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Projection of CO_2 emissions from road transport

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Summary

This report has been prepared by LAT/AUTh on behalf of the European Topic Centre on Air Emissions and Climate Change of the European Environment Agency, as a deliverable of Task 1.3.2.4. The objective of this task is to project the mean CO_2 emissions of the European passenger cars stock in real-world conditions to 2020, assuming different scenarios towards reaching the target of 95 g/km as an average of new car registrations. To this aim, a simulation exercise divided in two steps has been implemented. First, we have simulated the expected CO_2 emissions of forthcoming vehicle technologies in type-approval and real-world conditions. Second, we have simulated different penetration rates of these technologies in the European stock, based on established projections of stock growth in Europe. The study demonstrates that reaching an new registration average of 95 g/km may lead to different CO_2 emissions in the real world, depending on the mix of technologies considered to meet the type-approval target.

Keywords

CO_2 emissions, passenger cars, hybrids, electric vehicles with range extender

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1. Introduction – Objectives

The voluntary agreement of the European Commission with the automotive industry (Commission Recommendation 1999/125/EC) was the first attempt of the European Union to set CO_2 emission targets for new passenger cars. In this process, although significant emission reductions were achieved by the vehicle manufacturers in view of the 140 g/km target by 2008/09, it was not made eventually possible to reach the reductions proposed in this voluntary agreement.

As a result, the European Parliament and the Council issued Regulation No. 443/2009 introducing mandatory CO_2 emissions limits for new passenger cars. The regulation specifies that each vehicle manufacturer must achieve a fleet-average CO_2 emission target of 130 g/km by 2015 for all new cars registered in the EU. In order to meet the CO_2 emission target of 120 g/km, a further reduction of 10 g/km is to be provided by additional measures, such as the use of biofuels. According to the regulation, a so-called limit value curve sets specific emissions targets for each manufacturer based on the average vehicle mass sold by the particular manufacturer. The formula to calculate the limit value curve is:

$$\textit{Permitted specific emissions of } CO_2 = 130 + a \times (M - M_0)$$

Where M is the reference vehicle mass (in kg), M_0 = 1289 kg is a mass constant and a = 0.0457. This is an empirical curve which has been developed in order not to distort the market, taking into account the different market segments of various vehicle manufacturers. That curve is set in such a way that heavier cars will have to improve more than lighter cars compared to today, but that manufacturers will still be able to make cars with emissions above the limit value curve provided these are balanced by cars which are below the curve.

The regulation also defines a long-term target of 95 g/km to be reached by 2020. From 2016 onwards, the value of M_0 will be annually adjusted to reflect the average mass of passenger cars in the previous three calendar years.

Manufacturers' progress will be monitored each year by the Member States on the basis of new car registration data. To this aim, it is important that the manufacturer is clearly identified and distinguished from the make[1]. Table 1 below shows the actual position of the most prominent car manufacturers in terms of the average CO_2 emissions of the new cars they manufactured in 2006. These are based on detailed statistics included in the CO_2 monitoring database (European Commission, 2010). The database, which was established with Decision 1753/2000/EC of the European Parliament and of the Council, includes detailed volumes of vehicle models registered in each of the EU27 member states, providing information on the weight, power, capacity, fuel and type approval CO_2 emissions of each car.

[1] Manufacturer means the body responsible to the approval authority for all aspects of the EC type-approval procedure, whereas make means the trade name of the manufacturer and is that which appears on the certificate of conformity.

Table 1: *Average mass and CO_2 emissions of new cars per manufacturer in the EU27 in 2006*

Manufacturer	**mass (kg)**	**CO_2 (g/km)**	**Sales total**
BMW	1453	182	739 993
DaimlerChrysler	1472	184	860 816
Fiat	1112	144	1 050 885
Ford	1319	162	1 490 276
GM	1257	157	1 424 783
Porsche	1596	282	39 069
PSA	1201	142	1 882 210
Renault	1234	147	1 232 236
Volkswagen	1366	165	2 744 849
Toyota	1214	152	773 329
Nissan	1202	164	273 893
Mitsubishi	1245	169	101 124
Honda	1261	153	229 791
Mazda	1296	173	229 135
Suzuki	1152	164	178 614
Subaru	1384	216	31 541
Hyundai	1349	165	461 880
Total*	**1288.8**	**159.2**	**13 744 424**

* Mass and CO_2 are sales weighted

Table 2 shows the additional progress that the manufacturers will have to make in order to achieve their targets by 2015 under the proposed legislation, taking the limit curve into account and assuming the same average weight as in 2006. It is not possible to estimate the corresponding emission reductions required for 2020, as the M_0 of the limit curve has not been determined yet (it will be calculated on the basis of the average mass of passenger cars in the previous three calendar years, i.e. 2017-2019). Assuming the same limit curve and average mass, the reductions required to achieve the 2020 target have been also calculated and are shown in the same table. If the average mass of the vehicle increases (as it historically does) the necessary reductions should be even larger than those shown in Table 2. The table shows that some manufacturers are close to their average target while others are way beyond.

Of course, it should be recognised that manufacturers have the right to pool at will and to be monitored as one entity for the purpose of meeting their targets. This may be necessary for some of the top end manufacturers (like Porsche). In forming a pool, manufacturers must respect the rules of competition law and the information that they exchange should be limited to average specific emissions of CO_2, their specific emissions targets, and their total number of vehicles registered. In addition, independent manufacturers who sell fewer than 10,000 vehicles per year and who cannot or do not wish to join a pool can instead apply to the Commission for an individual target. Special purpose vehicles, such as vehicles built to accommodate wheelchair access, are excluded from the scope of the legislation.

Table 2: *CO_2 reductions required to meet 2015 and 2020 targets by manufacturer*

Manufacturer	**CO_2 reduction (g/km) in 2015**	**CO_2 reduction (g/km) in 2020**
PSA Peugeot-Citroen	16	51
Renault	20	55
Fiat	22	57
Honda	25	59
Toyota	25	60
GM	28	63
Ford	30	66
Volkswagen	31	66
Hyundai	32	67
Nissan	38	73
Suzuki	41	75
Mitsubishi	41	76
Mazda	43	78
BMW	45	80
DaimlerChrysler	46	81
Subaru	81	117
Porsche	138	173

The regulation does not specify the technology by which the CO_2-average level should be reached (technology-neutral approach) by manufacturer, i.e. whether small, gasoline, diesel, hybrid, plug-in hybrids, electric or alternative fuel vehicles will be introduced, as long as the average CO_2 emission level is reached. It should also be made clear that the mean CO_2 levels refer to the certification test procedure (i.e. the New European Driving Cycle – NEDC to be used for emission measurement). However, the CO_2 emission rate for each technology to be introduced will depend on the actual driving pattern in real-world operation. It has to be expected that different vehicle technologies will perform differently over real-world operation, despite meeting the target of 95 g/km over the NEDC. For example, a hybrid gasoline vehicle is a very good performer (low CO_2) in urban driving through the frequent involvement of the electric motor and the regeneration of braking energy back to the batteries. However, in highway driving where the electric motor has only a secondary role to play and braking is infrequent, a small diesel vehicle may actually be a better performer due to the higher efficiency of the diesel engine over the gasoline engine in the hybrid vehicle. Therefore, the NEDC value alone is not necessarily the only determinant of CO_2 emissions of each technology in real-world driving. As a result, the mean CO_2 emission of the stock in real-world conditions will depend on the penetration rates of different new technologies, and the difference in CO_2 emissions of each technology between real-world and type-approval driving conditions.

This study attempts a first assessment of the potential impact in CO_2 emissions of the introduction of new technologies at a different penetration rate. The simulation performs two tasks: First, it simulates the CO_2 emission of expected vehicle technologies in real-world conditions. Second, it simulates in different scenarios the penetration of these technologies in the European stock, based on established projections of stock growth in Europe.

2. Methodology – modelling

For the purposes of the present study, the CRUISE model, AVL's vehicle and powertrain level simulation tool (https://www.avl.com/cruise1), was used to simulate vehicle engine operation over certain driving cycles. CRUISE is a vehicle simulator. In principle, a vehicle is graphically setup, providing all kinds of powertrain details (wheel size, gearbox, differential, engine type, etc.). Then an engine map is given, where the engine characteristics (be it consumption, pollutants, noise, etc.) are provided as a function of the engine speed and power. Then the vehicle is allowed to operate over different speed profiles (driving cycles) and the software simulates the vehicle and engine operation by which it can produce total fuel consumed and total emissions produced. The success in the simulation depends on the quality of input data delivered both on the vehicle and engine fronts.

