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Review of in use factors affecting the fuel consumption and CO_2 emissions of passenger cars

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Title
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Abstract

This report analyses the factors influencing fuel consumption and CO_2 emissions of passenger cars in real-world operating conditions. Their effect generates the divergence between the officially reported fuel consumption and the one experienced by the drivers.

Review of in use factors affecting the fuel consumption and CO_2 emissions of passenger cars

By

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This report has been drafted in response to a request by DG Climate Action (CLIMA) to the Joint Research Centre (JRC) for an assessment of the factors which contribute to the fuel consumption and CO_2 emissions of passenger cars in real-world operation and in the laboratory.

The report is dedicated to all concerned drivers who are in search of information and practises on how to reduce their fuel consumption and carbon footprint.

Contents

Executive summary

This report analyses the factors influencing fuel consumption and CO_2 emissions of passenger cars in real-world operating conditions. The effect of the investigated factors can lead to a divergence, also referred to as 'shortfall' or 'gap', between the officially reported fuel consumption (or NEDC fuel consumption/CO_2 emissions) and the one experienced by the drivers. This divergence is attributed on one hand to the fact that the current certification test in Europe does not consider a variety of different real-world operating conditions, therefore not delivering realistic results. This variety of different operating conditions is investigated in order to identify the factors affecting fuel consumption. On the other hand, the divergence occurs also due to the so-called 'margins', 'flexibilities' or 'elasticities' associated with the testing procedure (1). By these terms we refer in this report to a specific provision or legitimate interpretation of the certification procedure, or the absence of such a provision, resulting in the measurement of lower CO_2 emission values compared to the values that would occur if provisions, interpretations or practices were reflecting more accurately average real-world conditions.

As a first approach, an extensive literature review has been performed, showing that the most important in-use factors affecting the difference between real-world and certification performance are the use of air conditioning devices, ambient temperature and environmental conditions, roof add-ons, driving style, tyre pressure and the increase of vehicle weight. The elasticities of the type approval (TA) test have also been identified as highly influential and were analysed separately due to their particular nature. Summarising the findings of the literature review and the subsequent analysis performed, the real-world-certification difference could range between 25-45 %, depending on the combination of factors and conditions. It should be noted that most of the parameters examined can be influenced directly by the driver, except for ambient and road conditions.

Subsequently, for each factor a simulation scenario was designed to better investigate its effect. The simulation was run for three types of vehicles: a petrol naturally aspirated (NA), a petrol turbocharged and a diesel vehicle. The vehicles and their characteristics were chosen to be largely representative of the European fleet. A baseline scenario was created from the settings of the official type approval procedure and was used for comparison with the scenarios simulating the investigated factors. In a few cases, a different baseline scenario was chosen due to the nature of the factor under investigation. The outcome of the simulations was assessed in terms of CO_2 emissions for the NEDC and specific WLTP (2) configurations. The simulation scenarios address cases that are well studied in the literature and their effect has been well defined and analysed in the past. However, in addition to the assessment of individual factors, we also include simulation cases that are not particularly well studied and where the mechanism that affects energy consumption has not been thoroughly investigated in previous studies. The challenges in these cases are pointed out to assist and promote future research on the subject. Summarising the findings from the different simulation scenarios, it can be concluded that the energy consumption

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(1) It is clear that flexibilities cannot be 'illegal' as by definition they are part of the regulated certification procedure. As a result, incorporation of such flexibilities in the testing practice is not a unlawful act; however their intentional exploitation to achieve benefits should be considered against the spirit of the law and the principle of good faith governing EU certification schemes.

(2) The NEDC (New European Driving Cycle) is the test procedure currently adopted for vehicle type-approval in Europe (and in several other countries around the world), while the WLTP (Worldwide harmonized Light-duty Test Procedure) is the test procedure expected to be used in the European type-approval for light duty vehicles as of September 2017.

and CO_2 emissions are affected by a combination of factors whether driver dependent or not. Detailed results are also presented as a weighted-average, using as weighting factors the shares in the reported registrations for each type of vehicle considered (petrol naturally aspirated, petrol turbocharged, diesel) according to the EEA (2013b) database.

Despite the fact that numerous data are reported during the type approval process of vehicles, little information is actually publicly available. Knowing the aerodynamic characteristics of a vehicle, the performance of auxiliary consumers, or other kind of energy losses, would be valuable information for assessing its real-world fuel efficiency. In this sense, future type approval and labelling mechanisms can be designed to be more market and information oriented allowing the customers to select their vehicle and customise it based on their actual needs. Similar approaches have already been adopted or are in the process of adoption for other vehicle segments (e.g. Heavy-Duty vehicles) in various countries. As a first step, a more detailed and possibly interactive CO_2 or fuel consumption database can overcome this gap which is presently addressed to a certain extent by private websites, magazines and drivers' forums.

The factors that were identified and investigated using the literature review and the vehicle simulation are briefly described in the following paragraphs.

Auxiliary systems

Auxiliary systems refer to the elements and accessories that improve driving safety and comfort like air cleaning, heating and A/C, lighting, wipers, electric windows, parking assistance, collision warning and avoidance (Huhn 2008, Dudenhöffer and John 2009, Reif and Dietsche 2011). These are usually not operated continuously, however this work does not consider in detail the usage factors due to the lack of information. The use of auxiliaries requires an increased mechanical or electrical supply, which in turn increases engine power demand and fuel consumption. The latter is estimated in the order of 9 % for the use of A/C, up to 4.5 % for the steering assist systems and up to 6.5 % for the other auxiliaries. Optimisation and advanced technologies could provide benefits in fuel consumption by up to 2 % according to the literature. Purely mechanical auxiliary systems are losing ground to their electrical counterparts.

A range of energy demands for additional electrical and mechanical loads were assessed by means of simulation. The latter resulted in an average increase of 14.9 % for NEDC and 9.6 % for WLTP for an additional 0.6 kW of additional electrical demand, which is considered a relatively high value for average use. An extra 0.4 kW of mechanical load has resulted in an average increase of 3.8 % and 2.8 % respectively.

Aerodynamics

Aerodynamics refers to the shape and design of the car and its projected frontal area. Shape modifications and change of the frontal area, like the addition of a roof rack with an extra load can increase the aerodynamic resistances resulting in increased fuel consumption (EPA 2014b). Indicative estimates of the fuel consumption increase are about 5 % for roof add-ons and roof boxes, 5.1 % for open windows at 130 km/h, 2 % for the effect of side-winds although this is highly dependent on the overall vehicle shape and design, while various aerodynamic improvements such as properly designed spoilers and vortex generators are reported to decrease fuel consumption by 0.4 % compared to TA values but the number of relevant studies is limited.

The effect of various roof add-ons was simulated, with the most significant being the roof box, as it is the most common shape modification. Regarding their aerodynamic effect (3) the increase in emissions was on average 6.5 % and 9.7 % for NEDC and WLTP respectively. It was difficult to estimate a precise value of the air drag change due to open windows and side-winds, as this is closely related to the aerodynamic shape characteristics of the vehicle and for this reason a range of air drag changes was tested. Lower aerodynamic drag by 10 % can decrease CO_2 emissions by 2.2 % for NEDC and 3.3 % for WLTP. On the other hand an increase of 10 % in the air drag leads to additional emissions of 2.3 % and 3.5 % respectively.

Weather conditions

Ambient conditions refer to the external conditions such as wind, temperature and barometric pressure (4). They affect vehicle fuel consumption performance as they influence the engine operation (e.g. motor oil viscosity, engine intake air-flow, etc.). They might also affect driving behaviour, as the driver has to adjust his driving pattern accordingly. The influence of temperature is estimated in the order of a 0.5 % increase per °C below 20 °C (assumed certification temperature for Europe is 25 °C). Rain can potentially increase fuel consumption by 30 % or more depending on conditions.

Data retrieved from literature and simulation results have shown that the effect of engine cold start at 23 °C over NEDC is in the order of 10 % while for WLTP it was calculated to be in the order of 3.5-4 %. For an ambient temperature of – 7 °C cold start effect is almost doubled (about 20 % higher CO_2 emissions compared to fully warm operation) for NEDC and 6.7 % for WLTP. An ambient temperature of 15 °C, which is considered closer to the European average, led to an increase of 12 % and 4.5 % respectively.

Driving

Driving behaviour refers to the driving patterns that an individual driver follows, like acceleration and top speed. Aggressive driving can increase fuel consumption dramatically by up to 24 %, while eco-driving can provide estimated benefits in the order of 6-8 % compared to standard real-world operation with certain sources raising this figure up to 30 % (5). Trip type and proper planning can affect fuel consumption significantly as fuel consumption was found to differ by 10 % on average for different routes linking the same starting points and destinations.

There was no simulation scenario for this factor, as the research was focused on the type approval related cycles which have predefined speed profiles and gear shifting patterns.

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(3) The mass increase effect of such devices was investigated separately in a different paragraph

(4) Pressure changes considered in the study are assumed to be a result of altitude differences and not of weather conditions. It is assumed that the annual average barometric pressure at a given altitude remains constant, varying within a ± 30 mbar range. Driving continuously at a 500 m altitude would result in 50 mbar lower annual average barometric pressure.

(5) As mentioned, aggressive driving may increase emissions by 24 %. So the overall variation range in CO_2 emissions that can be attributed to driving behaviour appears to be indeed in the order of 30 %. Of course it is extremely difficult to define the 'standard' driving style which serves as reference for such calculations. It is expected that as drivers become more concerned about fuel consumption and as driver aids such as gear shift indicators proliferate the average driver behaviour should become more fuel efficient.

Vehicle condition

Vehicle condition refers to the state of the vehicle in terms of maintenance, like for example the timely change of oil, check of tyre pressure and proper tyre type usage. It was found that using low viscosity motor oil can lead to a reduction in fuel consumption of about 4 %. Additionally, decreasing the rolling resistance coefficient of the tyres by 10-20 % (i.e. corresponding to the next better energy efficiency class) could have benefits of 2.1 % in fuel economy. On the other hand, a tyre pressure 0.2 bar lower than recommended can result in an increase of 1.4 % in fuel consumption. Various other factors like clogged air filters and misaligned wheels can increase fuel consumption in the order of 4 to 5 %.

The effect of lubricant viscosity and rolling resistance were investigated via simulation. The use of lower viscosity engine oil led to reduced emissions by up to 2.2 % over the NEDC for petrol vehicles and up to 4.1 % for the diesel vehicle. Over the WLTP, petrol cars can benefit by up to 1.9 % in emissions, while the corresponding value for a diesel vehicle was calculated at 2.5 %. The differences between the petrol and diesel vehicle is attributed to the different oil types considered for each engine type, with diesel lubricants assumed to have higher viscosities.

