WHITE PAPER

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DEVELOPMENT OF TEST CYCLE CONVERSION FACTORS AMONG WORLDWIDE LIGHT-DUTY VEHICLE CO_2 EMISSION STANDARDS

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EXECUTIVE SUMMARY

Fuel consumption, fuel economy and carbon dioxide (CO_2) emission standards for light-duty vehicles (LDV) are implemented worldwide in the most important automobile markets. The stringencies of the different regional standards and values measured under different boundary conditions are not directly comparable. While the unit conversion is clearly defined and straightforward (e.g., from *miles per gallon* to *g CO_2 per km*), the different testing conditions raise high uncertainties within the conversion process. Especially the test driving cycles applied on the chassis dynamometers reflecting local driving conditions cause large differences regarding engine loads and emission behavior.

This report compares the dynamics of the driving cycles and their impacts on fuel consumption and CO_2 emissions on an equal basis. The driving schedules from the three most relevant national regulations were chosen for this exercise: the U.S. CAFE standards (a composite of FTP75 and HWFET), the European Union's NEDC, and the Japanese JC08. In addition, the recently developed 'Worldwide harmonized Light-duty Test Cycle' (WLTC) was included. This cycle is foreseen to replace the NEDC in a matter of years and will therefore gain high importance on a global level.

CO_2 and efficiency results were simulated over the test cycles for a variety of vehicle and technology packages using a sophisticated vehicle emission model developed by Ricardo Engineering. Model runs based on the speed courses of the five driving cycles were resolved on a second-by-second basis. Current vehicle architectures and advanced innovative technologies focusing on the 2020/2025 horizon were covered.

The main features of the actual study in comparison to a similar investigation performed by ICCT in 2007 are:

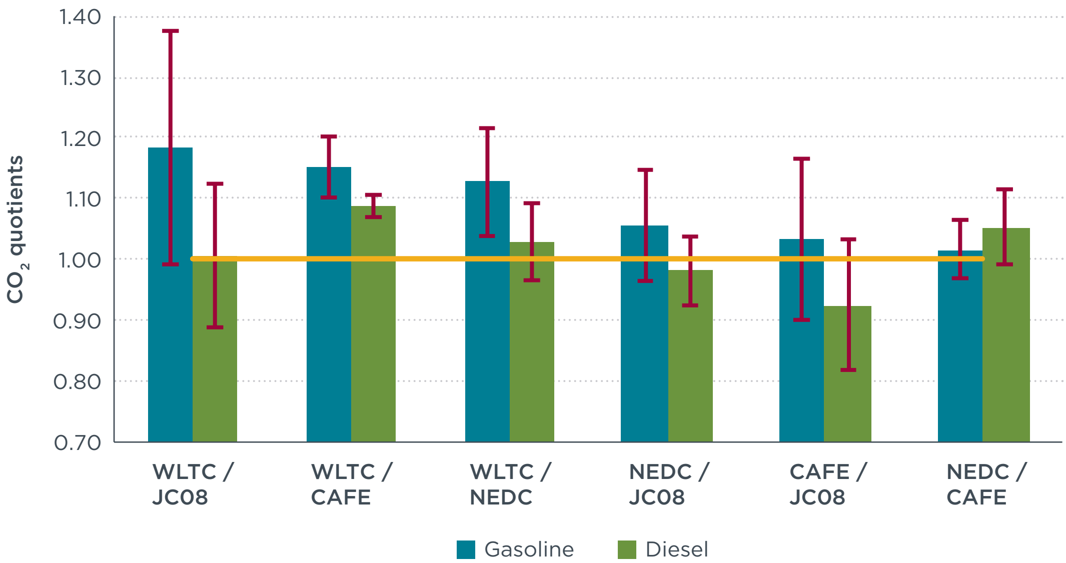
2007 work	2014 work
Use of vehicle model data from the Modal Energy and Emissions Model (MEEM)	Use of vehicle model data from Ricardo's Data Visualization Tool (DVT) based on MSC.Easy5
Simulation results for 12 current technology LDV (gasoline only, internal combustion engine only)	Simulation results for a large variety of innovative technologies, including advanced gasoline, hybrids and advanced diesel technologies
2015 projection	2020/2025 projection
Multiplier logarithmic regression method	Different linear and nonlinear regression approaches evaluated, higher level of technical details
Resulting algorithms converting CAFE (mpg), NEDC (g CO_2/km) and JC08 (l/km)	Resulting g CO_2/km-based algorithms converting CAFE, NEDC, JC08 and WLTC

Different types of regression analyses were applied to the modeled CO_2 emission data in order to describe the dependencies for each pair of the different driving cycles. The resulting regression functions were based on the least squares approach. The tested regression types differ by the mathematical nature (linear vs. nonlinear approaches), the inclusion or exclusion of the y-intercept, the differentiation into different vehicle technologies and the inclusion of additional independent variables (multiple regression analyses). Therefore, the level of complexity and the achievable quality of the regression results vary among the different types. In general, a higher complexity is linked with a

higher outcome quality and a more precise emission translation. The standard deviation of the single data points was used as a measure for the quality of the regression types.

A general pattern was developed to assist the user in finding out which conversion approach is most appropriate in each case and which regression coefficients should be applied. The direct comparison of CO_2 or FC standards' stringencies from different regions not only depends on the different driving cycles applied but also on the technical characteristics of the regional vehicle fleets. The use of comprehensive adjustment factors therefore requires simplifying assumptions concerning the assessment of averaged fleet compositions.

Averaged results including all relevant technologies were derived by applying a basic single regression approach with zero intercept. The slopes of the regression lines of this type may be interpreted as simple quotients of the distance-based CO_2 emissions of both cycles:



The error bars here represent the standard deviations caused by individual vehicle technology packages. Gasoline vehicles emit strongest under the WLTC schedule. CO_2 emissions under the JC08, U.S. CAFE and NEDC regimes are 18%, 15% and 13% lower. The behavior of the diesel vehicles is clearly different. Here, the cycle-specific deviations are generally lower and show a different pattern. For example, averaged WLTC and JC08 emissions (the highest deviations for the gasoline vehicles) are almost equal, while CAFE emissions are lower than JC08 (the opposite of the gasoline vehicles). These results reflect the fundamental differences in the structures of gasoline and diesel engine maps.

Results of higher quality were achieved by applying more sophisticated regression types. Regression coefficients including y-intercepts and more detailed technical data like aerodynamic drags and drivetrain technologies were developed and are provided in this report.

1. INTRODUCTION

Fuel consumption (FC), fuel economy (FE) and carbon dioxide (CO_2) emission standards for light-duty vehicles (LDV) have been implemented worldwide in the most important automobile markets. These regulations were developed under national or regional conditions and follow specific traditions and preferences. Hence, the stringencies of the isolated standards and values measured under different boundary conditions are not directly comparable.

From an environmental perspective, it would be desirable to apply similarly stringent requirements concerning vehicle energy efficiencies and greenhouse gas (GHG) emissions all over the world. At any given time, the region with the most stringent regulations can be seen as the one defining the most ambitious technical challenges for manufacturers in the global market. The identification of this regulatory front-runner reveals that there is substantial room for many governments to make policy improvements and that further political debate is essential. Identifying the front-runner could give incentives for other regions to adapt their standards to the given benchmark or to even surpass them.

Two main issues have to be taken into account when converting FC, FE or CO_2 emission standards or measured or modeled values from one regional regulation to another:

1. The physical metrics have to be converted by applying physical unit conversion factors and fuel property data. The most common measures are fuel economy or fuel efficiency (miles per gallon or kilometers per liter), fuel consumption (liters per 100 kilometers) and greenhouse gas emissions (grams CO_2 per kilometer).
2. The testing conditions underlie strong regional variations. These include driving patterns, ambient temperatures, start conditions, vehicle preconditioning, determination of vehicles' road loads and masses, state-of-charge corrections and others.

While the unit conversion is clearly defined and straightforward, the different testing conditions raise high uncertainties within the conversion process. The test driving cycles applied on chassis dynamometers cause especially large differences concerning driving conditions, stop time and engine loads. This exercise is about exploring the sensitivity of LDV CO_2 emissions to these driving cycle differences.

ICCT undertook an earlier investigation in 2007 (ICCT, 2007). The main features of this cycle comparison work were:

- Use of vehicle model data from the Modal Energy and Emissions Model (MEEM)
- Simulation results for 12 gasoline LDV (internal combustion engine [ICE] only — no hybrids, no diesels)
- 2015 projection
- Multiplier logarithmic regression method
- Resulting algorithms converting CAFE (mpg), NEDC (g CO_2/km) and JC08 (l/km)

However, it has been recognized that the 2007 results should be revised and extended by applying a more sophisticated vehicle emission model and by including larger databases of different vehicle technologies covering also the 2020/2025 time horizon. In addition, the 2014 work aimed for pure CO_2 emission-based conversion algorithms because of their better applicability. These issues were included:

- Use of vehicle model data from Ricardo's Data Visualization Tool (DVT) based on MSC.Easy5 (MSC 2012)
- Simulation results for a large variety of innovative technologies, including hybrids and advanced diesel technologies
- 2020/2025 projection
- Different regression approaches were evaluated, using a higher level of technical details
- Resulting CO_2-based algorithms converting U.S. CAFE, NEDC, JC08 and WLTC

This exercise includes all effects being directly linked with the respective driving cycle (cycle dynamics, cold or hot start effects, share of stop phases, etc.). Other regulatory issues within the complete testing procedure that may also affect the emissions in different ways, such as road load determinations, legal tolerances, tire selections and pressures, etc., were not addressed here.

2. DRIVING CYCLES AND REGULATORY FRAMEWORKS

This study focuses on the direct effects of driving cycles' specific time-speed patterns. The impacts of cycle dynamics and speed levels on the emission behavior of LDV were quantified by applying a sophisticated Ricardo-developed vehicle emission model. The driving cycles from the three most relevant national regulations on CO_2 emissions and fuel consumption (or fuel economy) for LDV were chosen for this exercise:

» U.S. government fuel economy measurement method (40 CFR 600.113)

» European Union's type approval regulations for Euro 5 and Euro 6 standards on CO_2 emissions and fuel consumption (EC 715/2007 and EC 692/2008)

» Japanese exhaust emission standards and 2015 fuel efficiency regulation (MLIT Road Vehicles Act and Act Concerning the Rational Use of Energy)

In addition, the recently developed Worldwide harmonized Light-duty Test Cycle (WLTC) was included. This cycle is foreseen to replace the NEDC in a matter of years and will therefore gain high importance on a global level.

The modeled results and the correlations presented in this report reflect the thermal vehicle starting conditions as they are prescribed in the different national regulations within a certain range of model uncertainty.

There are other differences in testing procedures that were not taken into account for this study because they are difficult to quantify, or the model is not suitable to handle them in an appropriate way. Some of these testing conditions are defined explicitly diverging in national regulations, but others are not clearly prescribed and might be interpreted by the manufacturers to varying extent.

Some of these diverse testing conditions are:

» Ambient conditions in the test cell (temperature, humidity, pressure)

» Preconditioning procedures (soak area, precon cycles)

» Road load determination and dynamometer coast-down runs

» Cycle tolerances and driver behavior

» Compensation of battery state of charge at end of test

» Fuel composition

2.1 UNITED STATES: FTP, HWFET (CAFE)

The FTP75 (Federal Test Procedure—Figure 1) is used for emission certification and fuel economy testing of light-duty vehicles in the United States. It consists of the following segments:

1. Cold start transient phase (ambient temperature 20-30 °C), 505 s
2. Stabilized phase, 864 s
3. Hot soak (min 540 s, max 660 s)
4. Hot start transient phase, 505 s
5. For hybrid vehicles: repeated stabilized phase, 864 s

Emissions from phases 1, 2, 4 and 5 are collected and analyzed separately. The weighting factors to calculate the total emissions from the absolute bag results (e.g., grams CO_2) are 0.43 for the cold start transient phase, 1.0 for the stabilized phase and 0.57 for the hot start transient phase for non-hybrids. For hybrids, phase 2 is weighted at 0.43 and phase 5 at 0.57, resulting in the same total weighting of 1.0 for the stabilized phase. After weighting, all absolute emissions are added up and divided by the total driven distance to achieve the final distance-based emission result for the whole FTP75 cycle (e.g. grams CO_2 per kilometer).

The prescribed weighting procedure also affects the averaged technical parameters describing the characteristics of the cycle.

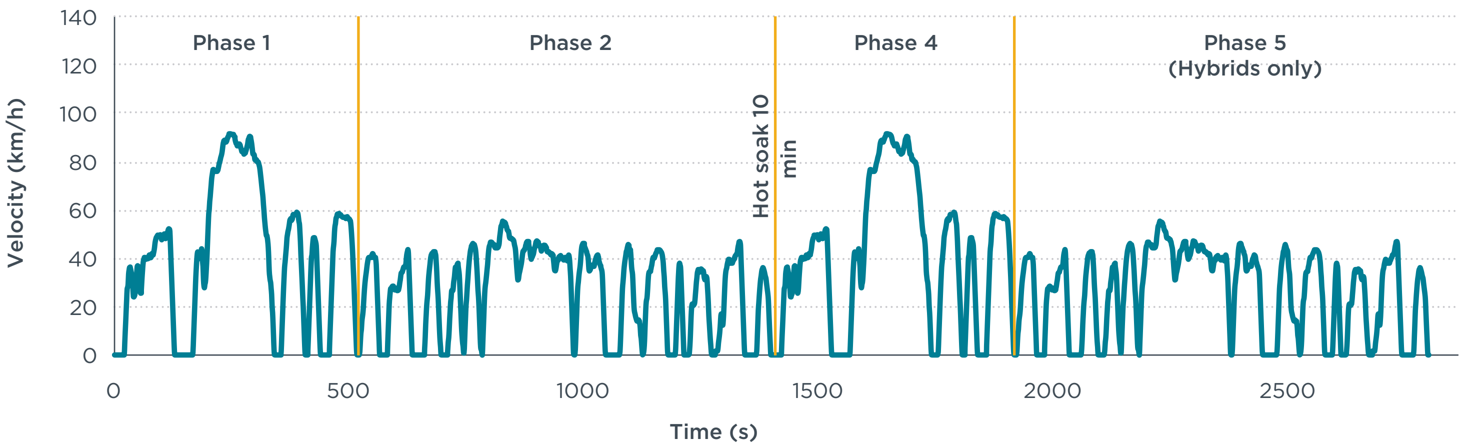


Figure 1: Driving schedule of the FTP75 cycle

Table 1 includes the most relevant features for the two subphases, the unweighted FTP75 cycle as driven on the dynamometer for non-hybrids and for hybrids and the weighted combination reflecting a phase 1 cycle followed by a phase 2 cycle.

Table 1: Technical parameters of the FTP75

	Units	Phase 1	Phase 2	FTP Non-hybrids	FTP Hybrids	FTP weighted
Duration	s	505	864	1874	2738	1369
Distance	km	5.78	6.21	17.77	23.98	11.99
Mean velocity	km/h	41.20	25.88	34.14	31.53	31.53
Max. velocity	km/h	91.2	55.2	91.2	91.2	91.2
Stop phases		6	13	23	35	18
Durations						
Stop	s	94	147	335	482	241
Constant driving	s	36	73	145	218	109
Acceleration	s	195	349	739	1088	544
Deceleration	s	180	295	655	950	475
Shares						
Stop		18.6%	17.0%	17.9%	17.6%	17.6%
Constant driving		7.1%	8.4%	7.7%	8.0%	8.0%
Acceleration		38.6%	40.4%	39.4%	39.7%	39.7%
Deceleration		35.6%	34.1%	35.0%	34.7%	34.7%
Mean positive acceleration	m/s^2	0.53	0.49	0.51	0.50	0.50
Max. positive acceleration	m/s^2	1.48	1.48	1.48	1.48	1.48
Mean positive 'vel * acc' (acceleration phases)	m^2/s^3	5.09	3.17	4.18	3.86	3.86
Mean positive 'vel * acc' (whole cycle)	m^2/s^3	1.97	1.28	1.65	1.53	1.53
Max. positive 'vel * acc'	m^2/s^3	19.19	11.18	19.19	19.19	19.19
Mean deceleration	m/s^2	-0.57	-0.58	-0.58	-0.58	-0.58
Min. deceleration	m/s^2	-1.48	-1.48	-1.48	-1.48	-1.48

The Highway Fuel Economy Test (HWFET or HFET—Figure 2) cycle is a chassis dynamometer driving schedule developed by the U.S. EPA for the determination of the highway fuel economy rating. The HWFET is a hot start test. Measurements start after a preconditioning cycle of the same schedule with a break of not more than 17 s.

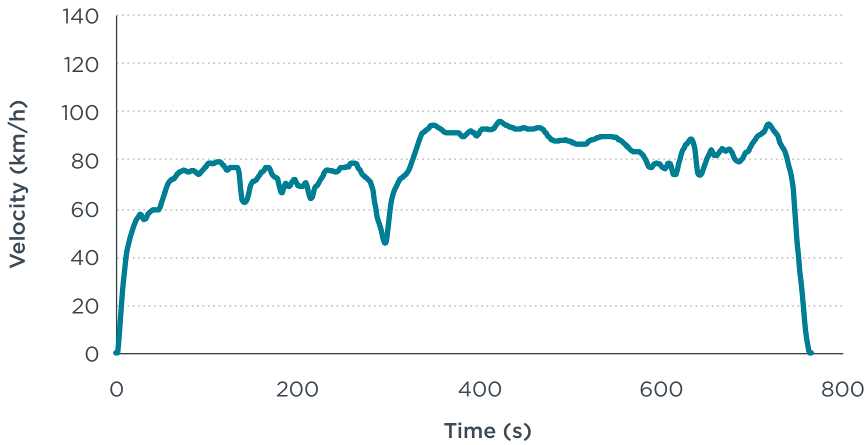


Figure 2: Driving schedule of the HWFET cycle

The Corporate Average Fuel Economy (CAFE) approach developed by the U.S. EPA was applied to determine the total CO_2 emissions taking into account both city and highway driving. The distance-based results (g CO_2/km) from the FTP75 and HWFET cycles were weighted as follows:

$$CO_{2\ CAFE} = 0.55 \times CO_{2\ FTP75} + 0.45 \times CO_{2\ HWFET}$$

2.2 EUROPEAN UNION: NEDC

The New European Driving Cycle (NEDC — Figure 3) is used for EU type approval testing of emissions and fuel consumption from light duty vehicles. It consists of two parts: (a) four segments of the Urban Driving Cycle (UDC, also known as ECE cycle) representing city driving conditions, and (b) the Extra Urban Driving Cycle (EUDC) to account for more aggressive, high-speed driving modes.

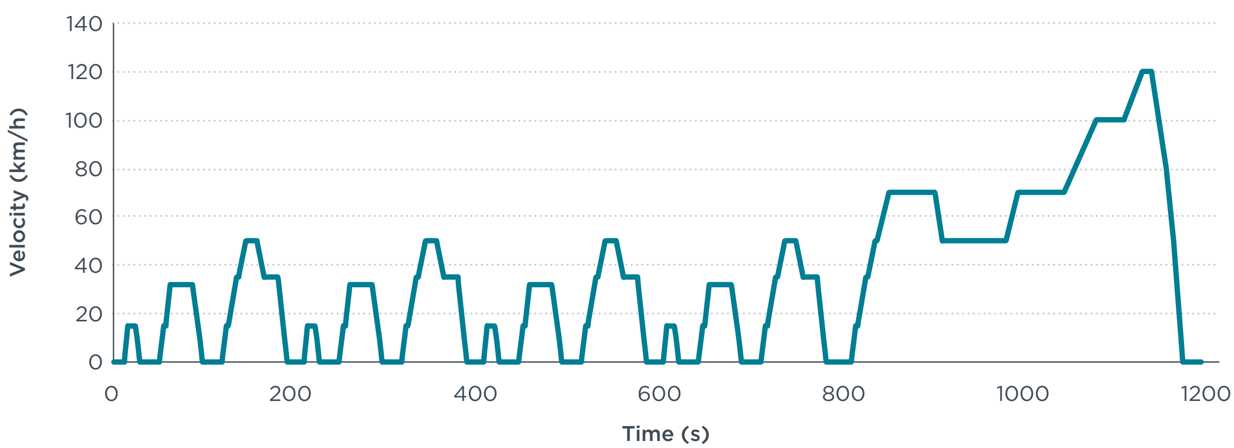


Figure 3: Driving schedule of the NEDC cycle

Emissions are sampled separately for urban and extra-urban driving. Fuel consumption and CO_2 emissions are stated for both parts and the complete NEDC. Distance-based emissions are reported as they are measured; there are no additional weighting factors to be applied among the two subcycles. This means that the NEDC implicitly weights the cold start effect at 100%.

2.3 JAPAN: JC08

The JC08 (Figure 4) was introduced in 2005 into Japanese emission regulation and fuel economy determination. The JC08 test was fully phased-in by October 2011. Measurement is made twice, with a cold start being weighted by 25% and a hot start being weighted by 75%.