For this study, the main variables which were used as an input to the model were fuel consumption engine maps, rated engine power, frontal area and aerodynamic drag, vehicle mass, rolling resistance coefficient(s), gear and final drive ratios, wheel diameter and dimensions and weight of various components. These data were retrieved from several sources such as measured coast down curves, measured engine maps, type approval data (VCA, 2010), literature (scientific papers, ordinary press, magazines, press releases) and specialised websites.

The following approach was implemented: First, some typical gasoline and diesel cars from the European stock were selected and converted through simulation to meet the 95 g/km target. This means that 'conventional' technology vehicles of today were further refined to meet future emission targets. This is one path of achieving the 95 g/km requirement, i.e, by gradual improvements on existing widespread technologies. The second approach was to simulate two advanced technology vehicles which may achieve CO_2 emissions already below the 95 g/km requirement. Two vehicle technologies were selected towards this target, the first being the well-known gasoline hybrid technology, where an electric motor is used to assist the engine during acceleration and high load conditions. The second advanced technology has been an electric car with a gasoline range extender. Such a configuration also consists by an internal combustion engine and electric motor by the power to the wheels is only provided by the electric motor. The engine is only used to power a generator that drives the electric motor.

Figure 1 shows some typical 'advanced' vehicle technologies and their characteristics. The power is shown combined and separately for the internal combustion engine (ICE) and the electric motor (EM). The tailpipe CO_2 emissions are according to the manufacturer over the certification test. The range is shown again combined and for vehicle operation only on the electric mode (EV). This table only serves as an example to demonstrate the foreseeable available technologies. Out of them we decided to model a full hybrid and an electric vehicle with a range extender, as two vehicle representatives that can achieve low CO_2 without compromises in the performance or the range achieved.

Technology /Type	Example	Power (kW)	Tailpipe CO_2 (g/km)	Range (km)
Mild Hybrid Honda Insight		72 (ICE: 65, EM: 10)	101	800 (EV:0)
Full Hybrid Toyota Prius		98 (ICE: 73, EM: 60)	89	1000 (EV:20)
Pluf-in Hybrid Toyota Prius		98 (ICE: 73, EM: 60)	59	1500 (EV:40)
EV+Range extender Opel Ampera		111 EM (ICE: 60)	0 – 40 g/km	800 (EV: 60)
Pure EV Tesla Roadster		212	0	EV: 400

Figure 1: *Typical 'advanced' vehicles and their characteristics*

3. Vehicle configuration

In view of the 95 g/km target for 2020, four technologies are examined, which are expected to meet or exceed this target. These include a small gasoline car, a small diesel car, a gasoline hybrid and an electric vehicle with range extender. Two different models from each of the former two categories were selected for the purposes of this study, as described in the following.

Two popular vehicle models, the *Peugeot 107 1.0* and the *Ford Ka 1.2 Duratec*, were selected as representatives of the small gasoline car category. The Peugeot has one of the lowest CO_2 emission value of conventional vehicles in the market today (108 g/km), while the Ford, mainly due to its size, is some 30 g/km off the 2020 target. This is however a widespread vehicle in the European stock. The two small diesel cars selected include the *Smart fortwo cdi*, which is already below the 95 g/km limit, and the *Fiat 500 1.3 MTJ*, which is a typical small diesel vehicle with CO_2 emissions close to the 2020 target. Key technical specifications for these vehicles are presented in Table 3. The type approval (TA) CO_2 emissions reported by the manufacturer for each vehicle are also included in the table.

Table 3: *Main technical data for the selected small gasoline and diesel cars*

Input parameter	Peugeot 107	Ford Ka	Smart fortwo	Fiat 500
Empty vehicle mass (kg)	790	940	650	960
Drag coefficient	0.30	0.34	0.34	0.32
Frontal area (m^2)	2.20	2.11	2.10	2.42
Engine capacity (l)	1.0	1.2	0.8	1.25
Gearbox	Manual 5 gear	Manual 5 gear	Manual 5 gear	Manual 5 gear
Fuel type	Gasoline	Gasoline	Diesel	Diesel

Max engine torque (Nm)	100	102	110	145
Max engine power (kW)	50	51	45	55
TA CO_2 emissions (g/km)	108	125	88	110

A full hybrid electric mid-size car (Toyota Prius) and an electric vehicle with range extender (Opel Ampera) were also selected. The CO_2 emissions of the third generation Toyota Prius (2010 model year) are as low as 89 g/km, significantly reduced compared to the 104 g/km of the previous (2nd) generation Pius. The Opel Ampera uses electricity (provided through the grid) as its primary power source and gasoline as a secondary power source to generate electricity through an internal combustion engine. In contrary to a hybrid or plug-in hybrid, that use both the internal combustion engine and the electrical motor to directly power the wheels, an electric vehicle with a range extender is only propelled by the electric drive unit and the engine is only used to power a generator and produce electricity to recharge the batteries. This is why it is equipped with stronger electrical motor and larger batteries than hybrid vehicles. The Opel Ampera (expected in the European market at the beginning of 2011) will be the first vehicle introducing this technology and, according to the manufacturer, will have a battery range of 60 km. Within this range, it emits no tailpipe CO_2, as it is practically driven as an electric vehicle. Key technical specifications for these two vehicles are presented in Table 4.

TA CO_2 emissions for the Opel Ampera are determined by the test procedure described in UN-ECE Regulation 101 (2005). According to this, two tests are carried out, one with a fully charged battery and one with a battery in minimum state of charge. Weighted values of CO_2 emissions are then calculated with the following formula:

$$M_{HEV} = (D_e \times M_1 + D_{av} \times M_2) / (D_e + D_{av})$$

Where M_{HEV} is the mass emission of CO_2 (in g/km), M_1 is the mass emission of CO_2 (in g/km) with a fully charged electrical energy/power storage device, M_2 is the mass emission of CO_2 (in g/km) with an electrical energy/power storage device in minimum state of charge (maximum discharge of capacity), D_e is vehicle's electric range and D_{av} = 25 km is the assumed average distance between two battery recharges).

Table 4: *Main technical data for the hybrid and the electric vehicle*

Input parameter	**Toyota Prius**	**Opel Ampera**
Empty vehicle mass (kg)	1379	n.a.
Drag coefficient	0.25	n.a.
Frontal area (m^2)	2.61	n.a.
Engine displacement (l)	1.8	1.4
Gearbox	Automatic CVT	n.a.
Fuel type	Gasoline	Gasoline
Max engine torque (Nm)	142	125
Max engine power (kW)	73	66
Max electric motor torque (Nm)	207	370
Max electric motor power (kW)	60	111
Max battery capacity (Ah)	6.5	45
TA CO_2 emissions (g/km)	89	< 40

4. Baseline simulations

As a first step, the vehicles selected were set-up within the CRUISE model to calculate their type approval CO_2 emissions. To this aim, all input parameters collected related to vehicle, engine, transmission, wheel, electric motor and battery were introduced into the software. In case any of these data were not available, CRUISE default values were used (e.g. the default values for the electric vehicle with range extender were used for simulating the Opel Ampera). Since the specific engine performance maps for these vehicles were not available, generic maps from Euro 5 technology vehicles were used for the gasoline and the diesel engines respectively. These were scaled to match the rated power of the two vehicles. Once the vehicles were set-up, the combined legislated driving cycle was simulated. The NEDC consists of an urban sub-cycle (Urban Driving Cycle – UDC) and an extra urban sub-cycle (Extra Urban Driving Cycle – EUDC). Where necessary, the engine maps were calibrated to match the fuel consumption reported by each manufacturer.

For a correct calculation of energy consumption and CO_2 emissions of the hybrid and the extended range electric vehicle, the battery's state of charge (SOC) at the end of the test should be the same as in the beginning. Otherwise, the occurring difference (ΔSOC) has to be determined and accounted for in the calculation of energy consumption and CO_2 emissions. In order to correct ΔSOC in CRUISE, multiple runs over the NEDC were performed to phase out the SOC variations. These simulations showed that ΔSOC affected significantly fuel consumption and CO_2 emissions.

As a second step, various options to reduce fuel consumption and thus achieve the 95 g/km target were examined for the conventional technologies, i.e. small gasoline and diesel vehicles. The influence of the following parameters has been investigated by the model simulations:

- Vehicle weight
- Engine power
- Drag coefficient
- Frontal area
- Rolling resistance
- Inertia of rotating masses
- Type of gear box (automatic, manual)
- Number of gears and transmission ratio of gears and axis
- Energy consumption of auxiliaries
- Start stop function of the engine

From the above parameters, those with the greater influence on fuel consumption were selected. These include vehicle weight, aerodynamics, transmission, rolling resistance and engine efficiency. The range by which these parameters were varied depends on the market information of the respective vehicle category.

