions from the complete vehicle on the individual road-load parameters of the trailer.

The determination of the standardized trailer CO_2 equation requires running several VECTO simulations using a fixed standard tractor and varying the aerodynamic drag, rolling resistance, and curb mass of the trailer. The resulting data is then used to generate a multivariate linear regression model. Such an analysis was carried out in this study. The standard tractor used in the VECTO simulations is the generic 4×2 tractor contained in the software.

In a first step, VECTO[13] was used to evaluate the impact on the simulated CO_2 emissions

13 VECTO version 3.2.1.1133 was used in this analysis.

from changes to the road-load parameters of trailers. The range and steps used to evaluate the effect of changes in air drag area, rolling resistance, and curb mass relative to a standard trailer[14] are shown in Table 2. The resulting test matrix contains 512 possible trailer road-load combinations. Each one of these combinations was simulated in VECTO over the Long Haul and Regional Delivery cycles, using the default tractor truck defined in the simulation tool and the regulatory payloads.[15]

In a second step, a multiple linear regression was performed using only the results from the simulations to determine two VECTO-based CO_2 equations for trailers: one for the Long Haul cycle and one for the Regional Delivery cycle.

The resulting equations, shown below, calculate the change in CO_2 emissions from changes in the road-load parameters using an absolute CO_2 metric (g/t-km) and a relative percentage metric.

Table 2. Change in trailer road-load parameters analyzed for the trailer CO_2 equation.

Parameter	Unit	Range	Step
Change in drag area ($\Delta C_d A$) versus standard trailer	m²	0 to −1.4	− 0.2
Change in rolling resistance (ΔC_{rr}) versus standard trailer	N/kN	0 to −1.4	− 0.2
Change in curb mass (ΔM) versus standard trailer	kg	0 to − 2100	− 300

LONG HAUL CYCLE:

$$\Delta CO_2\ [\text{g/t-km}] = 2.019\ \Delta C_d A + 1.256\ \Delta C_{rr} + 8.099 \times 10^{-4}\ \Delta M \qquad (1)$$

$$\Delta CO_2\ [\%] = 4.072\ \Delta C_d A + 2.533\ \Delta C_{rr} + 1.634 \times 10^{-3}\ \Delta M \qquad (2)$$

REGIONAL DELIVERY CYCLE:

$$\Delta CO_2\ [\text{g/t-km}] = 2.82\ \Delta C_d A + 1.647\ \Delta C_{rr} + 1.303 \times 10^{-3}\ \Delta M \qquad (3)$$

$$\Delta CO_2\ [\%] = 4.082\ \Delta C_d A + 2.384\ \Delta C_{rr} + 1.887 \times 10^{-3}\ \Delta M \qquad (4)$$

Figure 10 shows the quality of the regression model. Three different metrics are used to assess the quality of the regression model: coefficient of determination (R^2), mean squared error (MSE), and the distribution of the model residuals.[16] The regression models for the Long Haul and Regional Delivery cycles show R^2 values very close to 1, meaning that almost all of the variation in the results is explained by the linear model. The low MSE reinforces this finding. However, a comparison between the MSEs of the Long Haul and Regional Delivery models shows that the linear regression model is more successful at the constant-speed operating points occurring in the Long Haul cycle, and that the urban portion of the Regional Delivery cycle introduces some unexplained variability.

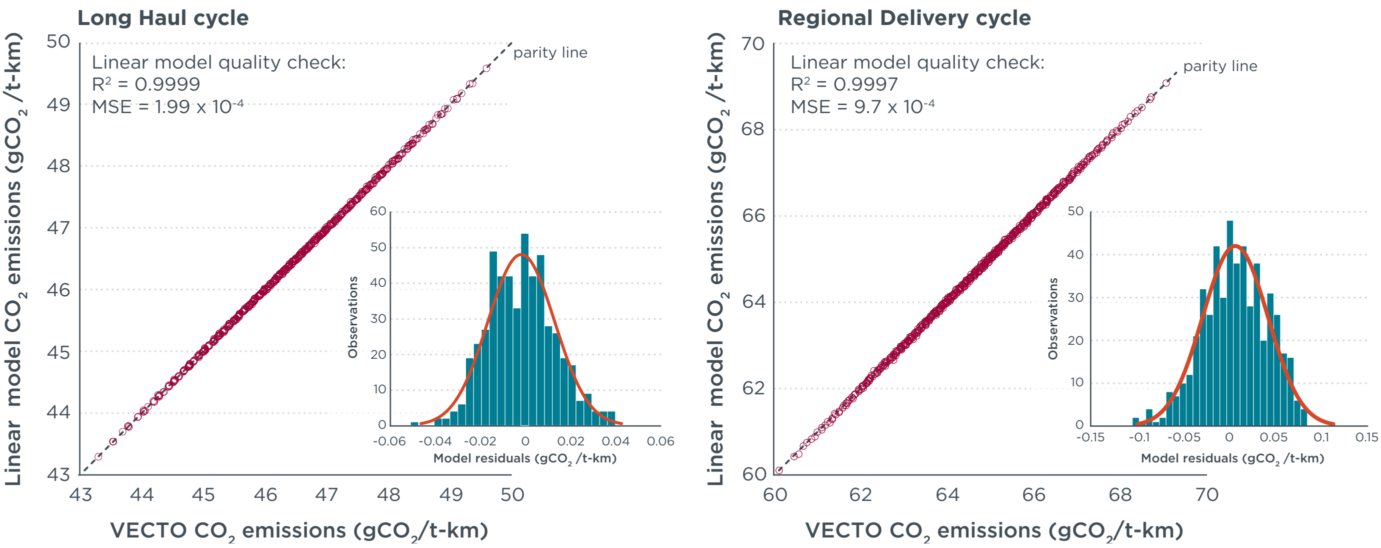


Figure 10. Quality of linear models for the trailer CO_2 equation for the Long Haul and Regional Delivery cycles from VECTO simulations.

