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BRIEFING

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A roadmap for heavy-duty engine CO_2 standards within the European Union framework

Four countries around the world – Japan, the United States, Canada, and China – now have CO_2 or efficiency standards for heavy-duty vehicles (HDVs). Two of the four, the United States and Canada, have separate engine standards in addition to full-vehicle regulations to specifically drive improvements in engine efficiency. Japan's standard, although officially a vehicle-level requirement, is designed mainly to promote improvements in the engine and powertrain, since aerodynamic and rolling resistance advances are not credited in the existing regulation. The European Union is currently evaluating the available options for the regulatory design of its future CO_2 standards for HDVs.

Studies show that there is potential to reduce fuel consumption from that of today's HDVs by 30% to 40%[1] using conventional technologies that mainly work to increase the diesel engine's efficiency and reduce the vehicle's road-load power demand. On average, a third to half of this projected fuel efficiency gain comes from improvements in engine thermal efficiency, although some of these benefits are facilitated by transmission improvements and the deep integration of transmission and engine controllers.

1 Oscar Delgado, Felipe Rodriguez, and Rachel Muncrief, *Fuel Efficiency Technology in European Heavy-Duty Vehicles: Baseline and Potential for the 2020–2030 Time Frame* (ICCT: Washington DC, 2017). http://theicct.org/EU-HDV-fuel-efficiency-tech-2020-2030.

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A previous ICCT study[2] found a number of benefits to instituting a separate engine standard in conjunction with a full vehicle standard. The benefits identified in that study include:

1. Ensuring long-term investment in engine efficiency technology R&D. Developing more-efficient diesel engines requires up-front investment in R&D. A regulation with periodic mandated improvements in engine efficiency gives manufacturers the certainty to make these investments.

2. Maintaining the link between NO_x and CO_2 and therefore ensuring that CO_2 targets are met without compromising very low in-use criteria pollutant emission levels. Regulating CO_2 and NO_x over the same test cycle minimizes potential gaming in which an engine might be tuned for low NO_x/high CO_2 emissions during engine type approval (referred to as certification in the U.S.) versus high NO_x/low CO_2 emissions over full vehicle tests or in-use operation.

3. Minimizing the testing burden by using existing test procedures with which industry is very familiar. Engine CO_2 standards do not require a new test protocol as CO_2 is measured during the existing engine type-approval test.

4. Acknowledging the current market structure by allowing engines to be certified individually and sold into many different vehicle platforms. In the heavy-duty market, a single engine model may be used in a range of vehicle types. A separate engine standard allows for benefits to be realized across all segments of the HD fleet.

There are three key steps to conceiving an engine standard: (1) setting the baseline, which would typically involve collecting and analyzing recent engine CO_2 data; (2) segmenting the market to determine how to group the HD engines for the purpose of regulation, a process that would typically take into consideration the type of vehicle in which the engine will be used; and (3) defining the stringency and timing to determine the ambition of the regulation. Using the U.S. HD engine CO_2 standard for guidance, this briefing paper investigates the potential for a similar standard in the EU.

HDV CO_2 POLICYMAKING STATUS IN THE EU

The EU has committed to ambitious and binding CO_2 targets. The EU's 2030 climate and energy framework[3] requires the transport, building, and agriculture sectors to reduce greenhouse gas emissions to 30% below a 2005 baseline by 2030. While the EU has imposed CO_2 emission limits on cars, no mandatory reductions have yet been put in place for HDVs. Such restrictions will most likely be needed to meet the EU's CO_2 targets.[4] In mid-2016 the European Commission announced a plan to propose

2 Ben Sharpe, Oscar Delgado, and Rachel Muncrief, *Comparative Assessment of Heavy-Duty Vehicle Regulatory Design Options for U.S. Greenhouse Gas and Efficiency Regulation* (ICCT: Washington DC, 2014). http://www.theicct.org/us-phase2-hdv-regulation-design-options.

3 European Commission, "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Policy Framework for Climate and Energy in the Period from 2020 to 2030" (2014). http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2014:15:FIN.

4 Joshua Miller, *Reducing CO_2 Emissions from Road Transport in the European Union: An Evaluation of Policy Options* (ICCT: Washington DC, 2016). http://theicct.org/evaluating-policy-options-reducing-CO2-from-transport-EU.

standards addressing CO_2 from HDVs. The statement left open the possibility of including engine or whole-vehicle standards with the objective of "curbing emissions well before 2030."[5]

On May 11, 2017, during the 67th meeting of the Technical Committee - Motor Vehicles, member states of the European Union unanimously adopted[6] the draft implementing act put forward by the European Commission on type approval of CO_2 emissions and fuel consumption for heavy-duty vehicles. The new type-approval procedure, based on a combination of component testing and a vehicle simulation tool known as VECTO, assigns an officially declared CO_2 value for a given HDV. In addition, the EU has a well-established framework to type-approve HD engines for pollutant emissions[7] such as NO_x and PM. The current pollutant regulation for HD engines in the EU, known as Euro VI, has been in effect since 2014. A key feature of the Euro VI regulation is the new transient and stationary test cycles that were developed for the regulation, known as the World Harmonized Heavy Duty Transient and Stationary Cycles, or WHTC and WHSC. These replace the previous cycles used in Euro IV and V type approval, known as the European Transient and European Stationary Cycles, ETC and ESC. Another requirement of the Euro VI regulation is that work-specific CO_2 emissions and fuel consumption are measured and reported to the relevant authority as part of the type-approval process.