As an example, the fuel consumption of the Ford Ka needs to be improved significantly in order to achieve a 30 g/km CO_2 reduction. Based on the technical data shown in Table 3 as well as technical data from other competitive cars, it is evident that vehicle weight reduction will be one of the first options for the manufacturer. On the other hand, though having a high CO_2 reduction potential, it is envisaged that the manufacturers will not opt for reducing engine power. This is based on observations of the market trend over the last years, where vehicles have become more efficient without reducing engine power. Therefore, only marginal reductions should be expected, if really necessary.

On the other hand, advanced engine technologies such as variable valve timing and lift, turbocharging, direct fuel injection, and cylinder deactivation can be used to reduce engine losses and thus increase engine efficiency. However, the margin for such technological improvements is rather limited.

The options assumed for the simulations are mainly lower vehicle weight, air drag and rolling resistance improvements, more dense gearbox ratios and, and secondarily lower engine power and improved engine efficiency. From the vehicles described above, both small gasoline cars and one small diesel car will need to cut their CO_2 emissions in view of the 95 g/km target. The assumed changes for these three vehicles to achieve the 2020 target are summarised in Table 5. The other three vehicles already comply with the emission standard and thus no further changes are assumed here, although it is possible that their CO_2 emission level will be reduced even further in view of the 2020 targets. The resulting reductions in type approval CO_2 emissions as calculated with CRUISE are also included in the same table.

Table 5: *Assumed changes in vehicle specifications of the two small gasoline cars and one small diesel car and calculated CO_2 reductions*

Input parameter	**Peugeot 107**	**Ford Ka**	**Fiat 500**
Empty vehicle mass	- 10 %	- 25 %	- 10 %
Drag coefficient	- 10 %	- 20 %	- 20 %
Engine power	0 %	0 %	0 %
Gear ratios	0 %	+ 15 %	0 %
Rolling resistance	0 %	0 %	0 %
Engine efficiency	+5 %	+ 5 %	+ 5 %
TA CO_2 emissions	- 11 %	- 22 %	- 11 %

It should be noted that the values assumed in Table 5 are not the only options, but they just present an example of how the 95 g/km target can be reached, based on observed current trends and expected future developments. Several other options exist; identifying all these options is however outside the scope of this study.

5. Real-world emission performance

In order to determine fuel consumption of the above selected vehicles under real-world driving conditions, and not only under type approval, the Artemis driving cycles were introduced in CRUISE. These were developed in the framework of a large-scale scientific programme (Assessment and Reliability of Transport Emission Models and Inventory Systems – ARTEMIS), funded by the European Commission and aiming at the development of a harmonised emission model. The Artemis cycles are distinguished into three driving cycles that simulate different road operating conditions: An urban cycle (Artemis Urban) resembling urban driving conditions, a semi-urban cycle (Artemis Road) simulating the operation of the vehicle in a regular medium-speed road, and an extra urban cycle (Artemis Motorway) simulating the operation in a high-speed road (André, 2004). The three Artemis cycles can be further split into sub-cycles, i.e. Artemis Urban (1-5), Artemis Road (1-5) and Artemis Motorway (1-4). The speed profile of the Artemis cycles and the NEDC are presented in Figure 2.

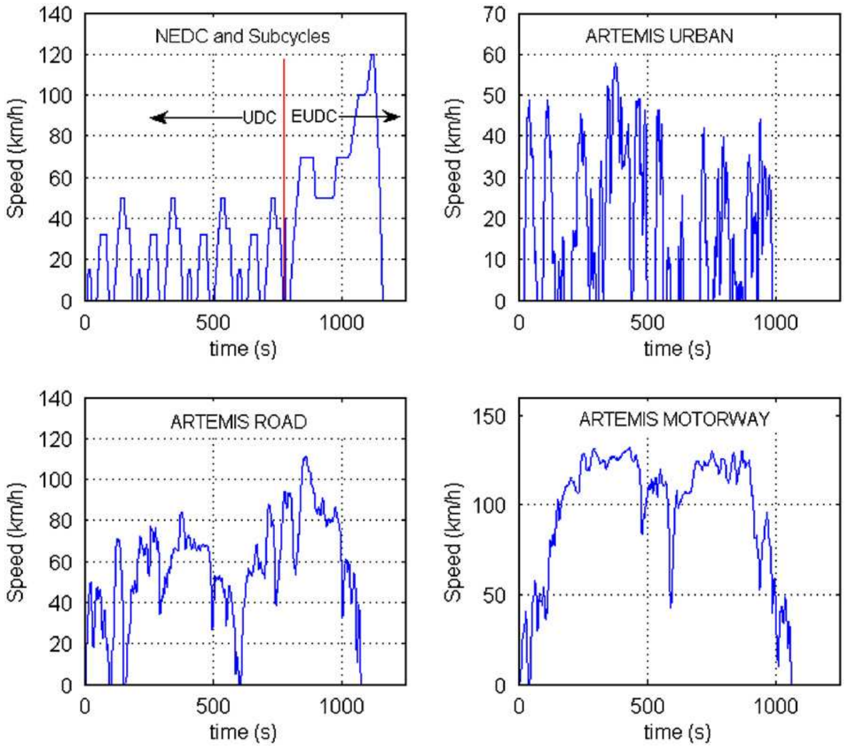

Figure 2: *The type approval (NEDC) and the Artemis driving cycles*

The simulated CO_2 emissions of the above vehicles over the NEDC and Artemis driving cycles are presented in the following tables. Emissions of the vehicles as they are presently and with the assumed changes in view of the 2020 target are included in the tables.

Table 6 summarises the simulated CO_2 emissions for the two small gasoline vehicles. The results show that the two vehicles are expected to have similar performance in terms of fuel consumption and CO_2 emissions in 2020 (differences below 5 %), which is largely due to the similar technical characteristics of the two vehicles after the changes introduced. Real-world emissions are higher by 11 to 17 % on average compared to type approval.

Table 6: *Simulated CO_2 emissions (in g/km) of the two small gasoline cars over the NEDC and the Artemis driving cycles*

Driving cycle	**Peugeot 107**		**Ford Ka**	
Year	2010	2020	2010	2020
UDC	143.4	132.8	163.2	137.1
EUDC	89.3	79.6	102.4	77.7
NEDC	109.0	97.0	124.8	97.5
Artemis urban	168.6	154.7	193.3	160.1
Artemis road	101.3	90.7	119.9	90.9
Artemis motorway	126.9	111.4	145.5	107.2
Artemis (all)	122.7	110.4	143.7	108.6

The simulation results for the two small diesel vehicles are summarised in Table 7. The Smart, compared to the Fiat, has lower CO_2 emissions ranging from 20-30 % in the low and high speed range (average speeds below 30 and above 90 km/h) to 5-20 % for intermediate average speeds. Similarly to the small gasoline cars, real-world emissions are higher by 10 to 15 % on average compared to type approval. The difference is considerably larger for urban cycles (by about 25-30 %) than for extra-urban conditions (up to 10 %).

Table 7: *Simulated CO_2 emissions (in g/km) of the two small diesel cars over the NEDC and the Artemis driving cycles*

Driving cycle	**Smart Fortwo**		**Fiat 500**	
Year	2010	2020	2010	2020
UDC	110.1	110.1	119.0	116.4
EUDC	81.3	81.3	100.4	85.2
NEDC	89.1	89.1	108.8	96.5
Artemis urban	141.6	141.6	163.3	144.2
Artemis road	76.0	76.0	119.0	94.9
Artemis motorway	104.9	104.9	134.2	107.2
Artemis (all)	97.0	97.0	131.1	111.4

Table 8 summarises the simulation results for the hybrid and the extended range electric vehicle. The hybrid vehicle has particularly low CO_2 emissions over the hot UDC (74.5 g/km), due to the electrical operation. However, the type approval is by definition a cold cycle and thus the CO_2 emissions over the urban part are increased by about 38 % due to the continuous operation of the ICE in order to heat-up the catalyst. Real-world emissions in urban conditions are in-between these two values, i.e. higher than hot UDC and lower than cold UDC by about 20 %, while they are on the same level for extra-urban cycles.

