WHITE PAPER

OCTOBER 2019

THE FUTURE OF VECTO:

CO_2 CERTIFICATION OF ADVANCED HEAVY-DUTY VEHICLES IN THE EUROPEAN UNION

Felipe Rodríguez and Oscar Delgado

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

www.theicct.org

communications@theicct.org

BEIJING | BERLIN | SAN FRANCISCO | WASHINGTON

ACKNOWLEDGMENTS

The authors thank all internal and external reviewers of this report for their guidance and constructive comments, with special thanks to Rachel Muncrief, Ben Sharpe, and Dale Hall (International Council on Clean Transportation); Milos Toulec (Eaton); Pete Williams (Cummins); and Luis Ramirez, Gandert Van Raemdonck, and Roy Veldhuizen (WABCO). Their reviews do not imply any endorsement of the content of this report.

For additional information:
International Council on Clean Transportation Europe
Neue Promenade 6, 10178 Berlin
+49 (30) 847129-102

communications@theicct.org | www.theicct.org | @TheICCT

Funding for this work was generously provided by the European Climate Foundation.

EXECUTIVE SUMMARY

The recent adoption of Europe's first standards for emissions of carbon dioxide (CO_2) by heavy-duty vehicles (HDVs) marks a new phase of technology development and deployment for truck manufacturers. To meet the mandatory fleet-average reductions in CO_2 of 15% in 2025 and 30% in 2030, manufacturers will have to introduce fuel-efficient technologies at a faster rate than they have done in past decades.

Furthermore, by the end of 2022, the European Commission must assess additional aspects that were left out in the first phase of the standards but that can increase the effectiveness of the CO_2 regulation. Some of these elements include incentivizing zero-emission trucks based on electric range, the introduction of CO_2 reduction targets for 2035 and 2040, and the inclusion of additional vehicle types such as trailers in the CO_2 regulation.

To meet these future regulatory requirements, the CO_2 certification framework should cover vehicles and advanced technologies that are not currently being captured. This report identifies the challenges that the CO_2 standards create for the certification procedure and puts forward recommendations to overcome them in a timely manner. The main findings are:

1. **The certification of heavy-duty hybrids can be achieved in two steps.** A simple simulation approach covering only parallel hybrids can enable the certification of products close to production. More-accurate testing protocols can be developed in a second step. Powertrain testing is recommended as a wide-encompassing certification pathway.

2. **Electric range certification should be prioritized,** as it is a prerequisite for the development of effective incentives in hard-to-electrify segments. The simulation of electric powertrains is less complicated than the simulation of hybrid ones. The rapidly growing electric truck portfolio in the EU warrants a prioritization over hybrid trucks.

3. **Waste heat recovery (WHR) is a robust technology close to commercialization.** The current certification methodology partially covers WHR systems. However, it does so with several limitations. The cycle-average mapping methodology, developed in the United States, is proposed as a certification option that overcomes some of these limitations.

4. **Trailer CO_2 certification is necessary** to incentivize the development and deployment of trailer technologies and to include trailers as a future regulated category in the CO_2 standards. To minimize the certification burden on manufacturers, it is desirable to set a simple regulatory design that accurately estimates CO_2 reductions from trailers.

5. **Innovative technology credits** can be a useful tool to incentivize the development and uptake of technologies not yet captured by the certification process. Yet they require a robust and transparent regulatory design with proper oversight. Such credits should be regarded as a stepping stone toward implementation in the CO_2 certification framework.

TABLE OF CONTENTS

INTRODUCTION

In December 2017, the European Union adopted Regulation (EU) 2017/2400 (European Commission, 2017) for the certification of carbon dioxide (CO_2) emissions and fuel consumption of heavy-duty vehicles (HDVs). The certification methodology rests on the simulation of CO_2 emissions and fuel consumption using a standardized vehicle simulation model called VECTO. The simulation tool uses as input the certified performance data of the different vehicle components. The certification requirement took effect in January 2019 for rigid and tractor trucks with a gross vehicle weight (GVW) of more than 16 tonnes and with 4x2 or 6x2 axle configurations (Rodríguez, 2018a).

The CO_2 emissions and fuel consumption certification procedure is the cornerstone of the recently adopted HDV CO_2 standards, Regulation (EU) 2019/1242 (Parliament and Council of the European Union, 2019). The standards mandate reductions in the average CO_2 emissions of new HDVs of 15% in 2025 and 30% in 2030. Compliance with the targets, which are defined relative to the certified data from July 2019 to June 2020, is determined using the certification data produced by the VECTO simulation tool (Rodríguez, 2019).

The HDV CO_2 standards leave open a policy window for increasing the effectiveness of the current regulation for reducing CO_2 emissions. By the end of 2022, the Commission must submit a report on the effectiveness of the CO_2 standards and assess several facets that were left out in the first phase of the standards. The following three aspects of the 2022 review would require modifications to the certification methodology to accommodate the anticipated future additions to the HDV CO_2 standards.

1. **The possibility of differentiating zero- and low-emission HDVs by their zero-emission driving range and payload:** The CO_2 standards include incentives for accelerating the development and deployment of zero- and low-emission HDVs. While large trucks carrying heavy payloads over long distances are harder to electrify, the provisions in the CO_2 standards do not differentiate between small and large trucks when assigning incentives. One way to correct this in the future is to differentiate zero- and low-emission HDVs based on their freight activity. However, to accomplish this, it is necessary to develop a certification procedure for the zero-emissions range of a vehicle. While VECTO's model architecture can be easily adapted to that end, VECTO's development is currently focused on the more complex hybrid certification approach.

2. **The appropriateness of the 30% CO_2 reduction target for 2030, and the introduction of reduction targets for 2035 and 2040:** The 15% reduction target for 2025 can be met with existing technologies already captured by VECTO (Delgado, Rodríguez, & Muncrief, 2017). However, meeting the 30% reduction target set for 2030, as well as future reduction targets for 2035 and 2040, will require that VECTO capture a wider set of advanced technologies. Otherwise, new vehicles incorporating these technologies would not be properly credited in the certified CO_2 values, creating barriers for the development, marketing, and deployment of new fuel-saving technologies.

3. **The setting of CO_2 reduction targets for other vehicle types including trailers, buses and coaches, and vocational vehicles:** While the first phase of the HDV CO_2 standards covers only trucks over 16 tonnes with 4x2 or 6x2 axle configurations, the certification requirements extend to trucks between 7.5 and 16 tonnes and to vehicles with 6x4 or 8x4 axle configurations. The European Commission is working on extending the certification procedure to HDVs with GVWs of less than 7.5 tonnes, as well as to buses and coaches. This is being done within the context of the HDV

CO_2 Editing Board, which is the stakeholder group led by the European Commission responsible for developing the CO_2 certification procedure for HDVs. The CO_2 certification of trailers, on the other hand, is not yet part of the activities of the HDV CO_2 Editing Board, and it is unclear what steps the Commission has taken to guarantee their timely inclusion into the certification framework.

The adoption of the HDV CO_2 standards and the scheduled 2022 review place demands on the development of the certification methodology to include vehicles and advanced technologies not currently being captured by VECTO. The timely expansion of the certification methodology is critical for ensuring that the 2022 review of the regulation can be implemented. This, in turn, increases the environmental benefits of the CO_2 standards.

This paper is divided into the following chapters, addressing the challenges that the CO_2 standards create on the certification procedure:

1. Hybrid powertrains
2. Fully electric powertrains
3. Waste heat recovery
4. Trailer technologies
5. Other advanced technologies

For each topic, the paper presents a brief overview of the technologies involved, the different technology certification options, the steps taken by the European Commission toward implementation, and the ICCT's recommendations.

HYBRID POWERTRAINS

OVERVIEW OF THE TECHNOLOGY

Powertrain hybridization can play a key role in the reduction of CO_2 emissions from on-road freight vehicles, even in long-haul transport. Simulations by the ICCT show that, by 2030 and compared with conventional tractor-trailers, hybrid powertrains can reduce tractor-trailer CO_2 emissions by as much as 6.5% over VECTO's long-haul cycle and as much as 20.9% over VECTO's regional delivery cycle (Delgado et al., 2017). The estimated cost of this would be €8,500 per vehicle in 2030 (Meszler, Delgado, Rodriguez, & Muncrief, 2018).

Hybrid powertrains coupling a conventional internal combustion engine (ICE) with one or more electric motors are available in different architectures: serial, parallel, or power-split. Simplified layouts of the different hybrid architectures are shown in Figure 1.

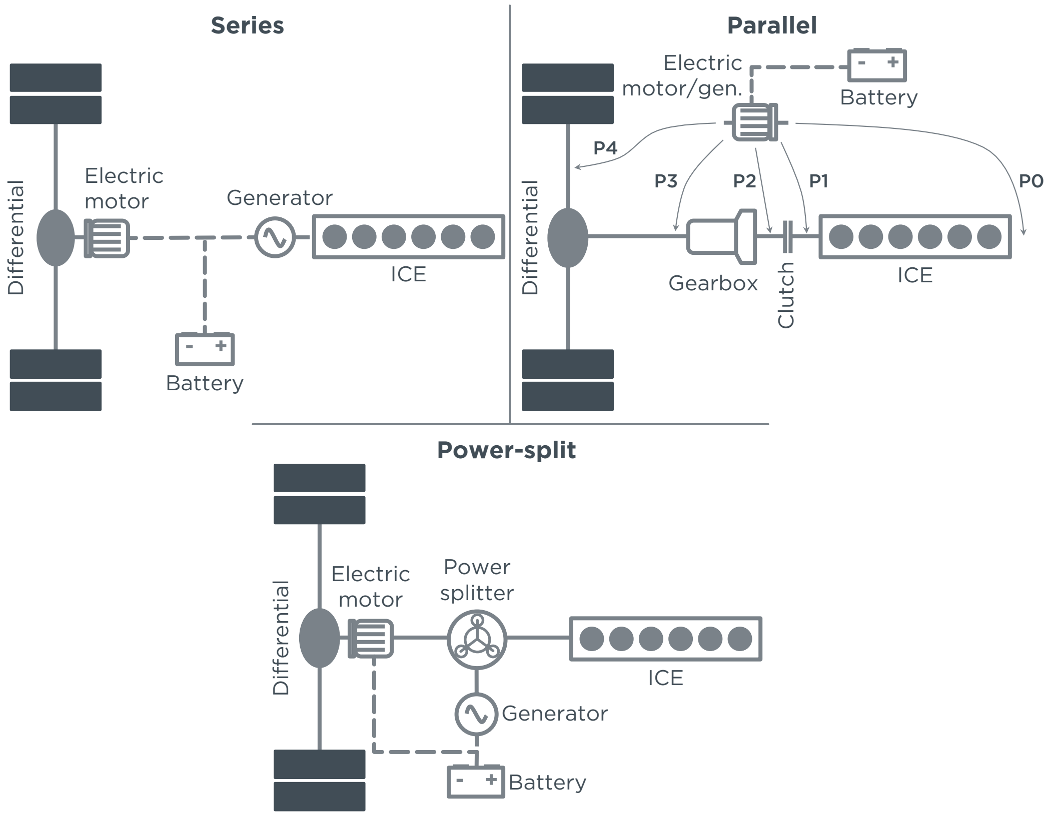

Figure 1. Powertrain diagram of series (left), parallel (right), and power-split (bottom) hybrids in their different configurations.

In serial hybrids the ICE powers an electricity generator, which in turn supplies energy to the battery or the electric motors; there is no mechanical connection between the ICE and the rest of the powertrain. Serial powertrains are common in hybrid urban buses.

In parallel hybrids the electric motor and the ICE are coupled mechanically, and both contribute to power the wheels in parallel. Parallel hybrids can be further divided based on the location of the electric machine. A parallel architecture in which the motor is located between the engine and the clutch (P2 configuration in Figure 1), is the preferred hybrid powertrain for trucks (see Table 1). In power-split hybrids, the serial and parallel concepts are combined. In this configuration two electric machines are mechanically coupled to the ICE through a power splitter.

Hybrid powertrains have been present in the European HDV market for more than a decade. However, market adoption of these alternative powertrains remains low for both trucks and buses. Figure 2 shows the number of trucks and buses with GVWs over 3.5 tonnes registered in the EU from 2005 to 2018.[1] Given the importance of the English hybrid bus market, it is shown separately.[2]

From 2005 to 2018, a total of 8,276 hybrid trucks and buses were put in the market. The hybrid heavy-duty vehicle market shares peaked in 2016, when hybrid vehicles represented 1.1% of the bus and 0.2% of the truck market. In 2018 vehicle registrations of hybrid HDVs amounted to 1,800 units and were the highest in the time period considered.