U.S. HEAVY-DUTY ENGINE CO_2 STANDARDS

The United States has in place engine CO_2 standards[8] that have covered new engines since 2014. These standards were designed and implemented in conjunction with full-vehicle CO_2 standards and have been rolled out in two steps, Phase 1[9] and Phase 2.[10]

For both phases, the engine CO_2 standards are segmented based on the type – tractor or non-tractor – and "primary intended service class" of the vehicle in which the engine will be used. For diesel engines, "the primary intended service classes" are light heavy-duty (LHD), medium heavy-duty (MHD), and heavy heavy-duty (HHD). Manufacturers identify the class that best describes the engine family. Gross vehicle weight (GVW) is

5 European Commission, "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A European Strategy for Low-Emission Mobility" (2016). http://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:52016DC0501.

6 At the time of writing this paper, the regulation had not been published in the *Official Journal of the European Union*. The final adopted draft text can be found in the Comitology Register: http://ec.europa.eu/transparency/regcomitology/index.cfm?do=search.documentdetail&Dos_ID=14393&DS_ID=51106&Version=1.

7 "Regulation (EC) No 595/2009 of the European Parliament and of the Council of 18 June 2009 on Type-Approval of Motor Vehicles and Engines with Respect to Emissions from Heavy Duty Vehicles (Euro VI) and on Access to Vehicle Repair and Maintenance Information and Amending Regulation (EC) No 715/2007 and Directive 2007/46/EC and Repealing Directives 80/1269/EEC, 2005/55/EC and 2005/78/EC (Text with EEA Relevance)" (Brussels: European Commission, July 18, 2009), OJ L 188, 18.7.2009, p. 1009. http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32009R0595.

8 In the United States, the standards are referred to as GHG standards, since they also include separate limits on CH_4 and N_2O.

9 "Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles", 76 FR 57105. https://www.federalregister.gov/documents/2011/09/15/2011-20740/greenhouse-gas-emissions-standards-and-fuel-efficiency-standards-for-medium--and-heavy-duty-engines.

10 "Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles–Phase 2", 81 FR 73478. https://www.federalregister.gov/documents/2016/10/25/2016-21203/greenhouse-gas-emissions-and-fuel-efficiency-standards-for-medium--and-heavy-duty-engines-and.

the primary characteristic that distinguishes the classes.[11] Throughout this document we will use GVW instead of "primary intended service class" when discussing engine segmentation. The U.S. engine CO_2 standard includes five segments for diesel engines:

1. Engines that will be used in tractors of 11.8-15 tons GVW.
2. Engines that will be used in tractors of more than 15 tons GVW.
3. Engines that will be used in non-tractors[12] of 3.9-8.8 tons GVW.
4. Engines that will be used in non-tractors of 8.8-15 tons GVW.
5. Engines that will be used in non-tractors of more than 15 tons GVW.

The U.S. standard considers that tractor engines are more likely to be driven on the highway in a steady state and that non-tractors are more likely to be driven in transient operation. Therefore, the tractor engines are required to meet a CO_2 limit over a steady-state engine cycle, known as the Supplemental Emission Test, or SET, and the non-tractor engines are required to meet a CO_2 limit over the transient engine cycle, known as the Federal Test Procedure, or FTP.

The Phase 1 and Phase 2 engine CO_2 limits are shown in Tables 1 and 2. There are a few important details to note. Firstly, the standard is met for each manufacturer based on the sales-weighted average for each segment. For example, the sales-weighted average CO_2 emissions of all diesel engines sold by a given manufacturer for 15+ ton tractors in 2017 must be 617 g/kWh. This means that some engines may have lower or higher CO_2 values within a given segment. Secondly, the SET cycle used for Phase 1 and Phase 2 is slightly different. The SET cycle under Phase 1 gives a specific weighting to each of the steady-state speed and load points. This weighting is identical to the weighting used to certify HD engines for NO_X and other air pollutants. The discrete mode[13] of the Phase 1 SET cycle matches the European Stationary Cycle (ESC), one of the test cycles used to certify HD engines in Europe before Euro VI. The SET weightings for Phase 2 were changed to better reflect the operational points of modern engines. The weighting was shifted toward lower RPM points and away from the highest RPM points. The SET points and Phase 1 and Phase 2 weightings are shown in Table 3. Thirdly, the baseline values for Phase 2 do not match up precisely with the final step for Phase 1. For tractor engines, this is due to the recalculation of the SET baseline using the new Phase 2 weighting factors. For non-tractor engines, this is due to recalculation of the FTP baseline, based on the type-approval data over the FTP cycle from MY 2016 vehicles sold by Cummins, Daimler Trucks North America, Volvo, Navistar, Hino, Isuzu, Ford, GM, and Fiat Chrysler Automobiles.[14]

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11 See CFR Title 40, Part 1036.140 for further details. LHD typically includes any vehicle built from a light-duty truck chassis, van trucks, multi-stop vans, and some straight trucks with a single rear axle. MHD typically includes school buses, straight trucks with single rear axles, city tractors, and special purpose vehicles. HHD typically includes tractors, straight trucks with dual rear axles, and inter-city buses.

12 "Non-tractors" refers to all HDVs different than tractor trucks, such as light-duty truck chassis, van trucks, multi-stop vans, straight trucks, and buses.

13 For 2010 and later model years heavy-duty engines manufacturers in the U.S. must use the 2010 ramped mode SET. The ramped mode test is performed as a continuous cycle with ramped transitions of 20 seconds between the individual stationary operating points.

14 Environmental Protection Agency and Department of Transportation, "Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles–Phase 2. Regulatory Impact Analysis", EPA-420-R-16-900 (2016). https://nepis.epa.gov/Exe/ZyPDF.cgi/P100P7NS.PDF?Dockey=P100P7NS.PDF.