As mentioned previously, no tailpipe CO_2 is emitted from the extended range electric vehicle within the battery range and hence the zero values in the table for most driving cycles. When running the Artemis cycles the internal combustion engine is only used for a small part of the motorway cycle (in the last 5 km) to drive the electric generator. The CO_2 emissions for the full Artemis cycles is lower compared to the Motorway cycle as the same amount of CO_2 emissions are divided by a larger distance travelled (50.8 vs 28.7 km respectively).

As mentioned previously, these vehicles already meet the 2020 emission target and thus no further reductions are assumed here, although it is possible that their CO_2 emission level will be further reduced by 2020.

Table 8: *Simulated CO_2 emissions (in g/km) of the hybrid and the extended range electric car over the NEDC and the Artemis driving cycles*

Driving cycle	**Toyota Prius**	**Opel Ampera**
UDC	103.0	0
EUDC	78.9	0
NEDC	89.9	0

Artemis urban	89.9	0
Artemis road	72.3	0
Artemis motorway	105.2	20.9
Artemis (all)	81.1	11.8

6. COPERT-type emission functions

In order to assess the real-world performance of the above vehicles in 2020, their CO_2 emissions as a function of average vehicle speed are presented in Figure 3. As expected, fuel consumption and CO_2 emissions are higher at lower average speeds, they reach a minimum at around 50 to 80 km/h and they increase again for higher average speeds. In general, gasoline cars have higher CO_2 emission levels compared to diesel cars, due to the lower overall efficiency. Gasoline hybrids perform very well in urban conditions, as they are powered mainly by the electric motor. On the other hand, in highway driving that the vehicle is operated mainly by the thermal engine, CO_2 emissions are marginally lower than small diesel cars.

The emission curves clearly show that for vehicles with an internal combustion engine, there is a narrow "speed window" where the CO_2 emission level is below or close to the 95 g/km target. Outside of this window, the CO_2 emissions increase considerably. Another interesting observation is that for very low average speeds, such as in urban environments with heavy traffic and congested roads, the CO_2 emissions may increase dramatically by a factor of up to three for all vehicle technologies.

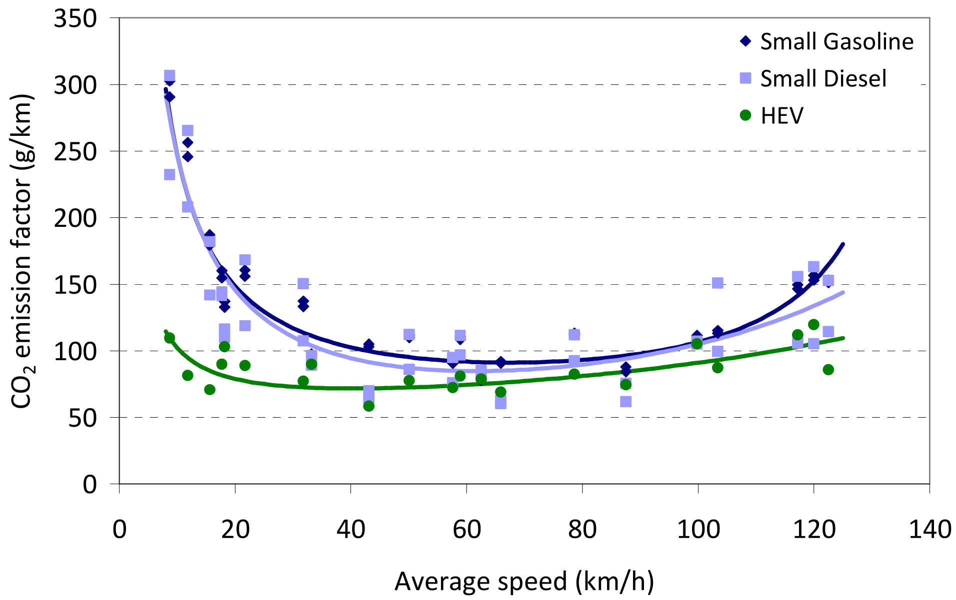

Figure 3: *CO_2 emission results of the various technologies as function of average speed*

From the values of Table 8 it is evident that the above definition of speed-dependent emission factors is not appropriate for the electric vehicles with range extender. This is because the internal combustion engine operates in a steady-state rather than in transient mode as in the case of a conventional vehicle. As a result, the tailpipe CO_2 emissions may vary substantially over driving cycles with the same average speed and same dynamics but different distances covered.

Therefore, the expression of emissions as function of the total trip length is proposed to be used instead. To this aim a set of additional simulations were performed to calculate energy consumption and CO_2 emissions over longer trips for the range extender vehicle. A simple and straightforward way is by adding additional Artemis Motorway cycles to the existing full set of Artemis cycles. This is a sensible assumption since longer trips (above 50 km) will be most probably run in highway conditions. The results of these simulations are summarised in Table 9.

Table 9: *Simulated CO_2 emissions and overall energy consumption of the extended range electric car over the NEDC and various combinations of the Artemis driving cycles*

	Trip length (km)	**CO_2 emission factor (g/km)**	**Energy consum. (kWh/km)**
UDC	10.94	0	0.107
EUDC	3.98	0	0.138
NEDC	6.96	0	0.126
Artemis Urban	4.87	0	0.140
Artemis Road	17.27	0	0.128
Artemis Motorway	28.7	0	0.164
All Artemis	50.9	11.8	0.150
All Artemis + 1 Motorway	79.6	51.1	0.095
All Artemis + 2 Motorway	108.3	69.6	0.070
All Artemis + 3 Motorway	137.0	80.3	0.055
All Artemis + 4 Motorway	165.7	87.4	0.046
All Artemis + 5 Motorway	194.5	92.3	0.039

It should be noted that the above driving cycles were simulated with a battery fully charged and can be thus considered as individual trips. This explains the fact that no CO_2 is emitted for any of the individual Artemis cycles (trip lengths up to 28.7 km), whereas an emission factor of 11.8 g/km has been calculated when simulating the full Artemis cycles (trip length of 50.9 km).

As shown in Figure 4, the CO_2 emission factor increases with trip length and remains within the 95 g/km limit for trips up to 200 km. For longer trips the emission factor converges asymptotically to the 120 g/km value corresponding to the steady-state fuel consumption of the engine.

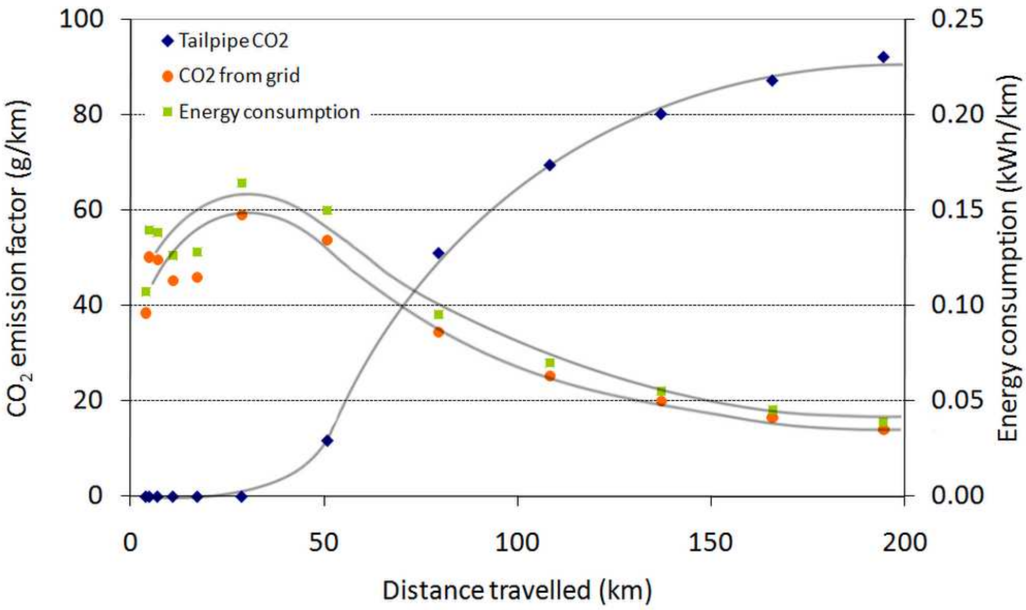

***Figure 4:** CO_2 emission factor from tailpipe and from electrical grid and energy consumption of the electrical motor of an extended range electrical vehicle as function of trip length*

Although no tailpipe CO_2 is emitted when running on battery, emissions are actually produced by upstream electricity generation. Therefore, CO_2 emissions generated by an electric car depend on the mix of power sources in the European electrical grid. Table 10 summarises the projected shares of the various sources in power generation and the implied CO_2 emission factors for power electricity in 2020 based on the PRIMES 2009 baseline scenario (2009). An average efficiency for each type of fuel was used to calculate CO_2 emitted per kilowatt-hour of electricity generated (carbon intensity).