The hybrid vehicle market is dominated by a few EU member states and a few manufacturers. The largest hybrid bus market is the United Kingdom. From 2005 to 2018, it accounted for three-quarters of hybrid bus registrations. Volvo is the leading hybrid bus manufacturer, accounting for more than 30% of the market, followed by Alexander Dennis and Wrightbus, which have a presence only in the English market.

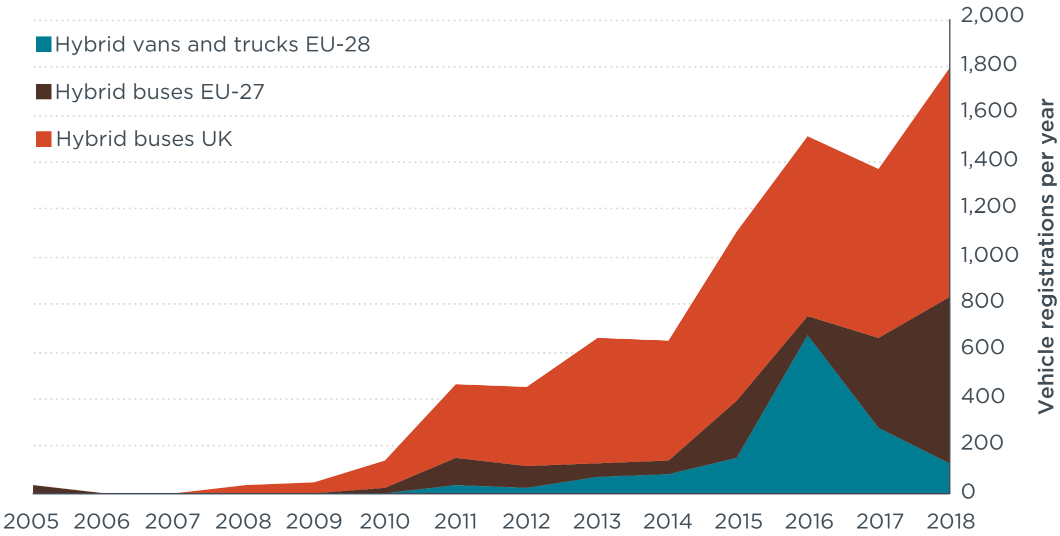

Figure 2. Hybrid trucks and buses registered in the EU from 2005 to 2018. EU-27 refers to the EU member states excluding the United Kingdom.

The biggest hybrid truck market is Germany. Cumulatively from 2005 to 2018, Germany accounted for half of hybrid truck registrations. Daimler's brand Mitsubishi Fuso, with its model Canter Eco Hybrid, is the leading hybrid truck manufacturer, accounting for more than 90% of the market in the same time period. Another Daimler brand, Mercedes-Benz, places a distant second with 2.3% of the market in this period, corresponding to the few Atego BlueTec Hybrid units commercialized in 2010 and 2011 (see Table 1).

Recently, a number of prototype and production-ready hybrid concepts have been announced. Hybrid systems can serve as a bridge technology on the way to full powertrain electrification. Tier 1 suppliers, especially transmission makers, are expanding their offerings of hybrid transmissions to satisfy this future demand. Table 1 summarizes commercially available hybrid trucks in the past decade and recent product announcements.

1 Content supplied by IHS Global SA; Copyright © IHS Global SA, 2018.

2 For the reporting years 2016, 2017, and 2018 the data supplier of IHS Global SA for the United Kingdom changed. The new data source does not include a detailed distinction for hybrid buses. Thus, the 2016, 2017, and 2018 U.K. hybrid bus figures are based on data gathered by LowCVP (Low Carbon Vehicle Partnership, 2019).

Table 1. Commercially available hybrid trucks in Europe 2005-2017 and 2018 product announcements.

	Last sold	Cum. Sales	GVW	Engine/ Motor power	Battery capacity	Type
DAF, CF Hybrid	Announced	-	18 tonnes	330 / 75kW	85 kWh	Parallel, P2
Scania, L320 Hybrid	Announced	-	26 tonnes	238 / 130kW	18 kWh	Parallel, P2
Fuso, Canter Eco-hybrid	2017	1,230	6 tonnes	92 / 35 kW	2 kWh	Parallel, P2
Scania, P320 Hybrid	2017	8	18 tonnes	238 / 130 kW	1.2 kWh	Parallel, P2
Volvo, FE Hybrid	2014	7	26 tonnes	250 / 120 kW	5 kWh	Parallel, P2
DAF, LF Hybrid	2013	8	12 tonnes	119 / 44 kW	1.9 kWh	Parallel, P2
Mercedes, Atego Hybrid	2012	34	12 tonnes	160 / 44 kW	1.9 kWh	Parallel, P2
Iveco, Eurocargo Hybrid	2011	6	12 tonnes	119 / 44 kW	1.9 kWh	Parallel, P2

CERTIFICATION OPTIONS

The United States, Japan, and China already have methodologies in place to certify the fuel consumption or CO_2 emissions of hybrid HDVs. However, their approaches have taken divergent pathways.

In the United States, hybrid HDVs can be certified through the use of the optional *powertrain test* (U.S. EPA & U.S. DOT, 2016). In such a test, the fuel consumption of the complete hybrid powertrain is measured on a powertrain dynamometer. This approach enables the measurement of the performance not only of individual powertrain components but also of the control algorithms used to integrate these components and to manage the energy between them.

Japan's methodology uses hardware-in-the-loop simulation (HILS), a well-established technique in the automotive industry for the development of software functions of electronic control units. The HILS method for hybrid HDVs has been developed within the context of UNECE's Global Technical Regulations (United Nations Economic Commission for Europe, 2015). In the HILS methodology, vehicle powertrain components are simulated in real time over the test cycle while the hybrid control unit, which is the hardware part of the HILS system, interacts with these virtual components. This approach allows the capture of the influence of the control algorithms on the energy and fuel consumption of the vehicle.

China's certification approach allows the use of vehicle simulation for variants of base vehicles. However, the fuel consumption certification for base vehicles is done on the chassis dynamometer (Delgado, 2016). While the fuel consumption testing procedure for hybrid HDVs has been detailed in a separate standard (AQSIQ, 2015), the methodology follows the same approach as the dynamometer testing of conventional powertrains. Since the complete vehicle is evaluated in chassis dynamometer testing, all powertrain technologies, including hybridization, are evaluated simultaneously.

The European approach will follow yet a different pathway from those being pursued in other markets. In 2017, the Graz University of Technology (TU Graz) was contracted by the European Commission to carry out a study assessing the different possibilities for the integration of hybrid powertrains into the current certification framework (Silberholz & Hausberger, 2017). As shown in Table 2, TU Graz's evaluation favored the direct simulation of hybrid HDVs in VECTO over other methodologies, and the European Commission opted for following this certification pathway.

Table 2. TU Graz's assessment of certification options for hybrid HDVs.

Method	Simulation based	Hybrid simulation	Development effort	Facilities effort	Certification effort	Accuracy	Suited for the EU
Simulation in VECTO	yes	yes	-	++	+	+	yes
Simple crediting scheme	yes	no	+	++	+	--	no
Post-processing	yes	no	0	++	+	-	yes
Complex off-cycle credits	yes	no	-	++	+	0	yes
Hardware in the loop	yes	yes	--	+	--	++	no
Powertrain testing	mix	no	--	-	-	++	yes
Chassis dyno testing	no	no	-	--	-	0	no
On-road measurement	no	no	-	+	0	-	no

Note: Scale --/-/0/+/++ ranks the options from least to most favorable. Adapted from Silberholz & Hausberger (2017).

In the European approach, the hybrid vehicle will be completely simulated in VECTO. In the simulation model, the conventional and hybrid powertrain components interact at each computation step. This option requires the development of hybrid component sub-models in VECTO, the development of a standardized control strategy deemed representative and applicable to all manufacturers, the development of standardized hybrid component testing, and the validation of the simulation model. To carry out these tasks, the Commission awarded a contract to VECTO's developers, TU Graz. The project launched in November 2018 and is expected to be completed by the end of 2020 (TU Graz, 2019).

RECOMMENDATIONS FOR THE CO_2 CERTIFICATION OF HYBRID HDVS

To incentivize the early development and commercialization of hybrid HDVs, it is necessary to provide certification pathways that capture the benefits of different hybrid architectures as early as possible.

The certification pathway currently being developed—the direct VECTO simulation of hybrid powertrains—is advantageous for ensuring compatibility with the current VECTO-based certification scheme for nonhybrid HDVs as well as for limiting certification efforts. On the other hand, direct VECTO simulation also raises some challenges as presented below.

The first challenge is that the VECTO hybrid model will need to use generic control algorithms for the energy management strategy of the simulated powertrain. Given the constraints imposed by the software architecture of VECTO and by the CO_2 certification regulation it is not currently possible to use the proprietary energy management strategies.

The fuel consumption of hybrid powertrains is highly sensitive to the energy management strategy. The control algorithms decide the distribution of the energy and power flows between the components, based on a large set of vehicle parameters and states. As a result, the number of possibilities for the design of the control strategy is vast, and the strategies can vary between manufacturers, hybrid powertrains architectures, or even vehicle models.

It is not yet clear whether such a generic algorithm, capturing the key features of the different possible control strategies, can be developed while providing accurate results and satisfying the requirements of different manufacturers.

Another challenge is that the certification approach will most likely not be able to handle many different hybrid architectures, being limited to P2 parallel and series hybrid powertrains as VECTO's developers have indicated (TU Graz, 2019). Given the wide variety of possible power-split architectures and operating strategies, it is not feasible for all of them to be implemented and accurately simulated by the VECTO hybrid model.

The last challenge has to do with the model's input data. The VECTO-based methodology rests on providing accurate input data of the various vehicle components for the simulation model. However, since standardized component testing does not yet exist for the hybrid powertrain componentry, the first iteration of the model will have to rely on generic data for the different energy storage systems such as batteries and supercapacitors; electric machines such as permanent magnet motor, induction motor, or switched reluctance motor; and other hybrid components.

The impact of using generic data on the accuracy of the model still has to be determined.

Bearing in mind the trade-offs between accuracy and simplicity, we recommend considering an alternative hybrid certification pathway addressing the challenges mentioned above. This optional certification pathway would be concurrent with the development of the VECTO hybrid simulation tool. In particular, the ICCT recommends considering the optional use of powertrain testing as an alternative certification pathway.

Powertrain testing

Powertrain testing can capture the effect of the control algorithms of different manufacturers, can be used for different powertrain architectures, and does not require the use of generic input data. Powertrain testing is similar to engine dynamometer testing, differing on the connection point to the dynamometer and on the software used to command the dynamometer testing set points. A schematic representation of a powertrain dynamometer is shown in Figure 3.

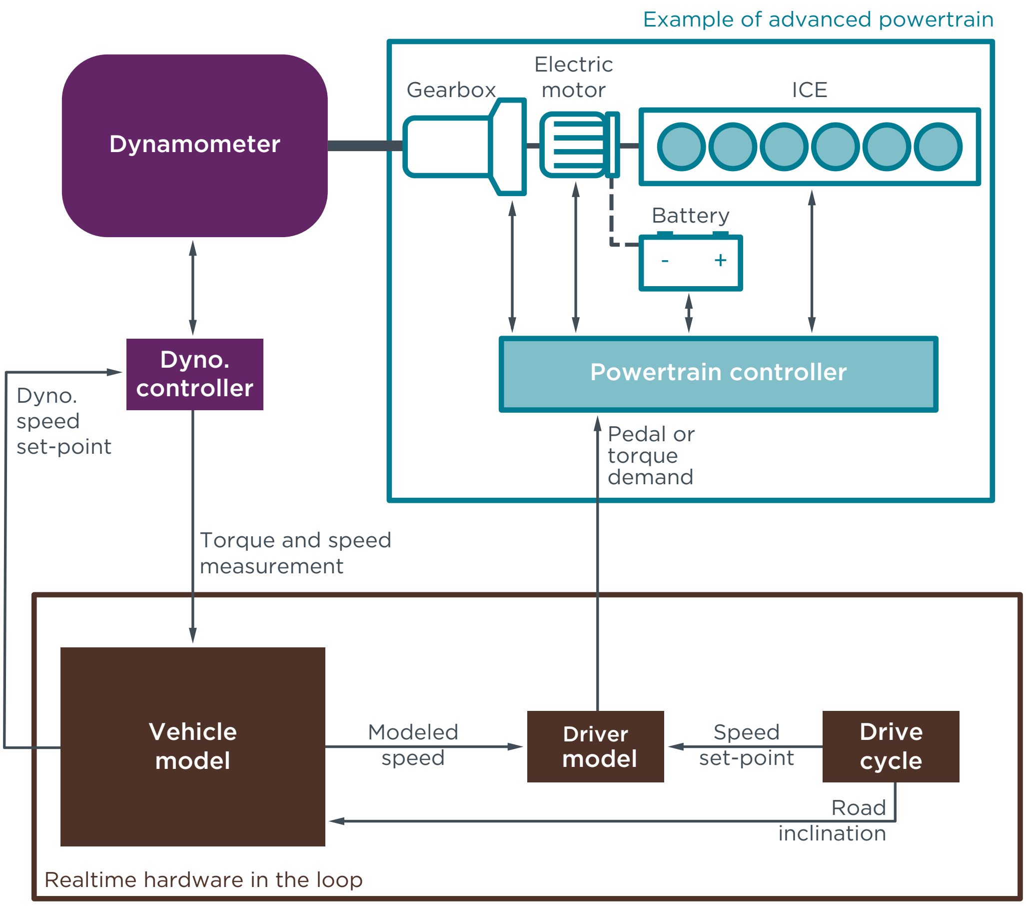

Figure 3. Diagram of a powertrain dynamometer. Adapted from Chambon & Deter (2016).