Table 1. Summary of U.S. Phase 1 heavy-duty diesel engine standard CO_2 limits

Vehicle Type	GVW (tons)	Base (2010) g/kWh	Step 1 (2014) g/kWh	Step 2 (2017) g/kWh	Phase 1 reduction (%)	Test Cycle	Full Vehicle Reduction (%)	Engine share of full vehicle reduction (%)
Tractor	11.8 to 15	695	673	653	6.0	SET (Phase 1)	10.2-13	46-59
	15+	657	637	617	6.1	SET (Phase 1)	9.1-23.4	26-67
Non-tractor	3.9 to 8.8	845	805	772	8.6	Composite FTP[a]	8.6	100
	8.8 to 15	845	805	772	8.6	Composite FTP	8.9	97
	15+	783	760	744	5.0	Composite FTP	5.9	85

a. The cycle is run as both a cold- and a hot-start test. The composite FTP results are obtained by using a weighting factor of 1/7 for the cold-start results and 6/7 for the hot.

In Phase 1, the engine CO_2 emissions were reduced between 5-8.6% from the 2010 baseline for Phase 1; this represents anywhere from 26-100% of the full-vehicle reductions for a given segment. In Phase 2, the engine CO_2 emissions were reduced between 4.1-5.1% from the 2017 baseline for Phase 2, representing 21-28% of the full-vehicle reductions.

Table 2. Summary of U.S. Phase 2 heavy-duty diesel engine standard CO_2 limits

Vehicle Type	GVW (tons)	Base (2017) g/kWh	Step 1 (2021) g/kWh	Step 2 (2024) g/kWh	Step 3 (2027) g/kWh	Phase 2 reduction (%)	Test Cycle	Full Vehicle Reduction (%)	Engine share of full vehicle reduction (%)
Tractor	11.8 to 15	645	634	618	613	5.0	SET (Phase 2)	19-21	24-26
	15+	610	599	585	579	5.1	SET (Phase 2)	18-24	21-28
Non-tractor	3.9 to 8.8	772	755	744	740	4.2	Composite FTP[a]	16	26
	8.8 to 15	748	731	721	717	4.1	Composite FTP	16	26
	15+	704	688	679	675	4.2	Composite FTP	16	26

a. The cycle is run as both a cold- and a hot-start test. The composite FTP results are obtained by using a weighting factor of 1/7 for the cold-start results and 6/7 for the hot.

Table 3. Phase 1 and Phase 2 SET weightings

Speed[a]	Load (%)	Phase 1 weighting (%)	Phase 2 weighting (%)
Idle	--	15	12
A (low)	25	5	12
A (low)	50	5	12
A (low)	75	5	12
A (low)	100	8	9
B (medium)	25	10	9
B (medium)	50	10	10
B (medium)	75	10	10
B (medium)	100	9	9
C (high)	25	5	1
C (high)	50	5	1
C (high)	75	5	1
C (high)	100	8	2

a. The modes of the SET cycle in Table 3 have been sorted by speed and torque. In the ramped mode version of the SET, the operating points are run in a different order from the one shown in Table 3. The engine speeds are defined as follows: $A = n_{lo} + 0.25(n_{hi} - n_{lo})$, $B = n_{lo} + 0.50(n_{hi} - n_{lo})$, $C = n_{lo} + 0.75(n_{hi} - n_{lo})$. n_{hi} = the highest engine speed where 70% of the declared maximum net power occurs. n_{lo} = the lowest engine speed where 50% of the declared maximum net power occurs. The cycle is run as both a cold- and a hot-start test. The composite, brake-specific FTP results are obtained by dividing the weighted emissions and fuel consumption (in grams) by the weighted mechanical work (in bhp-hr), using a weighting factor of 1/7 for the cold-start results and 6/7 for the hot.

The Phase 1 and Phase 2 engine standards are technology-neutral; that is, manufacturers may use any combination of technologies that they wish to meet the sales-weighted average CO_2 limits. U.S. regulators, in setting the standards, took into account a certain level of technologies to calculate the CO_2 target. The main technologies U.S. agencies considered for meeting the Phase 1 standard included combustion system optimization; improvements in turbocharging, air handling, and EGR systems; engine parasitic and friction reduction; and aftertreatment systems designed for lower back-pressure.

Table 4. Phase 2 assumed engine technologies, reductions, and market penetrations for tractor engines

Technology	SET weighted reduction (%)	Market penetration (2021) (%)	Market penetration (2024) (%)	Market penetration (2027) (%)
Turbocompound with clutch	1.9	5	10	10
Waste heat recovery	3.6	1	15	25
Parasitic/Friction reduction	1.5	45	95	100
Improved aftertreatment	0.6	30	95	100
Air handling	1.1	45	95	100
Improved combustion	1.1	45	95	100
Downsizing	0.3	10	20	30
		Reductions (2021) (%)	**Reductions (2024) (%)**	**Reductions (2027) (%)**
Weighted reduction (%)		1.7	4	4.8
Downspeeding optimization (%)		0.1	0.2	0.3
Total reduction (%)		**1.8**	**4.2**	**5.1**

Table 5. Phase 2 assumed engine technologies, reductions, and market penetrations for non-tractor engines

Technology	FTP weighted reduction (%)	Market penetration (2021) (%)	Market penetration (2024) (%)	Market penetration (2027) (%)
Model based control	2.0	25	30	40
Parasitic/Friction reduction	1.5	60	90	100
Air handling	1.0	60	90	100
Improved aftertreatment	0.5	30	60	100
Improved combustion	1.0	60	90	100
		Reductions (2021) (%)	**Reductions (2024) (%)**	**Reductions (2027) (%)**
Weighted reduction (%)		**2.3**	**3.6**	**4.2**

For the Phase 2 standard for tractor engines the agencies considered eight main technology areas: turbocompounding, waste heat recovery, friction reduction, improved aftertreatment, improved air handling, improved combustion, downsizing, and downspeeding optimization. For Phase 2 technologies for non-tractor engines, the agencies considered five main technology areas: model-based control, friction reduction, improved air handling, improved aftertreatment, and improved combustion. The technologies, their associated reductions, and their assumed market penetrations in Phase 2 are shown in Table 4 for tractor and Table 5 for non-tractor engines.