Operating mass

The operating mass represents the total weight of the vehicle. As mass increases more energy will be required to accelerate and maintain constant speed (6). Hence fuel consumption increases with mass. Literature reports suggest that for an extra mass of 100 kg, fuel consumption can increase up to 6-7 % compared to the certification value, with an average estimate being in the order of 2-4 %. The effect of mass is even greater if roof boxes or the towing of a trailer is accounted for as additional conditions apply (e.g. increased air drag and rolling resistance). In such cases the increase in fuel consumption can reach up to 20 % and 37.2 % respectively (ADAC 2012a, Thomas et al. 2014).

The effect of additional mass, trailer towing and a laden roof box was investigated via simulations. An additional mass of 100 kg led to an average increase of 2.6 % for NEDC and 2.8 % for WLTP. The trailer was tested unladen and laden at 60 % capacity (additional 310 and 560 kg respectively). The results of the unladen trailer delivered increased emissions by 22.1 % for NEDC and 29.7 % for WLTP. In the case of the laden trailer the increase was 28 % and 37.3 % respectively. The increase for the laden roof box was 8.9 % for NEDC and 11.3 % for WLTP.

The increase in the latter two cases is attributed to a combined effect of increase in mass and air drag. This led to the investigation of different combinations of masses and air drag changes, which has shown that CO_2 emissions are linearly correlated to the increase of these factors.

Finally, the WLTP sub-cycles were also analysed in order to correlate CO_2 emissions, vehicle speed, air mass and air drag. The results have shown a significant increase at higher speeds when roof boxes are used compared to a vehicle with the same additional mass but without additional air drag. Over the High phase of the WLTP the increase was on

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(6) Braking phases are considered as fuel consumption neutral as most likely the engine operates in fuel cut-off mode.

average 16.8 % for a laden roof box, while for the same additional weight the increase was 1.5 %.

Occupancy rates

The addition of extra passengers increases the mass of the vehicle and subsequently fuel consumption. In terms of absolute value metrics, a higher number of passengers increases the gap between experienced and official fuel consumption but when viewed from an environmental perspective a reduced per passenger emission value is beneficial and shall be pursued. An extra passenger is reported to increase fuel consumption by up to 5 % adding another 6.5 g CO_2/km for a 130 g/km vehicle, although this value is probably overestimated. In the meantime there is a significant decrease in CO_2 emissions per passenger transported from approximately 130 g CO_2/km (when only the driver is taken into consideration) to 69 g CO_2/km. Simulations have shown that an extra passenger would increase CO_2 emissions on both cycles by approximately 1.5 %. However the decrease in emissions per passenger would be a bit less than 50 %.

Road (morphology, surface, traffic)

The 'Road' factor refers to the conditions of the road where the vehicle is driven and for the purpose of this report it includes both the actual characteristics of the road (pavement quality, inclination, straight or curved) and the actual traffic conditions (average speed, maximum speed, presence of traffic lights, free flow, etc.). Different road surface qualities can affect fuel consumption by 1.9 %. Road grade (i.e. slope) was reported to affect fuel consumption by 18 % (uphill driving) for grades higher than 2 %. While consumption is reduced over downhill operation, the net impact of travelling the same road uphill and downhill has an overall negative impact on fuel consumption, as far as conventional vehicles are concerned. Traffic conditions affect the actual movement of the vehicle, average and max speed, accelerations, start and stop incidents, prolonged travel time, etc., that can have a very negative impact on fuel consumption. Due to the great variety of traffic conditions it is difficult to quantify and summarise the impact of traffic in one figure. Maximum values reported in literature claim up to 50 % increases in fuel consumption compared to the corresponding baseline values.

A simulation scenario tested the impact of altitude and road grade. The altitude was simulated as lower barometric air pressure, which results in lower aerodynamic resistance. Differences in combustion properties were not taken into consideration as the available literature did not provide enough information. For an altitude of 2 000 m compared to sea level the decrease in CO_2 emissions was 4.4 % for the NEDC, while for the WLTP it reached up to 6.7 %. However it is recognised that driving at such altitudes in European roads is extremely rare. Regarding the grade, uphill driving at an inclination of 2 % resulted in an increase of approximately 34 %. On the other hand downhill driving at the same grade provided benefits of about 30 %. It is observed that increased energy consumption from uphill driving is not fully compensated by the benefit of equal downhill driving, as the energy required to move the vehicle uphill will result in additional thermodynamic losses. It has to be noted that these numbers refer to conventional vehicles with a simple brake energy recuperation system and limited electrical consumers. The situation for hybrid vehicles would probably be different as the energy stored during downhill driving can be later used for vehicle propulsion.

Fuel characteristics

Automotive fuels are blends of various types of hydrocarbons and other organic compounds (e.g. ethanol or methylesters in the case of biofuels). Their characteristics are regulated by the corresponding standards. Fuel composition varies depending on the time of the year, availability of certain blendstocks and also the geographical region where the fuel is produced or sold. Fuel composition and characteristics are also influenced by specific particularities related to weather conditions, different regional standards, market availability of blendstocks and regional policies. The latter becomes more evident when considering variations of bio-components in commercial fuels. Biofuels can provide benefit, e.g. in terms of a reduced carbon footprint, but during actual operation drivers may experience an increase in volumetric fuel consumption or deterioration in performance. The increase in volumetric fuel consumption (l/100km) for various biofuel blends can be from 0 to 2 % for a 10 % volume/volume biodiesel-diesel blend (B10) or up to 30 % for an 85 % ethanol Petrol blend (E85)).

The baseline fuel in all simulations was E5 for petrol vehicles and B5 for diesel. Dedicated calculations were made comparing the biofuel blends E10 for petrol vehicles and B100 for diesel with the reference fuels. The results have shown a marginal increase in CO_2 emissions of 0.4 % for E10 over both cycles, while for the B100 the increase was 0.6 %.

Certification test

The type approval test has many margins that could be exploited to deliver a better CO_2 performance. A variety of procedural elements need to be specified more accurately in order to create a more reliable, consistent and robust procedure. The introduction of the new harmonised test protocol (WLTP) is expected to address a substantial share of these flexibilities and lead to a more realistic estimation of the final fuel consumption of vehicles. The development of the WLTP has been indeed based on in-use vehicle operations and state-of-the-art statistical techniques. It is worth pointing out, though, that any lab-based test procedure is unable to account for all the effects of real-life conditions and therefore that the derived fuel consumption and CO_2 emissions will only be one among the infinite possible values achieved by a vehicle in real life.

A series of different scenarios were simulated in order to quantify the impact of some of the current test flexibilities and estimate emissions of the respective vehicles under WLTP and realistic conditions. This should be considered as an indicative rather than an exhaustive calculation as the full range of flexibilities exploited and the precise WLTP test conditions cannot be at the moment quantified with high accuracy due to the lack of necessary information. More information about the boundary conditions considered in each scenario is presented in Table 0-1 and the respective chapter.

Overall

A global summary of the main findings of the literature review is presented in Table 0-2. Table 0-3 summarises the main results from the simulations performed for this study.

Table 0-1: Summary of scenario boundary conditions considered in the simulations (7)

Scenario	Realistic scenario	WLTP-H	WLTP — L	NEDC Base	NEDC with margins	Certification value
Mass	Avg. WLTP H and L + 75 kg	WLTP-L + 150 kg	NEDC inertia class + 40 kg	NEDC inertia class		Same boundary conditions as for NEDC with margins. Final CO_2 value reduced by 4 % according to the family criterion in current T/A.
Road loads	Avg WLTP-H and L	WLTP-L + 30 % F0, + 7 % F1 and F2	Base + 20 % in F0, + 3 % in F1 and F2	Base RLs (RR: 0.009 kg/ton, F1: 0.3 N·h /km, F2: 0.038 N·h²/km²)	Base − 20 % F0 Reduced rotating inertia 1.5 %	
Driving profile	WLTC			NEDC	NEDC	
Gearshifting	Case specific WLTP gear-shifting depending on road loads			NEDC time-based		
Temperature	14 °C	23 °C			25 °C	
Alternator power consumption	0.5 kW Bat. Charge Neut.	0.15 kW — Battery charge Neutral			0 kW	
Road grade	0.15 %	0 %				

Figure 0-1 demonstrates a summary of the results of the six cases calculated according to the conditions of Table 0-1.

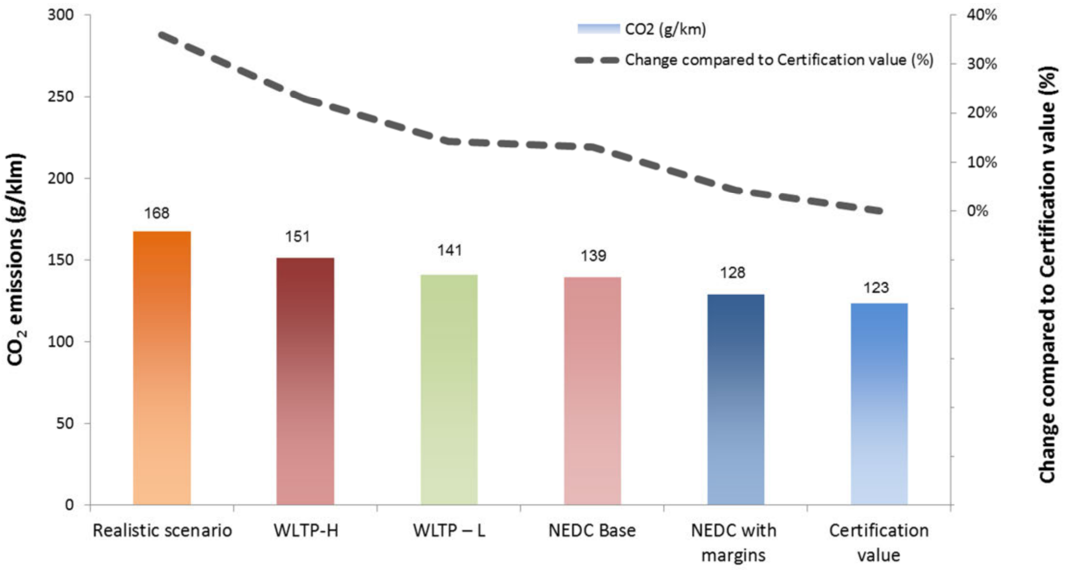

Figure 0-1: Comparison of the sales-weighted average value (8) of CO_2 emissions of the three vehicles (9) simulated over the six different scenarios. Dashed line indicates the % change compared to the certification emission value.