Engine testing on the dynamometer is a well-established certification methodology for type-approving the pollutant and CO_2 emissions of heavy-duty engines. Powertrain testing takes this approach one step further by also capturing the transmission and other active components of the powertrain, such as the hybrid system.

Powertrain testing is already being used in a regulatory context for certifying the CO_2 emissions and fuel consumption of HDVs. The U.S. EPA developed the methodology in cooperation with Southwest Research Institute (Anthony et al., 2015) and Oak Ridge National Laboratory (Chambon & Deter, 2016).

In a powertrain test, the vehicle components downstream of the powertrain such as axle, tires, and air drag; the driver; and the duty cycle are simulated by a virtual, real-time vehicle model. The powertrain dynamometer uses the road inclination of the drive cycle and the vehicle characteristics to inform the controller what resistive torque must be applied to the powertrain. The driver model takes into consideration the current vehicle speed and the targeted speed profile and commands an accelerator pedal position in the powertrain controller.

The advantage of powertrain testing is that it can be used on any type of hybrid system as well as other advanced powertrain technologies such as the deep integration[3] of engine and transmission, and waste heat recovery systems. Therefore, powertrain testing is a certification approach that can be applied in those circumstances when the fuel saving technologies cannot be simulated, or when the simulation method has not yet been developed.

TU Graz identified several disadvantages for the powertrain testing approach (Silberholz & Hausberger, 2017) and acknowledged advantages in the flexibility of the method and in its accuracy. Most of the disadvantages identified by the TU Graz team concern higher capital investments for the development of the test-cells, and the effort involved in the actual testing of the powertrains.

In the U.S. Phase 2 standards (U.S. EPA & U.S. DOT, 2016), the EPA assessed the capital investment of upgrading engine testing facilities to powertrain test-cells and found the impact on manufacturers to be reasonable. They estimated the capital investment at $1.2 million (in 2016 dollars for all cost estimates) for manufacturers that upgrade their own engine testing facilities and at $70,000 a year per powertrain family for manufacturers that outsource the powertrain testing and data analysis.

Powertrain testing should receive additional attention as a potential hybrid certification pathway. The cost and availability of powertrain test-cells and the required lead time for converting existing engine test beds into powertrain testing facilities should be analyzed in more detail.

3 Co-optimization in which the engine and transmission controls communicate closely to adjust shift logic and engine operational points based on driving conditions to reduce fuel use.

CERTIFICATION OF FULLY ELECTRIC POWERTRAINS

OVERVIEW OF THE TECHNOLOGY

Powertrain electrification is an important lever for the reduction of CO_2 emissions from on-road freight and passenger transportation. By 2030, fully electric powertrains can reduce the well-to-wheel emissions of long-haul trucks in Europe by more than 80% while at the same time reducing the total cost of ownership (Moultak, Lutsey, & Hall, 2017).

Battery electric powertrains have been present in the European HDV market in small numbers for more than a decade, as shown in Figure 4. In 2007, the heavy-duty battery electric market was composed of mostly 5.5-tonne delivery vans produced by the short-lived British company Modec. In 2009, the first electric buses came into the market in small numbers. However, since 2015 the electric truck and bus markets have been growing at considerably faster rates. The latest data[4] available show that electric truck registrations reached 434 units and bus registrations 672. This represents six times the 2015 figures for buses and 10 times for trucks. Cumulatively from 2005 to 2018, close to 2,900 electric trucks and buses were put in the market, with 2018 alone accounting for 1,100 units. In 2018 electric vehicles represented 2.4% of the bus market and 0.12% of the truck market.

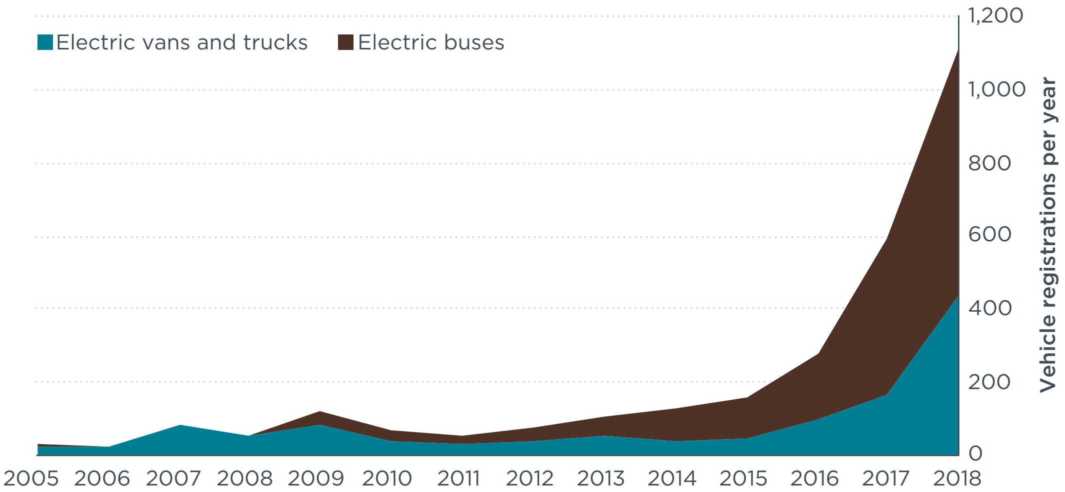

Figure 4. Electric trucks and buses registered in the EU from 2005 to 2018.

The largest electric bus market is the Netherlands with 22% of cumulative EU sales from 2005 to 2018, followed by the United Kingdom with 14%, and Germany with 11%. BYD and Solaris were the leading electric bus producers in 2018, each accounting for around 20% of the market. VDL, which in 2017 placed the most electric buses in the European market, attained a 13% market share in 2018. The European market is quickly ramping up, and most of the incumbent bus manufacturers—Daimler, Scania, MAN, Volvo, and Iveco—are expanding their electric bus portfolios and scaling up production (Mathieu, 2018).

The biggest electric truck market is Germany. It accounted for 54% of cumulative electric truck registrations from 2005 to 2018. In 2018 the leading electric truck maker was StreetScooter, totaling 214 units of its 4-tonne model Work XL. While incumbent vehicle manufacturers have not placed many electric trucks in the market, they are ramping up development efforts, particularly in the weight segment over 7.5 tonnes. Nearly all major European truck manufacturers have announced production of electric trucks in

4 Content supplied by IHS Global SA; Copyright © IHS Global SA, 2018.

coming years. Table 3 shows a summary of the current and planned zero-emission truck offerings in Europe of more than 7.5 tonnes. While there are few zero-emission trucks in production, zero-emission tractor-trailers are still in the prototype stage.

Table 3. Planned electric truck portfolio in the EU with gross vehicle weights above 7.5 tonnes.

	Model	Stage	Production	GVW	Battery	Range	Source
Daimler Trucks	eCanter	In production		7.5 tonne	83 kWh	120 km	(Mitsubishi Fuso, 2017)
	eActros	Customer tests	2021	26 tonne	240 kWh	200 km	(Daimler AG, 2018)
MAN	eTGM, 6x2	Customer tests	2021	26 tonne	225 kWh	200 km	(electrive.net, 2018)
	eTGM, 4x2	Customer tests	2021	32 tonne	149 kWh	130 km	(eurotransport.de, 2018)
	CitE	Prototype	2021	15 tonne	110 kWh	100 km	(MAN AG, 2019)
Volvo Trucks	FL Electric	Customer tests	2019	16 tonne	300 kWh	300 km	(AB Volvo, 2018a)
	FE Electric	Customer tests	2019	27 tonne	300 kWh	200 km	(AB Volvo, 2018b)
Renault Trucks	D Z.E.	Customer tests	2019	16 tonne	300 kWh	300 km	(Renault Trucks, 2018)
	D Wide Z.E.	Customer tests	2019	26 tonne	200 kWh	200 km	(Renault Trucks, 2018)
DAF	LF Electric	Customer tests	Not announced	19 tonne	222 kWh	220 km	(DAF, 2018a)
	CF Electric	Customer tests	Not announced	37 tonne	170 kWh	100 km	(DAF, 2018b)
Scania	R 450 Hybrid (pantograph)	Customer tests	Not announced	40 tonne	Not apply (overhead)	10 km (battery)	(Scania AB, 2018)
E-Force	EF18/26	Customer tests	Not announced	18/26/40 tonne	105 – 630 kWh	Up to 500 km	(E-Force AG, 2019)
BYD*	T5	Production (US, China)		7.5 tonne	155 kWh	250 km	(BYD, 2018)
	T7	Production (US, China)		11 tonne	221 kWh	200 km	(BYD, 2018)
	T9	Production (US, China)		36 tonne	435 kWh	270 km	(BYD, 2018)
Tesla	Semi	Customer tests (US)	2019 (US)	36 tonne	Not announced	800 km	(Tesla, 2019)
Nikola	Tre (battery)	Prototype	2023	40 tonne	500 – 1,000 kWh	Up to 650 km	(Nikola, 2019)
Nikola	Tre (fuel cell)	Prototype	2023	40 tonne	320 kWh	1200 km (H_2)	(Nikola, 2019)

*BYD electric trucks are not yet available in Europe; a roll-out in the EU was announced (electrive.com, 2019).

CERTIFICATION OPTIONS

Fully electric powertrains do not produce CO_2 emissions directly and thus are certified under the CO_2 emissions regulation as zero-emission vehicles. Still, electric vehicles have other metrics of interest, such as electric drive range and energy consumption. These metrics are of relevance to early adopters for making investment decisions and can be used by regulatory agencies to tailor the regulatory incentives for zero-emission HDVs.

Currently, there is no certification approach for the driving range of HDVs. Truck and bus manufacturers employ their own methodologies and boundary conditions to estimate the driving range of their products, as used to be the case for the fuel consumption of combustion engine powertrains before the VECTO-based certification was introduced. The rapid uptake of electric buses and the expected increase in zero-emission truck offerings (see Table 3) warrant the development of an energy consumption and driving range certification methodology that is compatible with the current regulatory framework for the certification of CO_2 emissions and fuel consumption.

VECTO's model architecture can be easily adapted to estimate the electric driving range of HDVs. Still, development efforts are focusing first on the more complex hybrid certification approach. In any case, estimating electric driving range is a necessary element for the certification of plug-in hybrid trucks, and a methodology to estimate range will have to be integrated within the structure of the VECTO hybrid model. It is not clear whether VECTO will include electric driving range as a certification metric or whether it will continue to be used exclusively for CO_2 and fuel consumption certification.

The simulation of electric powertrains in VECTO is more straightforward than the simulation of hybrid powertrains, since the energy management strategy does not need to account for the interaction between conventional and electric powertrain components. The extension of VECTO to simulate electric-only powertrains can be accomplished by extending VECTO's model architecture with additional electric modules.

In VECTO's backward-looking[5] calculation, a Driver module converts the drive cycle into an acceleration request. The information is passed to the Vehicle module, which, on the basis of total vehicle mass, drag coefficient, and rolling resistance, converts the acceleration request into a force request. The Wheel module then converts the force request into a torque request at the wheel hub and passes the information to the other powertrain components. In a final step, the Engine module receives the torque request from the powertrain and locates the operating point on the engine map, translating the torque and energy flows into fuel consumption values. Using this existing VECTO architecture, electric energy consumption and driving range can be simulated with the aid of additional modules that represent the key components of the electric powertrain, such as battery, inverter, and motor. An example of a modified VECTO architecture for the simulation of an electric HDV with a central electric motor is shown in Figure 5. Until the component certification procedures for the electric componentry are developed, the simulation tool can make use of generic data as intended for the first iteration of VECTO hybrid.