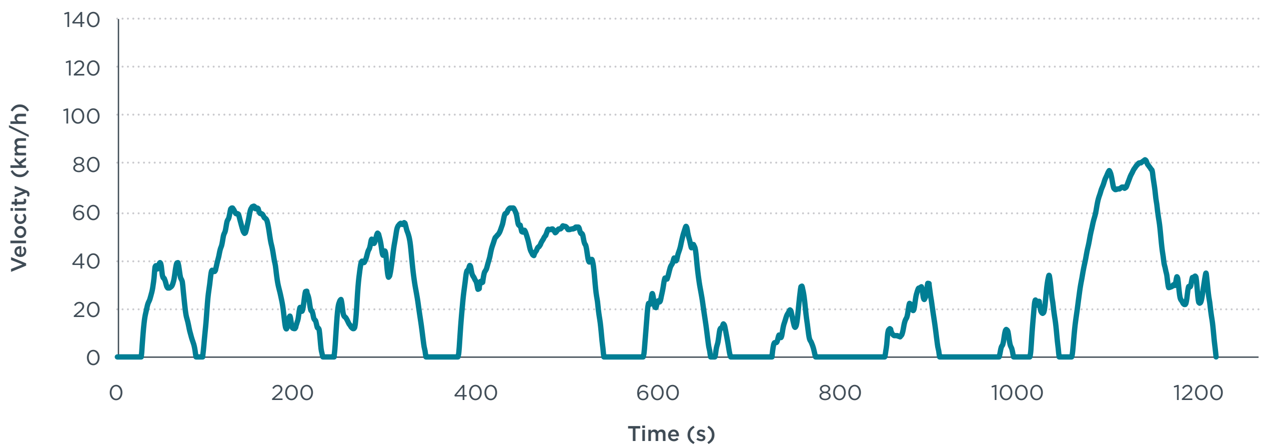


Figure 4: Driving schedule of the JC08 cycle

2.4 WORLDWIDE HARMONIZATION: WLTC

The Worldwide harmonized Light-duty Test Cycle (WLTC — Figure 5) is being developed by the UN ECE GRPE (Working Party on Pollution and Energy) group within the framework of the Worldwide harmonized Light Vehicles Test Procedure (WLTP). The WLTP is expected to replace the European NEDC procedure for type approval testing of light-duty vehicles with the transition to the Euro 6c emission standards in September 2017.

The WLTP procedure includes three test cycles applicable to vehicle categories of different power-to-mass ratios (PMR). Class 3 includes vehicles with the highest PMR and is representative of vehicles driven in Europe, U.S. and Japan. The class 3 WLTC in its current version (#5) consists of four parts: low, middle, high and extra-high load. Emissions from these four subcycles are collected and analyzed separately.

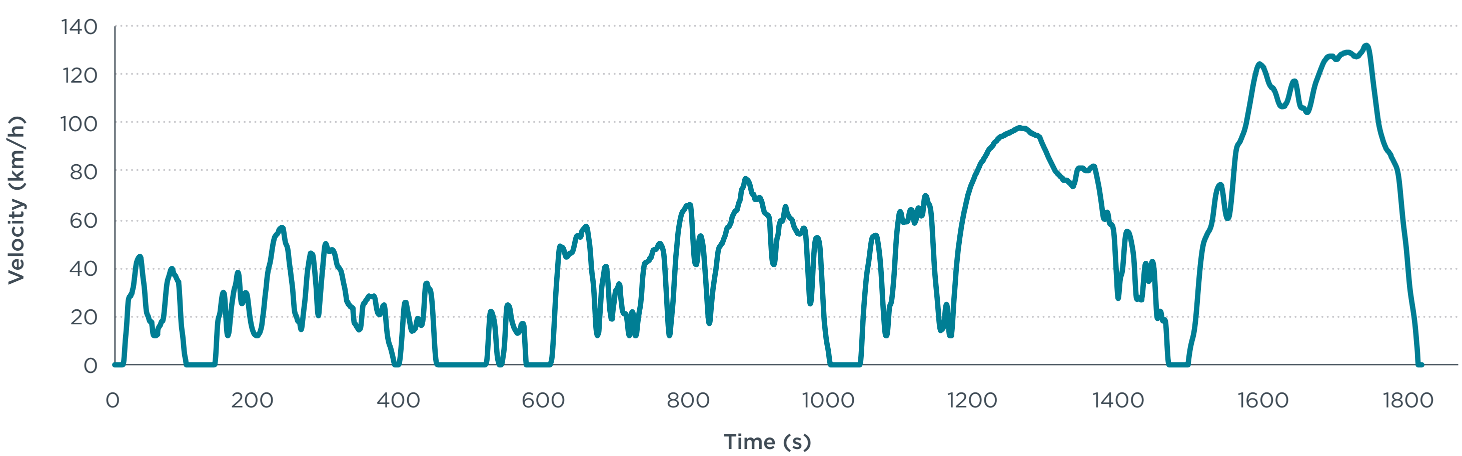


Figure 5: Driving schedule of the WLTC cycle (vehicle class 3, version 5)

2.5 SUMMARY OF DRIVING CYCLES

There are significant differences among the relevant cycles regarding the resulting vehicle and engine loads. Table 2 summarizes some important parameters revealing the main characteristics, including start conditions, durations, distances, mean velocities and accelerations. The parameter *mean positive 'vel * acc'* was calculated by summing up all *velocity by acceleration* products greater than zero on a second-by-second base and subsequently dividing the sum by the total number of seconds of all acceleration phases respectively of the whole cycle. These two parameters represent the power required by accelerations and, hence, give a good description of each cycle's dynamics.

The stop shares of the cycles were calculated by taking into account that the duration of each stop phase is one second shorter than the number of second points with zero velocity (Figure 6). The first and last second points at zero velocity set the boundaries. Only for the first stop phase at the beginning of the cycle that starts at zero velocity, the duration in seconds is equal to the number of zero velocity second points. Therefore, simply dividing the total number of second points at zero velocity by the cycle's total number of seconds would lead to an overestimation of the cycle's stop share.

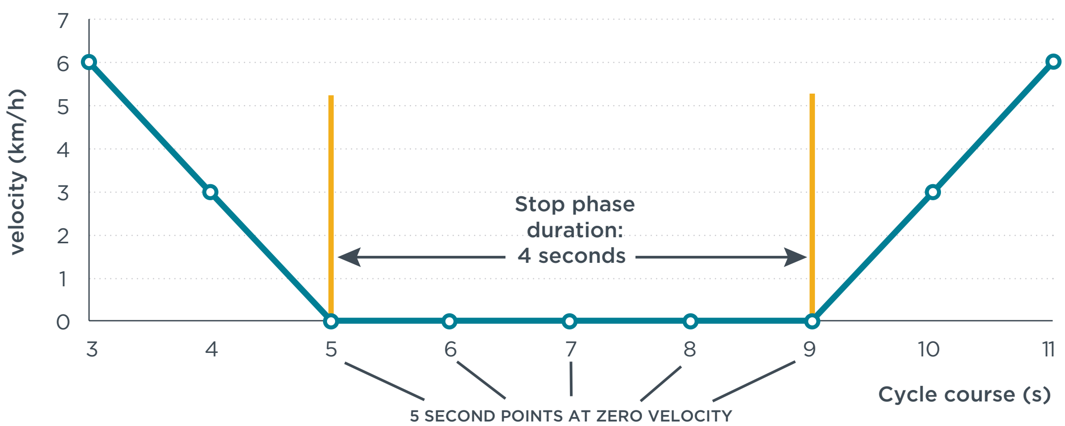


Figure 6: Example for the duration of a stop phase (= number of second points at zero velocity – 1)

The formula for calculating the stop share of a driving cycle is:

Stop share = (number of second points at zero velocity – number of stop phases + 1) / total number of cycle's seconds

Table 2: Descriptive parameters of the driving cycles

	Units	FTP75 weighted	HWFET	CAFE	NEDC	JC08	WLTC
Start condition		43% cold / 57% hot	hot		cold	25% cold / 75% hot	cold
Duration	s	1369	765		1180	1204	1800
Distance	km	11.99	16.51		11.03	8.17	23.27
Mean velocity	km/h	31.5	77.7	52.3	33.6	24.4	46.5
Max. velocity	km/h	91.2	96.4		120.0	81.6	131.3
Stop phases		18	2		14	12	9
Durations							
Stop	s	241	4		280	346	226
Constant driving	s	109	126		475	21	66
Acceleration	s	544	338		247	432	789
Deceleration	s	475	297		178	405	719
Shares							
Stop		17.6%	0.5%	9.9%	23.7%	28.7%	12.6%
Constant driving		8.0%	16.5%	11.8%	40.3%	1.7%	3.7%
Acceleration		39.7%	44.2%	41.7%	20.9%	35.9%	43.8%
Deceleration		34.7%	38.8%	36.6%	15.1%	33.6%	39.9%
Mean positive acceleration	m/s^2	0.50	0.19	0.36	0.59	0.42	0.41
Max. positive acceleration	m/s^2	1.48	1.43		1.04	1.69	1.67
Mean positive 'vel * acc' (acceleration phases)	m^2/s^3	3.86	3.45	3.67	4.97	3.34	4.54
Mean positive 'vel * acc' (whole cycle)	m^2/s^3	1.53	1.52	1.53	1.04	1.20	1.99
Max. positive 'vel * acc'	m^2/s^3	19.19	15.17		9.22	11.60	21.01
Mean deceleration	m/s^2	-0.58	-0.22	-0.42	-0.82	-0.45	-0.45
Min. deceleration	m/s^2	-1.48	-1.48		-1.39	-1.19	-1.50

The NEDC is an artificially constructed cycle with long phases of equal velocity or constant acceleration resulting in total in a narrow area of low load conditions. The required acceleration power of the NEDC is rather high during the acceleration phases, but because of the overall low temporal share of accelerations it is the lowest of all cycles on the total cycle level (1.04 m^2/s^3). In contrast, the WLTC is more dynamic and reaches the highest maximum speed of all cycles and also the highest load conditions, being well underlined by a value of 1.99 m^2/s^3 for the cycle averaged acceleration power. Also the U.S. cycles, summarized as composite CAFE, can be assessed as high dynamic and show the highest mean velocities, while the JC08 requires more aggressive accelerations but on a rather low velocity level.

Starting a test cycle with a cold engine causes higher engine loads, fuel consumption and CO_2 emissions because of higher engine and gearbox lubricant viscosities and other increased friction losses. CO_2 cold start surcharges can be expressed well in absolute emission numbers (in grams per start), while the total range of a specific cycle dilutes these supplemental emissions with increasing driven distance. Comparing the different driving cycles, the cold start effect is most distinct in the NEDC because of its relatively short driving distance, the long heating-up time during low load driving, and implicit cold start weighting of 100%. In comparison, the WLTC takes about 50% longer and is heating the engine quicker. The FTP75 weights the cold start by only 43%. Here, the JC08 lies at the other end of the scale because the result of the cold test is weighted by only 25%.

Estimations of the cold start effect on the total cycles' CO_2 emissions are summarized in Table 3. Relative scaling factors were determined for each cycle by dividing the driven distances by the regulatory cold start weighting factors and by normalizing them to the NEDC (scaling factor = 1). Assuming a realistic NEDC cold start impact range for current engine technologies on the total distance-based CO_2 test result between 9% and 15% (estimated by comparisons between measured NEDC results under cold and hot starting conditions) means for the other cycles clearly lower effects: 2% — 3% for CAFE, 3% — 5% for JC08 and 4% — 7% for WLTC.

Table 3: Cold start weightings and effects on total cycles' CO_2 emissions

	Distance (km)	Weighting factor	Scaling factor	Cold start effect on total CO_2 test result	
				low	high
FTP75	11.99	0.43	0.40	4%	6%
HWFET	16.51	0	0	0%	0%
CAFE*)			0.22	2%	3%
NEDC	11.03	1	1	9%	15%
JC08	8.17	0.25	0.34	3%	5%
WLTC	23.27	1	0.47	4%	7%

*) 55/45 FTP/HWFET relation by assuming similar CO_2 levels for both cycles

Stop-start systems directly benefit from the share of stop phases relative to the total duration of the cycle. There is a clear domination of the NEDC and the JC08, which have stop shares of 23.7% and 28.7% respectively, while testing these systems under CAFE (9.9% stop share) or WLTC (12.6%) schedules provides considerably lower CO_2 savings.

3. VEHICLE MODEL DATA

A sophisticated vehicle emission model developed by Ricardo Inc. was used to determine the CO_2 emission rates. The model runs based on the speed courses of the five driving cycles were resolved on a second-by-second basis. Current vehicle technologies and advanced innovations focusing on the 2020/2025 horizon were covered.

3.1 MODEL DESCRIPTION

A complete, physics-based vehicle and drivetrain system model was developed by Ricardo, Inc., and implemented in MSC.Easy5 (Ricardo 2012, MSC 2012). MSC.Easy5 is a commercially available software package for vehicle system analysis that models the physics in the vehicle drivetrain during a drive cycle. Torque reactions are simulated from the engine through the transmission and driveline to the wheels. The model reacts to simulated driver inputs to the accelerator and brake pedals, thus enabling the actual vehicle acceleration to be determined based on a realistic control strategy. The model determines key component outputs such as torque, engine speeds, and heat rejection. The combination of these engine load output data with fuel or CO_2 engine maps results in integral emission data for specific driving cycles.

Ricardo parameterized the CO_2 model for the predefined driving cycles and vehicle technologies and developed a user friendly application tool, called Data Visualization Tool (DVT) or Complex System Tool (Ricardo 2012, Ricardo 2013a). The DVT includes complex formulae derived from multiple regression methods and allows parameter variations within certain ranges as given in Table 4. The standard values (100%) were determined by Ricardo from technology studies and are vehicle class specific.

Table 4: Possible parameter variations of the DVT

Parameter	Variation range
Engine displacement	50% – 150%
Final drive ratio	75% – 125%
Rolling resistance	70% – 100%
Aerodynamic drag	70% – 100%
Vehicle weight	60% – 120%
Engine efficiency	96% – 104%
Power of electric motor	50% – 300%

The DVT does not allow variations of the underlying vehicle technologies, linked engine maps or driving cycles. A more detailed description of constraints and shortcomings of this tool are given in Appendix E.

3.2 VEHICLE TECHNOLOGIES

Ricardo, Inc., was commissioned by ICCT with the assessment of likely technology developments occurring until 2020/2025 (Ricardo 2012, Ricardo 2013b). The main focus of these studies lies on the European market, but experiences from other regions like North America also influenced the results of these reports. Six different LDV classes were taken into account: B, C, D, small CUV, small and large N1.

The CO_2 savings potentials were assessed separately for gasoline and diesel concepts. The most promising technologies in terms of both reduction potential and market penetration in 2020/2025 were identified and explored further. The most relevant developments relate to improvements in transmissions and clutches (automatic, dual clutch transmission [DCT], continuously variable transmission [CVT]), advanced engines (valve controls, lean combustion, exhaust gas recirculation [EGR], direct injection, Atkinson), system electrification (parallel and powersplit hybrids) and efficient operation strategies like stop/start systems. Appendix A includes a detailed list of the technologies applied.

Technology packages have been created to determine combinations that may be applied in a total vehicle system in a useful way. Table 5 gives an overview on the vehicle packages that were chosen for the model runs.

Table 5: Defined vehicle technology packages

Vehicle Architecture	Engine						Transmission			
	PI	STDI	LBDI	EGRB	ACPS	ADVA	AT-6	AT-8	DCT	CVT
GASOLINE										
Baseline	X						X			
Advanced ICE & AT		X	X	X				X		
Advanced ICE & DCT		X	X	X					X	
P2 Hybrid		X	X	X	X	X			X	
Powersplit Hybrid		X	X	X	X	X				X
DIESEL										
Baseline				X			X			
Advanced ICE & AT				X				X		

ICE Internal Combustion Engine

PI Port Injection

STDI Stoichiometric Direct Injection

LBDI Lean-Burn Direct Injection

EGRB Exhaust Gas Recirculation Direct Injection

ACPS Atkinson Cam-Profile Switching

ADVA Atkinson Digital Valve Actuation

AT-6 Six speed Automatic Transmission

AT-8 Eight speed Automatic Transmission

DCT Dual Clutch Transmission

CVT Continuously Variable Transmission (here: Planetary Gear)

The **pre-Baseline** concepts show the same main features as the Baseline vehicles, but:

1. Lack a stop-start system,
2. Lack a braking energy recovery system (micro hybrid for Baseline), and
3. Are equipped with a low efficiency alternator (55% in comparison to 70% for Baseline).

The fuel and CO_2 engine maps for each of the described technology packages were estimated and implemented for the MSC.Easy5 model runs by Ricardo.

3.3 APPLIED MODEL RUNS

For the purpose of this study the Ricardo DVT was used to determine the CO_2 emission data for the different legal driving cycles. The Ricardo reports (Ricardo 2012, Ricardo 2013b) already include CO_2 model output data for the pre-baseline, baseline and advanced technologies, for each of the six LDV classes. The reported data all are based on average vehicle driving resistances and weights, not taking into account possible improvements within the explored timeframe until 2020/2025. In order to cover realistic improvements of future driving resistances and to extend the amount of data for the subsequent regression analyses, model runs with the parameter variations in Table 6 were performed.

Table 6: Model runs with varied driving resistances and vehicle weight

Parameter	Variations
Aerodynamic drag	80%, 90%, 100%
Vehicle weight	80%, 90%, 100%
Rolling resistance, aerodynamic drag and vehicle weight	80%, 90%, 100%

3.4 MODEL OUTPUT

CO_2 emissions in g/km as averages for the driving cycles CAFE (composite), NEDC, JC08 and WLTC were calculated by applying the methodology described above. Altogether, considering all vehicle classes, technology packages and parameter variations, 175 data points for the diesel concepts and 763 data points for the gasoline concepts were created for each of the four cycles. This database provides the initial foundation for the investigations concerning cycle-specific emission behavior by applying comparative regression analyses as depicted in Chapter 5.

4. REGRESSION ANALYSES

Different types of regression analyses were applied to the modeled CO_2 emission data in order to describe the dependencies for each pair of the four different driving cycles. Every possible cycle combination was explored in both directions. Altogether 12 cycle pairs were examined. Standard statistical procedures were deployed, i.e., the resulting regression functions were based on the least squares approach. This standard method minimizes the deviations of the dependent variable, which in this case are the resulting CO_2 emissions of the second cycle. Interchanging the two cycles (Cycle 2 → Cycle 1) results in different regression parameters that are not identical to the inverse results of the original direction of translation (Cycle 1 → Cycle 2).

All performed regression calculations directly compare the CO_2 emissions of the two involved cycles. The tested regression types differ by the mathematical nature (linear vs. nonlinear approaches), the inclusion or exclusion of a y-intercept, the differentiation into different vehicle technologies and the inclusion of additional independent variables (multiple regression analyses). Therefore, the level of complexity and the achievable quality of the regression results also vary between the different types. In general, a higher complexity (and therefore a lower usability, from a practical perspective) is linked with a higher outcome quality and a more precise emission translation.

The standard deviation of the single data points is used as a measure for the quality of the regression types. This measure is independent from the sample size and therefore allows direct comparisons of the regression qualities between different approaches including different numbers of data points, e.g., between gasoline and diesel concepts or between ”all data” and ”technology differentiated” approaches. This standard deviation may also be interpreted as the maximum error of the resulting CO_2 number (Cycle 2) with a probability of 68.3% (two-tailed test). A summary of the standard errors of the different regression types averaged over all cycle combinations can be found in Chapter 5.6.

Gasoline and diesel data were always regarded separately because of the fundamental differences in the technologies and CO_2 emission behavior. However, it has been recognized that for some cases of application a summarizing approach is more appropriate. The stringency of CO_2 and fuel consumption standards not only depends on the quantities of the limit values and the assigned driving cycles, but the composition of the regional vehicle fleets plays an important role, too. For example, a fleet with a higher share of diesel passenger cars benefits under a fuel consumption-related regime compared to a pure gasoline fleet. When comparing standards from different regions, a reference fleet technology mix has to be determined. On a base level approach, this could be achieved by averaging the fleet diesel shares from the two regions considered for comparison. In Chapters 4.3 and 5.3, which cover single linear regression with intercept, the description and the results of this comprehensive standard comparison approach are given.

For this exercise CO_2 emissions of two cycles were always compared directly. Strong linear dependencies were found under these premises. Hence, linear regression approaches always led to the best results. Nonlinear regression types, such as logarithmic, exponential or polynomial estimates, also were tested. But because these results were worse than those of the linear attempts, they have not been documented in this report. The logarithmic approach is justified for only the 2007 approach (Chapter 4.1).

The following symbols are used throughout the discussion of statistical methods that follow:

C1	CO_2 emissions of the driving cycle being converted
C2	Converted CO_2 emissions of the target driving cycle
aero	Aerodynamic drag (= C_d * A), with m^2 as the unit
a	Regression coefficient applied to C1
b	Regression coefficient applied to aero
d	Regression intercept
StdErr(C2)	Standard error (68.3% confidence interval) of the converted CO_2 emissions for an individual data point

4.1 2007 METHODOLOGY (LOGARITHMIC APPROACH)

Regression type: $C2/C1 = a * \ln(C1) + d$

This regression type was chosen for the 2007 exercises (ICCT, 2007). It is assumed that the quotient of CO_2 (called *multiplier*) from both cycles correlates with CO_2 from Cycle 1. In contrast to direct linear comparisons there is a natural curvature in this regression methodology. Therefore, best results have been achieved with a logarithmic attempt. This type of regression previously was regarded as the standard method, and data quality of the subsequent regression estimates was matched with this approach in determining whether or not to deploy a new and better method.

Chapter 5.1 contains the results of this regression type in terms of tabulated regression coefficients and standard errors of the transformed CO_2 emissions of Cycle 2.

4.2 SINGLE REGRESSION WITH ZERO INTERCEPT — ALL DATA

Regression type: $C2 = a * C1$

The easiest way of exploring a correlation is implemented by a simple linear regression without y-intercept. The resulting regression coefficient represents a constant factor for converting CO_2 of Cycle 1 into CO_2 of Cycle 2. All available data were assessed together at this level without technology differentiations.

This approach provides the highest grade of usability, but also lowest translation accuracy. The achieved regression coefficients and calculated standard deviations of this step are included in Chapter 5.2.

4.3 SINGLE REGRESSION WITH CALCULATED INTERCEPT — ALL DATA

4.3.1 Gasoline and diesel concepts separated

Regression type: $C2 = a * C1 + d$

The inclusion of the y-intercept into the simple linear regression analyses increases the degrees of freedom and therefore reduces statistical uncertainties. Again the complete data set was evaluated at this regression level without taking into account possible technology specifics.