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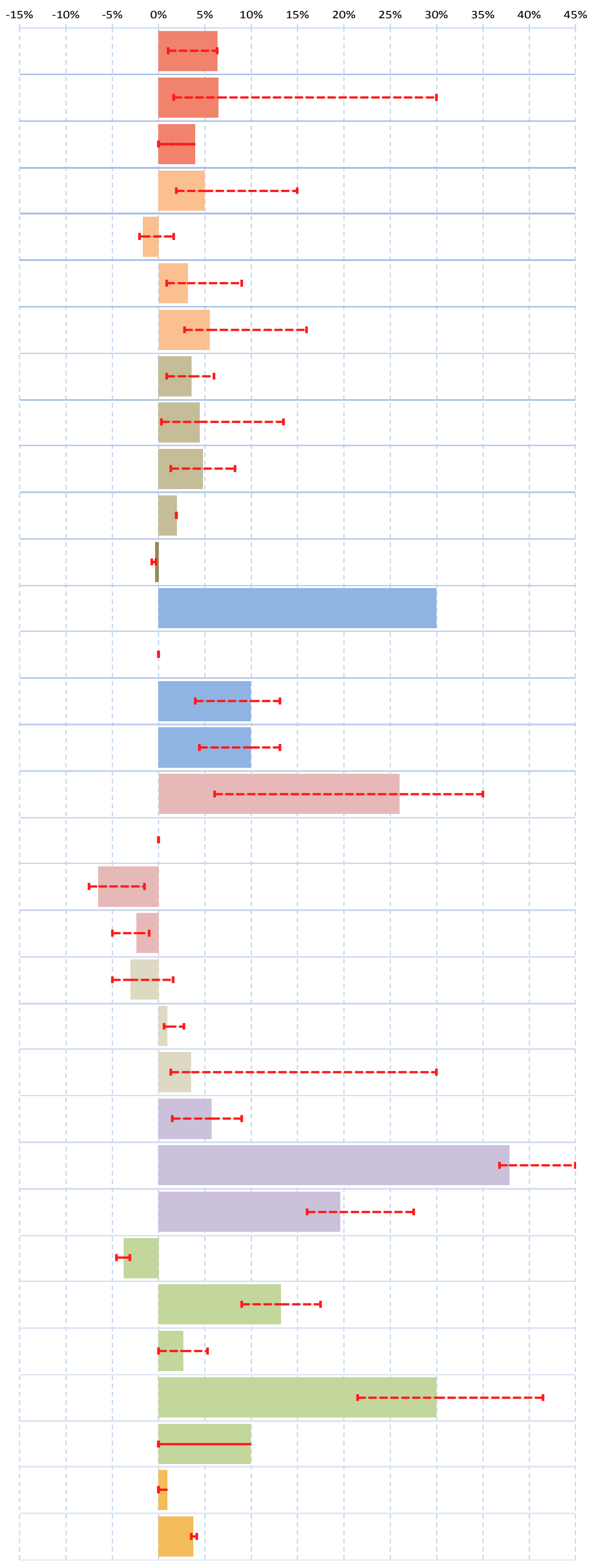
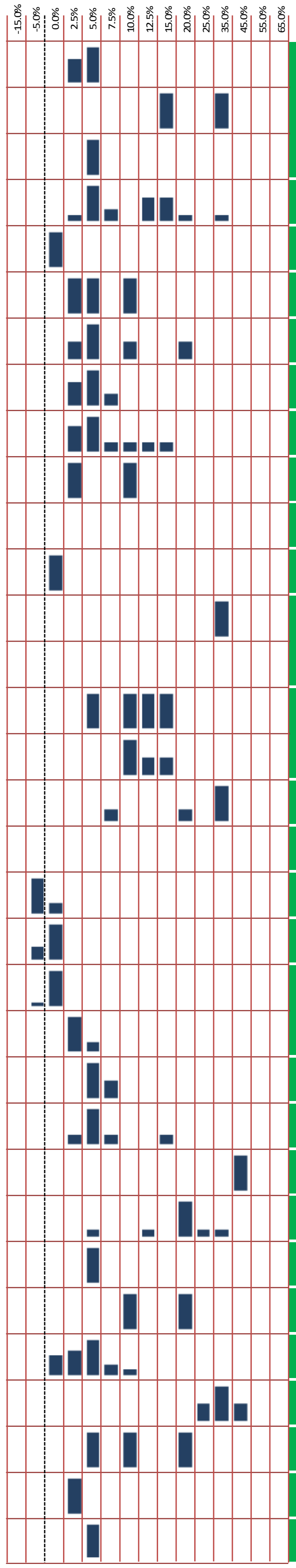
(7) Detailed information on how the values of the various factors were defined in each scenario are provided in Chapter 11.
(8) Petrol NA 25 %, Petrol turbo 25 % and 50 % diesel.
(9) See Chapter 11.

Table 0-2: Summary table of the various factors affecting fuel consumption (10). Bars correspond to the median value reported in literature. Error bars indicate minimum–maximum values found in the literature. No calculation or simulation results are included.

Category	Factor		Literature median value	Sources No.
Certificationt test margins	Various factors	Various factors involved in certification test	6.4%	13
	NEDC design	Smooth accelerations, decelerations and driving pattern	6.5%	
	Lower value declaration	Declared values is allowed to be lower than measured values	4.0%	
Auxiliary systems	Air conditioning	Increased electrical supply is required	5.0%	10
		Improved MAC systems, EV HVAC - heat pump, active seat ventilation, solar reflective paint, solar control glazing, solar roofs	-1.7%	8
	Steering assist systems	Hydraulic Power Assisted Steering, Electro - Hydraylic Power Assisted Steering, Electric Power Assisted Steering. Improved steering pump	3.2%	3
	Other vehicle auxiliaries	Engine management, fuel injection, fog lamps, brake lights, wipers, dipped beams, brake assist, heated windscreen, fan, etc	5.5%	6
Aerodynamics	Roof add - ons and modifications	Various add - ons that are attached to the roof, except for a roof box	3.6%	2
	Roof racks / boxes (air drag increase)	Effect on fuel consumption with the addition of an un - laden roof box. Increased aerodynamic resistance	4.5%	5
	Open windows	At a speed of 130 km/h, based mainly on an american study	4.8%	3
	Sidewinds effect	Change in aerodynamic drag and frontal area, depends on wind velocity and angle. Results for 10% air drag increase (caused from 15° to 30° yaw angle or from 4 - 8 m/s wind velocity)	2.0%	5
	Improvements	Spoilers, vortex generators	-0.4%	3
Weather conditions	Rain	Wheels have to push through water. Increase for 1 mm of water depth on road surface	30.0%	3
	Snow/Ice	Decreased tyre grip, wasting energy. Lower than normal driving speeds. Decreased tyre pressure	Qualitative data	
	Temperature, the type approval test current range is 20 - 29 °C	0 °C compared to 20 °C	10.0%	15
		-20 °C compared to 0 °C	10.0%	
Driving behaviour/style	Aggressive driving	High acceleration and deceleration, braking and maximum speed	26.0%	10
	Driving mode	Consumption varies according to Eco or Sport mode. Non scientific research claims increase up to 11% for Sport mode	Qualitative data	6
	Eco - driving	Optimal gear shifting, smooth accelerations and decelerations, steady speed maintenance, anticipation of movement and traffic, Green - Light Optimal Speed Advisory (GLOSA)	-6.5%	6
Vehicle condition	Lubrication	Use of low viscosity motor oil results in lower internal friction	-2.4%	13
	Tyres	Low resistance tyres by 10 - 20%	-3.0%	19
		Lower tyre pressure by 0.2 bar	1.0%	
	Other	Clogged air filters, misaligned wheels, poorly tuned engine	3.5%	5
Operational mass	Vehicle mass	Increased mass by 100 kg	5.8%	17
	Trailer towing	Affects weight, rolling resistance, aerodynamics and driving behavior	37.9%	3
	Roof racks / boxes (mass increase)	Fuel consumption increases as speed increases	19.7%	5
Road conditions	Road morphology	Altitude increase decreases consumption, as air density, aerodynamic resistance and oxygen concetration decrease	-3.8%	3
		Road grade increases fuel consumption as the car is driven uphill. Results based on American studies for a car driven on a hilly route	13.3%	3
	Road surface	Affected by roughness, surface texture and uneveness	2.7%	4
	Traffic condition	Reduced speed, increased idle time and start and stops at congestion	30.0%	3
	Trip type	Short trips. More cold starts and cold start emissions. Engine normal operation temperature not reached	10.0%	3
Fuel characteristics	Difference in fuel properties	B10 fuel blend compared to B0	1.0%	2
		E10 fuel blend compared to E0	3.8%	3



Distribution



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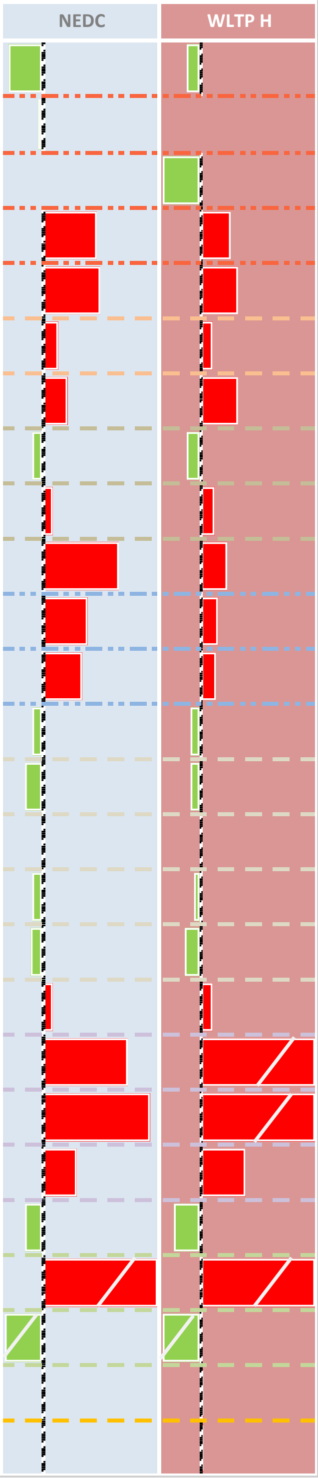
(10) These values express an average effect as reported in different literature sources. As there is no common reference for deriving these percentages they likely reflect different operating conditions depending for example on the country where each study took place. This is one of the reasons for the large variation. Nevertheless, the authors believe that this summary provides a good overview of the current understanding of the contribution of each factor to the tailpipe CO_2 emissions.