14 The specifications of the standard trailer used are those established in the HDV CO_2 certification regulation (EU) 2017/2400.

15 The regulatory payloads are 19.3 tonnes for the Long Haul cycle and 12.9 tonnes for the Regional Delivery cycle.

16 A residual is the difference between a predicted value (from the regression) and the corresponding observed value (from VECTO simulations).

Lastly, the analysis of the residuals shows that they are well-behaved (i.e., normally distributed). The residuals can be thought of as the variation in the data not explained by the regression model. The normal distribution of the residuals indicates that the regression model can be equally trusted across the full range and that the variables used in the regression model are sufficient to explain the trends observed. More specifically, the residuals' normality indicates that the inclusion of variables to account for the change in operating point of the engine or gear shifting is not necessary.

Conclusions and policy recommendations

VECTO is the European simulation tool developed to certify the CO_2 emissions from HDVs. Given the imminence of the CO_2 certification requirement for the largest share of HDVs in the EU by 2019, no major modifications to the certification tool are expected. Furthermore, attempting major modifications to the tool could prove disadvantageous for the policy initiatives targeting the reduction of CO_2 emissions, as it could result in delays in the implementation of the CO_2 certification procedure, which is the building block of future rulemaking, such as the Monitoring and Reporting (of CO_2 emissions) regulation and the HDV CO_2 standards.

Because trailers have a substantial impact on the road-load forces of freight vehicles, it is desirable to include trailers in the regulatory measures targeting efficiency improvements in HDVs. Despite the proven cost-effectiveness of trailer technologies (Sharpe, Garg, & Delgado, 2018), the uncertainty of return on investment, capital cost constraints, split incentives, and lack of technology availability reduce the efficacy of market forces to drive the adoption of these technologies. In light of these market inefficiencies, strong regulatory measures are warranted (Sharpe, 2017).

The inclusion of trailer road-load technologies in the current CO_2 certification methodology of HDVs is a necessary first step in the development of policies aimed at overcoming the prevailing market barriers that hinder the development and deployment of such technologies. On the basis of the above analysis and discussion, the following recommendations are made for extending the CO_2 certification regulation to include trailers, while at the same time minimizing the burden on trailer manufacturers and simplifying the regulatory design.

- **Regulatory CO_2 metric:** The use of a relative metric is recommended. The quantification of the CO_2 and fuel consumption reduction with respect to standard trailers eliminates the dependence of the CO_2 metric on the definition of the standard tractor. Furthermore, the metric provides direct information to consumers regarding the fuel-saving potential that can be achieved in comparison with standard trailers that do not feature aerodynamic, rolling resistance, or lightweighting improvements.
- **Definition of standard truck:** The proposed relative CO_2 metric is insensitive to variations in the vehicle specification of the hauling tractor. The current default 4×2 tractor defined in VECTO can be used as the standard tractor for assessing the CO_2 performance of trailers.
- **Trailer types to be certified:** The majority of trailer types belong to one of three categories: curtainsiders, refrigerated box vans, and dry-box vans. Furthermore, these three types have a similar geometry and can benefit from the same types of aerodynamic improvements. The remaining trailer types exhibit larger geometric variations within the same type, complicating the definition of standard geometries. Nonetheless, improvements in rolling resistance and lightweighting can still be easily accounted for. Therefore, two main categories can be defined for trailer CO_2 certification:
  - Aero: Curtainsiders, refrigerated box vans, dry-box vans
  - Non-aero: Container chassis, swap bodies, multi-axle, flatbeds, and others
- **Determination of the air drag area:** Air drag determination through CST or CDT requires substantial resources that can impose burdens on trailer manufacturers and on smaller companies in particular. The use of CFD simulations reduces the complexity of air drag determination. However, the boundary conditions (e.g., tractor geometry, mesh generation, turbulence model, CFD solver, etc.) need to be well defined to ensure comparability across different manufacturers. In a first phase, the use of standardized data for pre-approved aero devices can simplify the introduction of the CO_2 certification regulation for trailers while work on the standardized CFD tool continues.
- **Determination of weight reduction:** Predefined weight reductions from material substitution or component lightweighting can be used to capture the change in weight from technology application in specific trailer areas (e.g., chassis, wheels, suspension, doors).
- **Determination of the CO_2 performance:** The use of a trailer CO_2 equation for the certification of trailers reduces the administrative burden on trailer manufacturers. The proposed linear model (i.e., the trailer CO_2 equation) has very good agreement with full VECTO simulations, ensuring compatibility between the trailer and tractor CO_2 certifications.

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