The existence of a second regression coefficient worsens the usability of this approach somewhat, but the accuracy of translated data gets slightly better the higher the y-intercept turns out. The regression results for this low accuracy, high usability approach are summarized in Chapter 5.3.

4.3.2 Universal approach — weighted by diesel/gasoline market share

A differentiation between gasoline and diesel vehicles normally seems appropriate because of the fundamental technological differences and their impacts on engine load-dependent emissions and fuel consumption behavior. However, even such a basic technology differentiation causes practical difficulties when comparing the stringencies of CO_2 or FC standards from different regions, because: 1. Averaged CO_2 emissions or FC data differentiated between gasoline and diesel might not be available. 2. It might be more descriptive to go without any technology differentiation in order to join standards from different parts of the world together in one picture. Thereto, assumptions about a basic fleet composition have to be made. At the bottom level of technology differentiation, mean shares of gasoline and diesel driven vehicles are necessary to describe such an averaged fleet.

The resulting linear regression lines for gasoline and diesel vehicles were merged by weighting the two regression coefficients a (slope) and d (y-intercept) by the share of diesel vehicles in the total number of vehicles (DS). This comprehensive approach allows the translation of fleet CO_2 emissions (or standards) from one driving cycle (C1) into another (C2). Only the share of diesel vehicles in the assumed fleet has to be specified.

$$\text{Universal approach:}\quad C2 = (a1 * DS + a2) * C1 + d1 * DS + d2$$

with:

DS	Fleet diesel share (0..1)
a1	$a_{diesel} - a_{gasoline}$
a2	$a_{gasoline}$
d1	$d_{diesel} - d_{gasoline}$
d2	$d_{gasoline}$

The results for the coefficients a1, a2, d1 and d2 for each combination of cycle pairs are tabulated in Chapter 5.3.

4.4 SINGLE REGRESSION WITH CALCULATED INTERCEPT — DIFFERENT TECHNOLOGIES

$$\text{Regression type:}\quad C2 = a * C1 + d$$

Some of the explored vehicle technologies show cycle-specific emission behavior. Hence, better data quality can be achieved by differentiating the regression analyses among technology categories. For the gasoline vehicles significant improvements were found when performing separate regression calculations for

- pre-Baseline ICE,
- Baseline ICE (stop-start, braking energy recuperation, improved alternator),
- Advanced ICE and
- Hybrid technologies.

The benefits for a separate treatment of the hybrids occur only for some of the cycle combinations (see results in Chapter 5). Hence, analyses were also performed and documented for the combined technology class including advanced ICE and hybrid technologies.

Concerning diesel concepts, no significant differences were found in regression results between baseline and advanced ICE technologies. Diesel hybrids were not considered for this study. Thus, only two diesel classes were addressed separately,

» pre-Baseline and
» Baseline and Advanced ICE.

Deploying the regression results of this approach requires an increased expenditure and additional data about the technology levels of the affected vehicles. On the other hand, the separated data sets are more homogeneous and cause lower uncertainties. Chapter 5.4 includes the results of this mid accuracy, mid usability procedure.

4.5 MULTIPLE REGRESSION — DIFFERENT TECHNOLOGIES

Regression type: C2 = a * C1 + b * TP + d

with:

TP Technical regression parameter

The inclusion of additional technical parameters (TP) might further improve the quality of the regression functions. The Ricardo studies and the DVT were used to extract potential, quantifiable continuous parameters. The correlations of these parameters with the CO_2 multipliers (CO_2 of Cycle 2 / CO_2 of Cycle 1) were examined. Table 7 shows exemplarily the coefficients of determination, R^2, as an indicator for the quality of correlation for the CAFE/JC08 multipliers of the gasoline concepts.

Table 7: Correlations between CO_2 multiplier residuals ($C2/C1_{modeled}$ - $C2/C1_{regression}$) and different continuous variables (here C1: JC08; C2: CAFE)

Metric	R^2
Aerodynamic drag (C_d * A)	0.61
Vehicle weight	0.27
Tire rolling resistance	0.24
Final drive ratio	0.10
Peak torque	0.05
Peak power	0.05
Engine displacement	0.00

Overall, only the aerodynamic drag could be identified as a parameter with a high significant influence on the CO_2 multipliers. Vehicle weight and rolling resistance show only weak correlations, while the effect of the final drive ratio, peak torque, peak power and engine displacement is negligible.

Based on these results, linear multiple regression analyses were conducted by employing the aerodynamic drag ("aero") as a second independent variable. The same technology separations were applied as in the previous step (Chapter 4.4). This type of regression can be regarded as the ultimate level of accuracy because the inclusion of further parameters will not result in large further improvements. Of course, information about the aerodynamic drag is essential to use these equations. In good approximation, the predefined aerodynamic drags of the Ricardo reports as averages of different vehicle classes could be inserted (Table 8).

Table 8: Typical aerodynamic drag ("aero") values (Ricardo 2012)

Vehicle class	Aerodynamic drag C_d * A (m^2)
B	0.736
C	0.650
D	0.690
Small CUV	0.925
N1 (small)	1.040
N1 (large)	0.952

Chapter 5.5 contains the regression coefficients and the standard errors for this highest accuracy, lowest usability technique.

5. RESULTING CONVERSION ALGORITHMS AND UNCERTAINTIES

This chapter includes all tabulated results from the regression analyses. CO_2 emissions (g CO_2/km) are always translated from cycle C1 into cycle C2. The number of regression parameters a, b, d depends on the level of detail of each applied regression type. The standard error in the last column represents the standard deviation of a single data point. It stands for the maximum deviation between the real CO_2 emissions of cycle C2 and the calculated one, with a probability of 68.3%.

The documentation of results starts with the previous standard method applied for the 2007 report (ICCT, 2007). The following types of regression are sorted by the grade of complexity, starting with the simplest approach linked with the highest uncertainties of results. Further explanations and information about additionally required data input are given in Chapter 4.

Chapter 5.6 provides a summary of results and an overview on the achievable data qualities of the different regression methods.

5.1 2007 METHODOLOGY

Regression type: $C2/C1 = a * \ln(C1) + d$

All data

GASOLINE — ALL DATA

C2 (g CO_2/km)	C1 (g CO_2/km)	a	d	StdErr(C2) (g CO_2/km)
CAFE	NEDC	-0.0780	1.3625	3.80
NEDC	CAFE	0.0766	0.6455	4.40
CAFE	JC08	-0.2392	2.1994	7.35
JC08	CAFE	0.2309	-0.1658	10.27
CAFE	WLTC	0.0443	0.6469	4.48
WLTC	CAFE	-0.0829	1.5515	4.70
NEDC	JC08	-0.1736	1.9005	5.52
JC08	NEDC	0.1468	0.2225	6.58
NEDC	WLTC	0.1146	0.3113	7.65
WLTC	NEDC	-0.1640	1.9289	6.94
JC08	WLTC	0.2320	-0.3310	14.44
WLTC	JC08	-0.3587	2.9309	10.92

DIESEL — ALL DATA

C2 (g CO_2/km)	C1 (g CO_2/km)	a	d	StdErr(C2) (g CO_2/km)
CAFE	NEDC	-0.1501	1.6869	5.38
NEDC	CAFE	0.1486	0.3307	6.92
CAFE	JC08	-0.2754	2.2962	8.80
JC08	CAFE	0.2674	-0.2344	13.77
CAFE	WLTC	-0.0232	1.0331	2.20
WLTC	CAFE	0.0148	1.0164	2.44
NEDC	JC08	-0.1384	1.6703	5.10
JC08	NEDC	0.1299	0.3736	6.19
NEDC	WLTC	0.1104	0.4211	7.35
WLTC	NEDC	-0.1506	1.7733	6.36
JC08	WLTC	0.2121	-0.0708	14.25
WLTC	JC08	-0.2928	2.4643	10.14

5.2 SINGLE REGRESSION WITH ZERO INTERCEPT: LOWEST ACCURACY, HIGH USABILITY

Regression type: C2 = a * C1

All data

GASOLINE — ALL DATA

C2 (g CO_2/km)	C1 (g CO_2/km)	a	StdErr(C2) (g CO_2/km)
CAFE	NEDC	0.9810	5.48
NEDC	CAFE	1.0171	5.58
CAFE	JC08	1.0333	14.68
JC08	CAFE	0.9521	14.09
CAFE	WLTC	0.8671	4.92
WLTC	CAFE	1.1511	5.67
NEDC	JC08	1.0568	10.19
JC08	NEDC	0.9391	9.61
NEDC	WLTC	0.8810	9.28
WLTC	NEDC	1.1280	10.50
JC08	WLTC	0.8223	17.83
WLTC	JC08	1.1847	21.40

DIESEL — ALL DATA

C2 ($g\ CO_2/km$)	C1 ($g\ CO_2/km$)	a	StdErr(C2) ($g\ CO_2/km$)
CAFE	NEDC	0.9456	7.54
NEDC	CAFE	1.0537	7.96
CAFE	JC08	0.9251	14.43
JC08	CAFE	1.0666	15.50
CAFE	WLTC	0.9187	2.27
WLTC	CAFE	1.0882	2.47
NEDC	JC08	0.9815	7.62
JC08	NEDC	1.0155	7.75
NEDC	WLTC	0.9681	8.08
WLTC	NEDC	1.0291	8.33
JC08	WLTC	0.9799	15.63
WLTC	JC08	1.0067	15.84

The simple coefficients of this regression approach can be interpreted as averaged quotients of the CO_2 emissions of the two respective driving cycles. Hence, they provide a rough impression of how the cycle-specific dynamics may influence the CO_2 outcomes in different directions. Gasoline vehicles (Figure 7) emit strongest under the WLTC schedule. CO_2 emissions under the JC08, CAFE and NEDC regimes are 18%, 15% and 13% lower.

The behavior of the diesel vehicles (Figure 8) is clearly different. Here, the cycle-specific deviations are generally lower and show a different pattern. For example, averaged WLTC and JC08 emissions (the highest deviations for the gasoline vehicles) are almost equal, while CAFE emissions are lower than JC08 (the opposite of the gasoline vehicles). These results reflect the fundamental differences in the structures of gasoline and diesel engine maps.

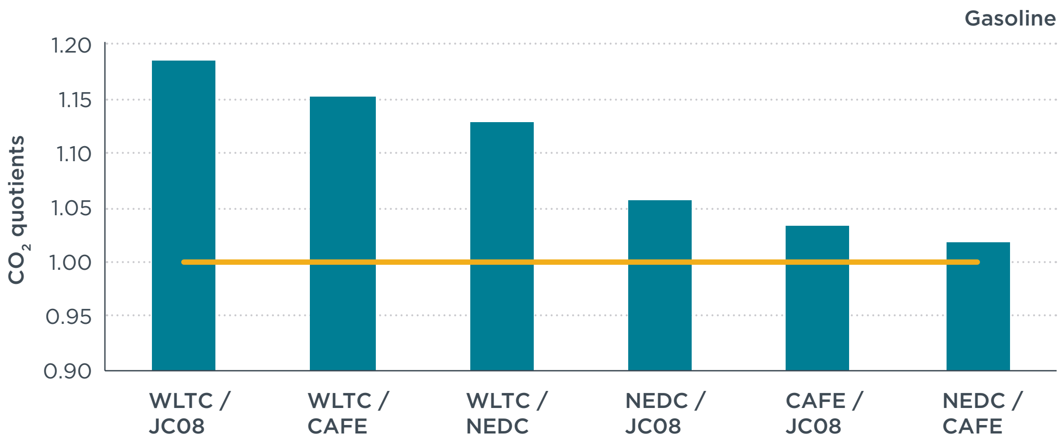


Figure 7: Cycle deviations of CO_2 emissions — averaged over all gasoline technologies

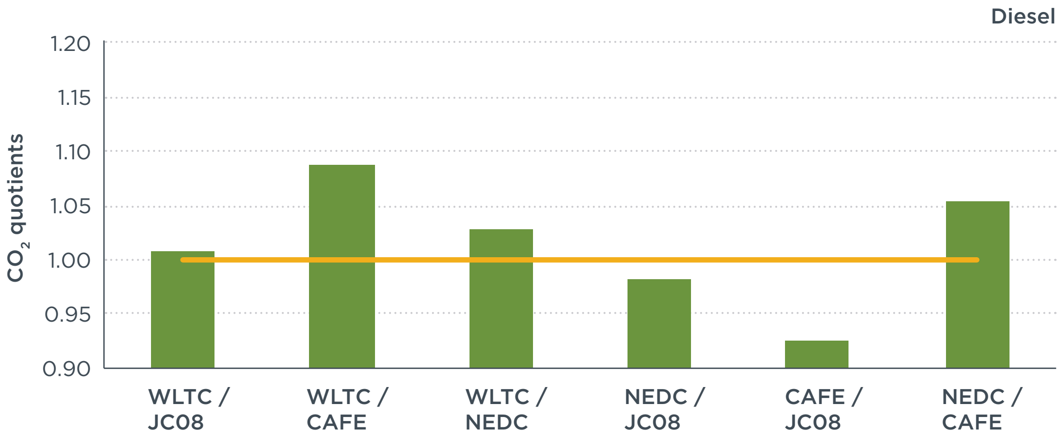


Figure 8: Cycle deviations of CO_2 emissions — averaged over all diesel technologies

5.3 SINGLE REGRESSION WITH CALCULATED INTERCEPT: LOW ACCURACY, HIGH USABILITY

5.3.1 Gasoline and diesel concepts separated

Regression type: C2 = a * C1 + d

All data

GASOLINE — ALL DATA

C2 (g CO_2/km)	C1 (g CO_2/km)	a	d (g CO_2/km)	StdErr(C2) (g CO_2/km)
CAFE	NEDC	0.8658	14.076	3.91
NEDC	CAFE	1.1325	-13.739	4.47
CAFE	JC08	0.7212	36.736	7.96
JC08	CAFE	1.2749	-38.423	10.58
CAFE	WLTC	0.9318	-8.827	4.51
WLTC	CAFE	1.0454	12.590	4.78
NEDC	JC08	0.8457	24.840	5.86
JC08	NEDC	1.1430	-24.907	6.81
NEDC	WLTC	1.0475	-22.727	7.78
WLTC	NEDC	0.8984	28.059	7.21
JC08	WLTC	1.1532	-45.172	14.72
WLTC	JC08	0.7319	53.293	11.73

DIESEL — ALL DATA

C2 (g CO_2/km)	C1 (g CO_2/km)	a	d (g CO_2/km)	StdErr(C2) (g CO_2/km)
CAFE	NEDC	0.7683	23.928	5.57
NEDC	CAFE	1.2209	-21.218	7.02
CAFE	JC08	0.6050	44.338	9.27
JC08	CAFE	1.3691	-38.393	13.94
CAFE	WLTC	0.8970	2.999	2.21
WLTC	CAFE	1.1040	-2.010	2.45
NEDC	JC08	0.8230	21.950	5.31
JC08	NEDC	1.1720	-21.122	6.33
NEDC	WLTC	1.0961	-17.690	7.43
WLTC	NEDC	0.8489	24.308	6.54
JC08	WLTC	1.2254	-33.942	14.40
WLTC	JC08	0.6665	47.123	10.62

5.3.2 Universal approach — weighted by diesel/gasoline market share

The linear weighting of the two corresponding gasoline and diesel regression lines (for each pair of driving cycles) results in linear equations, including the share of diesel vehicles, characterizing the fleet technology mix on a basic level. This allows the direct comparison of CO_2 or FC standards without knowing technology-specific CO_2 emissions or FC levels. The fleet diesel share, DS, is a value between 0 and 1. When comparing standards from different world regions relating to different technology mixes, an averaged diesel share could be assessed, depending on the question.

Universal approach: C2 = (a1 * DS + a2) * C1 + d1 * DS + d2

GASOLINE & DIESEL — ALL DATA — UNIVERSAL APPROACH

C2 (g CO_2/km)	C1 (g CO_2/km)	a1	a2	d1 (g CO_2/km)	d2 (g CO_2/km)	StdErr(C2) (g CO_2/km)
CAFE	NEDC	-0.0975	0.8658	9.852	14.076	4.40
NEDC	CAFE	0.0884	1.1325	-7.480	-13.739	5.10
CAFE	JC08	-0.1162	0.7212	7.602	36.736	8.35
JC08	CAFE	0.0941	1.2749	0.030	-38.423	11.30
CAFE	WLTC	-0.0348	0.9318	11.826	-8.827	4.20
WLTC	CAFE	0.0587	1.0454	-14.600	12.590	4.47
NEDC	JC08	-0.0227	0.8457	-2.891	24.840	5.76
JC08	NEDC	0.0290	1.1430	3.786	-24.907	6.73
NEDC	WLTC	0.0486	1.0475	5.037	-22.727	7.73
WLTC	NEDC	-0.0494	0.8984	-3.752	28.059	7.11
JC08	WLTC	0.0722	1.1532	11.230	-45.172	14.67
WLTC	JC08	-0.0653	0.7319	-6.170	53.293	11.56

DS Fleet diesel share (0..1)

The standard errors for the comprehensive approach were taken over from an additional regression analysis following the linear approach C2 = a * C1 + b * DS + d. They are rather similar to the gasoline and diesel differentiated results in the upper tables, but do not yet include the uncertainties of the estimated fleet diesel share, which have to be considered for a complete uncertainty analysis by following the principles of error propagation.

5.4 LINEAR REGRESSIONS FOR EACH TECHNOLOGY PACKAGE: MID ACCURACY, MID USABILITY

Regression type: C2 = a * C1 + d

Different technologies

GASOLINE — PRE-BASELINE

C2 (g CO_2/km)	C1 (g CO_2/km)	a	d (g CO_2/km)	StdErr(C2) (g CO_2/km)
CAFE	NEDC	0.8420	8.951	4.03
NEDC	CAFE	1.1722	-8.003	4.75
CAFE	JC08	0.6896	28.424	7.67
JC08	CAFE	1.3816	-29.587	10.85
CAFE	WLTC	0.8802	7.304	4.48
WLTC	CAFE	1.1177	-5.185	5.05
NEDC	JC08	0.8285	21.189	4.60
JC08	NEDC	1.1923	-22.756	5.52
NEDC	WLTC	1.0352	-0.072	6.25
WLTC	NEDC	0.9442	4.224	5.96
JC08	WLTC	1.2193	-20.077	12.00
WLTC	JC08	0.7728	26.176	9.55

GASOLINE — BASELINE

C2 (g CO_2/km)	C1 (g CO_2/km)	a	d (g CO_2/km)	StdErr(C2) (g CO_2/km)
CAFE	NEDC	0.8983	9.773	2.55
NEDC	CAFE	1.1051	-9.596	2.83
CAFE	JC08	0.8191	21.916	5.91
JC08	CAFE	1.1730	-19.193	7.08
CAFE	WLTC	0.8658	10.427	4.32
WLTC	CAFE	1.1308	-8.221	4.94
NEDC	JC08	0.9188	12.360	4.36
JC08	NEDC	1.0696	-10.345	4.70
NEDC	WLTC	0.9580	1.726	5.31
WLTC	NEDC	1.0171	2.623	5.47
JC08	WLTC	1.0165	-7.100	8.59
WLTC	JC08	0.9270	16.438	8.21

GASOLINE — ADVANCED ICE

C2 ($g\ CO_2/km$)	C1 ($g\ CO_2/km$)	a	d ($g\ CO_2/km$)	StdErr(C2) ($g\ CO_2/km$)
CAFE	NEDC	0.9927	1.916	1.15
NEDC	CAFE	1.0033	-1.476	1.16
CAFE	JC08	1.0527	2.866	4.01
JC08	CAFE	0.9042	2.490	3.72
CAFE	WLTC	0.8428	2.424	1.25
WLTC	CAFE	1.1810	-2.242	1.48
NEDC	JC08	1.0628	0.709	3.68
JC08	NEDC	0.9031	3.594	3.40
NEDC	WLTC	0.8461	0.896	1.60
WLTC	NEDC	1.1730	-0.051	1.88
JC08	WLTC	0.7539	5.755	4.57
WLTC	JC08	1.2300	2.539	5.84

GASOLINE — HYBRID

C2 ($g\ CO_2/km$)	C1 ($g\ CO_2/km$)	a	d ($g\ CO_2/km$)	StdErr(C2) ($g\ CO_2/km$)
CAFE	NEDC	1.0074	-0.467	1.85
NEDC	CAFE	0.9803	1.697	1.82
CAFE	JC08	1.1823	-2.501	3.52
JC08	CAFE	0.8075	5.934	2.91
CAFE	WLTC	0.8125	3.962	3.09
WLTC	CAFE	1.1879	-0.601	3.74
NEDC	JC08	1.1615	-0.970	3.76
JC08	NEDC	0.8153	5.384	3.15
NEDC	WLTC	0.8050	4.573	2.65
WLTC	NEDC	1.2096	-2.432	3.25
JC08	WLTC	0.6427	10.720	4.66
WLTC	JC08	1.3757	-1.081	6.81

GASOLINE — ADVANCED ICE & HYBRID

C2 (g CO_2/km)	C1 (g CO_2/km)	a	d (g CO_2/km)	StdErr(C2) (g CO_2/km)
CAFE	NEDC	1.0086	-0.321	1.67
NEDC	CAFE	0.9834	1.162	1.64
CAFE	JC08	1.0175	9.817	4.83
JC08	CAFE	0.9157	-2.601	4.59
CAFE	WLTC	0.8412	1.347	2.78
WLTC	CAFE	1.1619	1.224	3.27
NEDC	JC08	1.0012	10.760	4.99
JC08	NEDC	0.9242	-2.953	4.80
NEDC	WLTC	0.8326	1.825	2.45
WLTC	NEDC	1.1795	0.057	2.91
JC08	WLTC	0.7529	0.777	6.33
WLTC	JC08	1.1555	15.130	7.84