***Table 10:** CO_2 emissions from combustion of different fuels used for electricity generation and per kilowatt-hour of electricity consumed from the grid*

Fuel type	Share (%)	g/MJ	Efficiency	g/kWh
Liquid Fuels	1.8	75.6	0.30	907.6
Solid Fuels	24.9	100.4	0.40	903.6
Gaseous Fuels	22.8	56.7	0.55	371.0
Nuclear	24.5	0.0	–	0.0
Renewables	26.0	0.0	–	0.0
All energy sources	100	–	–	358.9

Combining the above values with data on the energy consumption of the extended range electric car over various driving cycles from Table 9, the CO_2 emissions produced from electricity generation can be calculated. The results of these calculations are summarised in Table 11 and are compared to tailpipe emissions from the internal combustion engine.

Table 11: *Simulated CO_2 emissions from electricity generation and from the tailpipe of the electric vehicle with range extender over the NEDC and the Artemis driving cycles*

	Tailpipe CO_2 emissions (g/km)	**CO_2 emissions from grid (g/km)**	**Overall CO_2 emissions (g/km)**
UDC	0	58.9	58.9
EUDC	0	75.8	75.8
NEDC	0	69.3	69.3
Artemis Urban	0	76.7	76.7
Artemis Road	0	70.3	70.3
Artemis Motorway	0	90.2	90.2
All Artemis	11.8	82.3	94.1

7. Scenario design

In order to demonstrate how the same new-stock average CO_2 target may be reached with different effects on real-world emissions, three scenarios for the penetration of the above technologies in the European vehicle stock were designed. It should be made clear that the scenarios are only means to demonstrate the sensitivity of real-world CO_2 emissions to engine technology and by no way they dictate a particular path that has to be followed to reach a target.

The options to meet the future target of 95 g/km (tailpipe only) include shift of new vehicles to smaller cars and penetration of hybrid and electric vehicles. Full electric vehicles may be introduced but it is still considered that their numbers will be relatively small to have a substantial impact on mean CO_2 emissions. Plug-in hybrids are the other option for an advanced technology. However, it is considered that their performance is similar to the electric with a range extender so they were not introduced not to unnecessarily complicate the calculations. Between the four available technologies, downsized gasoline, downsized diesel, hybrid and electric with range extender, any mix is considered possible as long as the average CO_2 target of the new registrations is met.

In order to demonstrate the real-world effect on CO_2 emissions of the various scenarios, the example of the German passenger car fleet has been selected. To this aim, projections of stock growth in Germany delivered by the EC4MACS project[2] (an EU-LIFE funded program) were used as the basecase. Germany was selected as a country with a fast stock replacement, such as that targets for new registration vehicles would be immediate reflected to the total stock as well.

Based on these projections, total numbers of new registrations for the main passenger car categories are summarised in Table 12 regarding the period 2015 to 2020.

[2] EC4MACS (www.ec4macs.eu) is a LIFE+ project which provides the modelling framework for integrated assessment of air emission policies in Europe. The project has developed detailed projections of activity, energy consumption and air emissions for all European Member States, based on the PRIMES 2010 baseline scenario. The data used to develop the scenarios in this project originate from the road transport projections within EC4MACS.

Table 12: *New registrations of passenger cars – Basecase*

Vehicle type	2015	2016	2017	2018	2019	2020
Small Gasoline	853 102	900 855	915 044	917 766	914 102	907 374
Medium Gasoline	1 272 288	1 291 960	1 281 772	1 268 857	1 255 702	1 243 982
Large Gasoline	297 470	317 847	327 100	330 653	330 560	328 580
Small Diesel	856 448	792 277	813 226	830 365	844 089	854 938
Large Diesel	481 721	446 204	453 463	459 552	464 770	469 352
Hybrid Diesel	299 652	228 306	239 640	251 694	264 339	277 451
Hybrid Gasoline	348 603	265 181	286 699	308 949	331 453	353 794
E-REV	0	0	0	0	0	0

In total, three scenarios were considered, assuming different penetration rates for small, hybrid and electric vehicles. In all scenarios, the new technologies are substituting medium and big cars, i.e. those with an engine capacity above 1.4 litres for gasoline and above 2.0 litres for diesel cars. The three scenarios were designed as a response to three main directions that are taking place in the effort to reduce CO_2 emissions. These are downsizing, hybridization, and electrification.

The assumed changes in new registrations, which are introduced gradually over the period 2015 to 2020, are summarised in Table 13 for the various scenarios.

Scenario 1 (downsizing) assumes a shift towards small vehicles at the expense of bigger cars. According to this scenario, 70 % of medium-size gasoline cars are substituted by small ones, whereas large gasoline and diesel cars are completely phased-out by 2020. In order to achieve the 2020 target, 6 % of hybrids are substituted by electric vehicles. This results in the vehicle market being dominated by small cars with a 77 % share in new registrations in 2020.

Scenario 2 (hybridization) assumes an aggressive penetration of hybrid vehicles. According to this scenario, 50 % of medium-size gasoline cars and 80 % of large gasoline and diesel cars are substituted by hybrid gasoline and diesel cars respectively by 2020. Again, 6 % of the basecase hybrids are substituted by electric vehicles. As a result, the penetration of hybrid vehicles increases from 15 to 42 % from 2015 to 2020, whereas it is in the order of 13 to 15 % in the basecase over the same period.

Scenario 3 (electrification) assumes an aggressive penetration of electric vehicles with a range extender. Compared to the previous scenarios, a smaller fraction of medium and large cars (20 % of medium-size gasoline cars and 30 % of large gasoline and diesel cars) is substituted by electric vehicles. This results in an 11 % share of E-REV in the total new registrations in 2020.

Table 13: *Relative changes in new registrations compared to EC4MACS basecase*

Vehicle type	2015	2016	2017	2018	2019	2020
Scenario 1: Downsizing						
Small gasoline cars	33%	50%	70%	91%	111%	132%
Small diesel cars	6%	11%	22%	33%	44%	55%
Phase-out of medium cars	-20%	-30%	-40%	-50%	-60%	-70%
Phase-out of large cars	-10%	-20%	-40%	-60%	-80%	-100%

Replacement of hybrids with E-REV	1%	2%	3%	4%	5%	6%
Scenario 2: Hybridization						
Small gasoline and diesel cars	0%	0%	0%	0%	0%	0%
Phase-out of medium cars	-20%	-20%	-20%	-30%	-40%	-50%
Phase-out of large cars	-5%	-10%	-20%	-40%	-60%	-80%
Penetration of hybrid cars	44%	66%	75%	120%	159%	194%
Replacement of hybrids with E-REV	1%	2%	3%	4%	5%	6%
Scenario 3: Electrification						
Small gasoline and diesel cars	0%	0%	0%	0%	0%	0%
Phase-out of medium cars	0%	-5%	-10%	-15%	-20%	-20%
Phase-out of large cars	-5%	-10%	-15%	-20%	-25%	-30%
Penetration of E-REV*	0.9%	3.3%	5.7%	8.0%	10.2%	11.0%

* These are absolute, rather than relative changes, i.e. the values are showing the share of E-REV in the total new registrations of the electrification scenario.

Based on the above vehicle/technology mix and the basecase figures in Table 12, the new registrations under the three scenarios were calculated and are summarised in Table 14. Diesel and gasoline hybrids have been pooled together, as no detailed data for the simulation of a diesel hybrid vehicle could be collected. Although this is a simplification, it is not expected to have a significant impact on the subsequent emissions calculations as the difference between these two technologies in terms of fuel consumption is rather small.