Table 0-3: Summary of the simulation results according to factor and test cycle

Factor	Case			Effect on CO_2 emissions (%)	
				NEDC	WLTP H
Certification test	Hot start			-8.7	-3.5
	NEDC at 25 °C starting temperature, alternator disconnected			-0.9	-
	WLTP L			-	-9.9
	Realistic scenario*			14.2	7.9
Auxiliary systems	Electrical load (0.6 kW)			14.9	9.6
	Mechanical load (0.4 kW)			3.8	2.8
Aerodynamics	Unladen roof box (air drag increase)			6.5	9.7
	-10% air drag			-2.2	-3.3
	+10% air drag			2.3	3.5
Weather conditions	Starting temperature compared to hot start (88 °C)	-7 °C		19.8	6.7
		14 °C		11.5	4.5
		20 °C		10.2	3.9
Vehicle condition	Lubricants (Petrol reference SAE 5W-30, Diesel reference SAE 10W-40)	SAE 5W-20	Petrol	-2.2	-2.2
			Diesel	-4.1	-2.5
		SAE 10W-30	Petrol	0.6	0.2
			Diesel	-2.3	-1.4
	Tires	-20% rolling resistance		-2.8	-3.7
Vehicle mass	Extra mass	+100 kg		2.6	2.8
	Trailer towing	Unloaded (+310 kg, +65% air drag)		22.1	29.7
		Loaded (+560 kg, +65% air drag)		28.0	37.3
	Laden roof box (mass and air drag increase)			8.9	11.3
Road	Altitude	2000 m (Decreased air density)		-4.4	-6.7
	Constant grade throughout the cycle	+2%		33.4	35.8
		-2%		-28.4	-31.2
Fuel	E10 and B100 (Petrol reference E5, Diesel reference B5)		Petrol	0.4	0.4
			Diesel	0.6	0.6



1. Introduction

1.1. Passenger car CO_2 emissions

Fuel consumption and carbon dioxide (CO_2) emissions from road transport, passenger and freight transport, increased by 36 % between 1990 and 2010 in the EU-27 countries. The share of road transport in the European Union's (EU) total CO_2 emissions is around 17.5 % of which approximately 70 % originates from passenger cars (PCs) (EEA 2012). Figure 1-1 presents greenhouse gas emissions by source in the EU-28.

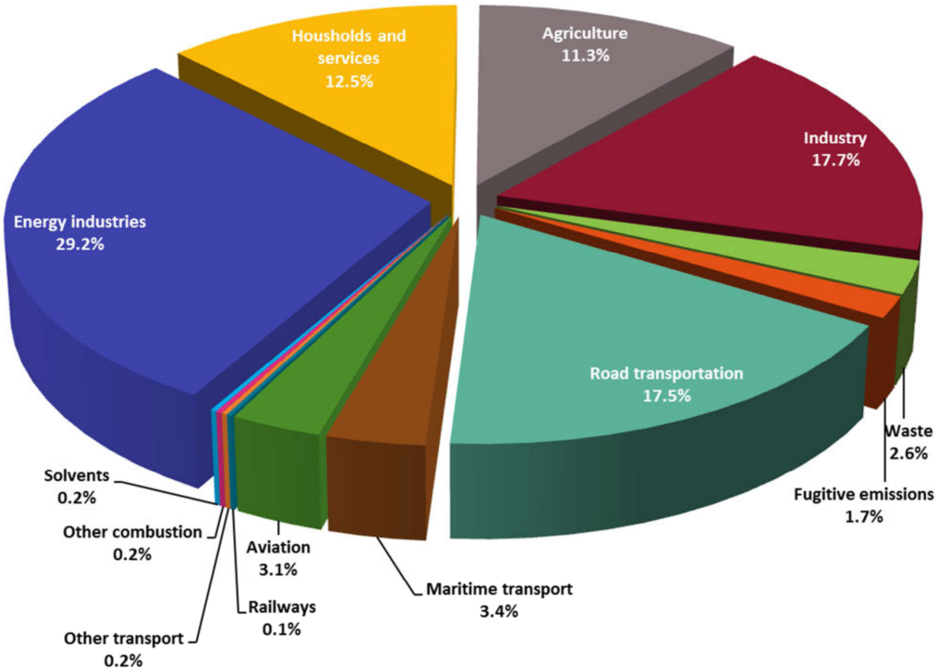


Figure 1-1: Greenhouse gas emissions by source in the EU-28 adapted from EEA (2012) and (DG-Clima 2015)

The EU has implemented since 2009 (European Commission 2009b) a strategy for reducing CO_2 emissions and fuel consumption from passenger cars (Regulation (EU) No 397/2013, Regulation (EU) No 333/2014). For the moment, emissions measurement and reporting is based on the New European Driving Cycle (NEDC) and the corresponding test protocol (Regulation (UN) No 83 2011). Emission targets of 130 g CO_2/km and 95 g CO_2/km have been set for 2015 and 2021 respectively. They are based on the sales-weighted and mass-corrected average CO_2 emissions of each vehicle manufacturer (OEM) and are measured using the New European Driving Cycle (NEDC) and the corresponding test procedure. Recent data suggest that OEMs have achieved their 130 g CO_2/km targets for 2015, as according to EEA (2014), the (provisional) average test cycle-based EU emissions of all manufacturers in 2015 was 119.6 g CO_2/km.

However, there is evidence that the certification test yields lower fuel consumption and CO_2 emissions than that actually experienced by drivers during real-world operation. This observation can be attributed to a series of factors such as the driving profile of the NEDC which is of low transience and the wide boundary conditions of the certification test (e.g. a temperature range of 20-30 °C, restricted use of auxiliaries or the lower vehicle mass, etc.). All together, they contribute to a systemic underreporting of CO_2 emissions compared to those occurring in the real-world operation. Hence, the difference between certified fuel consumption and the one actually experienced by the drivers (i.e. the shortfall) can be explained by two main factors: (a) the inherent variability of the vehicle operation and the inability of an experimental test to fully capture it, and (b) aspects of the type approval test which allow assumptions or practices that are non-realistic or are non-representative of real-world use.

The certification test is currently the main instrument used to regulate the environmental performance of light vehicles and to provide information to consumers regarding the fuel economy of their vehicle. It helps them to make educated choices based on their needs and wishes when buying a car. In addition, a series of policy instruments, such as taxation, incentive schemes, etc., which are not directly linked to environmental issues or consumer awareness revolve around the results of the certification test. Such a test needs therefore to have specific characteristics. It has to be reliable, robust, and repeatable, provide results understandable by the general public, be as simple as possible, representative for at least an average vehicle performance, provide a level playing field for different vehicle manufacturers and promote innovation and transparency. Inevitably, any fuel consumption and CO_2 certification test is in practice a trade-off between these prerequisites so it is hard to imagine a test procedure able to exhaustively satisfy all these conditions and cover all possible operating conditions at the same time.

Yet, it should be noted that in reality vehicle fuel consumption is affected by a great number of factors, which are not necessarily uniform and equal for all drivers or all operating conditions. In fact, there is no single fuel consumption value, but the fuel consumption of a specific vehicle under very specific conditions. Drivers who tend to keep logs of their refuelling recognise that the fuel they consume varies despite the fact that no apparent change in their habits or vehicle occurs. The same vehicle model can present a very wide range of consumption values depending on its use, the driver habits and other external factors, while the tested vehicle could vary from the production vehicles. Hence it would be impossible to predict with absolute accuracy the final fuel consumption of a vehicle based on a single experimental test like the certification test because it is impossible to specify one single experiment that can capture all possible variables affecting real-world fuel consumption.

- ➔ A difference, either positive or negative, between certification fuel consumption value and driver experienced fuel consumption will always occur depending in each case on the operating conditions and driving of the vehicle. However when considering average fleet performance such a difference **should not be systematic** and most importantly should **not significantly change with time**.

Ideally, the fuel consumption value reported should match as closely as possible the average consumption experienced in reality. As it has been demonstrated this is not possible on an individual vehicle level but rather on a fleet wide-basis and taking into consideration average operating conditions. Nonetheless, there is increasing evidence that the current framework largely fails in this sense as the shortfall between the existing certification test in Europe and real-world fuel consumption is increasing with time (Mellios 2011, Mock et al. 2013). In their study, Mock et al. (2014) have found that the gap has been constantly increasing from 8 % in 2001 to 24 % in 2011 and 37 % in 2014 (Figure 1-2). The figure is even greater for some OEMs who adopt fuel efficient technologies which offer substantial benefits over the type approval test compared to real world operation. Such rapid increases cannot be explained only by the in-use factors affecting the real-world fuel consumption, as those cannot change in such a short timeframe, as resulting from the reported figures, and in what appears to be a steady trend towards higher differences. These observations make clear that there are also factors contributing to the increase of the shortfall associated with the certification test. Optimising fuel consumption for type approval by exploiting test elasticities and by introducing assumptions and practices which are not reflecting real-world conditions is a fact reported by several studies (Dings 2013, Mock et al. 2014, Stewart et al. 2015).

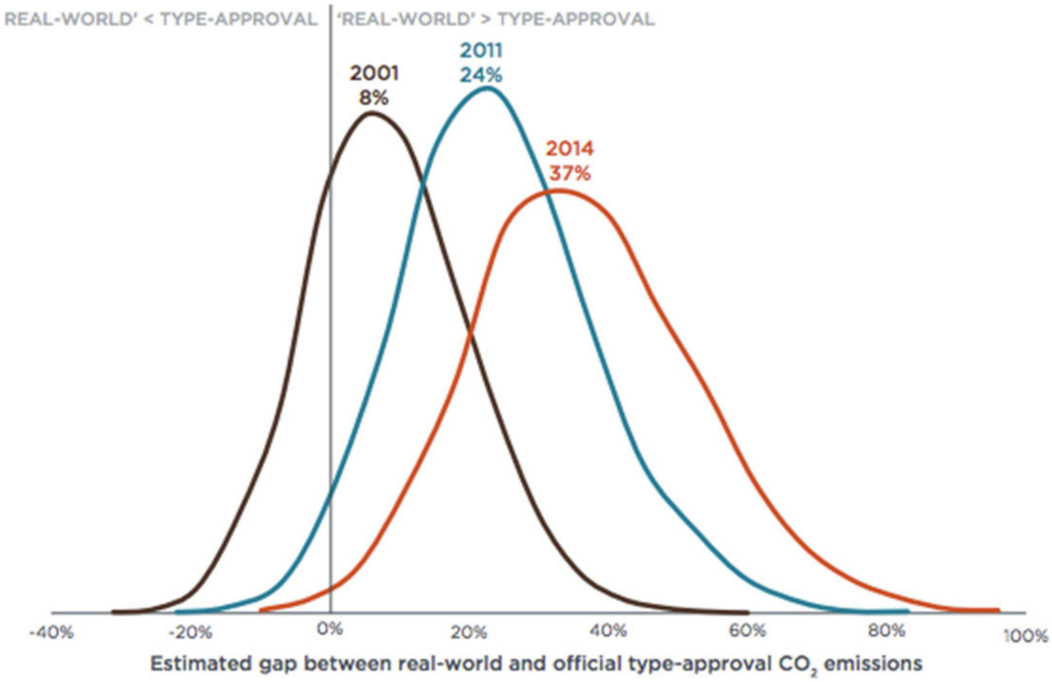


Figure 1-2: Estimated probability density function of reported real-world emission values as percentage of type-approval figures (Mock et al. 2014)

Meanwhile, the implementation of CO_2 reduction strategies at EU level and the pressure exerted to meet the mandatory targets has, among other things, stimulated vehicle OEMs to exploit the margins of the prescribed test conditions. These were originally designed to ensure a reproducible measurement of regulated pollutants but not to capture the fuel consumption of vehicles under real-world driving conditions. This practice has contributed to widen the difference between reported and certification CO_2. To address the shortcomings of the existing test procedure, a new Worldwide harmonized Light vehicles Test Procedure (WLTP), which includes a new test cycle (WLTC), was elaborated at United Nations level (Marotta and Tutuianu 2012) and will be implemented in the years to come in the European type-approval legislation (planned as of September 2017).