DIESEL — PRE-BASELINE

C2 (g CO_2/km)	C1 (g CO_2/km)	a	d (g CO_2/km)	StdErr(C2) (g CO_2/km)
CAFE	NEDC	0.8360	5.399	3.44
NEDC	CAFE	1.1648	-1.884	4.06
CAFE	JC08	0.6779	22.437	6.84
JC08	CAFE	1.3221	-10.785	9.56
CAFE	WLTC	0.9172	-0.454	1.30
WLTC	CAFE	1.0862	1.090	1.42
NEDC	JC08	0.8332	16.319	4.21
JC08	NEDC	1.1662	-13.894	4.99
NEDC	WLTC	1.0598	-1.050	5.34
WLTC	NEDC	0.9008	8.174	4.92
JC08	WLTC	1.1921	-8.124	10.98
WLTC	JC08	0.7239	27.722	8.56

DIESEL — BASELINE & ADVANCED ICE

C2 (g CO_2/km)	C1 (g CO_2/km)	a	d (g CO_2/km)	StdErr(C2) (g CO_2/km)
CAFE	NEDC	0.9847	-0.056	1.47
NEDC	CAFE	1.0094	0.785	1.49
CAFE	JC08	0.9682	4.036	5.05
JC08	CAFE	0.9582	4.575	5.03
CAFE	WLTC	0.8954	3.260	2.37
WLTC	CAFE	1.0991	-1.558	2.63
NEDC	JC08	0.9947	2.821	4.03
JC08	NEDC	0.9604	2.517	3.95
NEDC	WLTC	0.9028	4.195	2.95
WLTC	NEDC	1.0811	-1.485	3.22
JC08	WLTC	0.8499	8.730	6.04
WLTC	JC08	1.0541	4.053	6.72

5.5 MULTIPLE REGRESSION FOR EACH TECHNOLOGY PACKAGE WITH AERO DRAG: HIGHEST ACCURACY, LOWEST USABILITY

Regression type: C2 = a * C1 + b * aero + d

Different technologies

GASOLINE — PRE-BASELINE

C2 (g CO_2/km)	C1 (g CO_2/km)	a	b (g CO_2/(km*m^2))	d (g CO_2/km)	StdErr(C2) (g CO_2/km)
CAFE	NEDC	0.8037	17.013	3.309	3.48
NEDC	CAFE	1.2239	-18.186	-2.945	4.29
CAFE	JC08	0.6242	39.228	11.984	5.77
JC08	CAFE	1.5303	-52.278	-15.046	9.03
CAFE	WLTC	0.9529	-26.249	13.861	3.49
WLTC	CAFE	1.0322	30.076	-13.551	3.63
NEDC	JC08	0.7847	26.231	10.195	3.11
JC08	NEDC	1.2634	-31.665	-12.254	3.94
NEDC	WLTC	1.1830	-53.342	13.252	2.28
WLTC	NEDC	0.8414	45.720	-10.939	1.92
JC08	WLTC	1.4927	-98.707	4.578	5.33
WLTC	JC08	0.6595	67.939	-2.297	3.55

GASOLINE — BASELINE

C2 (g CO_2/km)	C1 (g CO_2/km)	a	b (g CO_2/(km*m^2))	d (g CO_2/km)	StdErr(C2) (g CO_2/km)
CAFE	NEDC	0.8669	10.839	6.977	2.20
NEDC	CAFE	1.1430	-11.203	-7.345	2.52
CAFE	JC08	0.7426	32.558	10.642	4.11
JC08	CAFE	1.3036	-38.523	-11.454	5.45
CAFE	WLTC	0.9424	-23.396	14.598	3.52
WLTC	CAFE	1.0363	27.902	-13.827	3.69
NEDC	JC08	0.8612	24.491	3.879	2.96
JC08	NEDC	1.1466	-26.542	-3.499	3.41
NEDC	WLTC	1.0874	-39.538	8.775	3.12
WLTC	NEDC	0.9068	38.026	-7.185	2.85
JC08	WLTC	1.2570	-73.462	5.998	3.10
WLTC	JC08	0.7874	59.453	-4.149	2.45

GASOLINE — ADVANCED ICE

C2 (g CO_2/km)	C1 (g CO_2/km)	a	b (g CO_2/(km*m^2))	d (g CO_2/km)	StdErr(C2) (g CO_2/km)
CAFE	NEDC	0.9840	1.323	1.897	1.15
NEDC	CAFE	1.0051	-0.258	-1.475	1.16
CAFE	JC08	0.8562	32.706	-1.300	1.59
JC08	CAFE	1.1433	-35.813	2.513	1.83
CAFE	WLTC	0.9108	-11.612	2.263	0.79
WLTC	CAFE	1.0921	13.310	-2.251	0.87
NEDC	JC08	0.8720	31.760	-3.337	0.86
JC08	NEDC	1.1399	-35.746	4.100	0.98
NEDC	WLTC	0.9172	-12.132	0.728	1.24
WLTC	NEDC	1.0766	14.561	-0.257	1.34
JC08	WLTC	1.0420	-49.171	5.072	1.99
WLTC	JC08	0.9357	48.981	-3.701	1.89

GASOLINE — HYBRID

C2 ($g\ CO_2/km$)	C1 ($g\ CO_2/km$)	a	b ($g\ CO_2/(km*m^2)$)	d ($g\ CO_2/km$)	StdErr(C2) ($g\ CO_2/km$)
CAFE	NEDC	1.0419	-4.498	-0.477	1.81
NEDC	CAFE	0.9269	7.210	1.533	1.71
CAFE	JC08	0.9827	25.476	-4.618	2.22
JC08	CAFE	0.9651	-21.297	6.418	2.20
CAFE	WLTC	0.9727	-24.175	3.458	2.53
WLTC	CAFE	0.9593	30.912	-1.303	2.51
NEDC	JC08	0.9290	29.673	-3.435	2.01
JC08	NEDC	1.0255	-27.411	5.322	2.11
NEDC	WLTC	0.9191	-17.207	4.214	2.33
WLTC	NEDC	1.0188	24.882	-2.376	2.45
JC08	WLTC	0.9375	-44.485	9.793	3.32
WLTC	JC08	0.9415	55.430	-5.686	3.33

GASOLINE — ADVANCED ICE & HYBRID

C2 ($g\ CO_2/km$)	C1 ($g\ CO_2/km$)	a	b ($g\ CO_2/(km*m^2)$)	d ($g\ CO_2/km$)	StdErr(C2) ($g\ CO_2/km$)
CAFE	NEDC	1.0292	-3.254	0.005	1.64
NEDC	CAFE	0.9544	4.735	0.609	1.58
CAFE	JC08	0.8457	33.938	0.072	2.45
JC08	CAFE	1.1354	-35.834	1.588	2.84
CAFE	WLTC	0.9566	-20.338	2.598	2.13
WLTC	CAFE	1.0140	24.133	-1.597	2.19
NEDC	JC08	0.8166	36.487	0.282	2.20
JC08	NEDC	1.1822	-40.779	1.123	2.65
NEDC	WLTC	0.9216	-15.684	2.790	2.02
WLTC	NEDC	1.0535	19.926	-1.934	2.16
JC08	WLTC	1.0893	-59.306	4.425	3.57
WLTC	JC08	0.8601	58.370	-1.632	3.18

DIESEL — PRE-BASELINE

C2 ($g\ CO_2/km$)	C1 ($g\ CO_2/km$)	a	b ($g\ CO_2/(km*m^2)$)	d ($g\ CO_2/km$)	StdErr(C2) ($g\ CO_2/km$)
CAFE	NEDC	0.7590	22.618	0.358	2.17
NEDC	CAFE	1.2927	-27.369	1.203	2.84
CAFE	JC08	0.5763	45.567	4.738	3.42
JC08	CAFE	1.6546	-71.148	-2.760	5.79
CAFE	WLTC	0.9587	-9.232	0.250	0.90
WLTC	CAFE	1.0397	9.960	-0.033	0.94
NEDC	JC08	0.7675	29.481	4.869	1.73
JC08	NEDC	1.2938	-37.504	-5.535	2.25
NEDC	WLTC	1.2341	-38.711	1.899	3.60
WLTC	NEDC	0.7858	33.811	0.638	2.87
JC08	WLTC	1.5761	-85.278	-1.627	6.68
WLTC	JC08	0.5953	57.688	5.316	4.10

DIESEL — BASELINE & ADVANCED ICE

C2 ($g\ CO_2/km$)	C1 ($g\ CO_2/km$)	a	b ($g\ CO_2/(km*m^2)$)	d ($g\ CO_2/km$)	StdErr(C2) ($g\ CO_2/km$)
CAFE	NEDC	0.9607	4.944	-0.879	1.34
NEDC	CAFE	1.0323	-4.491	1.437	1.39
CAFE	JC08	0.8735	22.956	-1.974	4.04
JC08	CAFE	1.0592	-19.766	7.448	4.44
CAFE	WLTC	0.9772	-15.900	4.673	1.60
WLTC	CAFE	1.0113	17.183	-4.056	1.62
NEDC	JC08	0.9201	18.090	-1.916	3.23
JC08	NEDC	1.0383	-16.063	5.191	3.44
NEDC	WLTC	1.1020	-21.204	6.080	1.79
WLTC	NEDC	0.9746	21.956	-5.141	1.76
JC08	WLTC	1.0414	-37.201	12.037	4.43
WLTC	JC08	0.8888	40.071	-6.438	4.10

5.6 SUMMARY OF ALL REGRESSION APPROACHES

Averaging the standard deviations of all cycle combinations gives a clear picture of the impacts on data quality of the different regression approaches. Figure 9 summarizes the gasoline results, and Figure 10 depicts the effects for the diesel vehicles. In absolute terms, gasoline and diesel uncertainties are rather similar. The stepwise improvements of data quality with increasing complexities of the regression method can be seen clearly.

Taking the 2007 logarithmic approach as a reference, it can be concluded that the simple linear regression approach including all data points provides the same data quality with a standard deviation of 7.5 g CO_2/km. Excluding the y-intercept from the linear regression with all data worsens data quality by approximately 30-35%. In the opposite direction, separating the fleet by technologies leads to improvements of 40%. Another 20% improvement can be achieved when including the aerodynamic drag in the regression analyses. At this final multiple regression level, averaged standard deviations remain around 2.5 g CO_2/km.

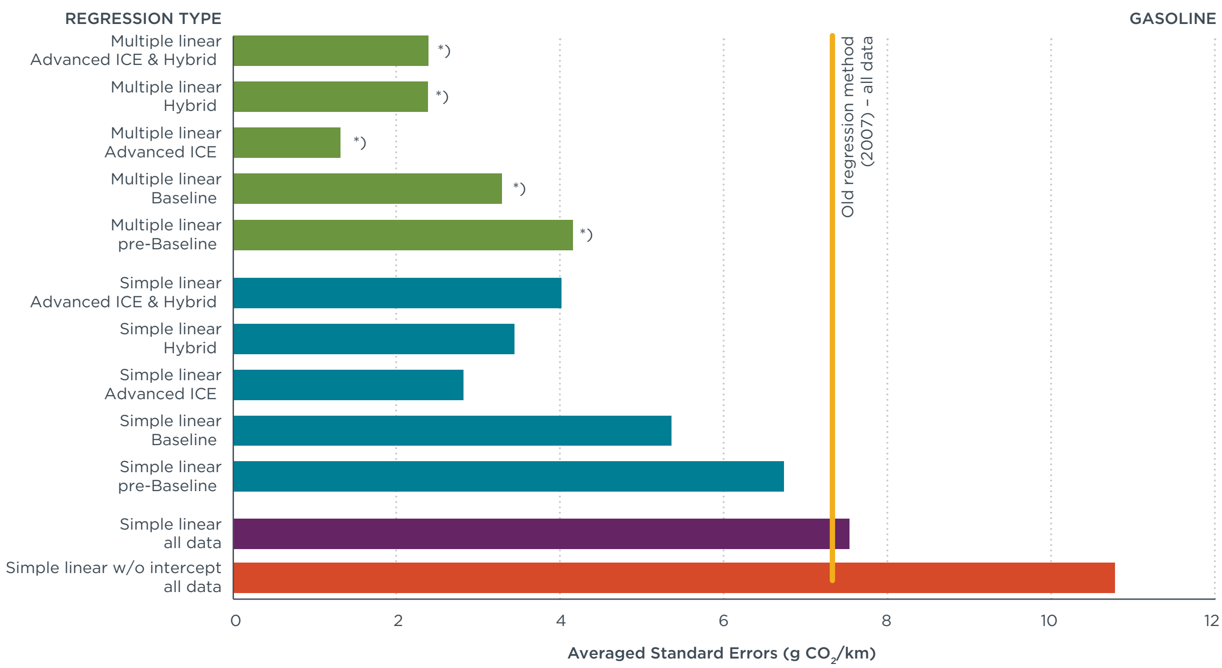


Figure 9: Standard deviations of single data points for gasoline concepts — averaged over all cycle combinations

*) Multiple linear regression type based on C1 (CO_2 emissions of cycle 1) and aerodynamic drag as independent variables

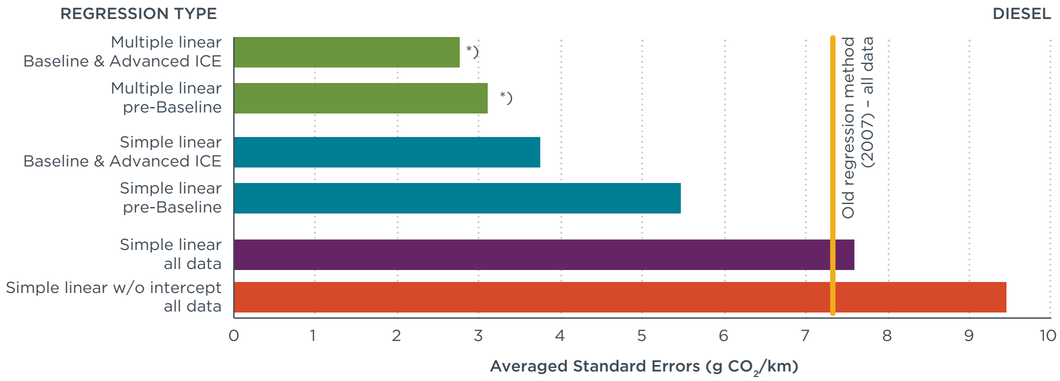


Figure 10: Standard deviations of single data points for diesel concepts — averaged over all cycle combinations

*) Multiple linear regression type based on C1 (CO_2 emissions of cycle 1) and aerodynamic drag as independent variables

Besides the clear improvements in data quality when applying more sophisticated regression methods, large technology-based effects on the standard errors can be observed in Figure 9 and Figure 10. Among all investigated technology packages, the pre-Baseline concepts (without stop-start system) show the highest scatter of data points. Table 9 indicates that the higher uncertainties of the regression results for pre-Baseline concepts against the Baseline technologies (equipped with stop-start) are also highly cycle-specific. Cycle pairs with a similar share of stops, such as CAFE/WLTC or NEDC/JC08, display rather uniform scatter, while the deviations between the standard errors go up with larger cycle discrepancies concerning vehicle stops.

Table 9: Standard deviation differences between pre-Baseline and Baseline gasoline concepts and cycle stop shares

Cycle pair	Standard deviation — pre-Baseline	Standard deviation — Baseline	Delta Standard Deviations	Delta Stop Shares
CAFE/NEDC	4.4	2.7	1.7	13.8%
CAFE/JC08	9.3	6.5	2.8	18.8%
CAFE/WLTC	4.8	4.6	0.1	2.7%
NEDC/JC08	5.1	4.5	0.5	5.0%
NEDC/WLTC	6.1	5.4	0.7	11.1%
JC08/WLTC	10.8	8.4	2.4	16.1%
Cycle stop shares				
CAFE	9.9%			
NEDC	23.7%			
JC08	28.7%			
WLTC	12.6%			

As shown in Figure 11, when comparing pre-Baseline (without stop-start) with Baseline (with stop-start) concepts, there is a strong correlation between the delta of the standard deviations of the CO_2 emissions and the delta of stop shares between the two driving cycles. In other words, CO_2 idle emissions of the pre-Baseline concepts show rather distinct differences among the different vehicle segments. Modeling a cycle with a high share of stop (idle) phases leads to some disordered shifts of CO_2 emissions among different vehicle types. Comparing such a high-stop-share cycle with a low-stop-share cycle results in a wider range of C1-C2 CO_2 paired data points and therefore to a larger scatter. This effect is largely eliminated with the introduction of stop-start systems because idle emissions no longer play such a big role and technology-specific impacts are smoothed.

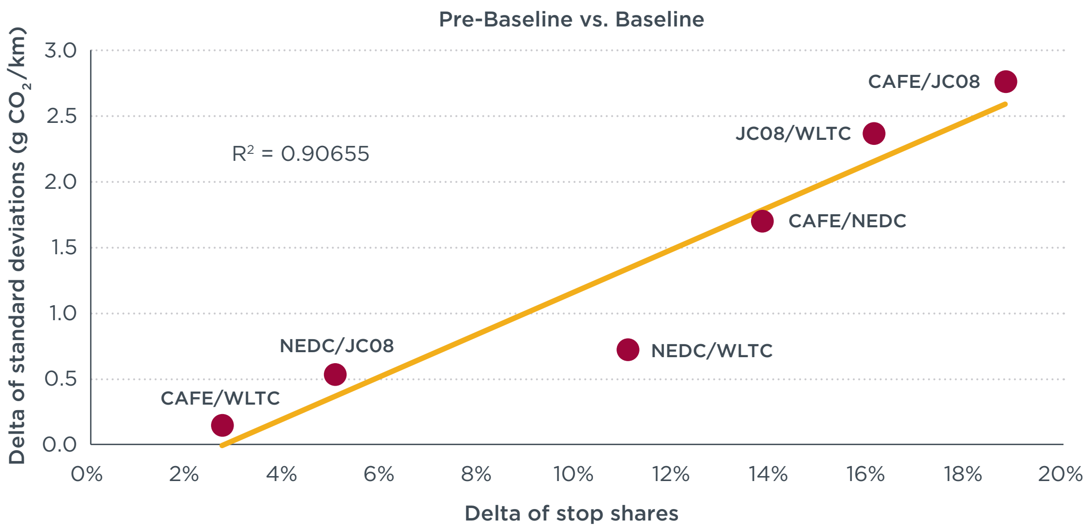


Figure 11: Difference of mean standard deviations between pre-Baseline and Baseline gasoline technologies depending on the differences of stop shares of the two cycles

6. CONCLUSIONS

A new methodology has been developed for the purpose of adjusting the dynamometer test cycle differences in engine loads and in related fuel economy and GHG emissions. The new conversion approach allows for transforming CO_2 emission values from one of the examined driving cycles from one world region (U.S. CAFE, NEDC, JC08, WLTC) into another. The main improvements compared to the similar 2007 approach (ICCT 2007) are summarized in Table 10.

Table 10: Comparison between the 2007 approach (ICCT 2007) and actual work (this study)

2007 work	2014 work
Use of vehicle model data from the Modal Energy and Emissions Model (MEEM)	Use of vehicle model data from Ricardo's Data Visualization Tool (DVT) based on MSC.Easy5
Simulation results for 12 current technology LDV (gasoline only, internal combustion engine only)	Simulation results for a large variety of innovative technologies, including advanced gasoline, hybrids and advanced diesel technologies
2015 projection	2020/2025 projection
Multiplier logarithmic regression method	Different linear and nonlinear regression approaches evaluated, higher level of technical details
Resulting algorithms converting CAFE (mpg), NEDC (g CO_2/km) and JC08 (l/km)	Resulting g CO_2/km-based algorithms converting CAFE, NEDC, JC08 and WLTC

Different mathematical approaches have been developed. They differ by the amount of data to be included in the translation algorithm and by the data quality to be achieved (in terms of standard errors of CO_2 emissions of the second cycle). The multiple regression approaches of Chapter 5.5 provide the highest quality results, but vehicle (fleet) specific technical data must be available in order to apply them (see Table 11).

Table 11: Regression approaches, accuracy and usability

Mathematical type of regression			Chapters in this report	Accuracy	Usability
Single (S) or multiple (M)	Intercept	All data (A) or technology-specific (T)			
S	No	A	4.2, 5.2	-	+
S	Yes	A	4.3, 5.3	-	+
S	Yes	T	4.4, 5.4	+-	+-
M	Yes	T	4.5, 5.5	+	-

In general, it is recommended to use the pattern in Table 12 to determine which conversion approach is most appropriate in which case and which regression coefficients should be applied, depending on the availability of necessary input data. The priority no. 1 approach delivers results with the lowest uncertainties but requires specific input data on aerodynamic drags and drivetrain technologies.

Table 12: Decision matrix for determining the appropriate type of regression

Priority	Aerodynamic drag of vehicle (fleet) available?	Vehicle class (distribution) known?	Technology class (distribution) known?	Use regression results of Chapter
1	Yes	-	Yes	5.5
2	No Note: use averaged data (Table 8)	Yes	Yes	5.5
3	No	No	Yes	5.4
4	No	No	No[1]	5.3.1
5	No	No	No gasoline & diesel fleet mixture[2]	5.3.2

[1] A differentiation between gasoline and diesel engines is mandatory.
[2] The fleet diesel share (DS) has to be assessed.

Easier approaches could be considered if lower requirements concerning data quality would allow their use. Under these circumstances, it is recommended to first check the magnitude of the calculated standard errors provided in Chapter 5 before making a choice.