Table 14: *New registrations of passenger cars – Scenarios*

Vehicle type	2015	2016	2017	2018	2019	2020
Scenario 1: Downsizing						
Small Gasoline	1 137 307	1 352 013	1 558 593	1 750 587	1 931 971	2 106 742
Medium Gasoline	1 017 830	904 372	769 063	634 428	502 281	373 195
Large Gasoline	267 723	254 277	196 260	132 261	66 112	0
Small Diesel	904 620	881 518	994 612	1 106 096	1 215 904	1 324 289
Large Diesel	433 548	356 963	272 078	183 821	92 954	0
Hybrid Gasoline	641 772	483 618	510 549	538 217	566 003	593 370
E-REV	6 483	9 870	15 790	22 426	29 790	37 875
Scenario 2: Hybridization						
Small Gasoline	1 122 433	1 191 032	1 236 819	1 430 685	1 614 718	907 374
Medium Gasoline	1 017 830	1 033 568	1 025 418	888 200	753 421	621 991
Large Gasoline	282 596	286 062	261 680	198 392	132 224	65 716
Small Diesel	880 534	836 898	903 919	1 014 186	1 122 950	854 938
Large Diesel	457 635	401 583	362 771	275 731	185 908	93 870
Hybrid Gasoline	641 772	483 618	510 549	538 217	566 003	1 853 707
E-REV	6 483	9 870	15 790	22 426	29 790	37 875

Scenario 3: Electrification						
Small Gasoline	1 122 433	1 191 032	1 236 819	1 430 685	1 614 718	907 374
Medium Gasoline	1 017 830	1 033 568	1 025 418	888 200	753 421	746 389
Large Gasoline	282 596	286 062	261 680	198 392	132 224	98 574
Small Diesel	880 534	836 898	903 919	1 014 186	1 122 950	854 938
Large Diesel	457 635	401 583	362 771	275 731	185 908	140 805
Hybrid Gasoline	635 289	468 813	473 705	476 546	476 634	1 529 579
E-REV	12 965	24 674	52 634	84 096	119 159	157 811

The assumed changes in technology mix of the new registrations for the three scenarios are graphically represented in the bar charts of Figure 5 for the years 2015 and 2020. All changes are relative over the basecase, with the exception of E-REV, for which the bars show their absolute share in the total new registrations.

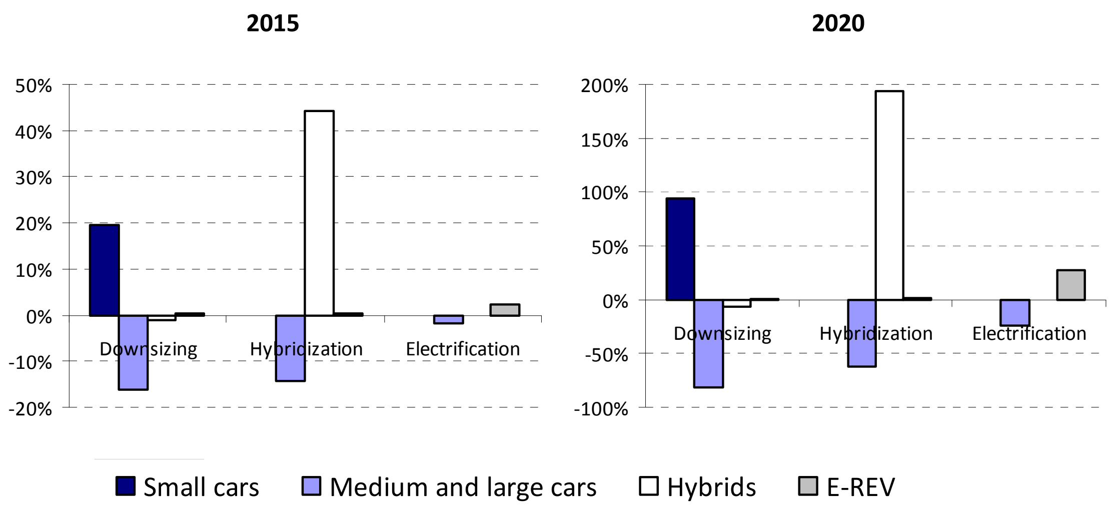

Figure 5: *Relative changes in the allocation of new registrations to technology classes compared to basecase under the various scenarios*

8. CO_2 emissions calculations

For the calculation of CO_2 emissions, average speeds of 20, 50 and 90 km/h were assumed for urban, rural and highway driving. Data for the annual mileage of each vehicle category were also taken from EC4MACS and values of 40, 30 and 30 % were assumed for the share of annual mileage driven in urban, rural and highway conditions respectively. The calculation is sensitive to the speed and share at each driving mode so final values may vary according to the conditions selected. This can be revealed with a sensitivity analysis but this was not attempted in this report, again in order not to introduce too many uncertainties in the calculation. However, it is highly recommended that the effect of different vehicle operation conditions according to their technology on total CO_2 emissions is investigated. To make it more clear, it could be expected that an electric vehicle (even equipped with a range extender) will be used at shorter trips (e.g. urban trips) than the diesel counterpart in order for the owner to be benefitted from the electrical operation. Therefore, real-world operation may be differently defined according to the vehicle type.

In any case, it was decided at this stage to keep the same vehicle behaviour regardless of technology. Therefore, the activity data selected were then combined with the real-world emission functions developed in section 6 for each technology, to calculate CO_2 emission factors for the year 2020 as shown in Table 15. For previous years a yearly decrease of 2% in fuel efficiency was assumed. This reflects the typical year-to-year efficiency improvement of passenger cars recorded by the monitoring procedure (mean CO_2 dropped from 172 g/km in 2000 to 146 g/km in 2009, i.e. with a rate of 1.8% per year). These emission factors are common for all scenarios.

For the electric vehicle with a range extender it was assumed that urban trips are within their electric range and thus no tailpipe CO_2 is emitted. For rural and highway conditions average trip lengths of 100 and 200 km respectively were assumed. CO_2 emission factors corresponding to these average trip values were then selected from Table 9, i.e. 69.6 and 92.3 g/km for rural and highway driving respectively.

Table 15: *Real-world CO_2 emission factors (in g/km) for new vehicles per vehicle class and year used in the calculations*

Vehicle type	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Small Gasoline	140.8	138.1	135.4	132.7	130.1	127.6
Medium Gasoline	163.1	159.9	156.8	153.7	150.7	147.7
Large Gasoline	207.6	203.5	199.5	195.6	191.8	188.0
Small Diesel	125.0	122.5	120.1	117.8	115.4	113.2
Large Diesel	144.7	141.9	139.1	136.4	133.7	131.1
Hybrid Gasoline	87.2	85.5	83.8	82.1	80.5	79.0
E-REV	54.0	52.9	51.9	50.9	49.9	48.9

Based on the assumptions and simulations presented above, the expected development in real-world CO_2 emission factors from 2010 to 2020 is graphically shown in Figure 6 for each of the technologies considered in the present study. Baseyear (2010) emission factors are derived from the COPERT model and are also used in EC4MACS.

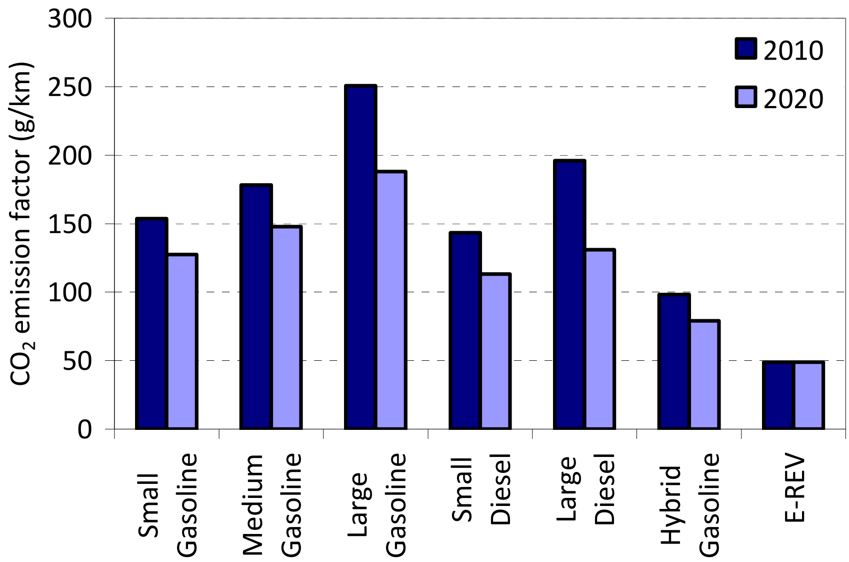

Figure 6: *Comparison of real-world CO_2 emission factors in 2010 and 2020*

Emissions were calculated for all passenger car classes, technologies (Euro 0 to Euro 6) and scenarios. In addition to the three scenarios developed above, CO_2 emissions were also calculated assuming an overall emission factor for the new registrations equal to the respective CO_2 target, i.e. 120 g/km in 2015 and reducing by 5 g/km per year down to 95 g/km in 2020. These emission factors are used in the following only to demonstrate the differences in CO_2 emissions between scenarios and targets set by the regulation. Figure 7 graphically shows the projected evolution of CO_2 emissions from new cars for each scenario over the period from 2015 to 2020.