5 In real operation, the driver commands the engine to provide torque at the wheels. In backward models, the simulation occurs in the opposite direction than in the actual vehicle; the calculation goes from wheel to engine.

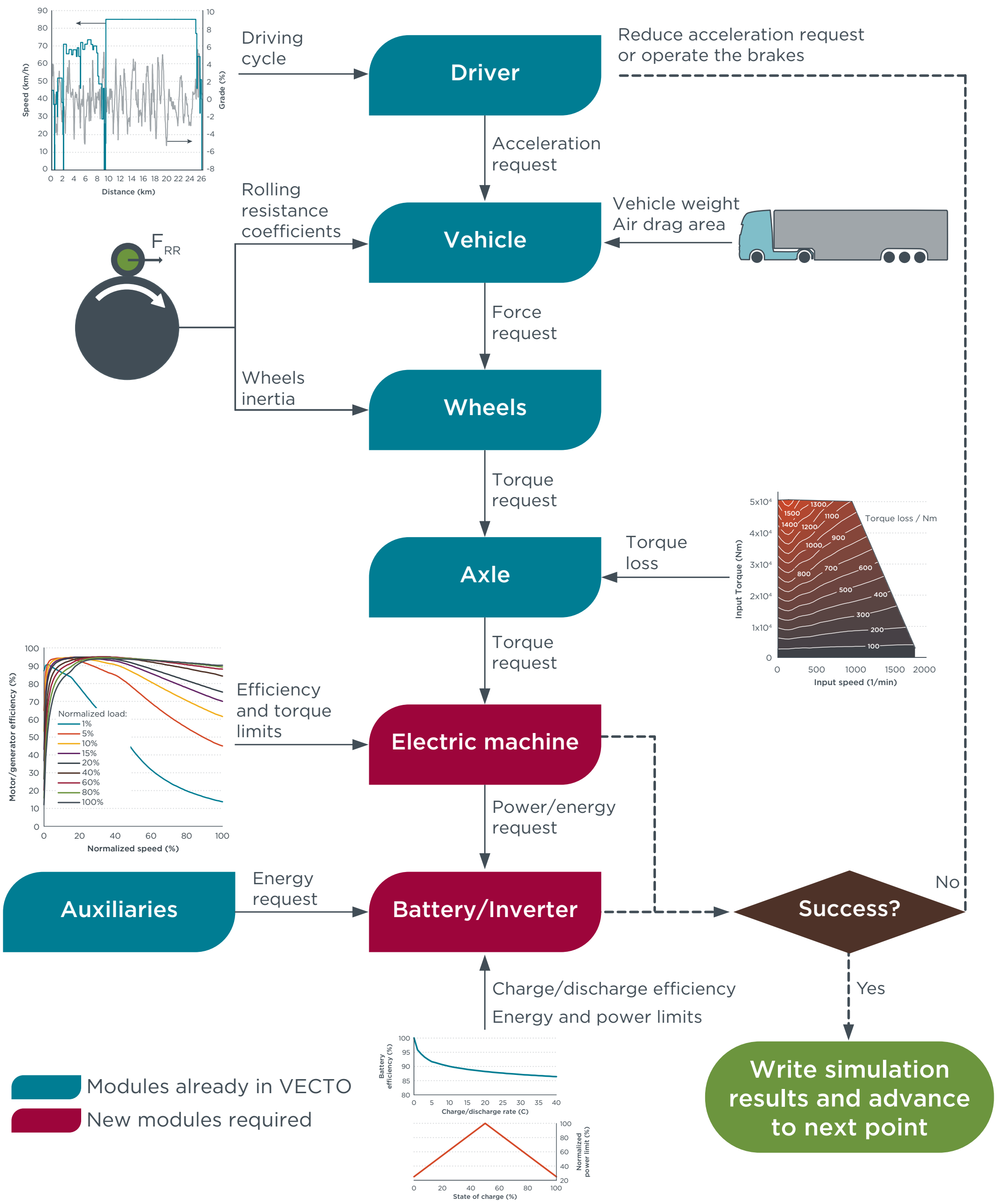

Figure 5. Example of a modified VECTO architecture for the simulation of an electric powertrain with a single central electric motor.

RECOMMENDATIONS FOR THE CERTIFICATION OF FULLY ELECTRIC HDVS

The simulation of electric-only powertrains can be accomplished by slight modifications of VECTO's architecture to accommodate new modules for the electric powertrain components. These new modules are being developed in the context of the extension of VECTO to simulate hybrid powertrains.

Prioritizing the development of a certification methodology for electric range will enable the differentiation of zero-emission HDVs based on their zero-emission driving range and payload. This differentiation is crucial for establishing incentives targeted at the development of zero-emission vehicles in the harder-to-electrify HDV segments, which are in turn also the ones with the highest contribution to CO_2 emissions from on-road freight.

WASTE HEAT RECOVERY

OVERVIEW OF THE TECHNOLOGY

Combustion engines convert less than half of the fuel's chemical energy into usable work at the crankshaft. The rest of the energy is dissipated as heat into the environment. Hot exhaust gases account for 35% of this wasted thermal energy and the cooling circuit accounts for 10% (Thiruvengadam et al., 2014). Waste heat recovery (WHR) systems attempt to recoup some of this energy and transform it into usable forms of energy including mechanical work or electric energy. Two main types of WHR approaches have been investigated in the past:

1. **Bottoming cycles:** The coolant fluid, engine oil, EGR flow, and exhaust gases are heat sources that can be used to drive a separate heat engine. Typically, the bottoming cycle and associated heat engines are designed on the principles of the ideal organic Rankine cycle (ORC) (Mahmoudi, Fazli, & Morad, 2018).

2. **Thermoelectric generators:** The temperature differential between the exhaust gases and the environment is exploited by semiconductors exhibiting a strong thermoelectric effect to generate electricity. They have, however, lower thermal efficiency than bottoming cycles (Orr, Akbarzadeh, Mochizuki, & Singh, 2016).

Due to the higher thermodynamic efficiency and, thus, the greater fuel consumption benefits, most of the recent WHR research and development efforts have been on ORC systems. In an ORC-WHR system the waste heat from multiple sources is used to evaporate an organic working fluid in a heat exchanger. The evaporated fluid is then passed through a turbine or a piston expander to create mechanical work. The mechanical work can be provided directly to the engine's crankshaft or converted into electric energy and stored as such. The working fluid is condensed in another heat exchanger and then its pressure is increased by a feed pump to restart the cycle. Figure 6 illustrates a typical ORC-WHR system.

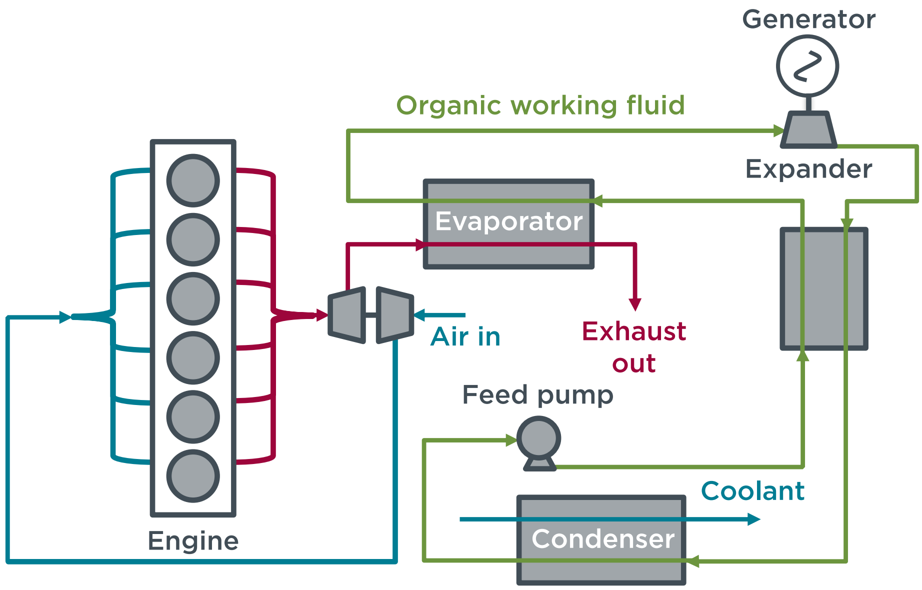

Figure 6. Typical WHR system architecture for capturing exhaust heat and converting it to electric energy (e-WHR).

Waste heat recovery systems have been identified by different stakeholders as a promising technology for the reduction of fuel consumption and CO_2 emissions of

HDVs, particularly in long-haul operation. Several studies have been carried out to quantify the potential of ORC-WHR systems for European long-haul trucks. The results indicate a range of fuel consumption reduction between 1.5% and 7.2% (Bettoja et al., 2016; Glensvig et al., 2016; Grelet, Reiche, Lemort, Nadri, & Dufour, 2016; Yang, Grill, & Bargende, 2019).

Although ORC-WHR systems are not offered on any in-production vehicle, several component suppliers, such as MAHLE (Scharrer, 2018), BorgWarner (Liu et al., 2017), and Eaton (Subramanian, 2017), have production-ready components that can be readily integrated by truck manufacturers.

CERTIFICATION OPTIONS

The design of the certification methodologies in the United States and China enables the measurement of powertrains equipped with WHR systems. In the United States, the fuel consumption benefits of WHR systems that are mechanically coupled to the engine are fully captured by the U.S. engine mapping approach, called cycle-average mapping. For e-WHR systems, U.S. powertrain testing provides an alternative certification pathway. In China, the fuel consumption certification for base vehicles is done on the chassis dynamometer. Thus, the methodology captures all powertrain technologies, including WHR systems.

Given the unbreakable relationship between engine and WHR system, the latter can be considered an engine component. An engine test protocol for generating the input data required by VECTO already exists. Thus, in principle, WHR systems are already covered by the current methodology. However, the accuracy and technology limitations imposed by the current method, presented in detail below, warrant the examination of additional certification pathways.

As was the case for hybrid powertrains, several certification options exist for including WHR systems in the European CO_2 certification framework. The following paragraphs describe the key elements, advantages, and disadvantages of possible certification approaches for WHR systems. The following methodologies are considered:

1. Current engine mapping method.
2. WHR correction factors for current engine mapping method.
3. Cycle-average mapping.
4. VECTO simulation with WHR component test.
5. Full simulation in VECTO.

Current engine mapping method

Currently, two types of tests are necessary for generating the engine data used as input by the simulation-based CO_2 certification procedure. First is the fuel consumption mapping cycle. In this test, the steady-state fuel consumption over about 100 operating conditions is measured on the engine dynamometer. To achieve steady-state conditions, each operating point is allowed to stabilize for about one minute. The results of this test directly provide the lookup table used in VECTO simulations for the interpolation of fuel consumption. The second test is the Worldwide Harmonized Transient Cycle (WHTC), which is used to perform a transient correction to the steady-state measurements.

In its current form, the engine certification approach established in the EU does not accurately capture the effect of WHR systems. The following limitations are identified:

- In the fuel consumption mapping test, the one-minute stabilization time is insufficient because of the large thermal inertia of WHR systems. As a result, the current steady-state test overestimates the fuel benefits of WHR systems at low loads and underestimates them at high loads.
- The current methodology to account for transient operation and cold-start uses the WHTC test to determine a set of correction factors. WHR systems are highly sensitive to exhaust temperature fluctuations. It has not yet been determined whether the correction factor based on the urban, rural, and motorway sections of the WHTC are representative of the Urban Delivery, Regional Delivery and Long Haul VECTO cycles for WHR systems. Furthermore, the WHTC correction does not consider the change in engine load and thus in exhaust temperature stemming from different payloads.
- In the case of electric WHR systems mechanically decoupled from the engine, such as the e-WHR from Figure 6, the fuel consumption reduction cannot be directly quantified in the current engine mapping procedure.
- WHR system effectiveness is dependent on condenser effectiveness, or how efficiently heat can be removed from the WHR system. This cooling performance is influenced by the integration of the WHR system with the vehicle, ambient conditions, vehicle speed, and other factors. Engine dynamometers have cooling capacities that go significantly beyond those found in vehicles. Consequently, the engine test protocol, which is based on UNECE Regulation 49, is not able to capture these cooling interactions between vehicle and the WHR system.

WHR temperature correction factors for current engine mapping method

The current certification pathway being considered by the European Commission contractor, TU Graz, involves the use of correction factors to account for the limitations of the current engine mapping procedure without needing to modify the procedure.

As mentioned, the stabilization time of the current engine test is too short to reach the steady-state temperature at the WHR inlet, potentially overestimating the WHR work at low load and underestimating it at high load. To circumvent this limitation, a methodology based on temperature correction factors is being examined. The proposed temperature correction factors would mimic the WHTC current transient correction approach in place for fuel consumption.