The basic level approach, no. 5, can be seen as a universal approach and includes regression coefficients for averaged complete LDV fleets, summarizing gasoline and diesel vehicles in comprehensive equations (see Chapter 4.3.2) of regression type:

$$C2 = (a1 * DS + a2) * C1 + d1 * DS + d2$$

The application of this formula to convert CO_2 emissions from cycle 1 (C1) into cycle 2 (C2) requires the assessment of a fleet diesel share, DS, as an only technical input parameter. The values of the correlation coefficients a1, a2, d1, d2 for the specific pairs of driving cycles are tabulated in Chapter 5.3.2.

No additional technical information or technology-separated CO_2 emission averages are needed at this level. This approach might be appropriate when comparing the stringencies of CO_2 or FC standards from different regions without requiring any further technology differentiations. A mean composition of the two compared regional fleets, characterized by the fleet diesel share, has to be estimated. The total uncertainties of this approach consist of the statistical errors of the regression analyses and the uncertainty of the averaged fleet diesel share.

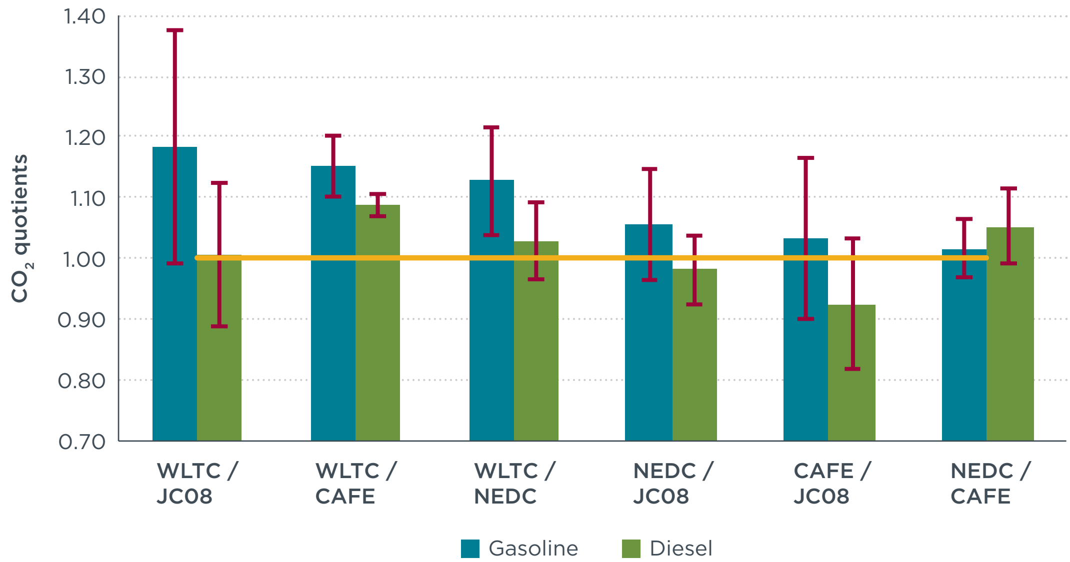


Figure 12: Averaged CO_2 emission quotients — results from basic single regression approach with zero intercept (approach no. 4 of Table 12). Error bars represent technology-specific standard deviations of single data points.

Figure 12 shows the averaged results of the basic single regression approach with zero intercept. The slopes of the regression lines may be interpreted as simple quotients of the distance-based CO_2 emissions of both cycles. The error bars represent the standard deviations caused by individual vehicle technology packages. Gasoline vehicles emit strongest under the WLTC schedule. CO_2 emissions under the JC08, CAFE and NEDC regimes are 18%, 15% and 13% lower. The behavior of the diesel vehicles is clearly different. Here, the cycle-specific deviations are generally lower and show a different pattern. For example, averaged WLTC and JC08 emissions (the highest deviations for the gasoline vehicles) are almost equal, while CAFE emissions are lower than JC08 (the opposite of the gasoline vehicles). These results reflect the fundamental differences in the structures of gasoline and diesel engine maps.

ABBREVIATIONS

a	Regression coefficient applied to C1
A	Frontal area
acc	Acceleration
ACPS	Atkinson Cam-Profile Switching
ADVA	Atkinson Digital Valve Actuation
aero	Aerodynamic drag (= Cd * A), with m^2 as the unit
AT-x	Automatic transmission (with x gears)
b	Regression coefficient applied to aero
B	Smalls cars
C	Medium cars
C1	CO2 emissions of the driving cycle being converted (Cycle 1)
C2	Converted CO_2 emissions of the target driving cycle (Cycle 2)
CAFE	United States Corporate Average Fuel Economy
Cd	Drag coefficient
CFR	United States Code of Federal Regulations
CI	Compression Ignition
CO_2	Carbon dioxide
CPS	Cam-Profile Switching valve train
CUV	Crossover Utility Vehicle
CVT	Continuously Variable Transmission
d	Regression intercept
D	Large cars
DCT	Dual Clutch Transmission (with x gears)
DI	Direct Injection
DS	Fleet Diesel Share
DVA	Digital Valve Actuation valve train
DVT	Data Visualisation Tool
EC	European Commission
EGR	Exhaust Gas Recirculation
EGRB	Exhaust Gas Recirculation Direct Injection
EPA	United States Environmental Protection Agency
EU	European Union
EUDC	Extra Urban Driving Cycle
FC	Fuel Consumption
FTP	Federal Test Procedure

GHG	Greenhouse Gas
GRPE	Working Party on Pollution and Energy (UN ECE)
HEV	Hybrid Electric Vehicle
HWFET	Highway Fuel Economy Test
ICE	Internal Combustion Engine
LBDI	Lean-Burn Direct Injection
JC08	Japanese test Cycle (2008)
LDV	Light-Duty Vehicles
MEEM	Modal Energy and Emissions Model
MLIT	Japanese Ministry of Land, Infrastructure, Transport and Tourism
MT-x	Manual transmission (with x gears)
N1	Light Commercial Vehicle having a maximum mass not exceeding 3.5 tonnes
NEDC	New European Driving Cycle
NO_x	Nitrogen Oxides
PI	Port Injection
PMR	Power-to-Mass Ratio
R^2	Coefficient of determination
SI	Spark Ignition
StdErr(C2)	Standard error (68.3% confidence interval) of the converted CO_2 emissions
TP	Additional Technical Parameter for multiple regression analyses
UDC	Urban Driving Cycle
UN ECE	United Nations Economic Commission for Europe
vel	Velocity
WLTC	Worldwide harmonized Light-duty Test Cycle
WLTP	Worldwide harmonized Light vehicles Test Procedure

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APPENDIX A VEHICLE TECHNOLOGIES EXPLORED

VEHICLE SEGMENTS

B

C

D

Small CUV (Crossover Utility Vehicles)

Small N1 LCV (Light Commercial Vehicles)

Large N1 LCV (Light Commercial Vehicles)

Unadjusted road load parameters:

Segment	Mass (kg)	Cd	Frontal area (m^2)	Aero drag, Cd*A (m^2)	Rolling resistance coefficient
B	1191	0.32	2.30	0.736	0.0094
C	1474	0.31	2.10	0.650	0.0083
D	1644	0.3	2.30	0.690	0.0082
Small CUV	1814	0.37	2.50	0.925	0.0069
Small N1	1644			1.040	0.0083
Large N1	2041	0.34	2.80	0.952	0.0072

GASOLINE SPARK IGNITION (SI) ENGINES

Engine displacement (cm^3):

Segment	Pre-Baseline	Baseline AT/MT	Advanced ICE	Hybrid	Atkinson Hybrid
B	1500	1500	740	590	1660
C	1600	2000/1600	780	620	1740
D	2400	2400	1040	830	2400
Small CUV	2400	2400	1130	900	2600
Small N1	2000	2000	890	708	2055
Large N1	3800	3800	1310	1050	3150

(All technology packages with 6-speed automatic transmission [AT-6] only — except pre-Baseline and Baseline C-segment: AT-6 and MT-6)

Peak power (kW):

Segment	Pre-Baseline	Baseline AT/MT	Advanced ICE	Hybrid	Atkinson Hybrid
B	82	82	72	59	65
C	88	86/88	76	62	68
D	118	118	101	83	94
Small CUV	128	128	110	90	102
Small N1	101	101	89	71	80
Large N1	154	154	131	105	124

(All technology packages with 6-speed automatic transmission [AT-6] only — except pre-Baseline and Baseline C-segment: AT-6 and MT-6)

Pre-baseline:

» No stop-start system
» No recovery of braking energy
» 55% alternator efficiency
» 6-speed automatic transmission (+ 6-speed manual transmission for C segment)

Baseline:

» Stop-start system
» Micro hybrid (recovery of a modest amount of braking energy)
» 70% alternator efficiency
» 6-speed automatic transmission (+ 6-speed manual transmission for C segment)

Advanced technologies (2020/2025):

» Engine efficiency is expected to approach the efficiency of diesel engines
» Atkinson cycle
» Lean-stoichiometric combustion
» Exhaust gas recirculation (EGR)
» Advanced valve trains
  » Cam-profile switching (CPS) valve train
  » Digital valve actuation (DVA) valve train
» Direct injection (DI) fuel systems
» Advanced boosting systems (for lean-combustion and EGR engines only)
» Engine friction improvements (blanket 3.5%)
» Hybrid technologies (in combination with downsized combustion engines)
  » P2 parallel hybrid
  » Input powersplit hybrid
» Transmissions
  » Automatic transmissions (eight gears for C class or higher; six gears for B class)
    » Multi-damper torque converter

- » Improvements in shifting clutch technology
- » Dual clutch transmission (DCT)
  - » Advanced dry clutch launch device
  - » Wet clutch launch device (large N1)
- » Continuously variable transmission (CVT) (planetary gearset in combination with the input powersplit hybrid)
- » Reduced friction
  - » Super finishing of surfaces
  - » Low viscosity lubricants
- » Improved kinematic design and component efficiency
- » Dry sump lubrication

» Intelligent cooling systems

» Electric power-assisted steering

DIESEL COMPRESSION IGNITION (CI) ENGINES

Engine displacements (cm^3):

Segment	Pre-Baseline	Baseline	Advanced ICE
B	1200	1200	1130
C	1600	1600	1270
D	2000	2000	1730
Small CUV	2200	2200	1780
Small N1	1800	1800	1100
Large N1	2200	2200	2040

(All technology packages with 6-speed Automatic Transmission [AT-6] only — except Pre-Baseline and Baseline C-segment: AT-6 and MT-6)

Peak power (kW):

Segment	Pre-Baseline	Baseline AT/MT	Advanced ICE
B	59	59	69
C	97	75/97	77
D	122	122	105
Small CUV	131	131	109
Small N1	66	66	67
Large N1	103	103	124

(All technology packages with 6-speed automatic transmission [AT-6] only — except pre-Baseline and Baseline C-segment: AT-6 and MT-6)

Pre-baseline:

- No stop-start-system
- No recovery of braking energy
- 55% alternator efficiency

Baseline:

- Stop-start system
- Micro hybrid (recovery of a modest amount of braking energy)
- 70% alternator efficiency

Advanced technologies (2020-2025):

- Series-sequential, two-stage turbocharging
- Charge air cooling (air to air heat exchanger)
- Enhanced exhaust gas recirculation (EGR) (including low pressure EGR circuit for increased flow rate and low temperature cooling circuit)
- Cam-profile switching (CPS) valve train
- Particulate filter and lean NO_x aftertreatment
- Engine friction improvements (blanket 3.5%)
- Advanced automatic transmissions (eight gears for C class or higher; six gears for B class)
    - Multi-damper torque converter
    - Improvements in shifting clutch technology
    - Reduced friction
        - Super finishing of surfaces
        - Low viscosity lubricants
    - Improved kinematic design and component efficiency
    - Dry sump lubrication
- Intelligent cooling systems
- Electric power assisted steering