The reductions included in the Phase 2 regulation were lower than was deemed technically feasible by several organizations. For example, work by Southwest Research Institute for NHTSA[15] indicates that fuel consumption reductions of 8-10% were feasible within the Phase 2 timeframe. Cummins[16] estimates that tractor engines could achieve 9-15% fuel consumption reductions and non-tractor engines, 5-11%, within the 2020-2030 timeframe compared with 2017. An analysis from West Virginia University[17] finds that tractor engines can improve by more than 10% from a 2017 baseline. Participants in the U.S. DOE SuperTruck program[18] achieved engine efficiency improvements of 12-18% from a 2010 baseline and have even higher objectives, setting a pathway for 55% brake thermal engine efficiency.

15 Thomas Reinhart, "Commercial Medium- and Heavy-Duty Truck Fuel Efficiency Technology Study – Report #2", DOT HS 812 194 (National Highway Traffic Safety Administration, February 2016). https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/812194_commercialmdhdtruckfuelefficiency.pdf.

16 Wayne Eckerle, "Engine Technologies for GHG and Low NO_x," Presentation, ARB Symposium on Phase 2 GHG, (April 22, 2015), https://www.arb.ca.gov/msprog/onroad/caphase2ghg/presentations/2_7_wayne_e_cummins.pdf.

17 Arvind Thiruvengadam et al., "Heavy-Duty Vehicle Diesel Engine Efficiency Evaluation and Energy Audit," October 2014, http://www.theicct.org/heavy-duty-vehicle-diesel-engine-efficiency-evaluation-and-energy-audit.

18 National Academies of Sciences, Engineering, and Medicine, *Review of the 21st Century Truck Partnership: Third Report* (National Academies Press: Washington DC, 2015). https://doi.org/10.17226/21784.

U.S. AND EU HEAVY-DUTY CYCLE COMPARISON

The U.S. and the EU use different stationary and transient cycles for HD engine type approval (see Table 6). The CO_2 emissions of a particular engine measured over a U.S. cycle will be different from those of the same engine measured over the corresponding EU cycle. To understand the level of correlation between the U.S. and EU cycles, we ran 26 engine fueling maps[19] over the six engine-specific cycles (WHTC, FTP, ETC, WHSC, Phase 2 SET, ESC/SET) using VECTO,[20] the vehicle energy consumption calculation tool developed by the European Commission. VECTO can be used to simulate the fuel consumption of an engine over different duty cycles. The engine-only mode simulates an engine dynamometer test and calculates the fuel consumption from a sequence of engine speed and torque points based on the steady-state fuel consumption map. The CO_2 emissions are then estimated from the fuel consumption value and the assumed carbon content of the fuel. The model is more sophisticated than just conducting an analysis using the individual points on the map, since it factors in the effects on engine inertia over the transient cycles.

Table 6. Stationary and transient heavy-duty engine cycles for U.S. and EU

	U.S.		EU	
	Phase 1/US 2010 Emissions	Phase 2	Euro V[a]	Euro VI
Transient	FTP	FTP	ETC	WHTC
Stationary	SET (ESC)[b]	SET (reweighted)	ESC	WHSC

a. Although not currently in use in the EU today, we opted to include the ESC and ETC cycles in our analysis as it could prove useful for other regions who still type approve engines using these cycles.

b. For the purposes of this study all U.S. steady-state cycles were run as discrete mode cycles (DMC), as opposed to ramped modal cycles (RMC) which are required by the regulation. The difference in the results from VECTO between the cycles run in DMC and RMC mode are minimal. Therefore, correlation factors (as reported here) would not be affected.

The U.S. transient and steady-state cycles were compared against their European counterparts, and a linear regression model was used to estimate the correlation between the different cycles. The results are presented in Figure 1. Overall, the data shows a good correlation between the CO_2 results for the different cycles, with R^2 values ranging from 0.91-0.99. The percent difference between the U.S. Phase 2 cycles and the Euro V and VI type-approval cycles, as well as the relevant R^2 values, are summarized in Table 7. For the transient cycles, the WHTC is predicted to produce on average a CO_2 value 5.12% lower than the FTP. For the stationary cycles, the WHSC is predicted to produce on average a CO_2 value 3.77% higher than the reweighted Phase 2 SET. Using these correlations, we can estimate the CO_2 values that would be obtained by engines complying with the U.S. Phase 1 and Phase 2 standards when tested over the European cycles. These are shown in Tables 8 and 9 for U.S. Phase 1 and Phase 2.

19 The set of engine fuel maps used was obtained from a diversity of sources including engine dynamometer measurements commissioned by the ICCT, engine maps purchased from a recognized engineering service provider, literature research, and the regulatory engine maps developed by the U.S. EPA.