Using exhaust temperature measurements from the steady-state engine test, the average temperature over the different portions of the WHTC can be estimated by interpolating the steady-state map. This temperature estimate is then compared with the actual average temperature measured over the WHTC sections. The ratios of the temperature estimates from the steady-state map interpolation to the WHTC measurements are the proposed temperature correction factors. A temperature correction factor can then be used to address the issues with the stabilization time of the steady-state map, or the overestimation of WHR work at low load and underestimation at high loads.

In a preliminary validation by TU Graz, the temperature correction factors reduced the difference between modeled temperature from the steady-state interpolation and the measured values. However, payload-dependent deviations were still observed. An approach to reduce these deviations is being explored. The proposed methodology would involve the development of a WHR function, a linear regression model to characterize the WHR power output as a function of average WHR temperature (Hausberger, 2019).

The methodology outlined above has the advantage that it builds upon the current engine certification approach, ensuring the coherence between non-WHR engines being certified since the start of 2019, and future WHR-engine combinations. The proposed approach, however, raises a number of additional challenges that need to be analyzed carefully:

» The temperature correction factors can reduce deviations observed between interpolated and measured exhaust temperatures. Still, they cannot be used directly to estimate the differences between the interpolated WHR work and the actual work. A characteristic function relating WHR work and temperature is required.
» A characteristic WHR function must be defined based on experimental data. This would imply additional tests on the engine dynamometer or an additional WHR-only component test.
» The correction factors are likely to be specific to the vehicle types, driving cycles, and simulated payloads currently defined in the EU regulatory framework. Consequently, the approach is sensitive to changes in these parameters and would need to be updated if the mission profiles or regulatory payloads change.

While WHR temperature correction factors have the potential to address many of the shortcomings of the current test protocol, their effectiveness and ease of implementation require further analysis.

The applicability to e-WHR systems and the interaction between test-cell cooling and WHR condenser performance are not addressed by this certification approach and would need to be considered separately.

Cycle-average mapping

The high sensitivity of WHR systems to exhaust temperature variations, and thus to transient operation, demands a robust transient correction methodology. For the U.S. Phase 2 GHG standards, the EPA in close cooperation with engine, transmission, and vehicle manufacturers developed a new fuel consumption mapping methodology called cycle-average mapping (U.S. EPA & U.S. DOT, 2016, §1036.540; Zhang et al., 2016). The cycle-average mapping process in the context of WHR certification can be summarized in the following steps (see Figure 7).

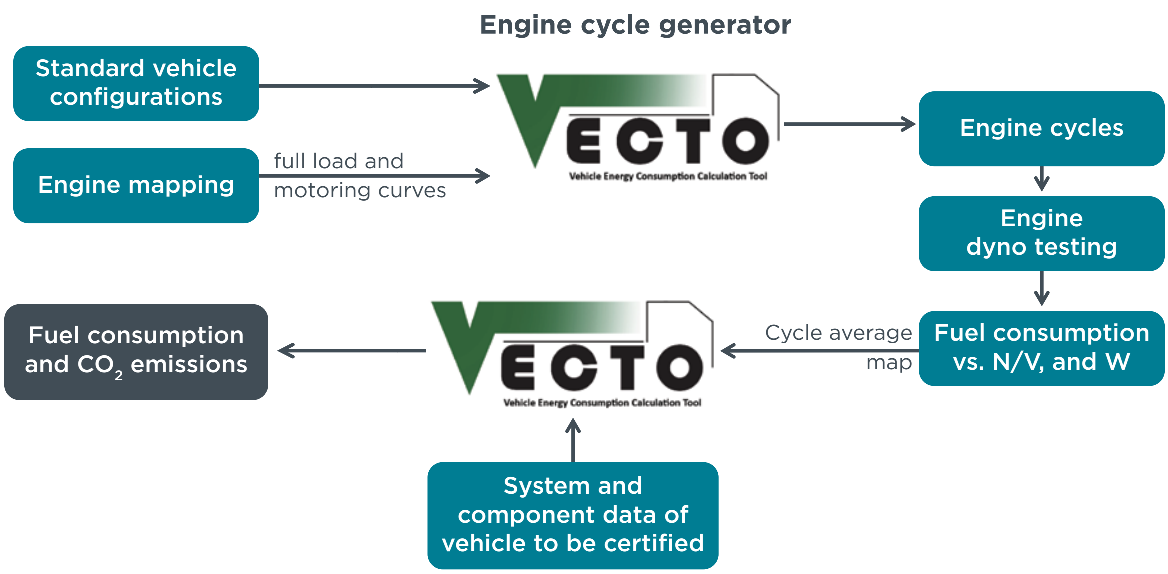

Figure 7. WHR system certification using the cycle-average map approach.

» Generate the full load and motoring curves of the engine-WHR combination.
» Define several standard configurations that span the range of trucks to be certified.

» Using the measured full load and motoring curves, simulate standard vehicle configurations in VECTO over different drive cycles—distance versus target speed and grade—and from the simulation results create respective engine cycles—engine speed versus engine torque.

» Test the engine-WRH combination on a dynamometer over the engine cycles defined in the previous step. For each test, report the cumulative fuel consumption. In the case of mechanically decoupled WHR systems, report the positive WHR work.

» Based on the test results, create a regression model for fuel consumption over the certification tests using independent variables that can characterize the whole vehicle operation. Researchers at the EPA assessed several regression possibilities and determined that a linear regression model using the ratio of average engine speed to average vehicle speed (N/V) and positive engine work (W) as the two independent variables resulted in the best accuracy (Zhang et al., 2016). Since the variable N/V is dependent on the drive-tire size, axle ratio, and transmission gear ratios, it can capture different powertrain configurations. The engine work, W, is useful for capturing average engine efficiency across different cycles (Zhang, Sanchez, & Spears, 2015). Figure 8 shows the visual representation of an example regression surface.

» By using the regression model, VECTO could estimate the fuel consumption and CO_2 emissions benefits of WHR systems in different vehicles by performing an interpolation over the resulting regression surface.

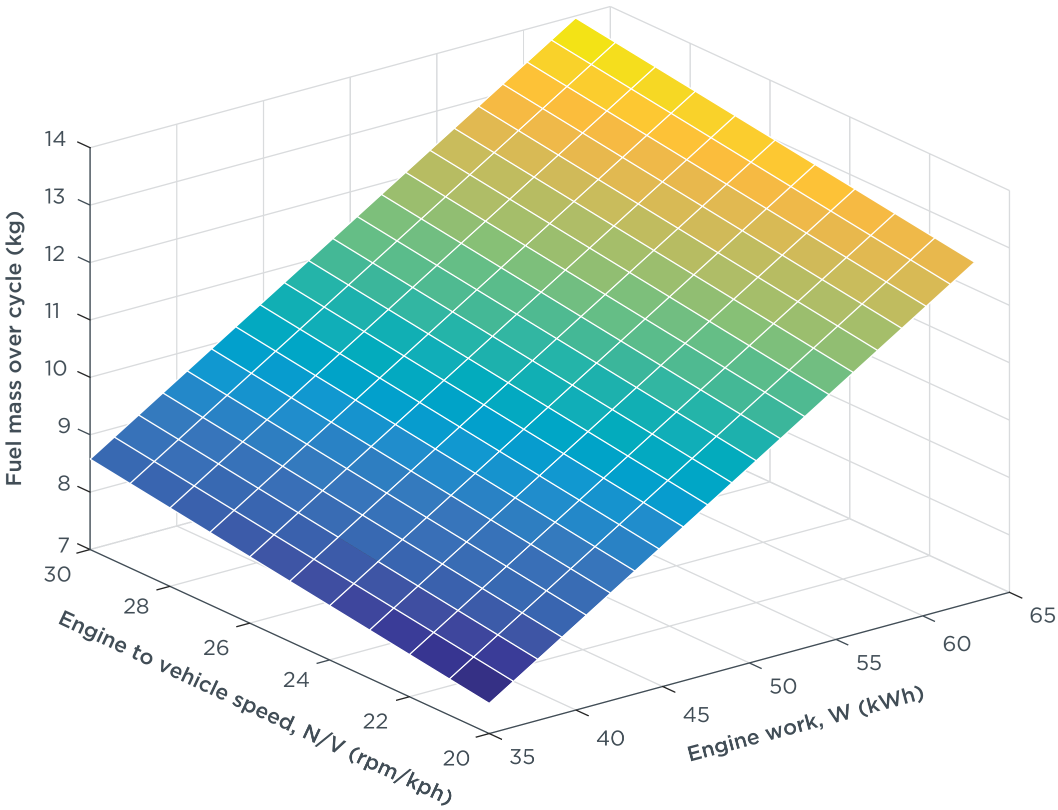

Figure 8. Example of regression surface for cycle-average mapping

The main advantage of the cycle-average engine test procedure is that it produces accurate results in both steady-state and transient conditions. Since the transient correction is done over the same drive cycles used by VECTO, it is more accurate than a transient correction based exclusively on the WHTC cycle. This is crucial for systems exhibiting high sensitivity to transient operation, such as WHR systems. Furthermore, the cycle-average methodology has already been extensively validated by the EPA with the support of truck manufacturers in the EU. Therefore, its performance is well documented and should be familiar territory for HDV manufacturers.

As in the previous case, the applicability to e-WHR systems and the interaction between the test-cell cooling and WHR condenser performance are not addressed by this certification approach and would need to be considered separately.

VECTO simulation with WHR component test

This approach involves the development of a WHR component test as a stand-alone unit, eliminating the need for detailed simulation of the processes taking place inside the WHR. The data from the component test are then used to generate a mathematical model of the WHR system, in much the same way as is currently done for engines and other complex components. In other words, the model would consist of a two-dimensional look-up table that would output the work generated by the WHR system based on the input exhaust temperature and mass flow. Given that those two quantities are not currently being measured as part of the fuel consumption mapping procedures of the engine, the test must be modified to capture these data and to allow the steady-state measurement of exhaust temperatures, such as the longer thermal stabilization periods in the fuel mapping. Furthermore, the component test must capture the effects of the thermal inertia of the various WHR components to avoid over- or underestimating the work output of the system in transient operation.

VECTO's architecture would also need to be adapted to accommodate such a model. The operation and effectiveness of a WHR system depends heavily on its interaction with other vehicle systems, most notably with the cooling system. In the absence of sufficient cooling power to deal with heat rejection from the condensation process, the WHR has to limit the exhaust mass flow it accepts to accommodate to the cooling conditions, thus reducing the WHR power output. Since VECTO does not include any simulation of the cooling system, the development of a cooling model would be a prerequisite to capturing these interactions.

In real vehicles, interactions between components and systems would be dictated by manufacturer-specific control algorithms. Thus, a generic control strategy would need to be developed to capture the model interactions within VECTO in a way that is representative of the actual control strategies. Accurately modeling these interactions among the vehicle, engine, electric storage system, and WHR systems poses several challenges that would require significant resources and time to overcome.

Full simulation in VECTO

The complete simulation of WHR systems and their interaction with the rest of the vehicle model require the development of a significant number of additional mathematical models in VECTO and additional component tests. The main components are the heat exchangers—evaporator, condenser, and recuperator—the feed pump, expander, and working fluid. In addition, the connection of the WHR to the rest of the powertrain must be modeled, either by a mechanical connection with associated power loss, or by an electrical system with its associated electrical efficiency. To add further complexity, different options are available for some of the WHR components with different thermodynamic properties. Lastly, the thermal, mechanical, and electric coupling of WHR systems with the rest of the vehicle must be accurately modeled.

As a result of the large number and variety of subcomponents, the full simulation of WHR systems and their interaction with the rest of the vehicle presents significant challenges for using this approach as a certification methodology.

RECOMMENDATIONS FOR THE CERTIFICATION OF WHR SYSTEMS

There are several certification options for HDVs equipped with WHR systems. Table 4 presents the ICCT's evaluation of the different certification options using the following criteria: development effort, intensiveness of infrastructure requirements to carry out the certification, certification effort, and accuracy of the methodology.

Table 4. The ICCT's assessment of certification options for WHR systems

Method	Engine dyno test	WHR-only test	Simulation based	Development effort	Facilities effort	Certification effort	Accuracy
Current engine mapping method	yes	no	yes	++	+	++	-
WHR temperature correction factors	yes	tbd*	yes	+	+	+	0
Cycle-average mapping	yes	no	yes	0	+	0	+
VECTO simulation with WHR component test	no	yes	yes	-	0	0	0
Full WHR simulation in VECTO	no	no	yes	--	++	++	-

Notes: Scale --/-/0/+/++ ranks the options from least to most favorable.
* To be defined. A linear WHR function, defined using test data, is required to characterize the change in work from changes in temperature. WHR-only test is an alternative for gathering such data.