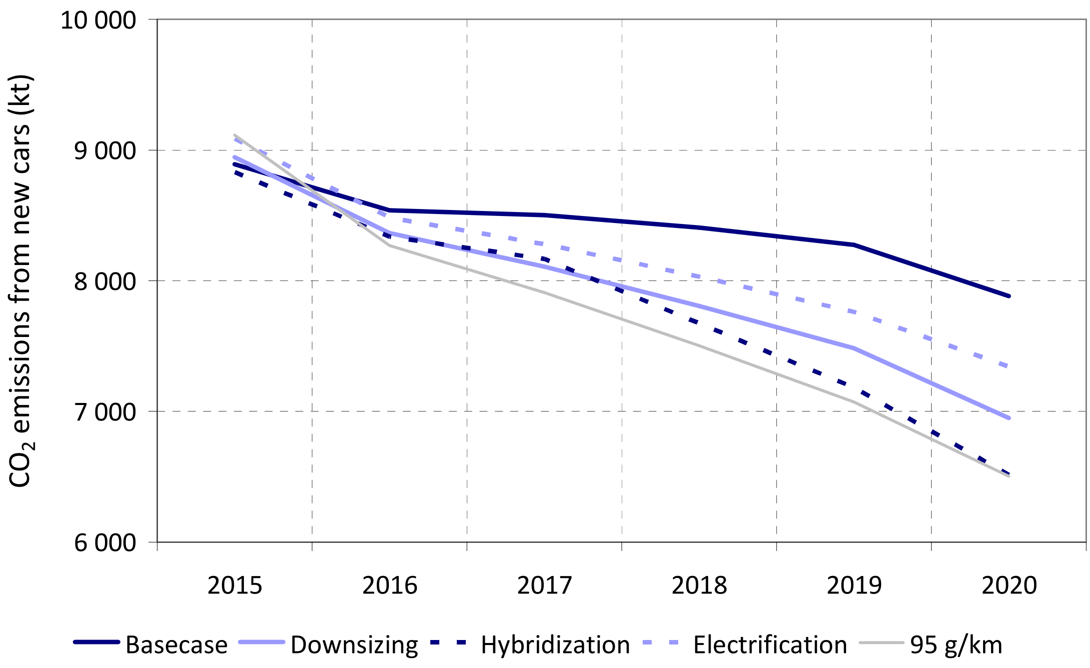

Figure 7: *Development of tailpipe CO_2 emissions from new registrations of passenger cars for the various scenarios compared to basecase*

Basecase CO_2 emissions are reducing with time mainly as a result of the assumed improvements in fuel efficiency of new cars. The basecase calculation follows the assumptions on efficiency improvement of the PRIMES 2009 baseline scenario. These are not necessarily as detailed as the calculations that we have performed in this report. In addition, the basecase calculation does not include the detailed real-world efficiency factors developed for hybrid and electric vehicles. Therefore, absolute differences over the basecase are not important, as the basecase is artificial as well. However, differences between the different scenarios are most important to study. All three scenarios predict a reduction in emissions, which is highest for the hybridization scenario and lowest for the electrification scenario, whereas the downsizing scenario is in-between. Marginal differences may be observed for 2015 as there are only slight differences in the composition of the fleet among the basecase and the various scenarios.

Although electric vehicles have the best performance (both in type-approval and real-world CO_2 emissions) of all vehicle technologies considered in this study, new cars CO_2 emissions in the electrification scenario are only 6.5 % lower compared to basecase in 2020. This is due to the fact that, compared to other scenarios, only a small fraction of the fleet has been substituted by electric vehicles (20 % of medium and 30 % of large cars), minimising thus many of their emission benefits. On the other hand, a considerable fraction of new registrations (50 % of medium and 80 % of large cars, i.e. the least energy-efficient types) is replaced by hybrids in the hybridization scenario, resulting in a 16.5 % decrease in CO_2 emissions. This fleet replacement is even larger in the downsizing scenario (70 % of medium cars replaced by small ones, whereas large cars are completely phased-out in 2020), but this is counterbalanced by the fact that small gasoline and diesel cars are less energy-efficient than hybrids.

When considering the total CO_2 emissions of the entire passenger cars fleet (i.e. not only new registrations) a similar picture may be observed as shown in Figure 8. As expected, basecase CO_2 emissions are reducing as a result of fleet renewal and penetration of new technologies with improved fuel efficiency (Euro 6).

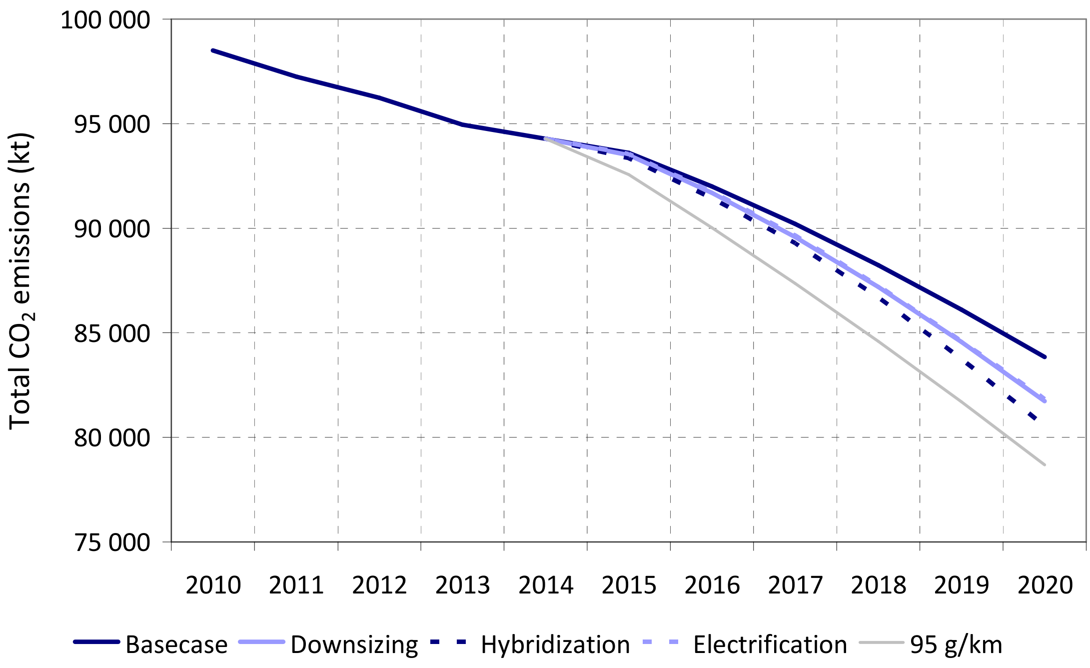

Figure 8: *Development of total CO_2 emissions (tailpipe only) from the passenger car fleet for the various scenarios compared to basecase*

However, this reduction is much lower compared to the 95 g/km CO_2 emission target specified in Regulation No. 443/2009 for new passenger cars. The differences among the three scenarios considered in this study are not significant in terms of CO_2 emissions, although the hybridization scenario predicts somewhat lower emissions (i.e. higher reductions) as explained above.

The above calculated emissions may further increase if CO_2 emissions from electricity generation (Table 11) are taken into account for the extended range electric cars in addition to their tailpipe emissions. Figure 9 demonstrates this effect, which is more apparent for the electrification scenario, in which the respective line has clearly moved closer to the baseline compared to Figure 8.