20 VECTO Version 3.1.2.748 was used in this analysis.

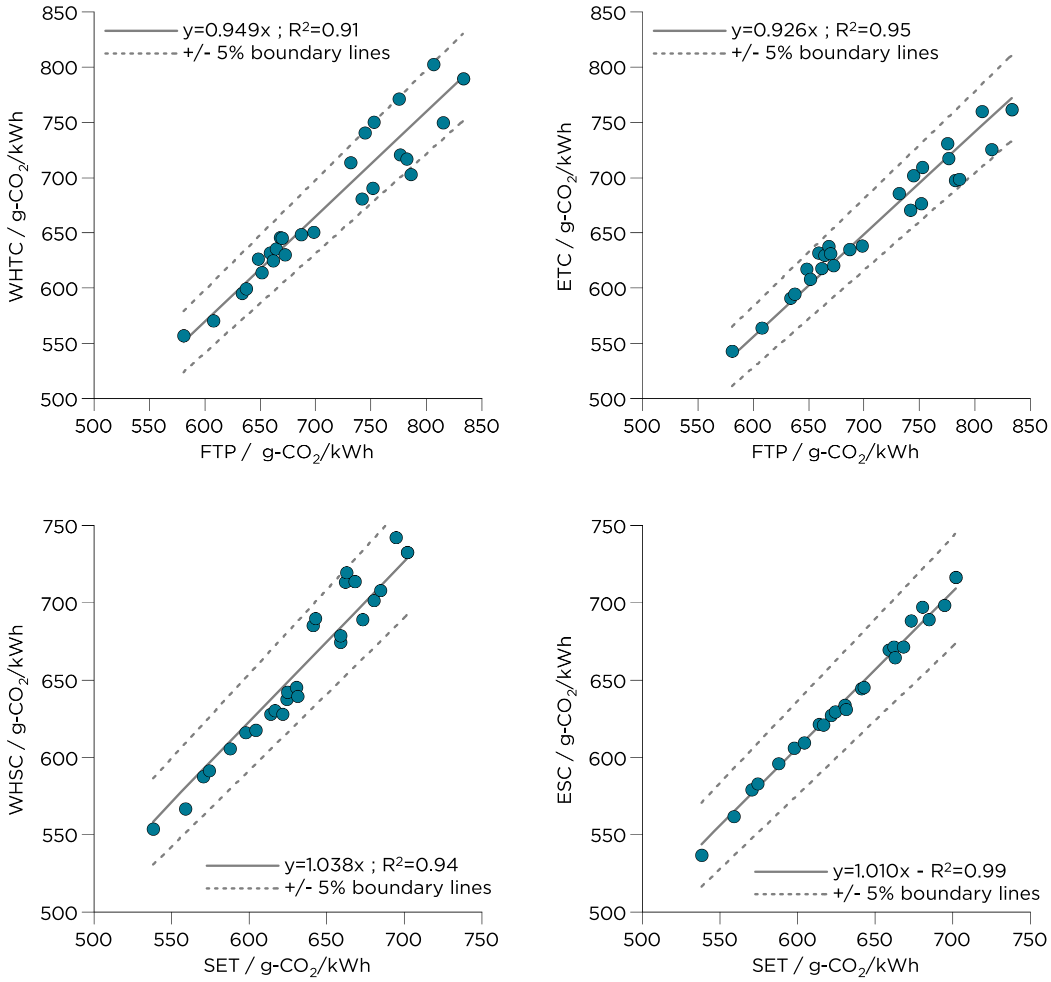

Figure 1: Correlation of engine simulation results between the U.S. and EU transient cycles (FTP, WHTC, ETC) and the U.S. and EU steady-state cycles (Phase 2 SET, WHSC, ESC).

Table 7. Comparison between U.S. Phase 2 and Euro V and VI transient and stationary cycles

	Cycle	% difference from U.S. cycle	R^2 value
Transient (vs. FTP)	WHTC	-5.12%	0.91
	ETC	-7.40%	0.95
Stationary (vs. Phase 2 SET)	WHSC	+3.77%	0.94
	ESC	+1.01%	0.99

Table 8. U.S. Phase 1 engine CO_2 values over U.S. cycles and predicted values for Euro V and VI cycles

Vehicle Type	GVW (tons)	Base (2010) g/kWh	Step 1 (2014) g/kWh	Step 2 (2017) g/kWh	Test Cycle
Tractor	11.8 to 15	695	673	653	SET (U.S. Phase 1 weighting)
		714	691	671	WHSC (Euro VI)
		695	673	653	ESC (Euro V)
	15+	657	637	617	SET (U.S. Phase 1 weighting)
		675	654	634	WHSC (Euro VI)
		657	637	617	ESC (Euro V)
Non-tractor	3.9 to 8.8	845	805	772	FTP (U.S. Phase 1)
		802	764	732	WHTC (Euro VI)
		782	745	715	ETC (Euro V)
	8.8 to 15	845	805	772	FTP (U.S. Phase 1)
		802	764	732	WHTC (Euro VI)
		782	745	715	ETC (Euro V)
	15+	783	760	744	FTP (U.S. Phase 1)
		743	721	706	WHTC (Euro VI)
		725	704	689	ETC (Euro V)

Table 9. U.S. Phase 2 engine CO_2 values over U.S. cycles and predicted values for Euro V and VI cycles

Vehicle Type	GVW (tons)	Base (2017) g/kWh	Step 1 (2021) g/kWh	Step 2 (2024) g/kWh	Step 3 (2027) g/kWh	Test Cycle
Tractor	11.8 to 15	645	634	618	613	SET (U.S. Phase 2 weighting)
		669	658	641	636	WHSC (Euro VI)
		651	640	624	619	ESC (Euro V)
	15+	610	599	585	579	SET (U.S. Phase 2 weighting)
		633	622	607	601	WHSC (Euro VI)
		616	605	591	585	ESC (Euro V)
Non-tractor	3.9 to 8.8	772	755	774	740	FTP (U.S. Phase 2)
		732	716	706	702	WHTC (Euro VI)
		715	699	689	685	ETC (Euro V)
	8.8 to 15	748	731	721	717	FTP (U.S. Phase 2)
		710	694	684	680	WHTC (Euro VI)
		693	677	668	664	ETC (Euro V)
	15+	704	688	679	675	FTP (U.S. Phase 2)
		668	653	644	640	WHTC (Euro VI)
		652	637	629	625	ETC (Euro V)