Methodologies based on testing the engine and WHR as a complete system are the most attractive in terms of development, facilities, and certification effort, given that they use the same established methodologies for engine certification. However, the two testing-based methodologies have different degrees of accuracy. The approach involving WHR correction factors is currently being developed, and the preliminary results are encouraging. Open questions are how to generate the WHR regression model and how accurate the correction factors can be across vehicle types, driving cycles, and payloads.

Higher accuracy can be expected using the cycle-average mapping methodology, as it provides a more robust transient correction and creates a clear link between the vehicle drive cycles and the cycles used in engine testing. However, it implies a large number of long engine tests to generate the data required for the regression model.

The full WHR simulation approach requires a significant development effort to simulate the thermodynamic processes occurring inside the WHR and would still result in unsatisfactory accuracy because of the necessary assumptions made in the model and in the control strategy. The last two methods considered rely on a WHR test as a stand-alone unit. These two methodologies are similarly evaluated, with the post-processing approach reducing the development effort at the cost of lower accuracy.

In summary, accurate simulations that appropriately capture the system architecture, hardware design and sizing, and control strategies can represent a development effort comparable to the development of VECTO itself. Therefore, methods based on the testing of the combination of engine and WHR are recommended. Because of the high impact that transient operation can have on the performance of WHR systems, it is important to use a sound methodology that accurately captures the transient performance. Cycle-average mapping can provide a robust alternative to the approach using WHR correction factors currently under development. Furthermore, since the cycle-average methodology is the engine certification pathway in the United States, it is well documented and has been proven for regulatory purposes.

TRAILER TECHNOLOGIES

OVERVIEW OF THE TECHNOLOGIES

Although trailers do not directly emit CO_2, their design affects the tractive force exerted by the pulling vehicle and therefore contributes substantially to the CO_2 emissions and fuel consumption of HDVs.

Figure 9 illustrates the key areas where energy losses occur on a trailer during typical operation and the technologies that can reduce these losses. Fuel consumption reductions due to technology interventions in each of these areas depend on several factors, including average speed, topography, climate conditions, vehicle weight, and driver behavior. Also, in addition to the areas for aerodynamic and tire-related improvements shown in the figure, weight reduction using material substitution is a way to reduce the inertia loads associated with the trailer.

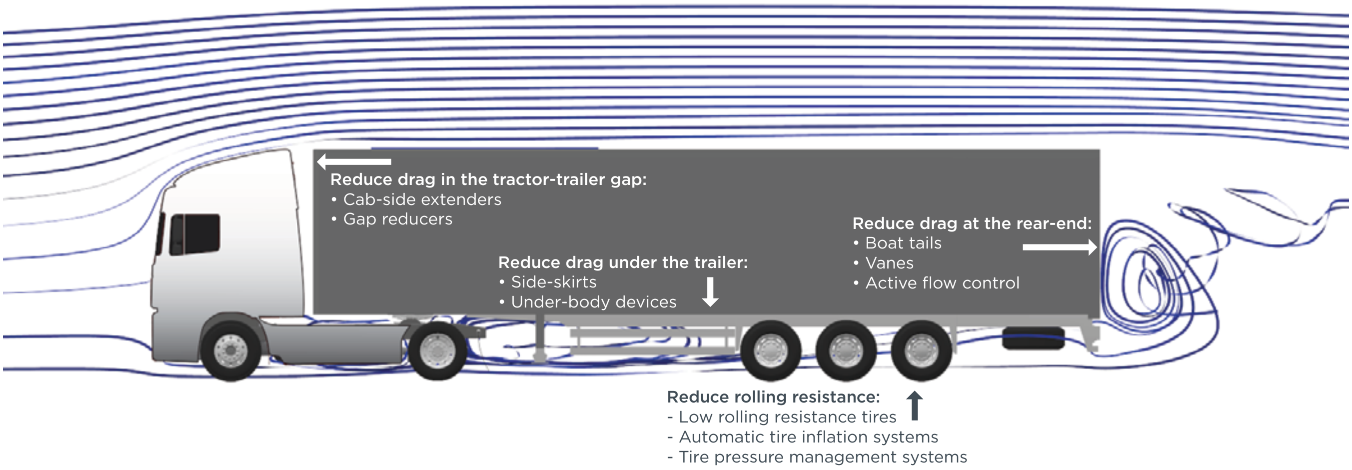

Figure 9. Key energy loss areas on a trailer during typical operation and technologies to reduce these losses.

For trailer aerodynamics, there are many technologies that exist or are in development to target each of the three primary areas where drag occurs: 1) the side and underbody of the trailer, 2) the rear end of the trailer, and 3) the tractor-trailer gap. Compared with a baseline curtain-side trailer with no aerodynamic features, trailer technologies can reduce fuel burn by an estimated 6.3% over the Long-Haul drive cycle and 3.6% over the Regional Delivery cycle (Sharpe & Rodríguez, 2018).

Lowering the rolling resistance of tires through enhanced design and proper inflation can also reduce the power required to move the tractor-trailer down the road. Looking at the specific contribution of trailer tires to overall tractor-trailer rolling resistance drag, improvements can yield estimated fuel savings of 4.4% over the Long-Haul cycle and 2.6% over the Regional Delivery cycle (Sharpe & Rodríguez, 2018).

Alternative materials such as composites and aluminum can be used in trailer wheels as well as the structural supports to decrease the empty weight of the trailer. Decreasing weight reduces the force needed to accelerate or decelerate the vehicle as well as the force needed to overcome rolling resistance. Compared with a typical curtain-side trailer, a 15% reduction in empty weight is possible using available materials. This results in estimated fuel savings of 1.6% the Long-Haul cycle and 2.4% in the Regional Delivery cycle (Sharpe & Rodríguez, 2018).

By 2030, the combined application of aerodynamic, tire, and weight reduction improvements can result in fuel savings of 11.9% over the Long-Haul cycle and 8.4% over the Regional Delivery cycle, compared with the baseline curtain-side trailer (Sharpe & Rodríguez, 2018).

CERTIFICATION OPTIONS

The inclusion of trailer road-load technologies in the CO_2 certification procedure does not require major modifications to VECTO, as the model can already simulate changes in the road-load parameters of the whole vehicle: drag area, rolling resistance, and curb weight. Nevertheless, several options exist for the appropriate CO_2 metric, the trailer types impacted by the regulation, the standard tractor truck specifications, and the aerodynamic drag determination procedure for trailers (see Figure 10).

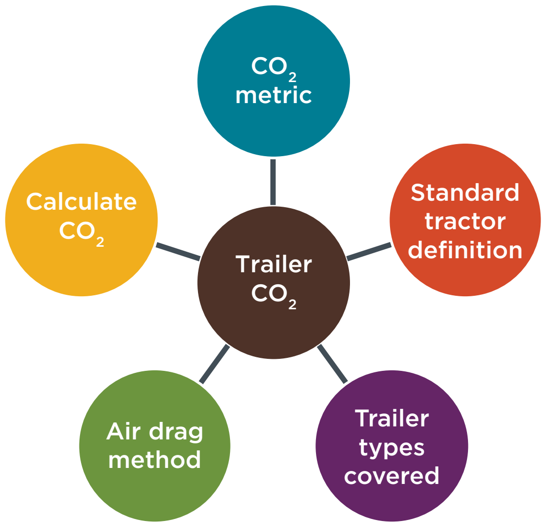

Figure 10. Areas of trailer certification where different options exist.

There are two possible options for the regulatory CO_2 metric: an absolute or a relative metric. The choice of metric has direct implications on the requirements for the selection of a standard tractor for trailer CO_2 certification. The use of absolute values is advantageous to harmonize the metrics across trucks and trailers. 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 measures only the change in CO_2 emissions compared with standard trailers, relaxes the constraints placed on the definition and characterization of the standard tractors used in VECTO simulations (Rodríguez, 2018b).

The selection of trailer types to be covered by the CO_2 certification can be done by using available market data. The trailer market is diverse, with a great variety of trailer designs produced by manufacturers large and small. As a consequence, the CO_2 certification of all trailer types would require significant resources for determining the base CO_2 performance of combinations of standard tractors and standard trailers. This warrants a narrower focus on the trailer types that have the greatest impact on CO_2 emissions. Market data (Sharpe & Rodríguez, 2018) shows that curtain-side semi-trailers are the most popular trailer type, accounting for 43% of new registrations in 2016. Refrigerated semi-trailers have 15% of the market and dry box, 10%. These three trailer types share a common geometry, categorized as box trailers, making them ideal candidates for the application of aerodynamic technologies. Trailers with more-complex geometries, which amounted to 32% of the EU market in 2016, can still be covered by the CO_2 regulation by considering lightweighting and rolling resistance improvements only.

Aerodynamic technologies can be certified using an absolute metric where the air drag area (CdA) of a standard tractor pulling the trailer being is measured, or as the change in air drag area (ΔCdA) relative to a baseline trailer. The latter is the methodology adopted in the U.S. GHG Phase 2 trailer standards under the name of "A to B testing" (U.S. EPA & U.S. DOT, 2016). A to B testing also minimizes the impact of the tractor design on the ΔCdA results (Rodríguez, 2018b).

The CO_2 certification framework for HDVs already includes provisions for aerodynamic testing, the EU constant speed testing (CST). The high complexity of the CST procedure, however, justifies the consideration of alternative aerodynamic determination procedures for trailers that can lower the compliance cost for small trailer manufacturers. Wind tunnel and computational fluid dynamics (CFD) are suitable candidates for this. Nevertheless, these methodologies must be well defined for regulatory purposes. The use of pre-approved aerodynamic devices provides yet another possible pathway for trailer aerodynamic certification. Under this approach, the certification burden shifts from trailer manufacturers to aerodynamic device manufacturers. This approach is allowed in the United States under the GHG Phase 2 standards (U.S. EPA & U.S. DOT, 2016).

The last area of different policy options to consider (see Figure 10) is how to calculate the CO_2 performance of trailers. This can be achieved by performing vehicle simulations in VECTO, or by the use of a standardized equation determined with VECTO. A previous analysis by the ICCT (Rodríguez, 2018b) shows that the use of a standardized equation can reduce the compliance burden on trailer manufacturers without compromising accuracy or compatibility with VECTO. This is the approach followed in the U.S. Phase 2 GHG standards for trailers.

The possible options for certifying trailer CO_2 performance are summarized in Table 5.

Table 5. Summary of options for establishing a trailer CO_2 certification procedure.

Trailer CO_2 certification element	Regulatory design options
CO_2 metric and standard tractor	• Absolute metric, determined with a tightly defined standard tractor • Relative metrics capturing the change in CO_2 compared with a standard trailer. The requirements for the definition of the standard tractor are relaxed.
Trailer types covered by CO_2 certification	• All trailers • Trailers for which at least one road-load technology is applicable • Trailers for which aerodynamic technologies are applicable
Aerodynamic drag	• Metric: Absolute drag area or change in drag area (ΔCdA) relative to baseline. • Determination: Constant-speed test, wind tunnel testing, computational fluid dynamics (CFD) simulation, pre-approved aerodynamic devices
Determination of CO_2 performance	• VECTO simulation • Standardized equation depending on only the key parameters (i.e., mass, air drag, and rolling resistance)

RECOMMENDATIONS FOR CO_2 CERTIFICATION OF TRAILERS

The inclusion of trailer technologies in the current HDV CO_2 certification methodology is a necessary first step in the development of policies aimed at overcoming the prevailing market barriers that hinder the development and deployment of trailer technologies. Based on the previous 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 to 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 4x2 tractor defined in VECTO can be used as 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: Curtain siders, refrigerated box vans, and dry box vans. These three types have a similar geometry and can benefit from aerodynamic improvements. The remaining trailer types exhibit larger geometric variations, complicating the definition of standard geometries. Nevertheless, improvements in rolling resistance and lightweighting can still be easily accounted for. Therefore, two main categories are recommended for trailer CO_2 certification: Aero, applying to curtain-siders, refrigerated box vans, and dry box vans; and non-aero, applying to container chassis, swap body, multi axle, flatbeds, and others.
- **Determination of air drag area:** Air drag determination through constant speed testing requires resources that can impose significant burdens on trailer manufacturers and negatively impact small companies. The use of CFD simulations reduces the complexity of air drag determination. However, the boundary conditions, such as 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 CO_2 performance:** The use of a trailer CO_2 equation for certification reduces the administrative burden on trailer manufacturers. A trailer CO_2 equation—a linear model depending on the change of aerodynamic drag, rolling resistance, and weight reductions—has very good agreement with full VECTO simulations. This ensures compatibility between trailer and tractor CO_2 certifications.