APPENDIX B GRAPHS CO_2 WITH LINEAR REGRESSION — ALL GASOLINE

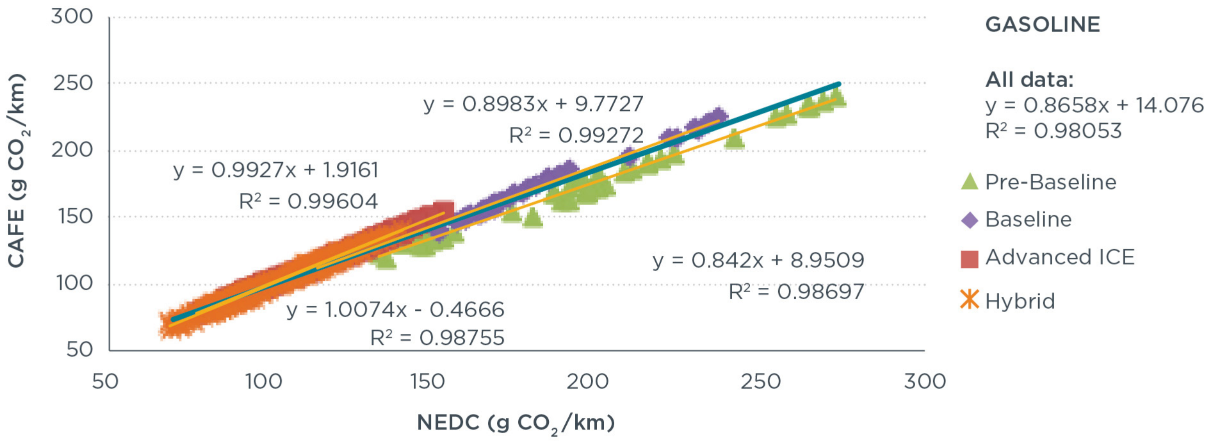

Figure B-1: Gasoline regression results: CAFE over NEDC

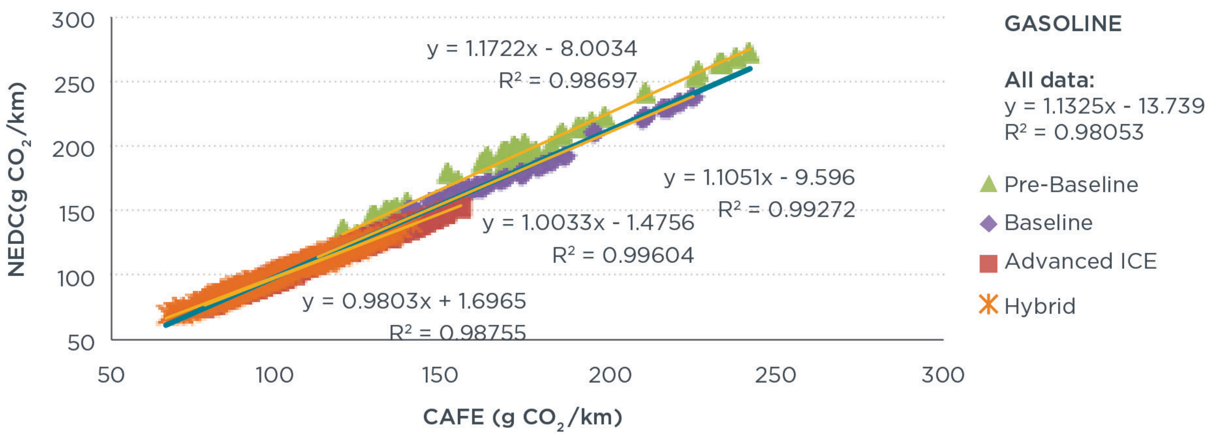

Figure B-2: Gasoline regression results: NEDC over CAFE

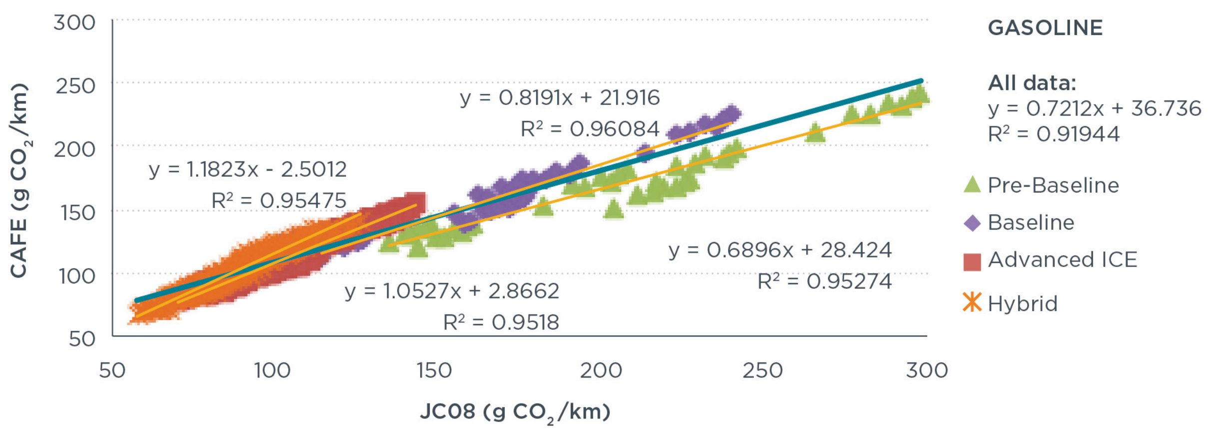

Figure B-3: Gasoline regression results: CAFE over JC08

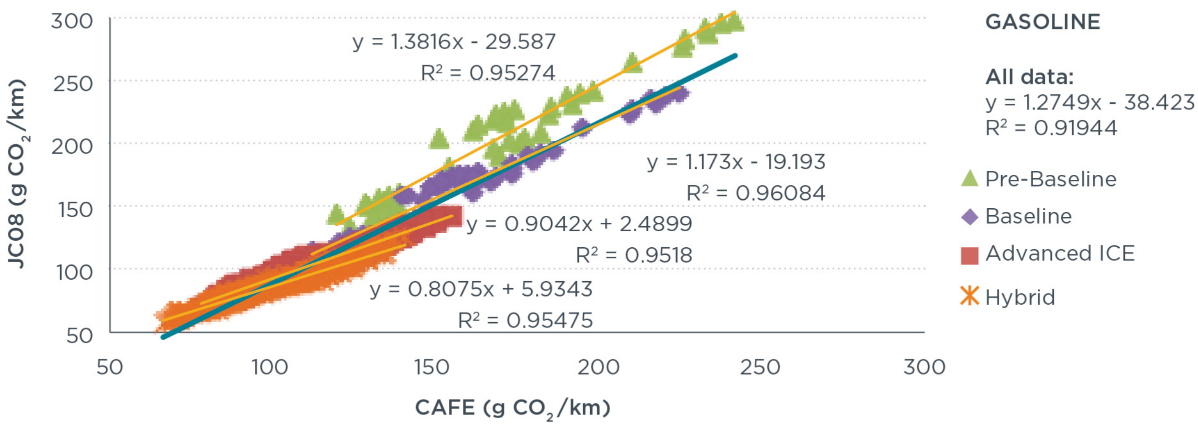

Figure B-4: Gasoline regression results: JC08 over CAFE

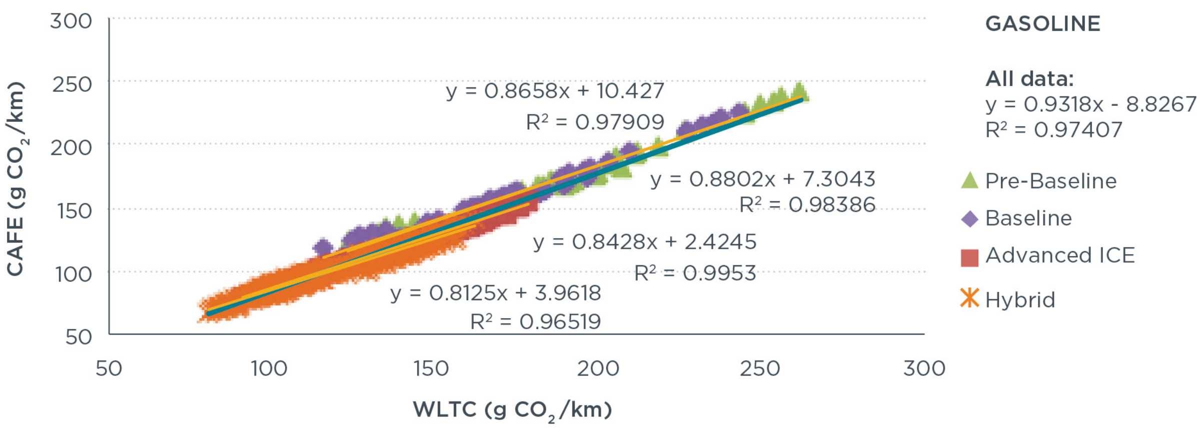

Figure B-5: Gasoline regression results: CAFE over WLTC

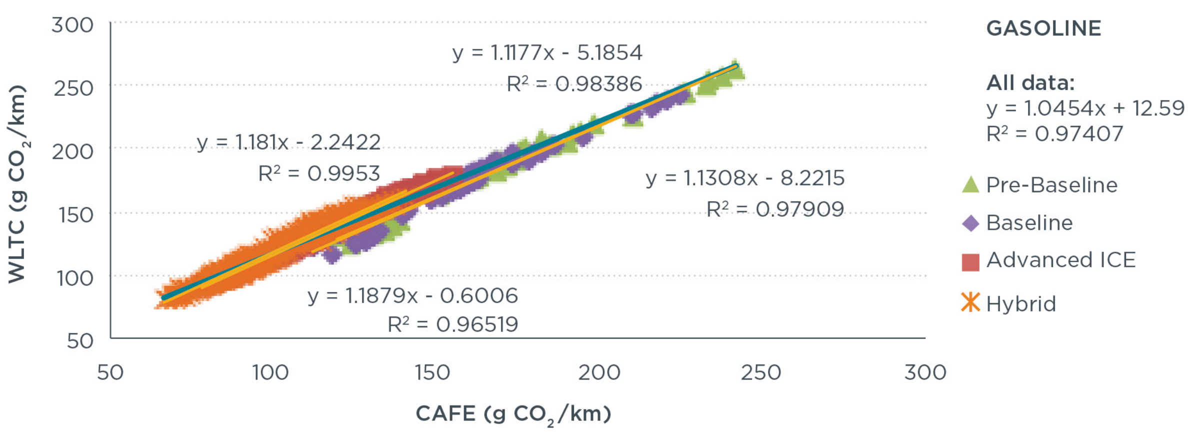

Figure B-6: Gasoline regression results: WLTC over CAFE

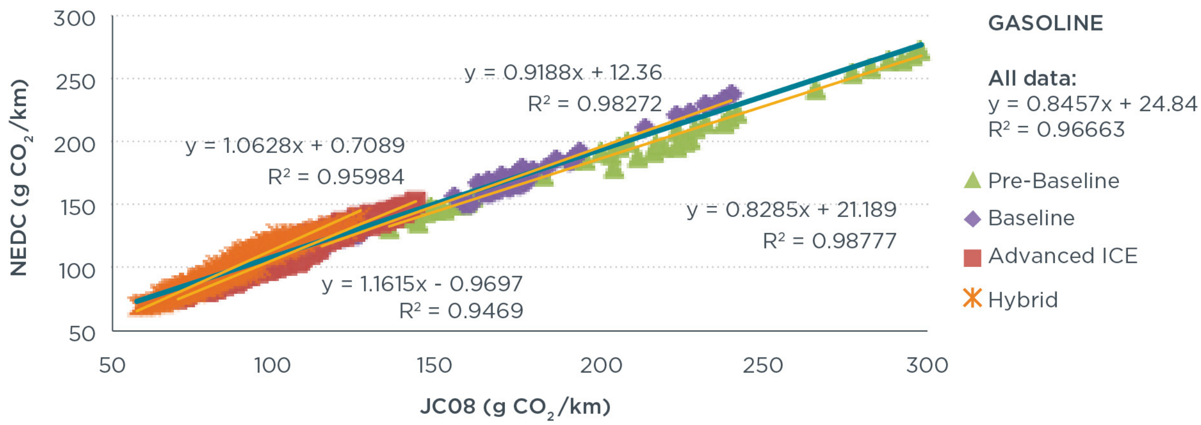

Figure B-7: Gasoline regression results: NEDC over JC08

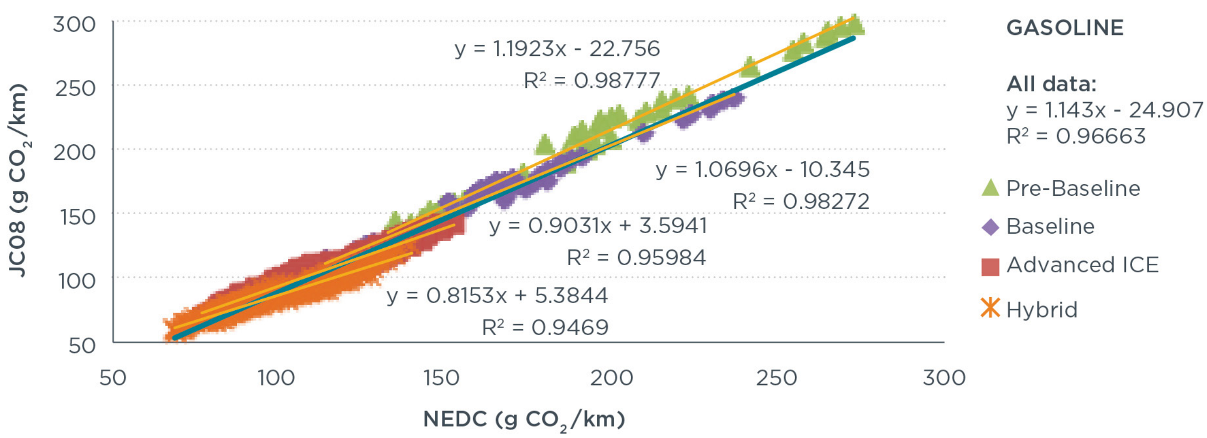

Figure B-8: Gasoline regression results: JC08 over NEDC

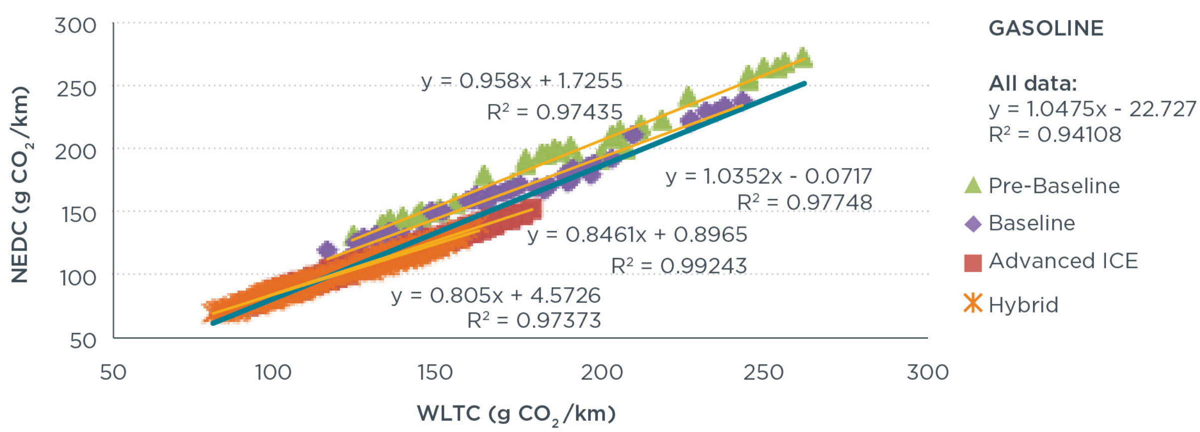

Figure B-9: Gasoline regression results: NEDC over WLTC

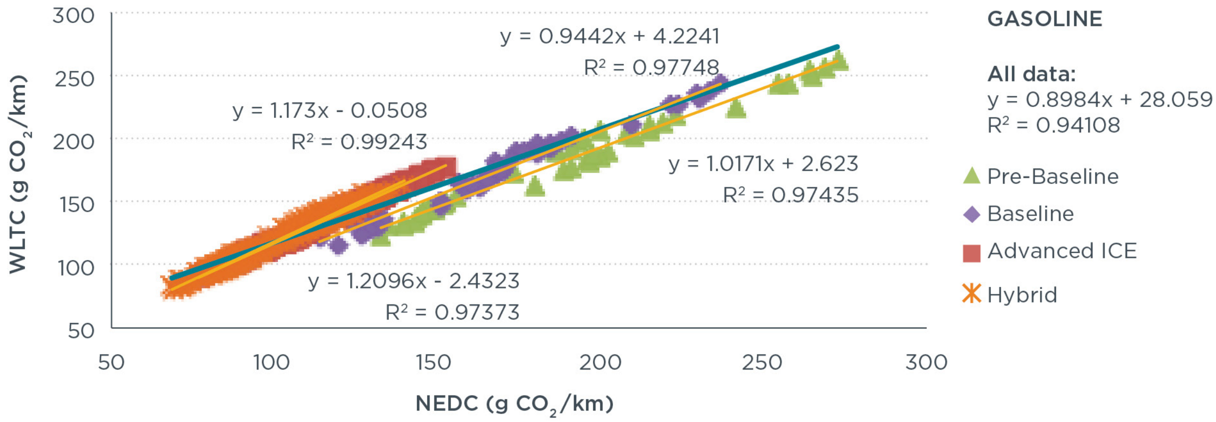

Figure B-10: Gasoline regression results: WLTC over NEDC

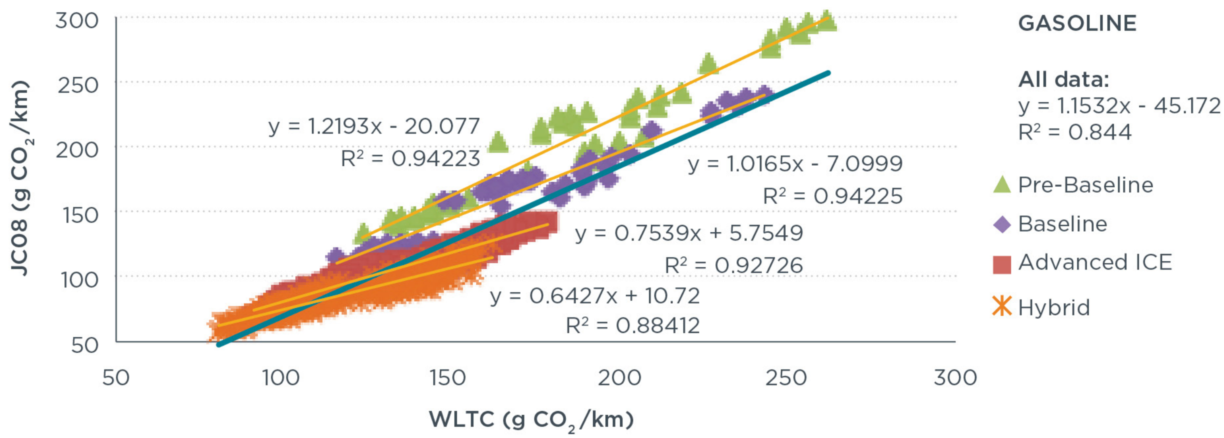

Figure B-11: Gasoline regression results: JC08 over WLTC

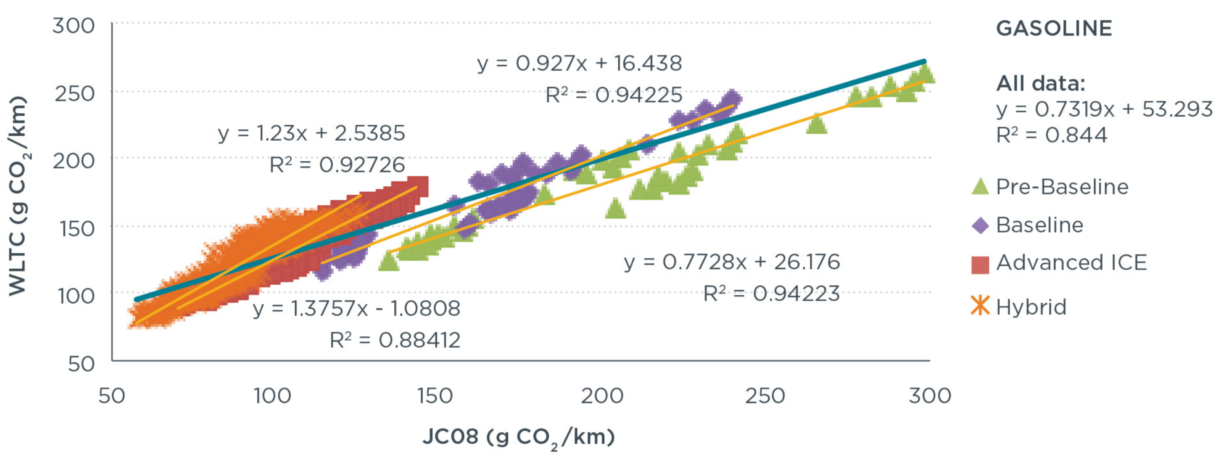

Figure B-12: Gasoline regression results: WLTC over JC08

APPENDIX C GRAPHS CO_2 WITH LINEAR REGRESSION — ALL DIESEL

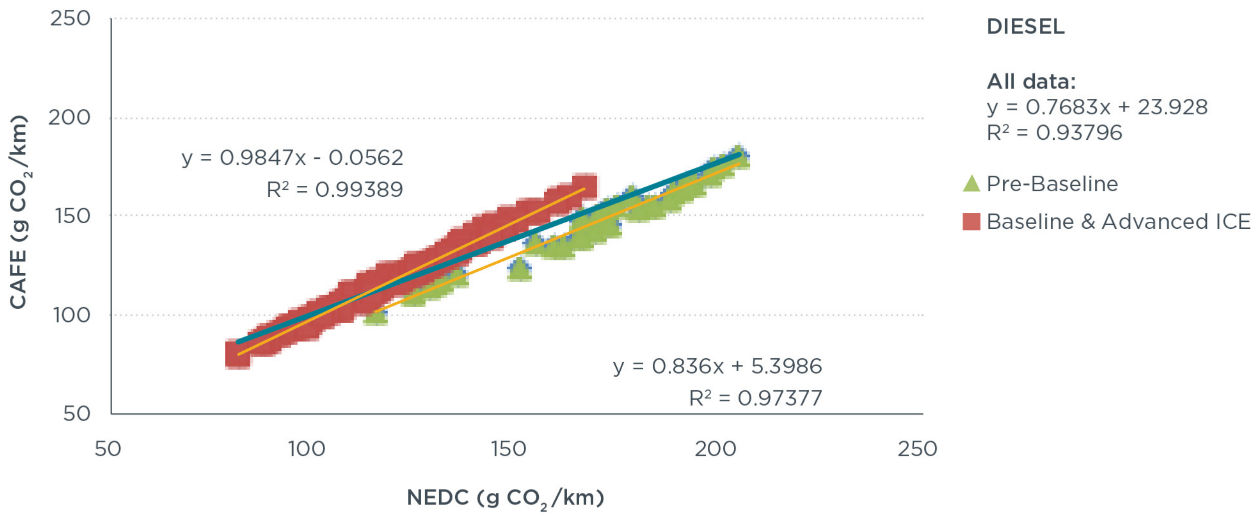

Figure C-1: Diesel regression results: CAFE over NEDC

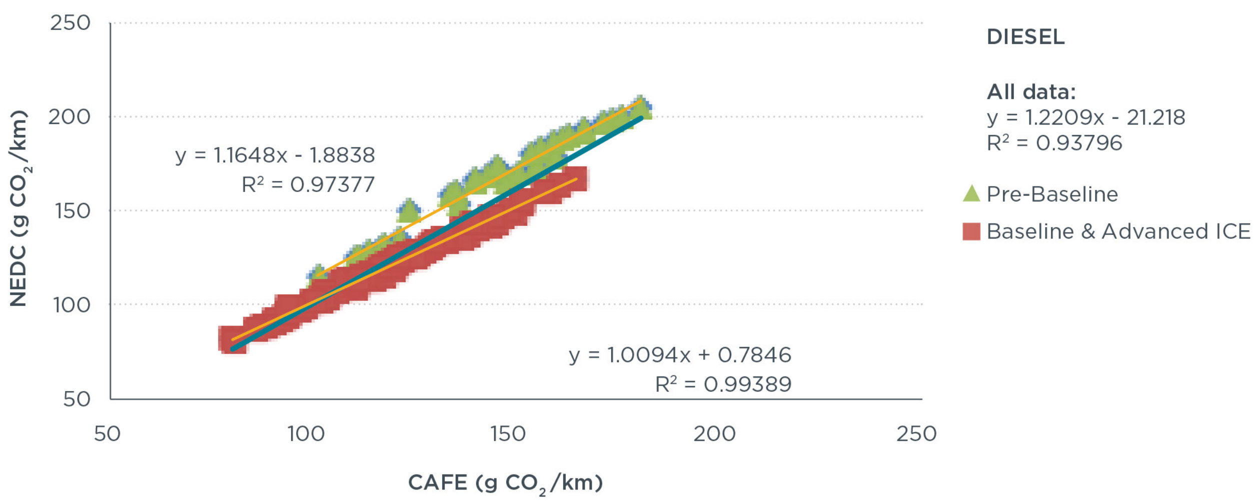

Figure C-2: Diesel regression results: NEDC over CAFE

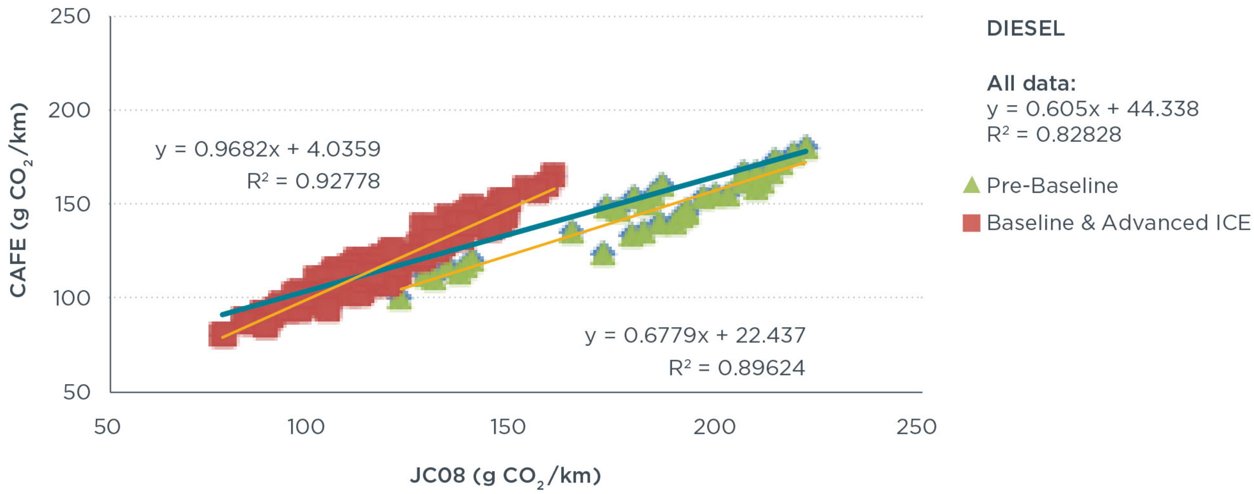

Figure C-3: Diesel regression results: CAFE over JC08

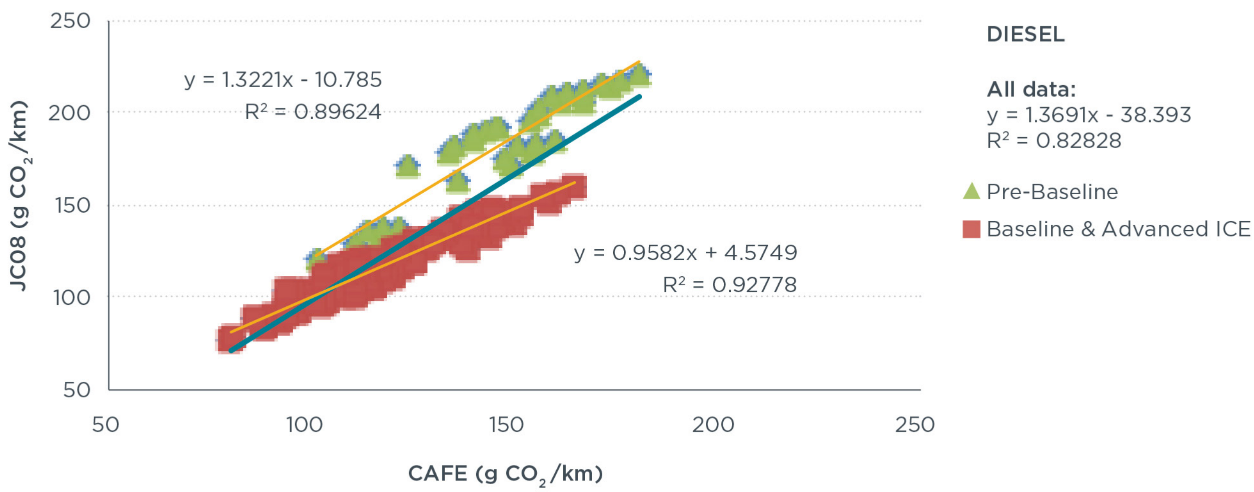

Figure C-4: Diesel regression results: JC08 over CAFE

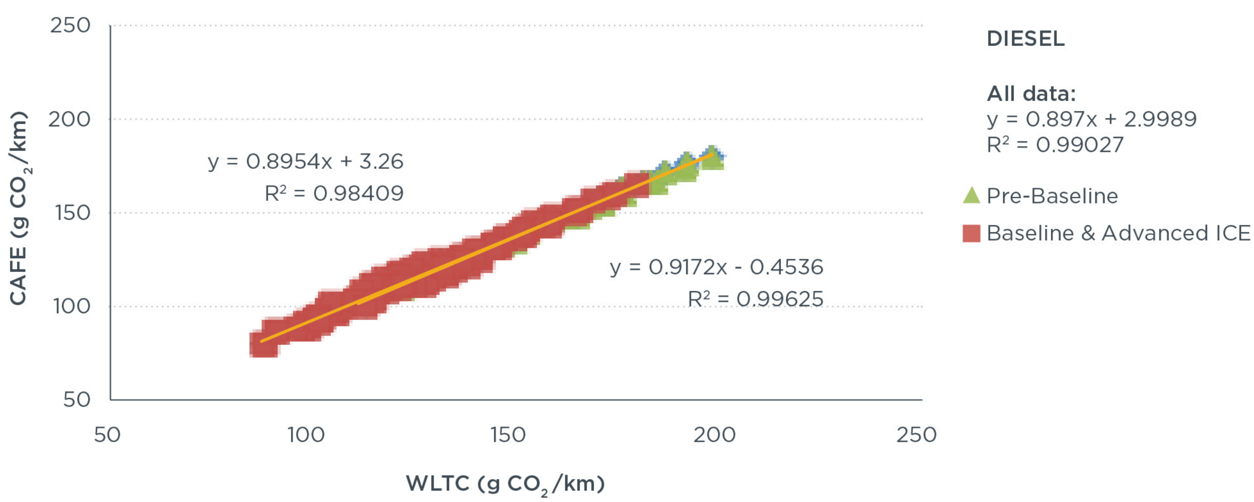

Figure C-5: Diesel regression results: CAFE over WLTC

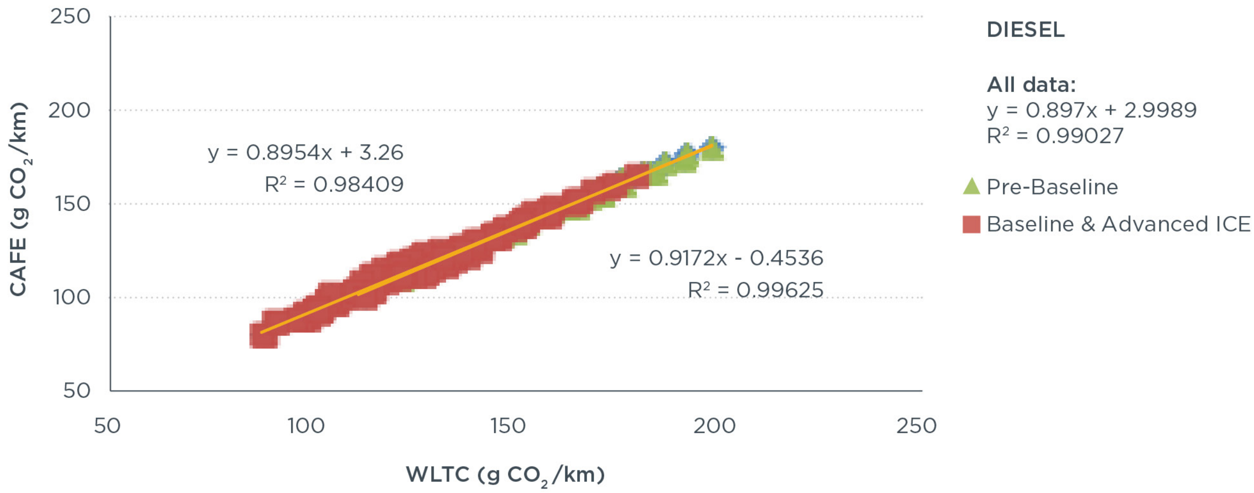

Figure C-6: Diesel regression results: WLTC over CAFE

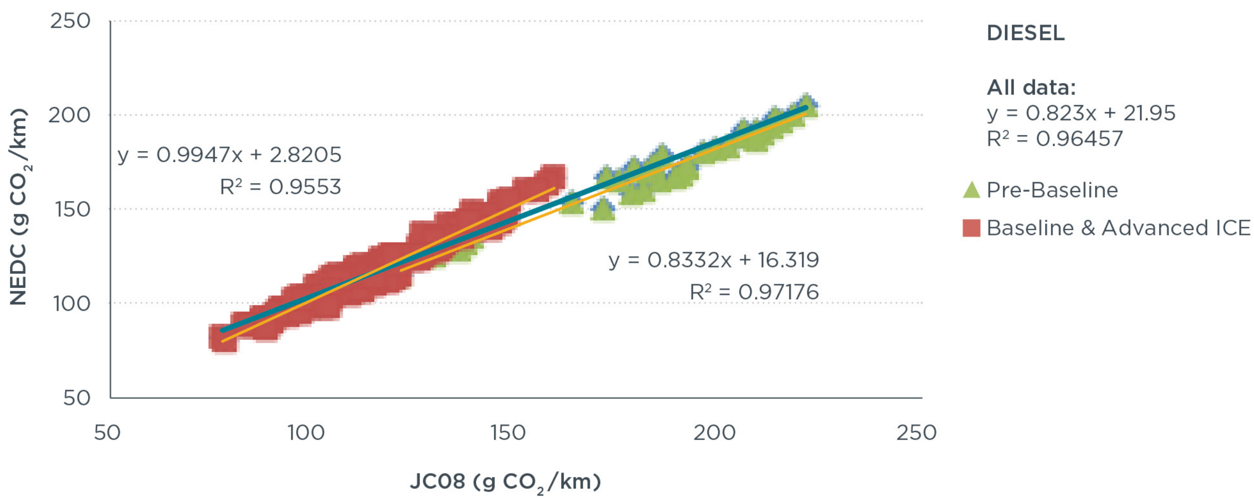

Figure C-7: Diesel regression results: NEDC over JC08

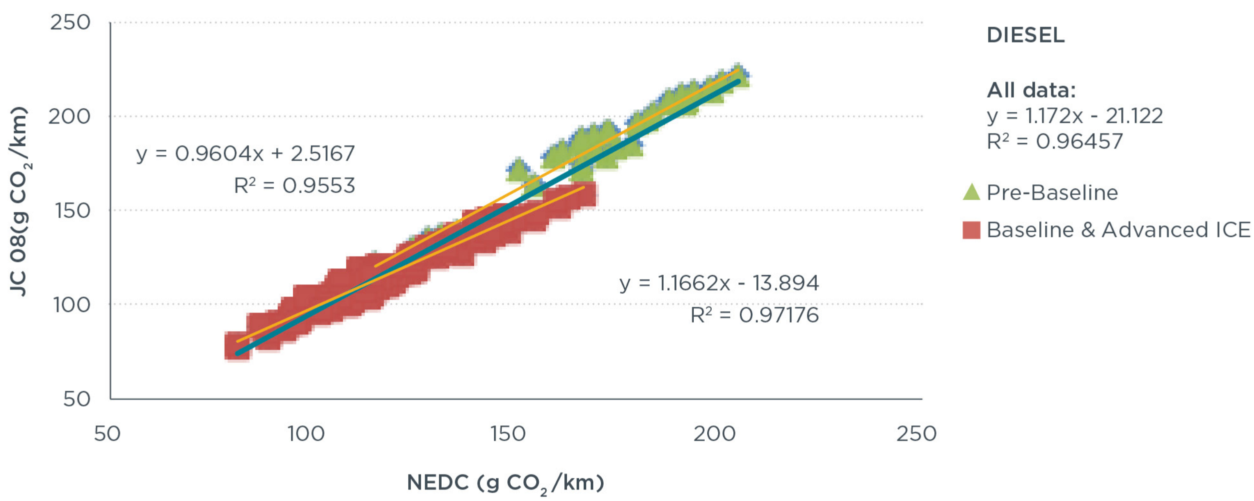

Figure C-8: Diesel regression results: JC08 over NEDC

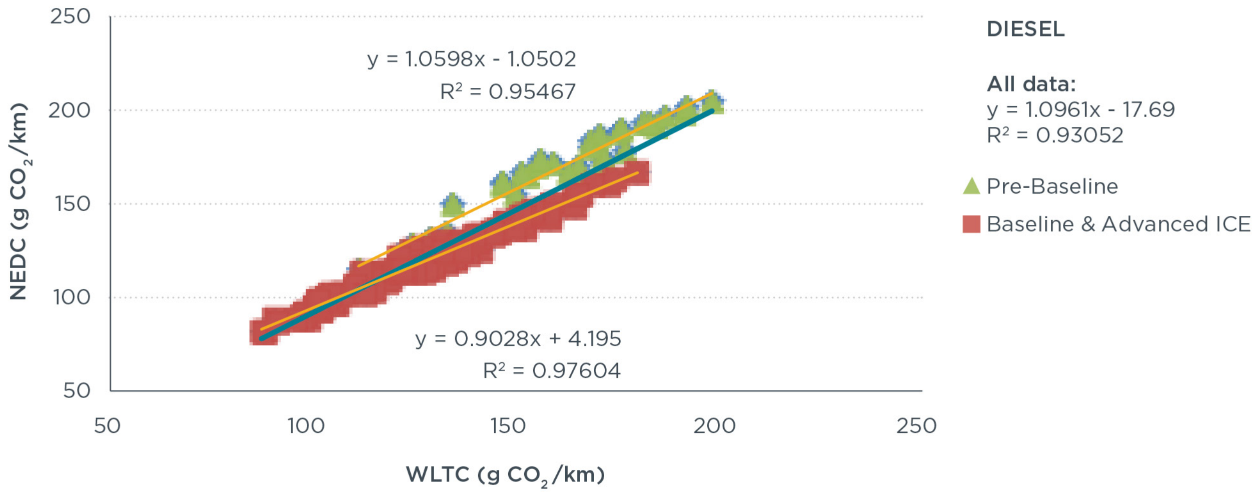

Figure C-9: Diesel regression results: NEDC over WLTC

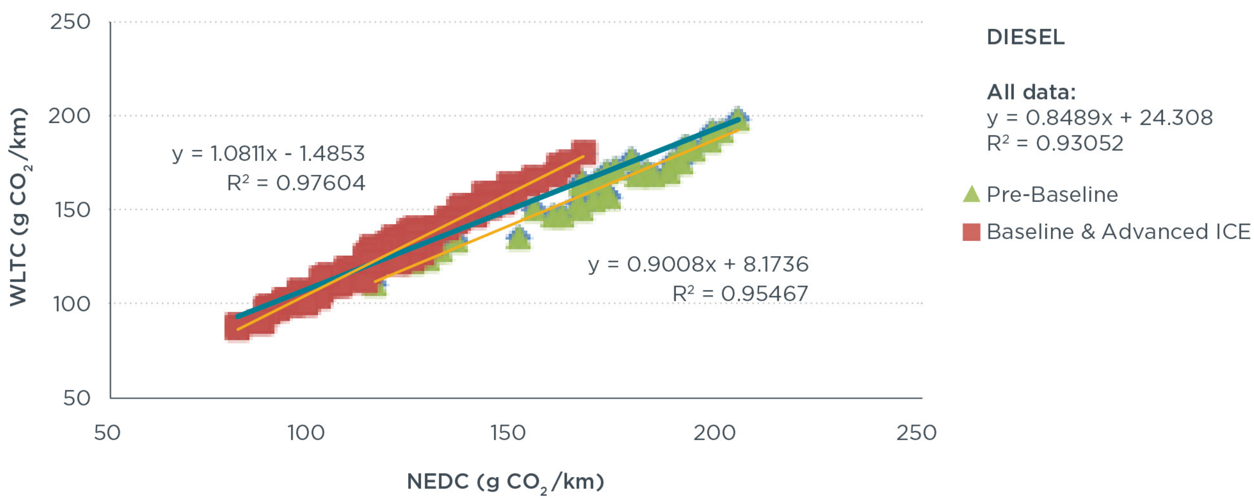

Figure C-10: Diesel regression results: WLTC over NEDC

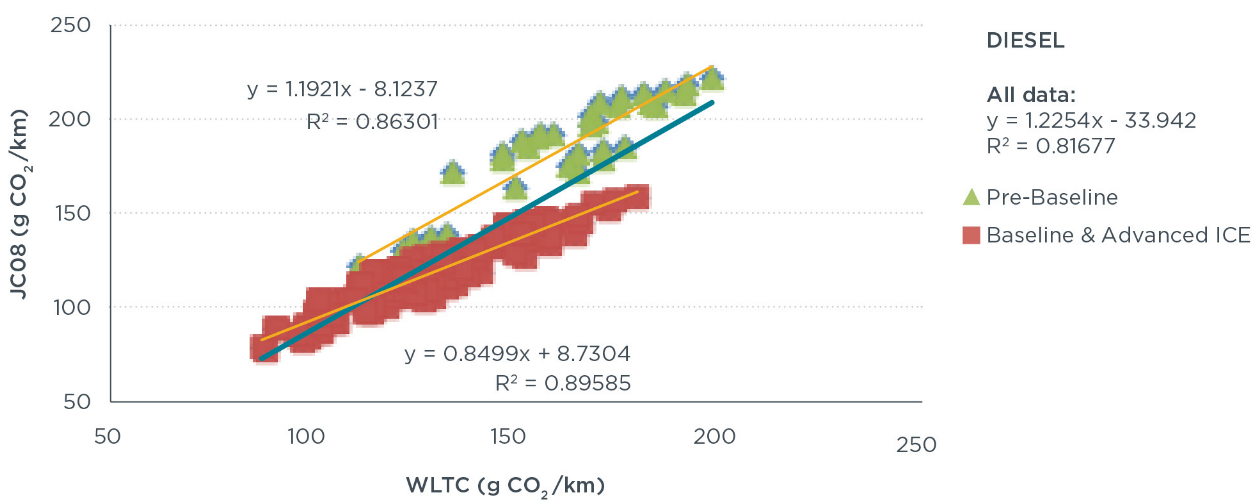

Figure C-11: Diesel regression results: JC08 over WLTC

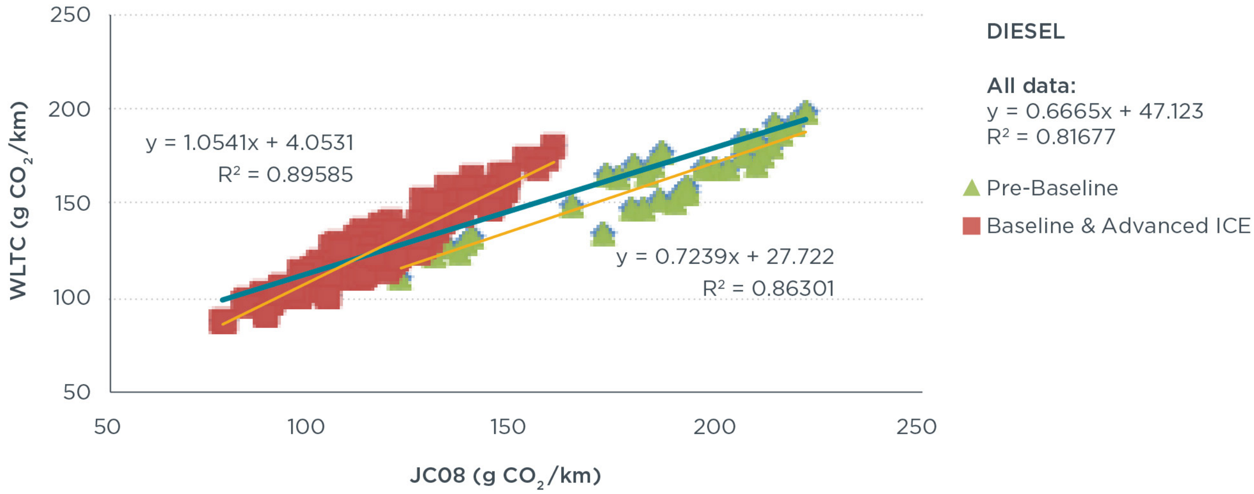

Figure C-12: Diesel regression results: WLTC over JC08

APPENDIX D GRAPHS CO_2 WITH LINEAR REGRESSION — UNIVERSAL APPROACH

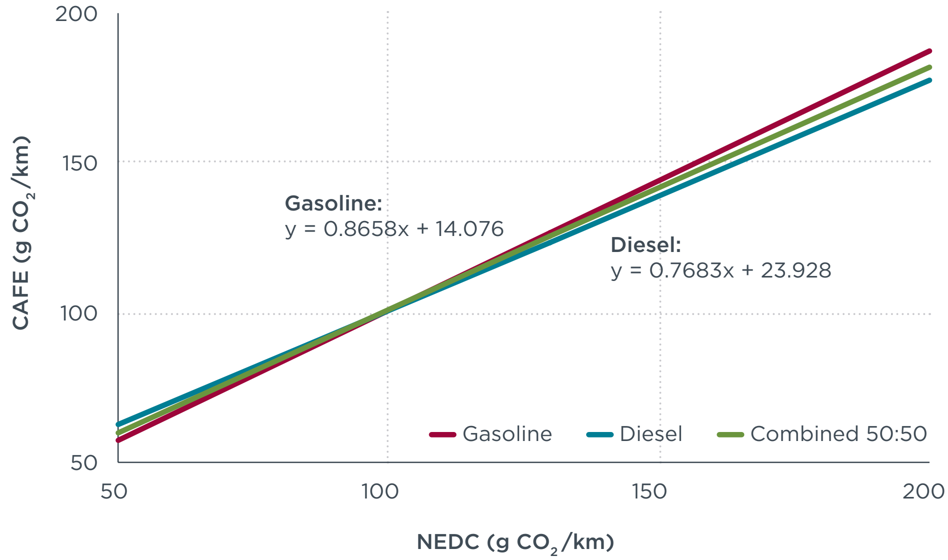

Figure D-1: Comprehensive regression results: CAFE over NEDC

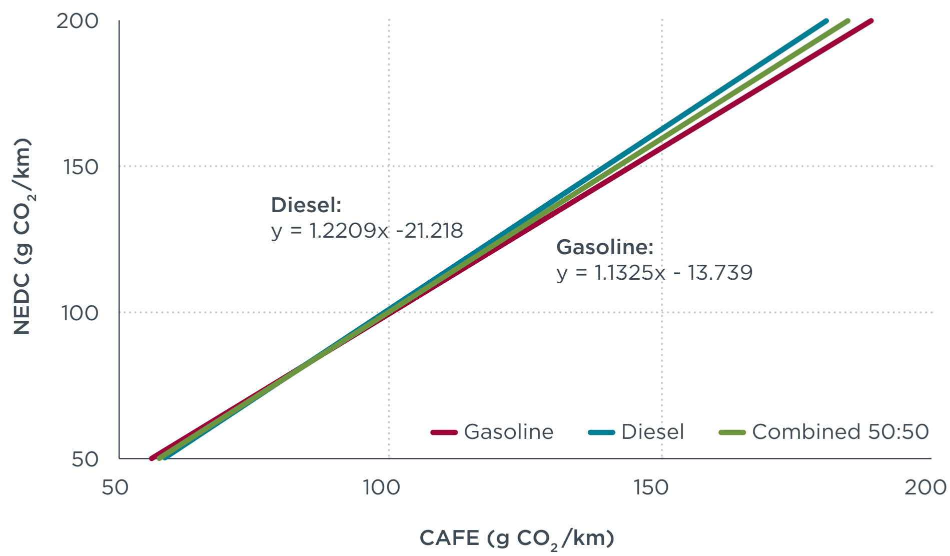

Figure D-2: Comprehensive regression results: NEDC over CAFE

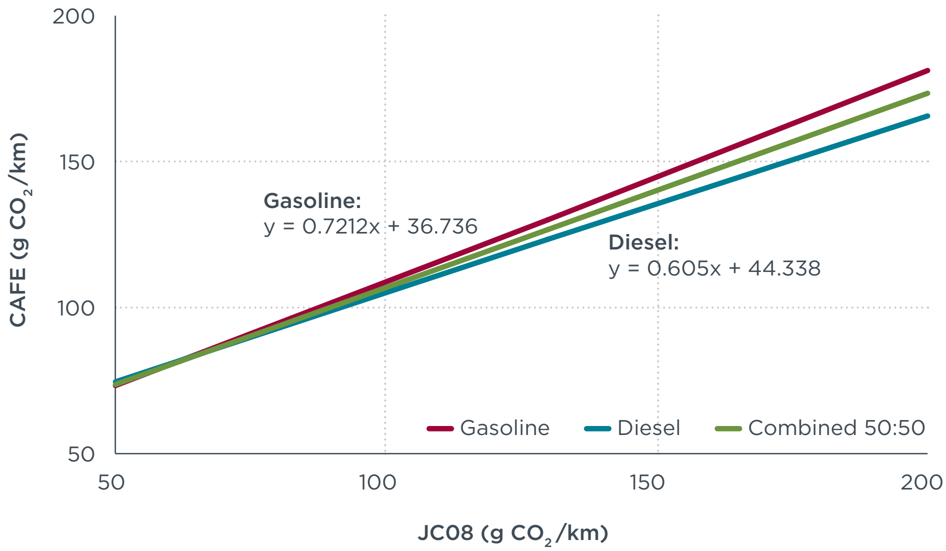

Figure D-3: Comprehensive regression results: CAFE over JC08

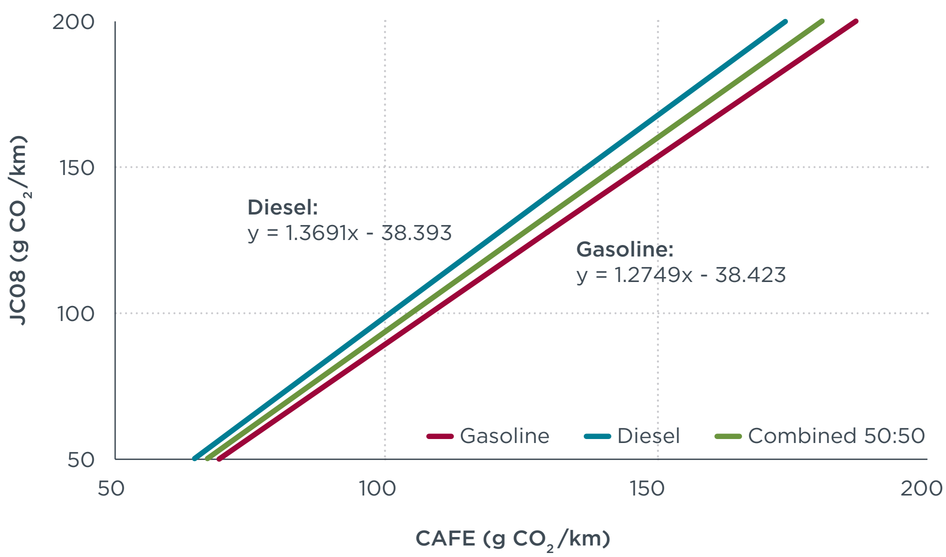

Figure D-4: Comprehensive regression results: JC08 over CAFE

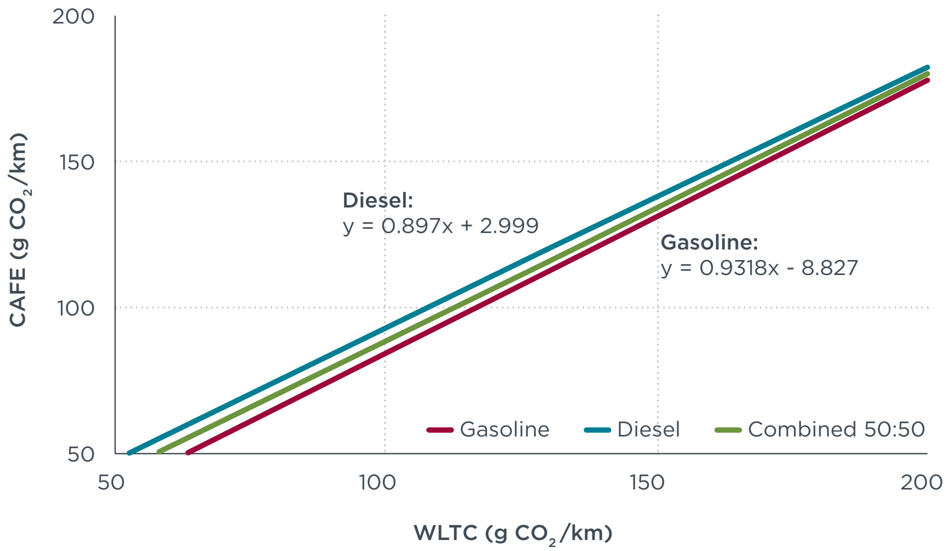

Figure D-5: Comprehensive regression results: CAFE over WLTC

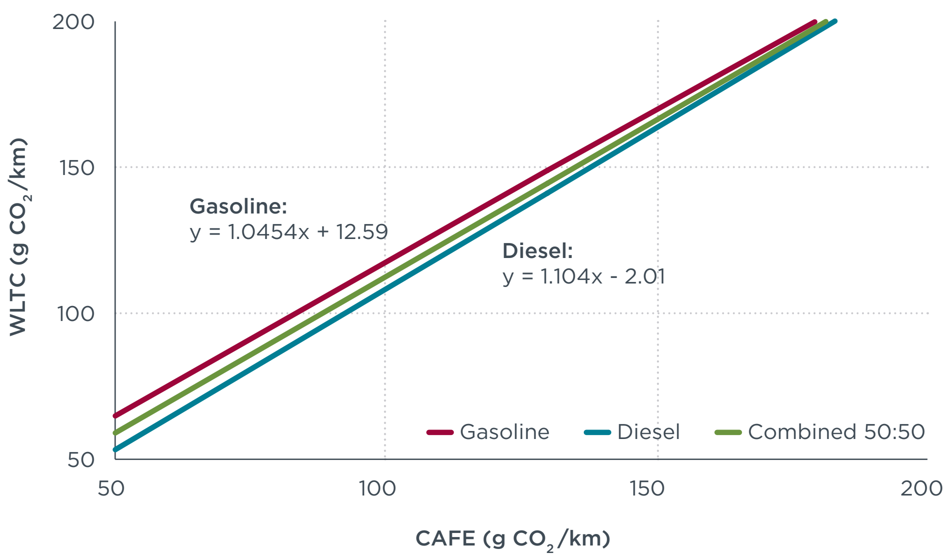

Figure D-6: Comprehensive regression results: WLTC over CAFE

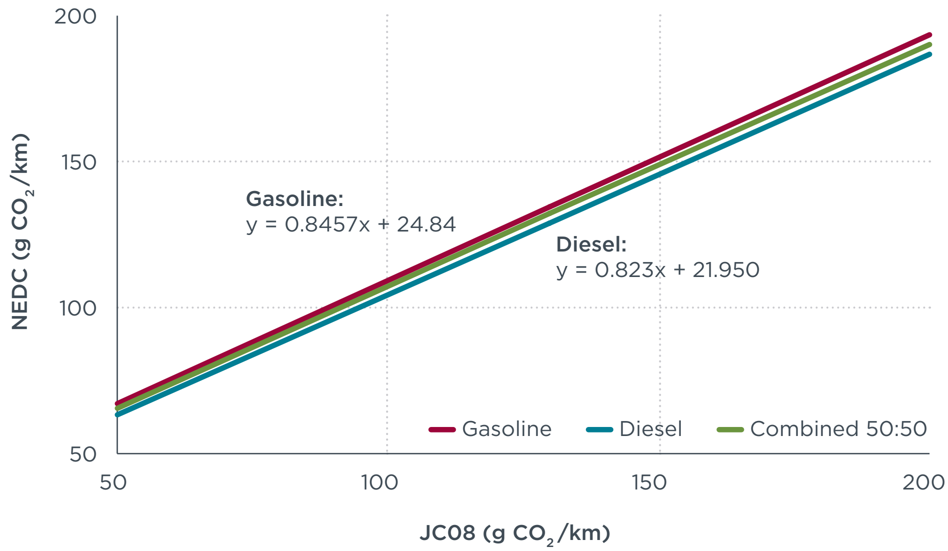

Figure D-7: Comprehensive regression results: NEDC over JC08

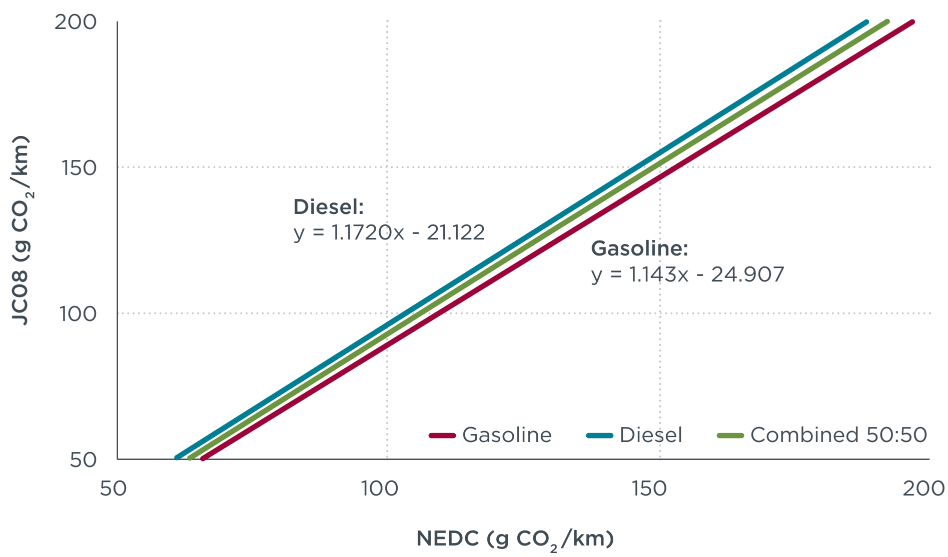

Figure D-8: Comprehensive regression results: JC08 over NEDC

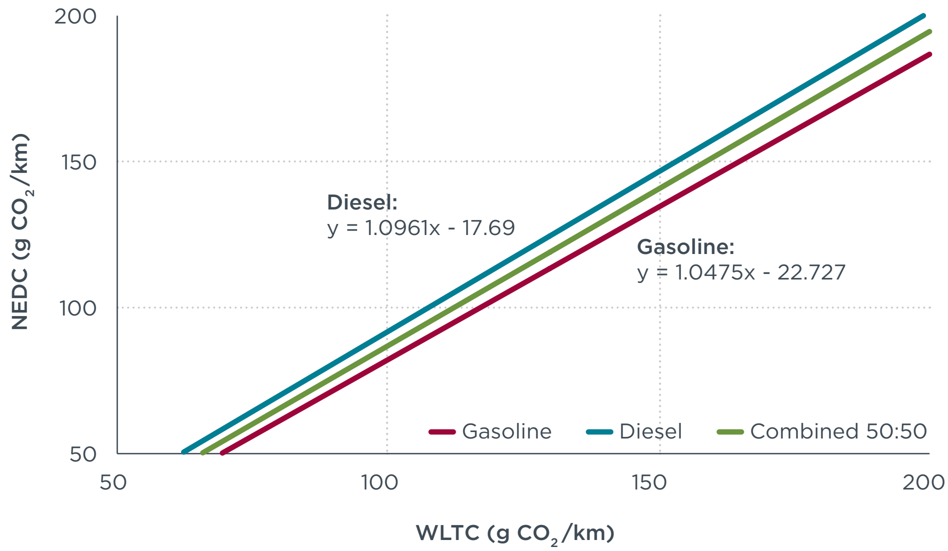

Figure D-9: Comprehensive regression results: NEDC over WLTC

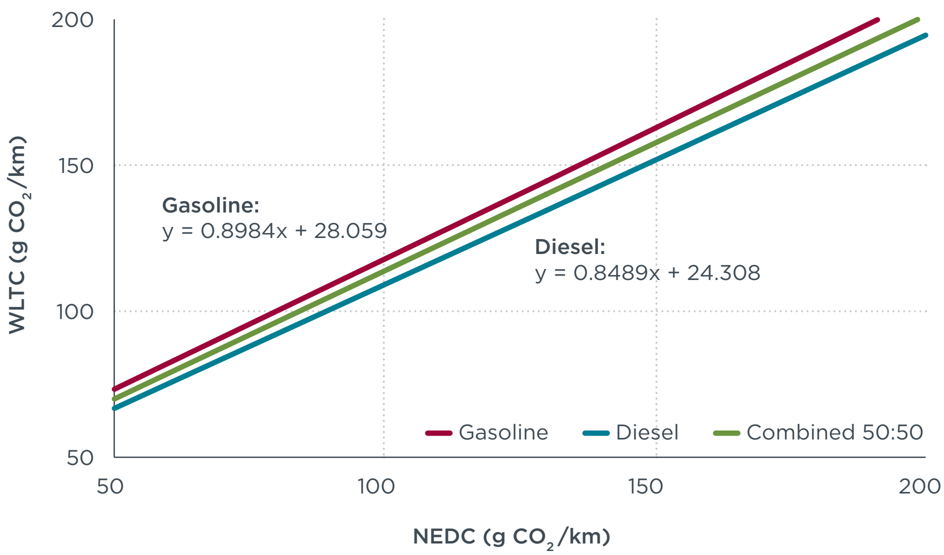

Figure D-10: Comprehensive regression results: WLTC over NEDC

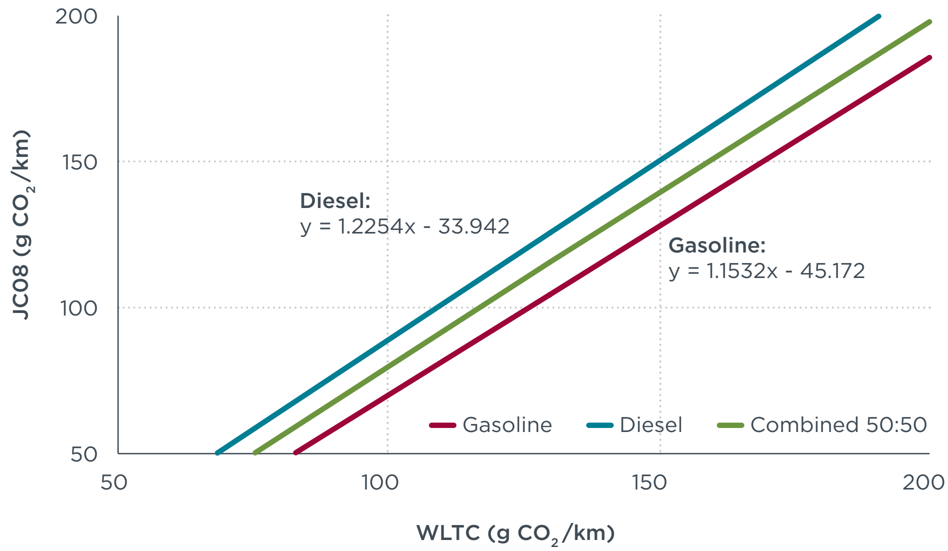

Figure D-11: Comprehensive regression results: JC08 over WLTC

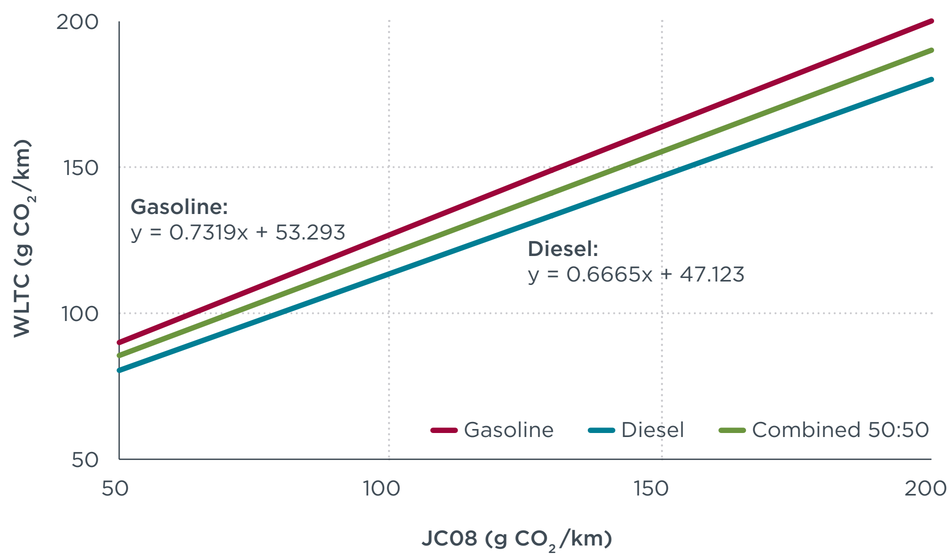

Figure D-12: Comprehensive regression results: WLTC over JC08

APPENDIX E CONSTRAINTS OF MODEL APPROACH

(Basis: Ricardo reports C000908 C004670)

When applying model approaches, simplifications of the real-world situation have to be taken into account and accepted by the user. The applicability of a model usually contrasts with the accuracy of the results. In the following, some constraints and shortcomings of the Ricardo model approach are listed. These points show the high complexity of quantifying emissions from road vehicles and shall not discredit the high quality of the Ricardo model and the extensive input data used for the model runs.

VEHICLE SAMPLE REPRESENTATIVITY

Ricardo studies claim to reflect current and future EU fleet technology mix representatively, but:

» A-class vehicles (mini or city cars such as Smart, Fiat 500, Renault Twingo) are not considered even though they are very popular, especially in southern Europe.

» Diesel concepts are clearly underrepresented. Actual 2012 share in Europe: 55%.

» Manual transmissions are clearly underrepresented. Actual share in Europe: ~65%. The model considers MT only for C-class pre-Baseline and Baseline vehicles.

» Baseline diesel vehicles use mass, capacity and power that are too low (lower than gasoline vehicles of same vehicle category).

» Assumed engine displacement for spark ignition (SI) engines is much too high. The most common engine in Europe is 1.2 TSI 77 kW, but one of the model's bases for C-class pre-baseline vehicle is the VW Golf 2.0 MPI 63 kW. That engine does not exist on the European market. The Ford Focus 2.0 MPI 107 kW engine is also used, but that exotic model was produced only until 2010. (The most common engine in Europe currently is: 1.2 TSI 77 kW)

» Assumed diesel engines are smaller than gasoline engines, with a difference of approximately 0.2-0.4 l. By contrast, the EU averages for 2012 were 1820 cm^3/97 kW for diesel and 1420 cm^3/80 kW for gasoline.

» Assumed vehicle weights are too high. For example, the C-class SI weight is 1472 kg, closer to the Euro 5 CI assumed weight (1547 kg) than its SI assumed weight (1222 kg).

» Assumed tire rolling resistance (e.g., C-class: 0.0083) is rather low. European standards are 0.0120 for 2014 and 0.0105 for 2018. The assumed Euro 5 average is 0.0105.

» Assumed air resistance matches well. For example, the C-class assumption for the aerodynamic drag is 0.650 m^2 whereas the Euro 5 assumption is 0.663 m^2.

» Assumed aerodynamic drag for small N1 (1.040 m^2) is higher than for large N1 (0.952 m^2).

FUTURE TECHNOLOGY ASSESSMENTS

» Diesel technologies' potentials are underestimated; some considered technologies are already state of the art (DI, EGR, air charge). Definition of the 2020 diesel is unclear.

» Diesel hybrids are not considered. The electrification trend most likely will not bypass diesel systems.

» Cylinder deactivation is not considered. However, the first gasoline Euro 6 models (VW) are available, and the results are very promising in terms of both CO_2 and particle numbers (PN). Cylinder deactivation is a flexible system. The cylinder volume can be adapted to the actual power demand, thus lowering friction losses and leading to lower fuel consumption.

- Assumption regarding constant brake mean effective pressure (BMEP) for future concepts is in contradiction to the development of high-power downsized (charged) engines.
- Two-step approach for alternator efficiencies (70% for pre-Baseline and 55 % for Baseline and all advanced technologies) is too coarse to reflect the technical improvement potentials.
- No advanced concepts for manual transmissions are considered.

BIAS OF RESULTS

- Simplification of models in general causes bias in results, so FC engine maps are the most sensitive parameter. Having a bias in the engine maps (e.g., because the baseline sample of measured vehicles is too small for or not representative of the total fleet) means that the model results could also be biased to a variable extent.
- Differences in models used in 2007 (MEEM model) and 2013 (MSC.Easy5 model) possibly result in systematic deviations in results (e.g., CO_2 multipliers) for the same vehicle input parameters.
- Is the 2013 model more reliable than the 2007 one? This could be determined in additional studies by comparing underlying engine maps using runs with different models.

COLD START

- Model assumptions about warm-up behavior during the NEDC are too optimistic. Warm-up is assumed complete after 390s, i.e., +22% CO_2 emissions for the first two UDC subcycles (11% for advanced vehicles) is equivalent to 4.4% (2.2%) for the complete NEDC. A realistic average from NEDC measurements is +12%. In contrast, available measurement data shows that in reality larger diesel-fueled cars, for example, do not reach the final engine operating temperature even after one complete NEDC.
- Cold-start effects are basically underestimated for the NEDC (around -8% of total CO_2) and for the WLTC (around -4%).