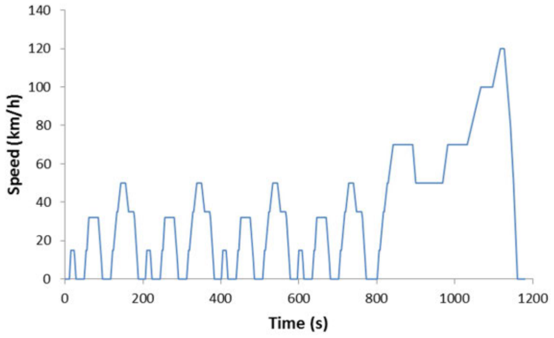


Figure 1-3: NEDC profile.

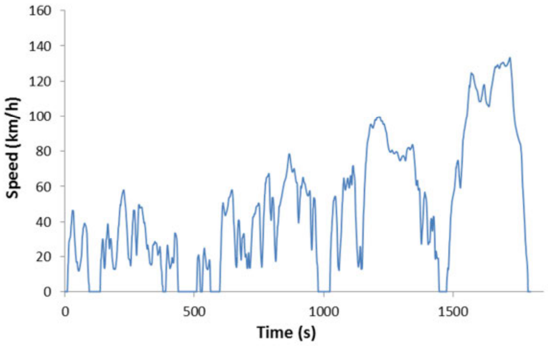


Figure 1-4: WLTC profile.

Table 1-1: Key parameters of the driving cycles NEDC and WLTC source (Marotta et al. 2015)

Parameter	Unit	NEDC	WLTP
Duration	(s)	1 180	1 800
Distance	(km)	11.03	23.27
Average speed	(km/h)	33.6	46.5
Maximum speed	(km/h)	120	131.3
Stop duration	(%)	23.7	12.6
Constant driving	(%)	40.3	3.7
Acceleration	(%)	20.9	43.8
Deceleration	(%)	15.1	39.9
Average positive acceleration	(m/s^2)	0.59	0.41
Maximum positive acceleration	(m/s^2)	1.04	1.67
Average positive ‘speed·acceleration’	(m^2/s^3)	1.04	1.99
Maximum positive ‘speed·acceleration’	(m^2/s^3)	9.22	21.01
Average deceleration	(m/s^2)	− 0.82	− 0.45

Due to the diversity of operating conditions, drivers’ behaviour, car usage and other external factors, no test protocol, no matter how carefully designed, can manage to capture the real-world performance of vehicles with absolute accuracy. As a result, there will always be a need to assess either qualitatively or quantitatively the fuel economy impact of external factors, which can vary stochastically and are thus difficult to reproduce under laboratory conditions. To date, a detailed quantitative understanding of factors affecting the on-road fuel consumption and CO_2 emissions of passenger cars is still lacking. As a first step towards this direction this report attempts a first scanning of the knowledge available in literature regarding the factors affecting CO_2 emissions over real-world and certification conditions.

1.2. Structure of the report

As will be presented further on, despite the fact that numerous studies address this divergence or the factors contributing to it, few of the estimations presented in literature are purely focused on the European certification framework and fewer of them provide a detailed analysis on the combined effect of the different factors. In this report we attempted to address this gap through a comprehensive review and detailed vehicle simulations. To achieve this, each chapter of the report deals with a family of factors and contains:

- a comprehensive review of the impact of various factors on real-world fuel consumption as reported in literature from 2000 onwards;
- where possible, a quantification of the impact on a 2014 average passenger car based on simulation scenarios and qualified assumptions.

A brief summary of the report's structure is presented below.

Auxiliary systems
Modern cars incorporate an increasing number of auxiliary systems, resulting in an increased energy demand. This additional demand has an impact on fuel consumption, which is neglected by the current type approval test.

Aerodynamics
Vehicle aerodynamics highly affect fuel consumption. In addition to the aerodynamic characteristics of the vehicle other factors such as side-winds and small shape modifications like open windows, can have a significant impact on fuel consumption, especially at high speeds. This effect is investigated together with the corresponding deviation from the type approval values.

Weather conditions
Vehicles are tested in a controlled environment in the laboratory which poorly replicates outdoor conditions. In this chapter the effect of real-world weather conditions on fuel consumption and the deviations from type approval values are investigated.

Driving
A real-world driver's behaviour is different that of the type approval test. Different driving styles, driving patterns and trip planning can have a significant impact on fuel consumption compared to type approval values.

Vehicle condition
For the type approval test vehicles are well maintained and properly prepared, while these aspects can be neglected in real-world conditions. In this chapter the effect of maintenance, whether poor or good, on fuel consumption is examined.

Operating mass
The mass of the vehicle may differ significantly from the parameters set for the type approval test. The effect of extra load is examined in this chapter.

Road (morphology, surface, traffic)
Road properties in terms of morphology, surface and traffic have an effect on driving behaviour and vehicle performance. The overall driving profile that results from these conditions can be completely different from the one used in the type approval test. For this reason these factors were isolated and examined one by one.

Fuel characteristics

Real-world fuel composition varies depending on the season, geographical region and biofuel blend. The addition of certain bio-components in fuel standards offers the benefit of reduced CO_2 emissions when the lifecycle emissions of the fuel are considered but at the same time may lead to marginal increases of vehicle CO_2 emissions.

Certification test

This chapter presents an overview of the flexibilities of the current certification test that can be exploited to deliver emission results lower than the anticipated. This overview aims at a better understanding of these factors and the way they de facto affect final emission results.

The report concludes with a discussion of the findings of the review and an analysis of the combined effect of the different factors influencing CO_2 performance of vehicles under test and real-world conditions.

2. Methodology

2.1. Literature review — overview

To identify factors which affect on-road fuel consumption and CO_2 emissions of passenger cars, engineering books and manuals, research papers, magazines and web pages were reviewed. The most significant aspects of the shortfall between type approval and real-world consumption were mainly found and covered by research papers, while the theoretical background of these aspects (e.g. aerodynamics or electrical systems) is explained mainly in specialised books. A data analysis was made in order to provide an overview of the collected findings and also to draw conclusions.

If not mentioned differently, the average values used for calculations refer to the average European car as presented by EEA (2013a). The collected values from the literature were compared and rough statistical data, like the mean average, were produced where possible. These values are indicated as 'JRC estimations'. The number of references of each chapter is listed in Table 2-1 and illustrated in
Figure 2-1.

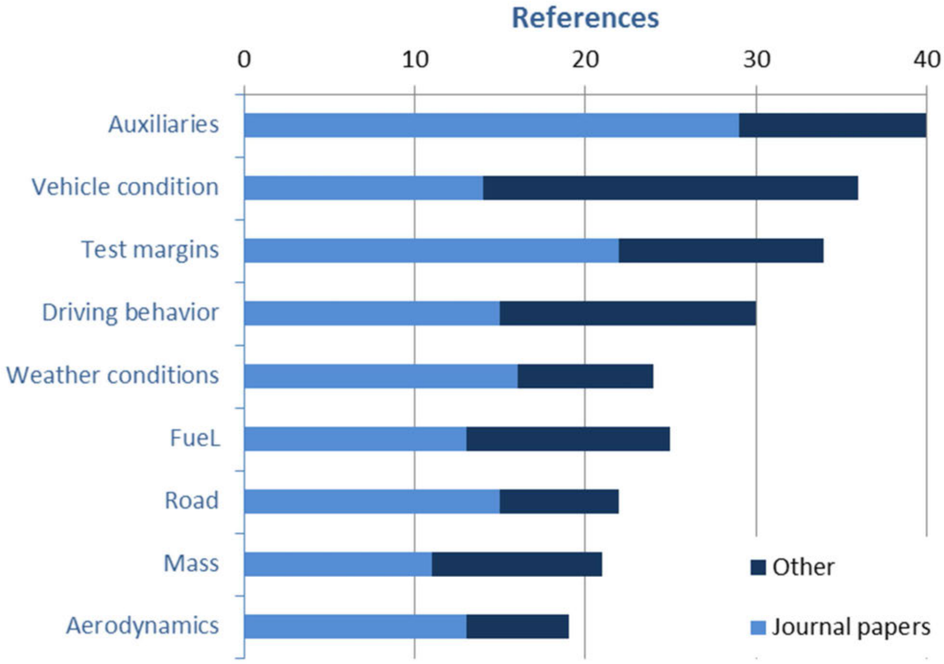


Figure 2-1: Bar chart of total references per category.

At the end of each chapter a paragraph was included to discuss the quality and the quantity of the retrieved sources and whenever possible to report references of public concern from non-scientific sources on specific topics. This is achieved by summarising a number of web-based discussions (from magazines, forums, etc.) retrieved through an online search. The opinions expressed should be considered as indicative, as the relatively low number of reporting users does not allow for statistical relevance.

Table 2-1: Number of references per chapter

Chapter	No of references/of which journal papers	Average year	Indicative keywords
Certification test	35/22	2010	Vehicle emissions, type approval, test procedure, driving cycle, NEDC, test margins, test flexibilities
Auxiliary systems	40/29	2009	A/C, auxiliaries, accessories, climatic condition, solar energy, future applications
Aerodynamics	19/13	2010	Vehicle aerodynamics, aerodynamic drag, aerodynamic coefficient, CO_2 emissions, passenger car
Weather conditions	24/16	2009	Low ambient temperature, cold-start emissions, rain, snow, weather conditions
Driving	30/15	2010	Driving behaviour, driving patterns, aggressive driving, eco-driving
Vehicle condition	36/14	2009	Lubrication, tyres, rolling resistance, under inflation, vehicle maintenance, vehicle condition
Operating mass	21/11	2011	Vehicle mass, curb weight, towing, trailer, laden roof rack, occupancy rates
Road (morphology, surface, traffic)	22/15	2009	Traffic conditions, road conditions, grade, road surface, altitude
Fuel characteristics	25/13	2010	Fuel composition, biofuels, biodiesel, ethanol, ethers, emissions

2.2. Simulations methodology

In order to assess the impact of various factors and their combination on CO_2 emissions, computer simulations were performed. Three vehicles that had been previously tested in the JRC over NEDC and WLTP conditions were selected and subsequently the respective computer models were created for running the simulations. Once the first 'reference' models were validated against the tests their characteristics were slightly modified in order to better match European fleet average characteristics. This resulted in the 'baseline' simulation models, on which all subsequent simulations in this study make reference. In the following paragraphs we summarise the model-set up and validation process for the reference vehicle models and we introduce the baseline models used for the analyses in this report.