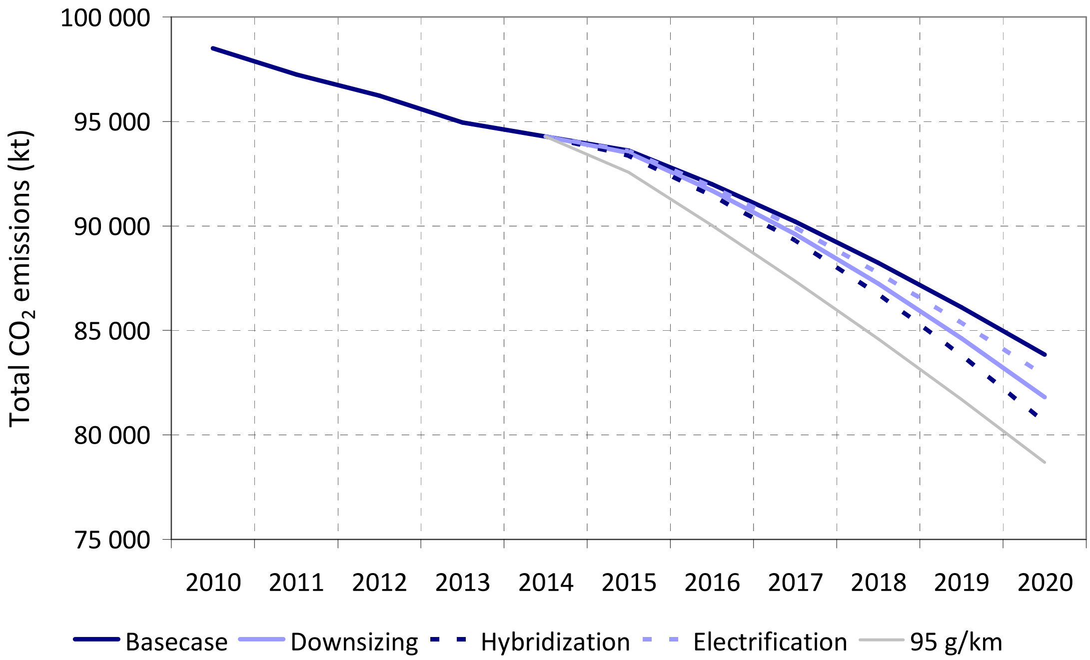

Figure 9: *Development of total CO_2 emissions (tailpipe and upstream) from the passenger car fleet for the various scenarios compared to basecase*

9. Discussion and Conclusions

CO_2 emissions from passenger cars in Europe are gradually decreasing in an effort to reduce the impact of road transport on greenhouse gas emissions and climate change. The main tool that the European Union has introduced to improve CO_2 emissions from passenger cars is Regulation 443/2009 that stipulates that passenger cars to be first time registered in 2020 need to emit 95 g/km CO_2 at an average over the certification test. The regulation does not infer into the technologies that need to be introduced to achieve this neither it addresses the impact that real-world vehicle operation may have on actual CO_2 emissions, compared to the certification test. Therefore, how actual CO_2 emissions will evolve and how effective this Regulation will be in controlling real-world CO_2 emissions are important issues that will have to be revealed into the future.

In order to provide some preliminary response to such a question, we performed a simulation study by projecting CO_2 emissions of passenger cars into the future. The projection was made with three alternative scenarios, trying to capture possible options of vehicle technology implementations into the future. The scenarios reflected three main directions that are currently pursued to reduce CO_2 emissions:

- Downsizing: Scenario 1 assumed that new registrations of vehicles are shifted from larger to smaller cars. This is a tendency which is even today obvious, with all mainstream manufacturers extending the range of smaller cars offered (i.e. below 1.4 l engine capacity). Downsizing reduces emissions as a result of less energy required to operate small and lighter vehicles.
- Hybridization: Scenario 2 introduced a large number of gasoline hybrid vehicles. Hybrid vehicles benefit from the combined operation of an internal combustion engine and an electric motor which assists the engine over accelerations and high load conditions. As a result, a smaller engine than in a conventional vehicle may be used which operates under less transient conditions. This results to higher overall efficiency
- Electrification: Scenario 3 considered the introduction of electric vehicles, i.e. vehicles where power to the wheels is delivered by an electric motor and which can be charged directly from the power grid. An electric vehicle with range extender was considered as the best example, i.e. a vehicle where an internal combustion engine charges the batteries when depleted. This differs from hybrid because power to the wheels is provided only through the electric motor. However, such an electric vehicle is not compromised by a small range. Therefore, it appears as the best of both worlds.

In all scenarios, the mix of technologies was such as to achieve 95 g/km average CO_2 emissions of new registrations in 2020.

The different vehicle technologies were simulated using an appropriate vehicle model and their CO_2 emissions were determined over both type-approval and real-world driving conditions. Emission factors were developed in this way. These emission factors were used to calculate CO_2 emissions over real-world driving conditions.

The three scenarios developed were compared against a basecase scenario. This is also an artificial scenario, based on the EC4MACS efficiency improvements considered for passenger cars.

The main conclusions from this work can be summarised in the following points:

- The actual real-world emission factors of improved future technologies of conventional diesel and gasoline passenger cars are higher than the certification test of 95 g/km. The difference for gasoline cars is +12±1% cars and +10±1.2% for diesel cars.
- Advanced vehicle technologies (hybrid and electric with range extender) may achieve real-world CO_2 emissions which are already much lower than the 95 g/km target. In particular for the electric vehicle, this depends a lot on the mean trip distance travelled. Starting with fully charged batteries, the 95 g/km target is achieved approximately after 170 km and the emission asymptotically reaches 120 g/km for longer trip distances.

- Because of their unique characteristics, the mix of technologies to be introduced does have an impact on real-world CO_2 emissions, even if one considers a fixed new stock average CO_2 of 95 g/km in 2020.
- The scenario mostly based on downsizing achieves 12 % CO_2 reductions over the basecase, the hybridization scenario achieves 17 % reduction and the electrification scenario achieves 7 % reduction. For comparison, if the real-world CO_2 emission factor was 95 g/km, the actual reduction would have been 18 %.
- For the German passenger car stock, the difference of Scenario 3 (electrification) over Scenario 2 (hybridization) is 12.7 % higher CO_2 emissions of new passenger cars in 2020, while both scenarios meet the 95 g/km target.
- The sometimes counter-intuitive conclusions are based on the following effects:
    - Introduction of an electric vehicle with very high CO_2 reductions provides the margin to introduce heavier vehicles with high CO_2 emissions. Therefore, introduction of electric vehicles leads to lower real-world CO_2 reductions than any of the other three scenarios. It should be recognized that this conclusions greatly depend on how electric vehicles are used. If electric vehicles are only used for short urban trips then actual CO_2 reductions will be higher.
    - Hybridization achieves the best overall result because hybrid vehicles seem to perform very well under all driving conditions. By having a certification CO_2 values close to the target, they do not allow the introduction of heavy cars if the target is to be met. This safeguards that the certification CO_2 value holds true for most of the real-world conditions.
    - Downsizing is also a good option. However, small vehicles still behave worse than hybrids under certain conditions (urban driving).
- The benefit of introducing electric vehicles to meet the CO_2 target is further compromised if one considers the upstream CO_2 emitted for electricity production. By taking the average European carbon intensity into account, the benefits of the electrification diminish, reaching only 1.6 % over the base case.

The impacts of these results are at least two-fold:

1. The actual effect of regulation 443/2009 strongly depends on the technology mix to be introduced. Between the best and the worst scenario developed, the difference in CO_2 emissions of new passenger cars is approximately 13%. In other words, it is like having a target of 107 g/km instead of 95 g/km in 2020.
2. Electric vehicles can be the most efficient in terms of CO_2. Because of this, they leave room for CO_2 inefficient vehicles to survive. As CO_2 emissions of inefficient vehicles differ significantly between real-world and type-approval, the net effect of electric vehicles can be negative compared to alternative scenarios.

One needs to recognise that this has been only an exploratory study trying to identify possible side-impacts of regulation 443/2009. In this direction, the scenarios developed and the technology mix considered per scenario are plausible but not the only possibilities. In addition, a number of issues may require additional attention. For example, real-world conditions may differ according to vehicle types and characteristics. Similarly, technology of 'conventional' vehicles may evolve in a direction not foreseen in this analysis (e.g. brake energy recuperation, more efficient start and stop systems, new engine concepts, etc.).

Still, despite these limitations, our analysis demonstrates that there are possible ways to meet the regulation requirements into the future while greatly deviate in real-world CO_2 emissions.

This requires some further attention in order to avoid a situation where the letter of the regulation is met but the target (actual CO_2 reduction) is not.

10. References

André, M., 2004. The ARTEMIS European driving cycles for measuring car pollutant emissions. Science of the Total Environment 334–335, 73–84.

EC4MACS, 2010. European Consortium for Modelling of Air Pollution and Climate Strategies. A project funded by the EU-LIFE program. Information available on www.ec4macs.eu.

European Commission, 2010. Measures for monitoring the average specific emissions of carbon dioxide from new passenger cars. CO_2 monitoring database downloaded from http://ec.europa.eu/environment/air/transport/co2/co2_monitoring.htm

PRIMES, 2009. EU energy trends to 2030 — UPDATE 2009. Directorate-General for Energy in collaboration with Climate Action DG and Mobility and Transport DG.

UN-ECE, 2005. Regulation No. 101 - Rev.2 -Emissions of carbon dioxide and fuel consumption. http://www.unece.org/trans/main/wp29/wp29regs101-120.html

VCA, 2010. Type approval data of the UK Vehicle Type Approval authority downloaded from www.vca.gov.uk