- The FTP bag results were not weighted properly. Ricardo did a simple average of the fuel consumption from each of the three phases of the FTP based on the distance driven for each phase. However, EPA's method is to weight the first phase (cold transient) by 0.43, the second phase (stabilized) by 1.0, and the third phase (hot transient) by 0.57. Ricardo's failure to include the weighting factors artificially increases the cold start effect on the FTP by about 59%, except for hybrids, for which Ricardo included a second stabilized phase in the calculation.
- Cold-start effects are basically overestimated for the FTP and CAFE (around +2.5% of total CO_2 for the FTP and +1.2% for CAFE).

METHODOLOGICAL ISSUES

- Normalization of vehicle performance (same acceleration times 0-60 mph) does not reflect the temporal trend of power increase. In EU, we see a mean annual increase of about 1 kW rated power.

- Hybrids' normalization: Peak power for hybrids is lower than for the exemplary vehicles with combustion engines of the same vehicle class. This is in contrast to market vehicles, e.g., Toyota Prius III (1.8l 73 kW SI + 60 kW E-motor) compared with Toyota Corolla (1.6l 97 kW SI).
- Diesel fueling maps lack data sources. Model runs for diesel are not validated by measurements.
- Validation model runs (2010 vehicles) were performed using only U.S. tests (FTP and HWFET).
- Diesel baseline CO_2 model results are much lower than for gasoline, with an NEDC difference of approximately 20 to 40 g/km. However, 2012 EU type approval data show almost identical values (diesel 131.6 g/km, gasoline 133.7 g/km) and SI model results are more realistic. Considering that diesel cars in EU are heavier and are equipped with larger engines than gasoline vehicles, the Ricardo approach of comparable performance does not reflect the European situation.
- Ford Focus (C-class) NEDC results have been validated by the EPA database, that includes only emission data of the U.S. driving cycles.
- Ford Focus simulations are only for the NEDC.

GEAR SHIFT MODEL

- Simplification of the gearbox model enables only unique transmission ratios.
- Baseline uses 6-speed transmissions, but 5-speed MT is still dominant for gasoline vehicles under Euro 5.
- Only the final drive ratio can be varied in the model.
- Tire sizes were not varied, and it is unclear which sizes were used. Tire sizes can be handled by varying the final drive ratio. But to assess the total transmission ratios you need to know which tire sizes are implemented in the model runs. This information is missing in the reports.

STOP-START SYSTEMS

- Assumed penetration rates are absolute. Pre-Baseline technologies: 0%; Baseline technologies and follow-ups: 100%. No smooth technology transition was implemented (e.g., Euro 5 assessed by 50% penetration).

TESTING CONDITIONS OTHER THAN THE CYCLES

- Only effects of the drive cycles were investigated. Effects of other parameters associated with the test rules in different regions, e.g., temperatures, preconditioning, coast-down, and dyno calibration, cannot be addressed with the available tool.

COMPARISONS OF CYCLE RESULTS

- Deviations between cycles: Are they caused mainly by average speed or cycle dynamics or stop percentages or other? Including more artificial cycles and constant-speed driving in the modeling would enable exploration of the effects these parameters have on emissions.

FUEL — REGIONAL VARIATIONS

- Carbon content in fuel varies by region. Therefore, different conversion factors must be applied when comparing FC and CO_2 emissions in different regions.

Conversion factors ($g\ CO_2/l$)	Gasoline	Diesel
EU	2330	2640
USA	2400.8	2667.6
Mexico	2347.7	2689.3

GREENHOUSE GASES

- Only model results for CO_2; other GHG are not incorporated.

REPORT BUGS:

- Fig. 6.2 is missing the scale for the y-axis.

BUGS AND SHORTCOMINGS OF THE COMPLEX SYSTEM TOOL (DVT):

- New C-class (Ford Focus) is not yet included.
- C-class pre-baseline does not work with AT-6 transmission.
- MT is only available in combination with C-class.
- No variation of continuous parameters is possible for all Baseline concepts.
- In exporting to .xls, continuous parameters are not transferred.
- Efficient Frontier is based only on performance metrics, not on continuous parameters.
- Upper limits for drag and especially rolling resistance are rather low and should be adjustable to much more than 100%.
- Error in calculations: Large N1, 2020_Diesel, Advanced DCT, JC08.
- Error in calculations: B-class, 2020_Diesel, Advanced AT, WLTC.
- Error in calculations: Powersplit Hybrid, weight parameter variations are less than 100% in all classes.