2.2.1 Reference simulation models

The main characteristics of the original three test vehicles are presented in Table 2-2. Two were petrol-fuelled vehicles, with vehicle 1 featuring a turbocharged (TC) engine and vehicle 2 a naturally aspirated (NA) engine. The third vehicle was equipped with a diesel high fuel injection pressure turbocharged engine. All vehicles met the Euro 5 norm regarding pollutant emissions and can be considered typical for the European passenger car fleet.

Table 2-2 Characteristics of the vehicles used for the simulation assessment. In the first column, TC stands for Turbo-charged; while NA for Naturally Aspirated

Engine type	Capacity	Stroke	Power	Nominal RPM	Idle RPM	Vehicle Inertia NEDC	Vehicle mass WLTP High	Vehicle mass WLTP Low
	[cc]	[mm]	[kW]	[rpm]	[rpm]	[kg]	[kg]	[kg]
Petrol TC	1 368	84	121.5	5 500	750	1 360	1 570	1 430
Petrol NA	1 368	84	57	6 000	750	1 130	1 250	1 182
Diesel	2 200	90	110	4 500	650	1 470	1 626	-

These vehicles in their original configurations were simulated over the NEDC, WLTP test mass high and WLTP test mass low cycles respecting the boundary conditions of the original measurements. WLTP gear shifting strategy adopted in these validation simulations and later to all simulation runs included in the study was conducted according to WLTC Class 3.2 and that is described in more detail in Tutuianu et al. (2013). WLTP tests followed the requirements of the WLTP, in terms of test temperature (23 ˚C instead of 25 ˚C for NEDC), vehicle test mass and road loads as prescribed in the official, recently released UNECE GTR (UNECE 2015).

In particular, the WLTP sets two test mass values, a Test Mass High (TMH) and a Test Mass Low (TML) (11) with correspondingly increased road loads compared to NEDC. The TMH and TML are calculated according to Annex 4 of the UNECE GTR as:

$$\mathrm{TMH} = \mathrm{MRO} + \mathrm{OM} + 25 + \varphi * \mathrm{MVL} \qquad (1)$$

$$\mathrm{TML} = \mathrm{MRO} + 25 + \varphi * \mathrm{MVL} \qquad (2)$$

Where:

MRO: is Mass in Running Order
OM: is mass of optional equipment
MVL: is maximum vehicle load and is equal to $\mathrm{LM} - \mathrm{MRO} - \mathrm{OM} - 25$
LM: is technically permissible maximum laden mass
φ: is the percentage of the vehicle load included in the definition of the test mass, and is equal to 15 % for M1 category (passenger cars) and to 28 % for N1 category vehicles (light commercial vehicles).

The simulation software used for the purpose of this study is CO2MPAS, a physical-based vehicle simulation tool developed by the JRC for the purpose of supporting the transition from NEDC to WLTP. The user is able to adjust various inputs regarding the technical specifications of the vehicle and the testing environment. The tool is virtually running the

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(11) For CO_2 certification, and a given vehicle certification family, TMH will be used for the worst-case scenario of CO_2 emissions as well as to determine WLTP road load coefficients for the same scenario, while TML will be applied for the best case CO_2 emissions for that same vehicle family. Based on TML and TMH results a linear regression for CO_2 emissions over cycle energy (which is calculated from vehicle test weight and RL) will be determined. This regression line will be used to determine CO_2 emissions of all other vehicles within the respective vehicle family without TA certification if their mass is between TML and TMH.

NEDC and WLTP cycles generating emission results in gCO_2/km for the cycles and their sub-cycles. The simulation scenarios are included at the end of each chapter.

The models created were validated against measurements previously performed at the JRC. Table 2-3 demonstrates the CO_2 emissions in g/km, over each phase of WLTP and NEDC. Results are provided for both measurements (Meas.) and simulations (Sim.) and for the two different configurations of the WLTP test, with TMH and TML as described previously. Hence WLTP-H corresponds to the highest and WLTP-L to lowest power-consuming configurations in the same CO_2 family respectively.

Table 2-3 Measurement vs simulation results for CO_2 emissions (g CO_2/km). In the first column, Gas stands for Petrol; TC for Turbo-charged; while NA for Naturally Aspirated

Veh.		**WLTP — H**					**WLTP — L** (12)					**NEDC (Base)**		
		Phase 1	Phase 2	Phase 3	Phase 4	WLTP	Phase 1	Phase 2	Phase 3	Phase 4	WLTP	UDC	EUDC	NEDC
Gas TC	Meas.	203.2	153.4	143.6	177.1	165.4	188.7	137.1	128.0	159.1	148.9	188.0	124.7	148.0
	Sim.	200.8	152.1	144.6	177.7	165.3	190.0	136.6	130.0	158.1	149.3	183.4	128.0	148.4
Gas NA	Meas.	185.6	135.9	136.9	185.3	160.3	175.9	125.3	125.3	167.9	147.1	182.3	120.7	143.3
	Sim.	185.3	136.2	137.8	185.8	160.8	175.6	125.2	125.2	167.1	146.8	176.2	123.1	142.4
Diesel	Meas.	176.1	129.0	110.9	138.3	132.9	-	-	-	-	-	159.7	102.9	123.8
	Sim.	180.7	127.8	115.3	135.3	133.6	-	-	-	-	-	156.8	103.3	123.0

As shown in Table 2-3, simulation results matched the measurements well for both WLTP — H and L configurations of the vehicles, with results in most cases within ± 3 g CO_2/km of the measured value of the WLTP sub-phases and within ± 0.5 g CO_2/km for the emissions over the entire cycle. In the NEDC a tendency to underestimate the cold part of the cycle (UDC) by ~ 4.5 g/km and overestimate the warm part (EUDC) by 3 g/km was observed. However the final NEDC result remained always within a range of ± 1 g CO_2/km compared to the measurement, hence no post simulation corrections were applied to the results.

2.2.2 Baseline simulation models

Having verified that the reference models could accurately reproduce measured CO_2 emissions over WLTP and NEDC, their basic characteristics (mass, capacity, power) were slightly modified and three different configurations were assumed based on the reported characteristics for the European passenger car sales of year 2013. Based on the EEA (2013b) data, the basic characteristics of an average naturally aspirated (NA) petrol, an average turbocharged petrol (TC), and an average diesel vehicle were identified and considered in the calculations. In particular for petrol vehicles the distinction between charged and NA engines was made based on power-to-capacity ratio with cars with ratios lower than 0.065 kW/cc considered as NA. The average characteristics identified and applied to the preconfigured vehicle simulation models are summarised in Table 2-4.

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(12) No WLTP-L test data were available for the diesel vehicle.

Table 2-4: Characteristics of baseline car versions and comparison with reported averages in 2013. In the first column, TC stands for Turbo-charged; while NA for Naturally Aspirated

Vehicle	Reference (EEA 2013b)			Assumptions made in calculations				
	Test Mass (kg)	Capacity (cc)	Power (kW)	NEDC Inertia Class (kg)	WLTP H Mass (kg)	WLTP L Mass (kg)	Capacity (cc)	Power (kW)
Petrol TC	1 360	1 463	107	1 360	1 540	1 414	1 460	105
Petrol NA	1 159	1 344	67	1 130	1 315	1 209	1 340	67
Diesel	1 530	1 803	97	1 470	1 730	1 587	1 800	100

The simulations mimicking the type approval test cycle produced results that lay close but are consistently higher compared to the values found in the EEA monitoring database for year 2014, as presented in Table 2-5. The boundary conditions for the specific simulations were chosen to be as close as possible to the certification test conditions. It should be noted that current homologation foresees an extension of CO_2 certification for vehicles with similar characteristics whose CO_2 emissions do not differ more than 4 %. As a result it is expected that reported CO_2 values are lower by up to 4 % compared to the actual measured values. When correcting simulation results by 4 % to account for this effect the final values lay within 2.5 g from the reported CO_2 emissions. Hence it is expected that the performance of the simulation models used in this analysis is representative of the performance of Euro 5 European passenger cars with characteristics similar to those of the fleet average. The official and resulting values are presented in Table 2-5.

Table 2-5: Presentation of CO_2 emissions of reference and simulated vehicles (TA values). . In the first column, TC stands for Turbo-charged; while NA for Naturally Aspirated

Vehicle	Reported (EEA 2013b) CO_2 emissions (g/km)	Simulation CO_2 emissions (g/km)	Corrected (– 4 %) (13) Simulation results CO_2 emissions (g/km)
Petrol TC	131.5	136.8	131.4
Petrol NA	119.5	125.2	120.3
Diesel	123.2	126.5	121.5

2.2.3 Simulation of individual and combined factors

Based on the abovementioned baseline vehicle configurations simulations were run for analysing the effect of each factor. Each factor under analysis was tested individually and in certain cases sensitivity runs were performed for quantifying the effect on fuel consumption and CO_2 emissions over NEDC and WLTP High (14). The corresponding results

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(13) Extending certification to vehicles that may have CO_2 emission up to 4 % lower from a reference tested vehicle as a way of simplifying the TA process.

(14) The high power configuration of WLTP was considered in the analysis and will be referred to simply as WLTP through the document, unless stated otherwise.

are presented following the literature review in each chapter. The baseline scenario, which was always used for comparison, used the parameters defined for the NEDC and the WLTP — H test as presented in Table 2-5 and Table 2-4.

On occasions where reference is made to single values, the results of the simulations performed with the three models were averaged using weighing factors according to their percentage in the new European fleet registrations as reported by EEA (2013b). The weights used were 23 % for petrol NA and petrol turbo, and 54 % for diesel.

Finally, the combined effect of the different factors on fuel consumption and emissions was explored. Considering all possible combinations was however not feasible and beyond the purpose of this study. This attempt focused mainly on the most common combinations, like for example the towing of a trailer which captures the combination of increased mass and air drag. These results are presented separately.

3. Auxiliary systems

3.1. About auxiliary systems

The auxiliary systems of a car are comprised of all the elements and accessories such as air conditioning (A/C), steering assist systems, driver aids or luxury systems, which improve driving safety and comfort. This happens however at the price of an increased electrical, or less frequently, mechanical power load that in turn increases fuel consumption (Schipper 2011, EPA 2014b). As depicted in Figure 3-1 there has been a clear trend over the past 40 years towards a higher installed electrical power supply capacity (US cars data) which had been increasing at least until 2005 (ADL 2006) in order to meet the increasing electric power demands. As new and more sophisticated auxiliary systems like GPS, air cleaning, air conditioning, adaptive cruise control, collision warning and avoidance, are incorporated (Reif and Dietsche, 2011) in the fleet this trend is likely to continue. Electric auxiliary devices impose higher electrical loads resulting in increased alternator operation which in turn increases the engine power demand and subsequently fuel consumption. Mechanical auxiliaries directly draw energy from the engine resulting also in increased power demands.