OTHER ADVANCED TECHNOLOGIES

A simulation-based CO_2 certification methodology must seek a balance between the complexity of simulation models, the effort for collecting component data, and the resulting accuracy of calculations. As a result, it is unfeasible for simulation models such as VECTO to include all possible technologies for the reduction of CO_2 emissions. Still, to incentivize the development and deployment of technologies not captured by VECTO, it is desirable to reward manufacturers and consumers adopting such technologies within the CO_2 regulatory framework. Understandably, manufacturers and component suppliers have called for a procedure to rapidly implement new technologies into the certification procedure (ACEA, 2019; CLEPA, 2019).

In the United States, technologies not captured by the U.S. vehicle simulation model (GEM) can receive off-cycle credits. Any credits for these technologies have to be based on real-world fuel consumption and CO_2 reductions that can be measured with verifiable test methods and using representative driving conditions typical of the vehicle application. The regulatory agencies must approve on a case-by-case basis the test procedure and the resulting off-cycle credits proposed by the manufacturer. The test plan detailing testing methodology must be approved before collecting any test data and may be subject to a public evaluation process in which the public would have opportunity for comment. The application for off-cycle credits requires the following items:

1. A detailed description of the technology and how it reduces CO_2 emissions.
2. A list of the vehicle configurations that will be equipped with the technology.
3. A detailed description and justification of the selected test vehicles.
4. A complete description of the methodology used to estimate the off-cycle benefit of the technology and all supporting data, including vehicle testing and in-use activity data, plus any other data considered in the analysis.
5. An estimate of the off-cycle benefit by vehicle model, and the fleetwide benefit based on projected sales of vehicle models equipped with the technology.
6. A demonstration of the in-use durability of the off-cycle technology, based on any available engineering analysis or durability testing.

Off-cycle technology credits are not part of the European regulatory framework for HDVs, although they already exist in the framework for light-duty vehicles (LDVs). The post-2020 CO_2 standards for LDVs allow the use of eco-innovations to incentivize the development and uptake of efficiency technologies. At their core, the eco-innovations mechanism rewards innovative technologies that produce real-world CO_2 savings beyond what is measured over the standardized test cycle during vehicle type approval. Both vehicle manufacturers and component suppliers can apply for eco-innovations certification in the LDV framework.

Reflecting the differences in certification methodology between HDVs and LDVs, the eco-innovations approach cannot be directly transposed into the CO_2 certification framework for HDVs. However, the recent addition of advanced driver assistance systems (ADAS) as a new technology in the HDV CO_2 certification framework offers valuable lessons for the crediting of technologies not yet captured by VECTO and for streamlining their inclusion in the certification methodology. The ADAS case is presented in detail below.

ADVANCED DRIVER ASSISTANCE SYSTEMS

Advanced driver assistance systems contribute to lowering CO_2 emissions by reducing the influence of driving behavior, minimizing idling, and optimizing the use of vehicles' kinetic energy. Some of these technologies, such as predictive cruise control (PCC) systems, have experienced a significant increase in market penetration during the past decade and are expected to be thoroughly deployed in the coming decade (Rodríguez, Muncrief, Delgado, & Baldino, 2017). Table 6 provides an overview of the commercial names of PCC systems and their years of introduction to the market.

Table 6. Predictive cruise control systems by manufacturer

Manufacturer	PCC name	Introduction year
Daimler	Predictive Powertrain Control	2012
Volvo	I-See	2013
Scania	Opticruise	2014
DAF	Predictive Cruise Control	2015
MAN	EfficientCruise	2015
Iveco	Hi-Cruise	2016
Renault	Optivision	2016

The original HDV CO_2 certification regulation (EU) 2017/2400 did not include provisions for the certification of ADAS systems. However, the regulation has been recently amended to consider the following technologies (European Commission, 2019):

» **Engine stop-start:** Designed to reduce engine idling time during vehicle stops longer than 3 seconds by automatically shutting down and restarting the engine.

» **Eco-roll with engine idling:** Designed to minimize engine drag during downhill driving by automatically decoupling the engine from the drivetrain. In the decoupled phase the engine idles.

» **Eco-roll with engine shutdown:** Designed to eliminate the fuel use associated with engine drag and idling during downhill driving by automatically decoupling the engine from the drivetrain. In the decoupled phase the engine is shut down.

» **Predictive cruise control:** Predictive cruise control (PCC) systems incorporate advanced telematics and digital road maps to control vehicle speed and shifting logic of automated manual transmissions. By using GPS technology to determine vehicle location and driving conditions and combining them with upcoming road grade from the digital road maps, the PCC determines the ideal vehicle speed and shifting pattern for reduced fuel consumption. For example, when approaching a crest, the vehicle velocity is reduced to allow gravity to accelerate the vehicle back to its set speed and reduce braking during the downhill phase. Alternatively, when approaching the bottom of a downhill phase, the PCC increases the allowed over-speed to end the downhill event with higher vehicle velocity and reduce engine work during the subsequent uphill operation.

The European Commission decided to certify ADAS in a two-step approach. As an initial step, a *quick fix* was finalized in 2018 in which fixed CO_2 reduction factors are given for the different ADAS combinations as a function of vehicle group, mission profile, and payload. TU Graz estimated the different CO_2 reduction factors by post-processing results of VECTO simulations of typical vehicles and by applying a *conservatism factor* aimed at ensuring that the long-term approach for ADAS certification does not produce lower CO_2 reduction factors than the quick fix. The CO_2 reduction factors are then hard-coded directly into VECTO (European Commission, 2018).

The long-term implementation of ADAS into the certification system involves developing an in-the-loop simulation approach, in which the driver, engine, transmission, and brake modules within VECTO interact following a generic control strategy that uses as input the vehicle operating conditions and the grade profile of the drive cycle. The challenge, as in the other advanced technologies presented in this paper, is to design a generic control algorithm that can be accepted by all manufacturers as a satisfactory representation of their proprietary systems.

RECOMMENDATIONS FOR THE CERTIFICATION OF OTHER ADVANCED TECHNOLOGIES

The experiences gathered in the development of a rapid certification approach for ADAS in the EU, as well as the regulatory approach used in the United States to credit off-cycle technologies, provide useful elements for establishing a robust methodology to credit innovative technologies into the CO_2 certification framework. The following elements are recommended in any innovative technology credits framework:

» **Innovative technology credits should be transparent and open for scrutiny by regulators and researchers.** Because innovative technology credits can have great significance toward compliance with CO_2 targets, it is necessary to ensure that the regulatory provisions are immune to manipulation and remain relevant over time. The experience of the United States with passenger vehicles (Lutsey & Isenstadt, 2018) shows that off-cycle technologies and related regulations should be closely monitored to avoid adverse impacts on fuel-efficiency standards. While the timeline of market introduction and deployment strategies of a given technology by a given manufacturer can be considered confidential, the technology and testing procedure rarely are. Therefore, the test procedure for determining innovative technology credits should be subject to a public evaluation process and should not disclose intentions by individual manufacturers.

» **Limits should be placed on the definition of an innovative technology.** To ensure that any innovative technology credits incentivize novel technologies, the application and approval procedure for such credits should be restricted to technologies meeting minimum criteria. For example, technologies must have low market penetration, not be mandated by any other regulation, and produce measurable CO_2 reductions in a statistically significant manner, and their effectiveness should not depend on drivers' decisions.

» **Standardized methods for determining innovative technology credits should be developed and enshrined in the regulation.** The methods and boundary conditions to evaluate the benefits of innovative technologies should be defined in the certification regulation. Chassis dyno testing, powertrain testing, and on-road testing as defined in the Verification Test Procedure (European Commission, 2019) are well established methods for that end. While software innovations can be evaluated using software in-the-loop (SIL), a standardized SIL methodology must first be developed.

» **Detailed documentation should be required for approval of innovative technology credits.** A detailed description of the innovative technology and its working principle as well as the test plan for estimating its benefits should be submitted and approved by the type-approval authority. This information, together with all supporting data—vehicle testing, in-use activity, fleetwide benefit estimate, and durability demonstration—should be shared with the European Commission to assess the full implementation of the technology into VECTO.

- **Innovative technology credits must be part of market surveillance activities.** Clear provisions are necessary to regularly verify the CO_2 savings of innovative technologies. If discrepancies are identified, manufacturers should provide evidence that certified CO_2 savings are accurate; otherwise the CO_2 savings should be disregarded for compliance purposes and penalties should be introduced.
- **A two-step approach should be pursued.** Any innovative technology credits should be just the first step toward implementation in VECTO. Such technology credits should be adjusted by a *conservatism factor* aimed at ensuring that the long-term implementation does not produce lower CO_2 reduction factors than estimated by the innovative technology credits.

CONCLUSIONS AND RECOMMENDATIONS

Several market barriers exist that hamper the uptake of cost-effective fuel-saving technologies in the HDV sector, warranting stronger regulatory action to correct these market inefficiencies. The European Commission has put forward a regulatory package that includes the certification, monitoring, and reporting of CO_2 emissions from new HDVs, as well as mandatory CO_2 reduction targets. To meet the CO_2 reduction targets, truck manufacturers will have to increase the deployment of commercially available fuel-saving technologies, as well as bring to the market technologies that, although mature, have not yet been produced in series.

Given that the regulatory package put forward by the European Commission rests on the CO_2 certification procedure, it is essential that the methodology capture as many technologies as possible, with a focus on those already in the market or close to breaking into it. Failing to do so can have long-lasting implications on the future technology landscape, as technologies on the brink of commercialization or with low market adoption would not have the right incentives to progress along the adoption cycle because they would not represent a viable compliance pathway.

This paper discusses the certification options for the following technologies that are currently not fully considered in the CO_2 certification procedure: powertrain hybridization and electrification, waste heat recovery, trailer technologies, and other advanced technologies.

The following policy recommendations can be extracted from the analysis:

Hybrid powertrains: The spectrum of potential hybrid architectures, component combinations, and control strategies is enormous. Development of new, complex certification methodology can be a lengthy process and can result in delays in technology adoption. A two-step approach is recommended. In the first step, a simple simulation methodology focused on the most prevalent hybrid configurations can be introduced to enable the CO_2 certification of products close to commercialization. The development of more accurate and complex approaches can continue in parallel, to be introduced in a second phase. In particular, we recommend the consideration of powertrain testing as an alternative certification pathway (Figure 3).

Electric powertrains: We recommend the timely development of an energy consumption and driving range certification methodology, compatible with the current regulatory framework. This can be easily accomplished by extending VECTO's model architecture with additional electric modules. The simulation of electric powertrains in VECTO is more straightforward than the simulation of hybrid powertrains, since the energy management strategy does not need to account for the interaction between conventional and electric componentry. Given the rapidly growing electric-truck portfolio in the EU, the extension of VECTO to simulate electric-only powertrains is a priority. A certified electric range is a prerequisite for the design of smart regulations that incentivize the harder-to-electrify segments and that provide a positive regulatory signal for manufacturers to plan their long-term investments in research and development.

WHR systems: Methodologies based on testing the engine and WHR as a complete system are the most attractive in terms of development, facilities, and certification effort. Since the thermal stabilization periods for the engine-WHR combination are longer than for the engine alone, it is necessary to extend the duration of the fuel mapping cycle when testing an engine-WHR combination. We recommend the use of the cycle-average mapping methodology, which provides a robust transient correction methodology, as it creates a direct link between the vehicle drive cycles and the cycles used in engine testing. The cycle-average approach has been thoroughly validated by U.S. EPA as a certification procedure, and its performance is well documented.

Trailer CO_2 certification: The starting point of any policy measure to incentivize the development and deployment of trailer technologies for reducing CO_2 emissions is the development of a certification methodology that captures their CO_2 and fuel consumption benefits. To minimize the certification burden on trailer manufacturers, it is desirable to simplify the regulatory design as much as possible. These simplifications are possible without compromising the accuracy of the certification process.

Other advanced technologies: Innovative technology credits can be a useful tool to measure and incentivize the development and uptake of efficiency technologies. However, a robust regulatory design is required to ensure that real-world CO_2 reductions are achieved that would otherwise not take place. Such credits should be transparent and open for scrutiny from regulators and researchers, and there should be limits on the definition of an innovative technology. Open and standardized methods should be developed for manufacturers to demonstrate and seek approval of innovation credits. Such approval process must be well documented to ensure the future verification of the claimed CO_2 savings of innovative technologies. These credits should not be an end in themselves but just a stepping stone toward implementation of additional technologies in VECTO.