To confirm whether engine efficiency improvements would be reflected similarly over both the U.S. and EU cycles, we analyzed four specific engine fueling maps in greater detail. These four engine fueling maps correspond to those used by the U.S. EPA in the development of the Phase 2 engine CO_2 standard. The four fueling maps are for a representative tractor and non-tractor engine for the years 2018[21] and 2027. For the non-tractor engines, the simulated CO_2 emissions reduction from the 2027 engine map with respect to the 2018 map is 4.0% over both the U.S. and EU transient cycles (FTP, WHTC and ETC) (see Table 10). For the tractor engines, the simulated CO_2 emissions reduction from the 2027 engine map with respect to the 2018 map is 4.6% for the SET (Phase 2) cycle, 4.7% for the WHSC, and 4.4% for the ESC. These results indicate it is likely that if technological improvements to an engine result in a given CO_2 reduction over a U.S. cycle, a similar reduction over the corresponding EU cycle would also be expected.

Table 10. Comparison of CO_2 reductions obtained over different cycles using EPA engine fueling maps that represent 2018 and 2027 tractor and non-tractor engines

Vehicle Type	Test Cycle	% Reduction from comparison of 2018 and 2027 engine fueling maps (regulatory engine maps from EPA Phase 2)
Tractor	SET (Phase 2)	4.6%
	WHSC	4.7%
	ESC	4.4%
Non-tractor	FTP	4.0%
	WHTC	4.0%
	ETC	4.0%

During the development of the Phase 2 standards, EPA[22] and West Virginia University (WVU)[23] developed engine maps that include the influence of the engine technologies listed in Table 5. The engine maps developed by EPA and WVU were used to quantify the reduction in vehicle fuel consumption originating only from engine improvements across eight different mission profiles. As can be seen in Figure 2, the reduction in engine fuel consumption translates into a similar vehicle fuel consumption reduction across a wide range of vehicle duty cycles, including urban, regional, and long haul driving. In the case of the EPA engine maps (Figure 2 top), the fuel consumption reduction achieved in the engine certification cycles is 4.8%, while the corresponding reduction in vehicle fuel consumption ranges from 3.9% to 4.9%. Similarly, the fuel consumption reduction achieved in the engine certification cycles for the WVU engine maps (Figure 2 bottom) is approximately 12.3%, while the corresponding reduction in vehicle fuel consumption ranges from 11.5% to 16.1%.

21 Note that the U.S. Phase 2 baseline is a 2017 engine, not a 2018 engine (which is being shown in Table 10). Therefore, the reduction from 2018 to 2027 as shown in Table 10 is lower than the reduction from 2017 to 2027 as shown in Table 2.

22 EPA, and DOT, "Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles–Phase 2. Regulatory Impact Analysis", EPA-420-R-16-900 (2016).

23 Thiruvengadam et al., "Heavy-Duty Vehicle Diesel Engine Efficiency Evaluation and Energy Audit," October 2014.

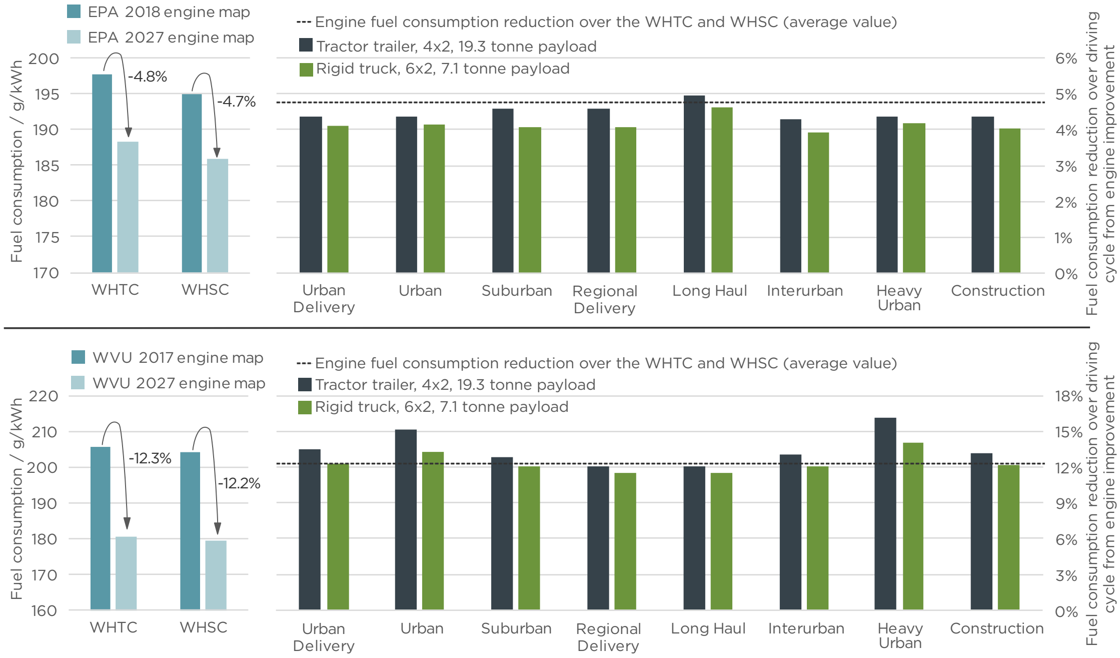

Figure 2: Fuel consumption reduction from engine improvement alone across diverse vehicle applications.