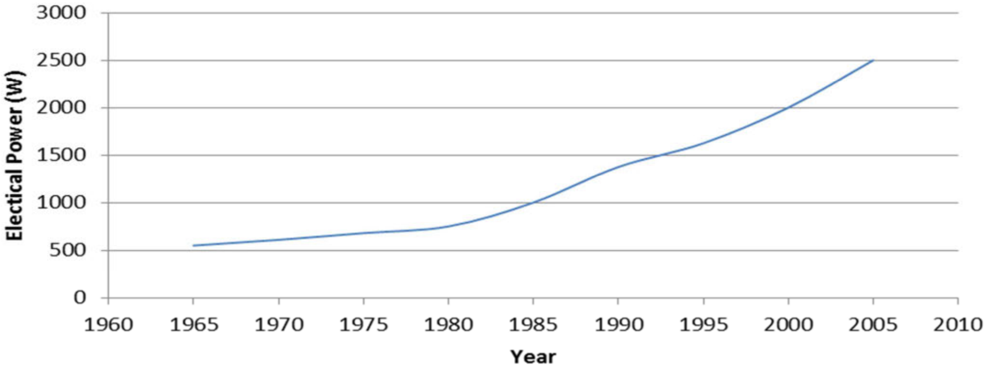

Figure 3-1: Increase in vehicle average electrical power supply capacity in a US car (ADL (2006))

An average European car is estimated to have total electrical power requirements of 750 W (European Commission 2013), which is substantially lower compared to the 2 500 W reported in the American study presented above. But for the type approval test, where all switchable electrical consumers are off, the total electrical requirements were estimated to be in the order of 350 W (European Commission 2013). OEM experts suggest that this value might be even lower in reality. This discrepancy suggests a measureable shortfall between type approval and real-world consumption.

In an earlier study, Farrington and Rugh (2000) examined the increase in fuel consumption as a result of the increased use of auxiliaries. Their results are presented in Figure 3-2, where the effect is expressed as a decrease in fuel economy for two cases. These cases refer to a conventional vehicle (1 406 kg, 3.0L, spark ignition, 8.78 l/100 km for combined cycle) and a hybrid (907 kg, 1.3L, compression ignition, auxiliary load of 400 W, 2.89 l/100 km for combined cycle). The cars were tested over the SC03 Supplemental Federal Test Procedure, which is a sub-cycle of the FTP-75 test cycle where the A/C is turned on, at an ambient temperature of 35 °C. Both vehicle characteristics and the type of test used reflect the situation in the US fleet, hence the absolute values are expected to be far from European reality. Nonetheless the trends presented are likely to be similar for both fleets.

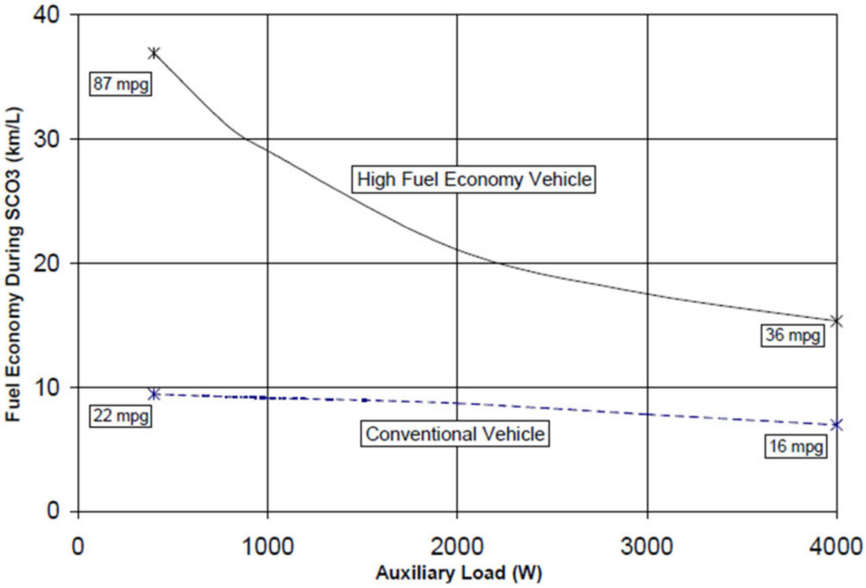

Figure 3-2: Decrease in fuel economy according to increase in auxiliary load (Farrington and Rugh 2000)

It should be noted that apart from the impact of the operation of electrical consumers, the state of charge of the battery during a trip affects fuel consumption, as the vehicle controllers are programmed to maintain a more or less fixed SOC range during actual operation. At present, the certification test is run with the battery fully charged (in some cases even with the battery-charging circuit disconnected), something that does not correspond to real-world conditions where battery status is subject to a series of factors ranging from weather conditions to frequency of vehicle use, traffic conditions and battery health. Recharging the battery creates an extra load on the engine, which directly increases fuel consumption. In the case of a completely depleted battery the increase in consumption could be up to 30 % for NEDC, although real-world cases like this are rare (Dings 2013).

The following paragraphs examine in further detail the effect of A/C, steering assist systems and other auxiliary systems. The reason for this categorisation is that A/C was found to be a major consumer of energy, while steering assist systems are always in use consuming energy even when in stand-by mode, hence their effect during the certification test is to some extent captured. The paragraph ‘Other vehicle auxiliaries’ contains information about various electric energy consumers, which may not be always in use or have varying energy demands.

3.2. Air conditioning (A/C)

One of the most influential factors affecting real-world fuel consumption, with a rich research background, is the operation of A/C systems (Welstand et al. 2003, ECMT 2005, Heinz 2005, Rugh et al. 2007, Roujol and Joumard 2009, Mock et al. 2013). The use of A/C is not currently included in the type approval tests. While in 1993 the share of cars sold with A/C as standard was ca. 10 %, it is reported to have risen to 85 % by 2011 (Hill 2011). Figure 3-3 shows a 2002 projection of the evolution of number of cars equipped with A/C in North America, Asia and Europe. It was expected that by 2014 the vast majority of the vehicles sold in the European market would be equipped with A/C systems. The authors were not able to retrieve reliable information regarding the present market shares of the air conditioning system in the newly registered European vehicles.

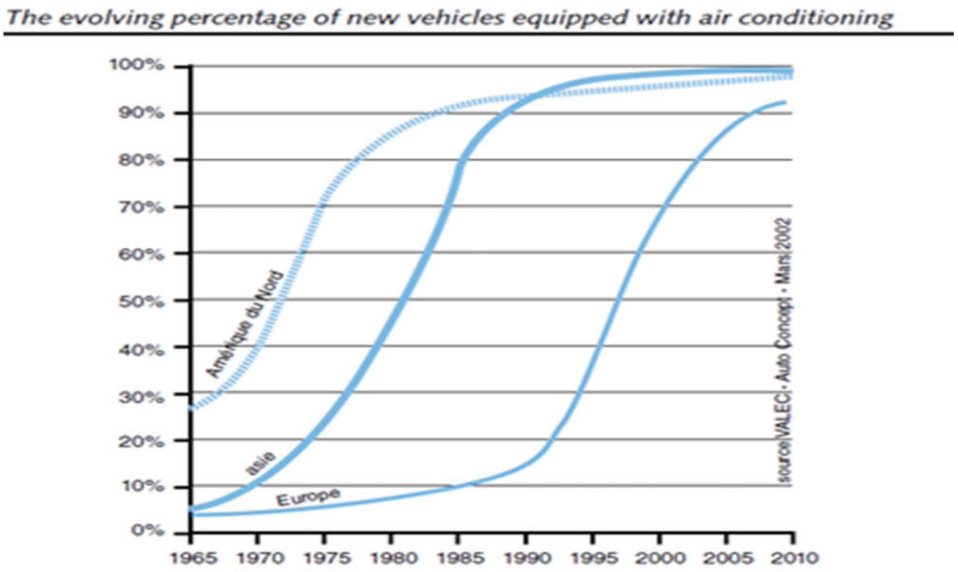

Figure 3-3: Evolving percentage of cars equipped with A/C for North America, Asia and Europe (VALEC — Auto Concept 2002).

The electrical energy consumption of the A/C system is affected by the ambient temperature. The greater the difference of the ambient temperature to the desired cabin temperature, the more effort is required to reach this. Similarly, other weather-related conditions, such as solar radiation, may have a significant impact on A/C power consumption and vehicle CO_2 emissions. Heinz (2005) measured CO_2 emissions in two cases on a vehicle conditioned without any heat soaking and with soaking under solar radiation of 850 W/m^2. An average increase in CO_2 emissions was found for various cycles of 1 414 g/h and 2 056 g/h respectively for NEDC. Other research (Dena 2013) suggested an increase in fuel consumption of 1 l/h, but does not make explicit reference to the conditions of A/C operation. An average increase of 1.25 l/100 km was found by TUG and of 1.23 l/100 km by KTI in the MAC project (15) (TUG et al. 2010). In their study regarding the improvement of A/C control systems De Moura and Tribess (2007) have found an increase in fuel consumption of 16 %, 11 % and 13 % for the urban, highway and combined cycle respectively. An overview of the values retrieved from the literature is presented in Figure 3-4 (See Table 14-1 in Annex).

The effectiveness and the use of the A/C depends on the desired interior temperature, outside temperature, air humidity and solar radiation (16) and is rather insensitive to other aspects affecting fuel consumption like speed and driving patterns (Kemle et al. 2008). For this reason, as stated by Kemle et al. (2008), only the use of litres per 100 km to estimate consumption is meaningful in order to make comparisons, while in the literature review it was common to find the variations in consumption and CO_2 emissions expressed in litres per hour and in grams per hour, respectively. The same study also claims that the indicated

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(15) Research project funded by the European Commission for the development of an A/C type approval procedure.

(16) So indirectly is connected also to ambient conditions discussed in later paragraphs.

increase in consumption of 1-3 l/100 km found in the literature applies only to certain operating points, which usually consist of high load points, which occur rarely in real-world conditions and pointed out the need for commonly accepted guidelines for determining A/C effect. The opinion that A/C use is independent from speed and traffic conditions is supported by Roujol and Joumard (2009). In their study for a large number of cars they concluded that the expression in l/h is more appropriate to express additional fuel consumption from the use of A/C.

Other researchers however claim an impact of traffic conditions on the extra fuel consumption induced by A/C operation with the relative influence being reduced as vehicle speed increases. For urban, rural and highway driving the increase in fuel consumption due to A/C operation is reported to be 4 %, 2.5 %, and 1 % respectively (Weilenmann et al. 2010). This reduction in percentage is expected and explained by the fact that cycles of higher speed require higher engine power to overcome driving resistances, resulting in higher fuel consumption, hence the relative fuel losses towards the A/C system are reduced. A method to incorporate traffic and A/C use in the experiments is suggested by (Kemle et al. 2008) and it is presented at the end of the paragraph.