REFERENCES

AB Volvo. (2018a). Premiere for Volvo Trucks' first all-electric truck. Retrieved January 25, 2019, from https://www.volvogroup.com/en-en/news/2018/apr/news-2879838.html

AB Volvo. (2018b). Volvo Trucks presents second electric truck model in three weeks. Retrieved January 25, 2019, from https://www.volvogroup.com/en-en/news/2018/may/news-2912374.html

ACEA. (2019, June 18). *Long-term development and future perspectives of VECTO*. Presented at the JRC Workshop on the long-term strategy and future perspectives of VECTO, Ispra, Italy.

Anthony, J. W., Sarlashkar, J. V., Phan, A., Roberts, C. E., Zhang, H., Sanchez, J., … Cullen, A. (2015). Powertrain test cell and its test procedure development for greenhouse gas emission measurements. *International Journal of Powertrains*, *4*(3), 263. https://doi.org/10.1504/IJPT.2015.071729

AQSIQ. (2015). *Test methods for energy consumption of heavy-duty hybrid vehicles* (No. GB/T 19754-2015). People's Republic of China.

Bettoja, F., Perosino, A., Lemort, V., Guillaume, L., Reiche, T., & Wagner, T. (2016). NoWaste: Waste heat re-use for greener truck. *Transportation Research Procedia*, *14*, 2734–2743. https://doi.org/10.1016/j.trpro.2016.05.456

BYD. (2018). Electric tough. Retrieved January 25, 2019, from http://en.byd.com/usa/truck/

Chambon, P. H., & Deter, D. D. (2016). *Powertrain test procedure development for EPA GHG certification of medium- and heavy-duty engines and vehicles* (No. ORNL/TM-2016/312). https://doi.org/10.2172/1295141

CLEPA. (2019, June 18). *CLEPA perspectives on the future of VECTO*. Presented at the JRC Workshop on the long-term strategy and future perspectives of VECTO, Ispra, Italy.

DAF. (2018a). Electric & hybrid trucks. Retrieved January 25, 2019, from https://www.daf.com/about-daf/innovation/electric-and-hybrid-trucks

DAF. (2018b). Jumbo takes delivery of first DAF CF electric. Retrieved January 25, 2019, from https://www.daf.com/en/news-and-media/news-articles/global/2018/q4/18-12-2018-jumbo-takes-delivery-of-first-daf-cf-electric

Daimler AG. (2018). All-electric Mercedes-Benz trucks for the heavy-duty distribution sector. Retrieved January 25, 2019, from https://media.daimler.com/marsMediaSite/en/instance/ko.xhtml?oid=33451264&relId=1001&resultInfoTypeId=175#toRelation

Delgado, O. (2016). *Stage 3 China fuel consumption standard for commercial heavy-duty vehicles*. Retrieved from the International Council on Clean Transportation http://www.theicct.org/publications/stage-3-china-fuel-consumption-standard-commercial-heavy-duty-vehicles

Delgado, O., Rodríguez, F., & Muncrief, R. (2017). *Fuel efficiency technology in European heavy-duty vehicles: baseline and potential for the 2020–2030 time frame*. Retrieved from the International Council on Clean Transportation http://www.theicct.org/EU-HDV-fuel-efficiency-tech-2020-2030

E-Force AG. (2019). E-Force One AG - products. Retrieved August 20, 2019, from https://eforce.ch/products/e-trucks

electrive.com. (2019). BYD all-electric trucks and vans coming to Europe. Retrieved January 31, 2019, from Electrive.com website: https://www.electrive.com/2019/01/31/byd-all-electric-trucks-and-vans-coming-to-europe/

electrive.net. (2018). MAN übergibt Elektro-Lkw eTGM an neun Kunden. (MAN hands over eTGM electric trucks to nine customers). Retrieved January 25, 2019, from https://www.electrive.net/2018/09/14/man-uebergibt-elektro-lkw-etgm-an-neun-kunden/

European Commission. (2017). 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*. Retrieved from http://data.europa.eu/eli/reg/2017/2400/oj

European Commission. (2018). *VECTO: FREQUENTLY ASKED QUESTIONS (FAQ)* (No. V4). Retrieved from https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/vecto/faq_en.pdf

European Commission. (2019). Commission Regulation (EU) 2019/318 of 19 February 2019 amending Regulation (EU) 2017/2400 and Directive 2007/46/EC of the European Parliament and of the Council as regards the determination of the CO_2 emissions and fuel consumption of heavy-duty vehicles (Text with EEA relevance.). *Official Journal of the European Union*, *L 58*. Retrieved from http://data.europa.eu/eli/reg/2019/318/oj

eurotransport.de. (2018). MAN eTGM bei Porsche. Elektro-Lkw für Elektro-Sportwagen. (MAN eTGM at Porsche. Electric truck for electric sports cars) Retrieved January 25, 2019, from https://www.eurotransport.de/artikel/man-etgm-bei-porsche-elektro-lkw-fuer-elektro-sportwagen-10634603.html

Glensvig, M., Schreier, H., Tizianel, M., Theissl, H., Krähenbühl, P., Cococcetta, F., & Calaon, I. (2016, September 27). *Testing of a long haul demonstrator vehicle with a waste heat recovery system on public road*. https://doi.org/10.4271/2016-01-8057

Grelet, V., Reiche, T., Lemort, V., Nadri, M., & Dufour, P. (2016). Transient performance evaluation of waste heat recovery Rankine cycle based system for heavy duty trucks. *Applied Energy*, *165*, 878–892. https://doi.org/10.1016/j.apenergy.2015.11.004

Hausberger, S. (2019). *Further development of VECTO. WHR related work* [WHR working group meeting]. TU Graz.

Liu, X., Yebi, A., Anschel, P., Shutty, J., Xu, B., Hoffman, M., & Onori, S. (2017). *Model predictive control of an automotive organic Rankine cycle system* (p. 20). Retrieved from BorgWarner website: http://www.orc2017.com/uploads/File/Presentations/23.pdf

Low Carbon Vehicle Partnership. (2019, February 6). Buses lead the way on the 'Road to Zero.' Retrieved June 17, 2019, from LowCVP website: http://www.lowcvp.org.uk/news,buses-lead-the-way-on-the-road-to-zero_3911.htm

Lutsey, N., & Isenstadt, A. (2018). *How will off-cycle credits impact U.S. 2025 efficiency standards?* Retrieved from the International Council on Clean Transportation https://www.theicct.org/publications/US-2025-off-cycle

Mahmoudi, A., Fazli, M., & Morad, M. R. (2018). A recent review of waste heat recovery by Organic Rankine Cycle. *Applied Thermal Engineering*, *143*, 660–675. https://doi.org/10.1016/j.applthermaleng.2018.07.136

MAN AG. (2019). The new MAN CitE. Retrieved January 25, 2019, from https://www.truck.man.eu/de/en/cite.html

Mathieu, L. (2018). *Electric buses arrive on time*. Retrieved from Transport & Environment website: https://www.transportenvironment.org/publications/electric-buses-arrive-time

Meszler, D., Delgado, O., Rodriguez, F., & Muncrief, R. (2018). *European heavy-duty vehicles – Cost effectiveness of fuel efficiency technologies for long-haul tractor-trailers in the 2025-2030 timeframe*. Retrieved from the International Council on Clean Transportation http://theicct.org/publications/cost-effectiveness-of-fuel-efficiency-tech-tractor-trailers

Mitsubishi Fuso. (2017). E-Canter. Retrieved January 25, 2019, from http://www.efuso.jp/ecanter/

Moultak, M., Lutsey, N., & Hall, D. (2017). *Transitioning to zero-emission heavy-duty freight vehicles*. Retrieved from the International Council on Clean Transportation http://theicct.org/zero-emission-freight-trucks-2017

Nikola. (2019). Nikola TRE. Retrieved January 25, 2019, from https://nikolamotor.com/tre

Orr, B., Akbarzadeh, A., Mochizuki, M., & Singh, R. (2016). A review of car waste heat recovery systems utilising thermoelectric generators and heat pipes. *Applied Thermal Engineering*, *101*, 490–495. https://doi.org/10.1016/j.applthermaleng.2015.10.081

Parliament and Council of the European Union. (2019). Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 setting CO_2 emission performance standards for new heavy-duty vehicles and amending Regulations (EC) No 595/2009 and (EU) 2018/956 of the European Parliament and of the Council and Council Directive 96/53/EC. *Official Journal of the European Union*, *L 198*. Retrieved from http://data.europa.eu/eli/reg/2019/1242/oj

Renault Trucks. (2018). Renault Trucks unveils its second generation of electric trucks: A complete Z.E. range from 3.1 to 26t. Retrieved January 25, 2019, from https://corporate.renault-trucks.com/en/press-releases/2018-06-26-renault-trucks-unveils-its-second-generation-of-electric-trucks.html

Rodríguez, F. (2018a). *Certification of CO_2 emissions and fuel consumption of on-road heavy-duty vehicles in the European Union* [Policy update]. Retrieved from the International Council on Clean Transportation https://www.theicct.org/publications/certification-co2-emissions-and-fuel-consumption-road-heavy-duty-vehicles-european

Rodríguez, F. (2018b). *Trailer CO_2 certification in the European Union*. Retrieved from the International Council on Clean Transportation https://www.theicct.org/publications/certification-hd-trailers-europe

Rodríguez, F. (2019). *CO_2 standards for heavy-duty vehicles in the European Union* [Policy update]. Retrieved from the International Council on Clean Transportation https://www.theicct.org/publications/co2-stds-hdv-eu-20190416

Rodríguez, F., Muncrief, R., Delgado, O., & Baldino, C. (2017). *Market penetration of fuel efficiency technologies for heavy-duty vehicles in the EU, US and China*. Retrieved from the International Council on Clean Transportation http://www.theicct.org/market-penetration-HDV-fuel-efficiency-technologies

Scania AB. (2018). Scania to supply 15 trucks for German e-highways. Retrieved January 25, 2019, from https://www.scania.com/group/en/scania-to-supply-15-trucks-for-german-e-highways/

Scharrer, O. (2018). *The power of innovation and regulation* (p. 5) [Presentation]. Retrieved from MAHLE International GmbH website: https://www.transportenvironment.org/sites/te/files/The%20Power%20of%20Innovation%20andRegulation.pdf

Sharpe, B., & Rodríguez, F. (2018). *Market analysis of heavy-duty commercial trailers in Europe*. Retrieved from the International Council on Clean Transportation https://www.theicct.org/publications/market-analysis-hd-trailers-europe

Silberholz, G., & Hausberger, S. (2017). *Feasibility assessment regarding the development of VECTO for hybrid heavy-duty vehicles: Final report.* Retrieved from https://publications.europa.eu/en/publication-detail/-/publication/03daabae-1851-11e8-ac73-01aa75ed71a1/language-en

Subramanian, S. N. (2017). *Affordable Rankine cycle waste heat recovery for heavy duty trucks* (No. DOE-EATON-0007286). https://doi.org/10.2172/1375960

Tesla. (2019). Tesla semi. Retrieved January 25, 2019, from https://www.tesla.com/semi

Thiruvengadam, A., Pradhan, S., Thiruvengadam, P., Besch, M., Carder, D., & Delgado, O. (2014). *Heavy-duty vehicle diesel engine efficiency evaluation and energy audit*. Retrieved from http://www.theicct.org/heavy-duty-vehicle-diesel-engine-efficiency-evaluation-and-energy-audit

TU Graz. (2019, October 4). *Workshop on hybrids in VECTO*. Presented at the Graz, Austria. Graz, Austria.

United Nations Economic Commission for Europe. (2015). *Addendum 4: Global technical regulation No. 4*. Retrieved from UNECE website: https://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29r-1998agr-rules/ECE-TRANS-180a4a3e.pdf

U.S. EPA, & U.S. DOT. (2016). *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]. Retrieved from https://www.gpo.gov/fdsys/pkg/FR-2016-10-25/pdf/2016-21203.pdf

Yang, K., Grill, M., & Bargende, M. (2019). Simulative investigation of the influence of a Rankine cycle based waste heat utilization system on fuel consumption and emissions for heavy duty utility vehicles. In C. Junior & O. Dingel (Eds.), *Energy and Thermal Management, Air-Conditioning, and Waste Heat Utilization* (pp. 172–193). Springer International Publishing.

Zhang, H., Sanchez, J., & Spears, M. W. (2015). Alternative heavy-duty engine test procedure for full vehicle certification. *SAE International Journal of Commercial Vehicles*, *8*(2), 364–377. https://doi.org/10.4271/2015-01-2768

Zhang, H., Sanchez, L. J., Spears, M., Sarlashkar, J., Robertson, D., & Ross, M. (2016). Cycle-average heavy-duty engine test procedure for full vehicle certification—numerical algorithms for interpreting cycle-average fuel maps. *SAE International Journal of Commercial Vehicles*, *9*(2), 105–119. https://doi.org/10.4271/2016-01-8018