POTENTIAL FOR EU ALIGNMENT WITH U.S. ENGINE CO_2 STANDARDS

The data presented above indicates that EU policymakers could achieve significant reductions in emissions by setting engine CO_2 limits that would align with the U.S. Phase 2 standards. The envisioned process for setting such aligned standards would be as follows:

Step 1 – Collect and analyze recent engine CO_2 type-approval data from national authorities. The main purpose of this would be to confirm correlation with the 2017 baseline of the U.S. Phase 2. Heavy-duty Euro VI engine type-approval documents include cumulative cycle CO_2 emissions from the WHTC and WHSC tests. This data is currently provided for the parent engine of the given emissions family. The national type-approval authority retains the documentation, so an official request or intervention may be necessary for the European Commission to obtain the data. It may not be necessary to obtain all existing such data, since the main purpose of the analysis would be to ensure that there is good agreement between the EU data and the U.S. Phase 2 baseline.

ICCT research[24] has found that historically, EU trucks have been on average more efficient than U.S. trucks, largely driven by higher fuel taxes in the EU. Our analysis shows that this gap has recently closed, in large part due to the U.S. Phase 1 HD efficiency standards. In fact, our modeling predicts that on average U.S. and EU HDVs

24 Rachel Muncrief and Ben Sharpe, *Overview of the Heavy-Duty Vehicle Market and CO2 Emissions in the European Union* (ICCT: Washington DC, 2015). http://www.theicct.org/overview-heavy-duty-vehicle-market-and-co2-emissions-european-union.

currently have similar efficiency.[25] Therefore, we expect that the EU CO_2 type-approval data should fall on average between the Phase 2 baseline (2017) and the Phase 2 Step 1 (2021) values.

Step 2 – Determine EU engine segmentation. The U.S. standards are segmented based on vehicle type and "intended service class" in which the engine is used. It is possible that the same engine model could be intended for multiple vehicle segments and that the final vehicle for an engine is not known during type approval. The U.S. standard handles this issue by requiring that manufacturers meet the standard based on the actual sales-weighted average once sales for a complete year are accounted for. Therefore, manufacturers must have a very good estimate at the beginning of a year as to their predicted sales breakdown. The U.S. regulation includes flexibility provisions for missed sales projections.

The EU engine sales breakdown using the U.S. segmentation is shown in Table 11 for 2016 EU sales data.[26] For EU tractors, the 15 ton+ segment is the only one of statistical significance, since only 107 tractors with a GVW between 11.8 and 15 tons were sold in 2016, representing less than 0.1% of tractor sales. For non-tractors, 20% of sales are in the lowest GVW bin; 15% are in the middle bin; and 65% are in the highest. The U.S. standards are based primarily on GVW of the vehicle in which the engine is sold, but it is notable that for non-tractor sales in the EU there is a decent correlation between vehicle GVW and engine rated power as shown in Figure 3. Therefore, it might be possible to consider regulating non-tractor engines based on rated power rather than GVW.

The European Commission has already determined an HD vehicle segmentation strategy as part of the development of the CO_2 type-approval methodology. The current segmentation includes 20 categories for HDVs – 17 truck segments and 3 bus segments. The trucks are divided based on axle configuration, chassis configuration, and GVW. The bus segments are based on mission profile such as city, interurban, or coach.

In the first phase of the CO_2 type-approval regulation for HDVs,[27] which will most likely be used for the first phase of an EU HDV CO_2 standard, four truck segments will be covered, accounting for 60% of total EU HDV[28] sales. This implies that 40% of the HDV fleet will not be covered under the EU's initial full-vehicle standard. Thus, a separate engine standard could help ensure some level of improvement in vehicles that are not covered under an initial full-vehicle standard.

25 Real-world fuel consumption in the two regions may differ due to duty cycle and payload differences, not the inherent efficiency of the vehicle.

26 EU new HDV sales data for 2016 supplied by IHS Global SA. The distribution of HDV registrations in France is assumed to mirror the rest of the EU. This is because of high aggregation in the available French data.

27 The HDV CO_2 type-approval regulation was adopted through comitology by the Technical Committee - Motor Vehicles on May 11, 2017. See footnote 6 for further details.

28 HDV with a GVW over 3.5 tons. EU new HDV 2016 sales data supplied by IHS Global SA.

Table 11: 2016 EU sales based on U.S. Phase 2 engine segmentation

Vehicle Type	GVW[a] (tons)	2016 EU Sales	Average rated power (kW) range (based on 2016 sales)	Fraction covered in first phase of VECTO
Tractor	11.8 to 15	107	188-223	0%
	15+	203,482	223+	96%
Non-tractor	3.9 to 8.8	29,200	120-142	0%
	8.8 to 15	22,621	142-195	0%
	15+	96,596	195+	68%

a. We have used GVW throughout this paper as a proxy for "intended service class."

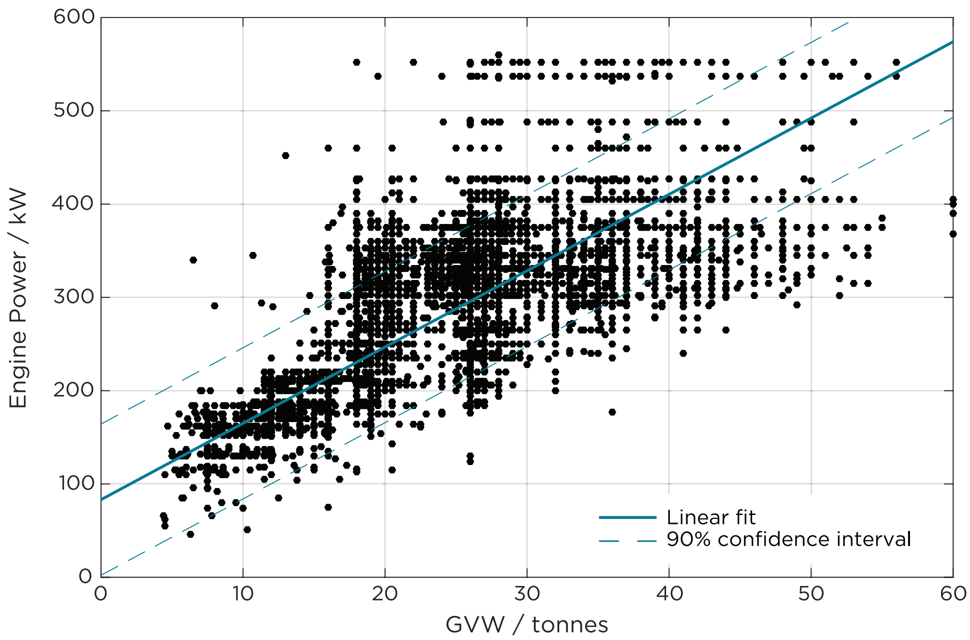

Figure 3: Correlation between engine power and GVW for non-tractor truck sales in the EU in 2016.

Step 3 – Confirm stringency and timing. The stringency and timing of the Phase 2 engine standard along with the correlated CO_2 values for the EU engine cycles are shown in Table 9. The first step of Phase 2 is in 2021, the second in 2024, and the third in 2027. Reductions from the 2017 baseline are approximately 5% for tractor engines and 4% for non-tractor engines. Based on the timing and other requirements of an EU standard, the timeline might need to be shifted or the preference might be to introduce a two-step standard instead of one with three steps.

The stringency of the U.S. engine standards is on the conservative side, based on feasibility estimates carried out by different organizations. For example, technologies such as high efficiency SCR systems, engine thermal encapsulation, and pump electrification were not considered. Additionally, the market penetration of certain technologies such as turbocompounding, waste heat recovery, and engine downsizing was conservatively estimated (see Tables 4 and 5). Lastly, the estimated improvement of technologies with 2027 full market penetration was conservative, particularly for combustion optimization and air handling. Therefore, we estimate it would be possible to increase tractor engine reductions from 5.1% to 10% and non-tractor engine reductions from 4.2% to 8%.

CONCLUSION

Development of a separate HD engine CO_2 standard could be accomplished in the EU using a combination of existing EU engine type approval data and analysis that was performed for the U.S. Phase 2 regulation. Based on correlation between U.S. and EU engine cycles, it is possible to convert U.S. CO_2 engine limits to the European test cycles used for the type approval of engines under the Euro IV/V and Euro VI pollutant standards.

There are a number of predicted benefits for the EU in setting a separate engine CO_2 standard in coordination with a full-vehicle standard:

» Establishment of a link between NO_x and CO_2 emissions. It is of particular importance for air quality that the low in-use NO_x emissions achieved under the Euro VI regulation are not diminished. Although off-cycle NO_x limits are part of the existing regulation, regulating CO_2 and NO_x over the same test cycle will create a link between these two emissions and make it less likely that real-world NO_x emissions could increase as an unintended consequence of a CO_2 standard for HDVs.

» Coverage of segments not covered in the first roll-out of the CO_2 type-approval methodology, referred to as VECTO. The EU's first full-vehicle HDV CO_2 standard will most likely be based on phase 1 of VECTO. Under this initial VECTO roll-out, 40% of HD sales will not be covered.[29] A separate engine standard will ensure that some reductions are achieved from these segments not currently covered by the proposed HDV CO_2 methodology.

» Use of existing regulatory framework. The standard would use the existing HD engine type-approval framework that has been in place for many years and would not require engine tests in addition to those mandated by the HDV type-approval regulations.[30] Using the existing conformity-of-production framework for engine type approval would also aid with ensuring regulatory compliance.

» Maintaining the EU's international leadership on HD engine regulations. Many countries around the world follow the Euro pathway for HD engine emissions regulations. A number of these countries, such as India and Brazil, are looking into the possibility of establishing an engine-based CO_2 standard. Engine CO_2 standards set using the Euro test cycles could be adopted by other countries, taking into account country-specific market conditions. In addition to showing strong leadership, this would also help create economies of scale for efficient engines, leading to reduced costs.

» Ensuring long-term investment in engine R&D. Developing more-efficient diesel engines requires up-front investment in R&D by engine manufacturers. The Commission signaling an intention to mandate improvements in engine efficiency will give manufacturers the certainty to make these investments. Aligning with the U.S. standards would enable manufacturers to take advantage of work they are already doing. This would create a level playing field for producers in both markets.

29 HDV with a GVW over 3.5 tons. EU new HDV 2016 sales data supplied by IHS Global SA.

30 Under the recently adopted CO_2 type-approval regulation all engine variants within an engine family are required to be tested under the WHTC and WHSC cycles.

- Complementing full-vehicle standards. As in the U.S. and Canada, separate engine standards developed and implemented in parallel with full-vehicle regulations could ultimately ensure stronger results. The two standards complement each other by allowing a significant amount of freedom in technology pathways for complying with regulations while also ensuring continued investment from all manufacturers in improving engine efficiency.
- Ensuring real-world, durable emissions reductions. In contrast with some vehicle-level technologies such low rolling resistance tires, engine technologies remain with a vehicle for its full lifetime. Furthermore, and in contrast with aerodynamic and rolling resistance improvements, engine efficiency improvements translate to CO_2 benefits across a wider range of vehicle duty cycles and payloads.