The type of A/C, manual or automatic (17) is also reported to have a different impact in fuel consumption. A study by ADAC (2012b) and OEAMTC (2012) tested the effect of manual and automatic A/C at 50 km/h and 100 km/h and their results are presented in Table 3-1.

Table 3-1: Increase in fuel consumption according to type of A/C, summary from ADAC (2012b) and OEAMTC (2012).

Type of A/C	Increase in consumption (l/100 km)	
	At 50 km/h	At 100 km/h
Manual	0.36	0.21
Automatic	0.28	0.25

A summary chart of the sources reviewed is presented in Figure 3-4. An average speed of 100 km/h was assumed for calculating the respective values (for detailed information see Table 14-3 in Annex). Different studies consider different assumptions regarding the ambient-cabin temperature difference.

The average increase in fuel consumption due to the use of A/C is estimated to be in the order of 9 %.

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(17) A/C systems are considered manual if they operate continuously, while automatic A/C systems try to maintain a predefined cabin temperature.

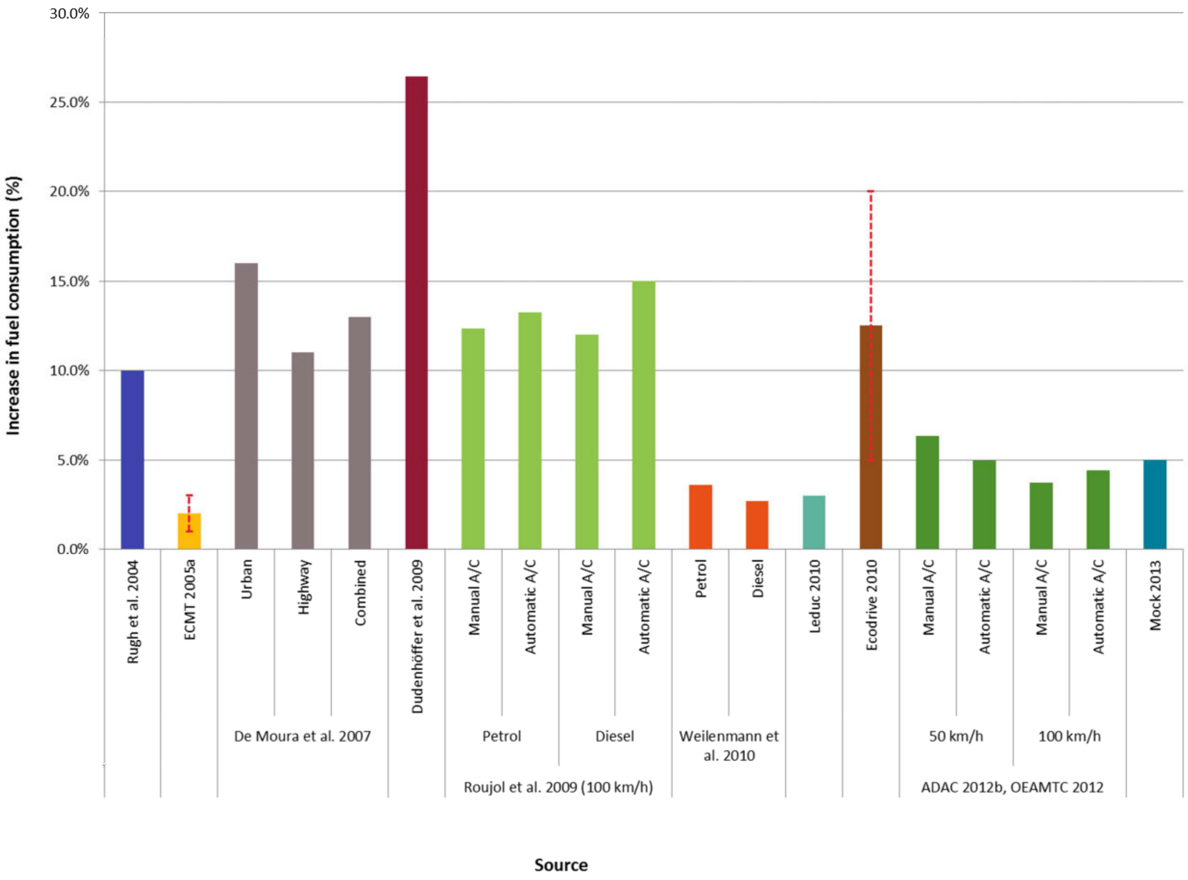
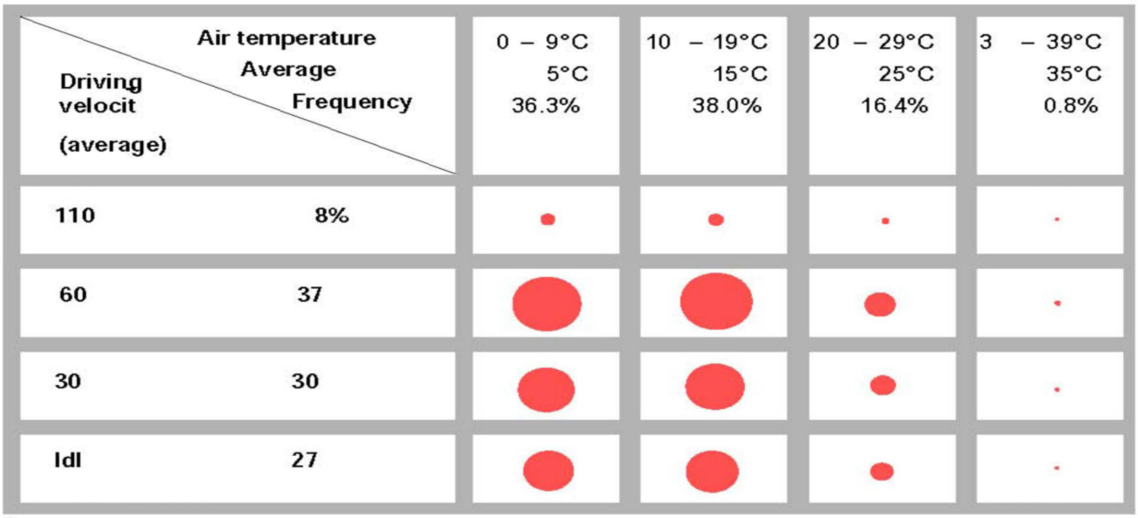


Figure 3-4: Estimated fuel consumption increase based on the findings retrieved from different sources. Use of A/C and an average speed of 100 km/h are assumed.

3.2.1 Load profile based on climatic and driving profile

Kemle et al. (2008) propose the creation of load profiles based on region- or country-specific climatic profiles under which A/C is used. The temperature, which is derived from the climatic profile, is divided into categories and assigned an annual frequency. Consequently, the same is done for the average driving velocity according to the driving profile, which could be a driving cycle. A load profile is derived from the combination of these two where the driving situation is classified in terms of temperature and average velocity. A fixed value of extra fuel consumption induced by the A/C operation is then considered.

An example of a load profile for the German city of Frankfurt is provided in Figure 3-5, where temperature is split into four classes, ranging from 0 to 39 °C and driving speed into the four velocity categories that are found in the NEDC.



Driving velocit (average)	Air temperature Average Frequency	0 – 9°C 5°C 36.3%	10 – 19°C 15°C 38.0%	20 – 29°C 25°C 16.4%	3 – 39°C 35°C 0.8%
110	8%	●	●	●	●
60	37	●	●	●	●
30	30	●	●	●	●
Idl	27	●	●	●	●

Figure 3-5: Load profile for Frankfurt climatic profile and NEDC categories (Kemle et al. 2008)

3.2.2 Methods for reducing A/C energy needs

This paragraph examines the effect of various methods and systems that can contribute to energy efficiency and conservation. The majority of the findings refer to ways to decrease the energy needs of the A/C or the heat transfer between vehicle interior and the environment, but these findings could potentially expand to other systems as well.

In order to lower the energy needs of the A/C several innovations were incorporated in the past which include (Kemle et al. 2008):

- Externally controlled compressors to maintain the temperature at the evaporator at the desired value;
- Cycle-based control of the blower and fan motors;
- Improved condenser module maintains a constant degree of sub-cooling in most load situation with an integrated sub cooling section;
- Reduced electric power consumption, with the use of cycle controllers and the deployment of a brushless motor;
- Decreasing the drive power.

De Moura et al. (2007) have found that the use of pistons with variable displacement in the air compressor is more fuel efficient than the use of pistons with fixed displacement. They have found that the benefits, while using variable displacement pistons could be about 5 % compared to the fixed ones. Farrington et al. (2000) described two types of glazing that reduce the transmission of infrared wavelengths in the interior of the car.

- o **Absorptive glazing**. This type of glazing absorbs solar radiation, which is re-emitted at longer wavelengths with a 50 % probability of being re-emitted into the vehicle.

- **Reflective glazing**. This type reflects selectively a certain percentage of infrared radiation, while allowing the transmission of the visible part of the spectrum.

The use of advanced glass products could control solar heating therefore reducing the vehicle's thermal load. According to Farrington et al. (2000) the use of appropriate glazing could reflect more than 500 W, which reduces the interior vehicle temperature by 9 °C. This could improve fuel economy of a compact American car by 0.3 km/l (about 1.5 % improvement in terms of fuel consumption considering a 5.5 l/100 vehicle) over the SC03 drive cycle. They also added that reducing the weight of the A/C system by 9.1 kg could increase fuel economy by 0.04 km/l.

Rugh et al. (2001) tested two vehicles, where the one served as a reference vehicle and the second one used solar reflective film. They measured the temperature at the level of the passengers' head (average value), the instrument panel and the windshield interior. They found that the application of the reflective film reduced the peak soak temperature. The obtained results are presented in Table 3-2.

Table 3-2: Reduction in maximum temperature (Rugh et al. 2001)

Glazing configuration	Average temperature decrease °C	Instrument panel temperature decrease °C	Windshield temperature decrease °C
Solar reflective film on all glazings	4.6	6.3	9.5
Solar reflective film on windshield	2.5	4.7	8.7

According to their measurements, the benefits in terms of fuel economy were 1.3 % in the SC03 cycle (Rugh et al. 2001).

In another study Rugh et al. (2007) tested a vehicle with various configurations of solar-reflective glazing, solar-powered parked car ventilation and solar-reflective paint. They found that with the use of all the previously mentioned systems the cooling load is reduced by 30 % (see cool down characteristic curves in Figure 3-6).

According to Glass for Europe (2013) a decrease of 5 % in thermal load would reduce A/C energy consumption by 10 % and could improve fuel consumption by 2 %.

Another aspect that is being discussed is the incorporation of solar panels on the car that could diminish the energy demand from the engine. Solar energy is free and more evenly distributed compared to other sources, although there are variations due to the weather and during the year (Rizzo 2010). Despite this, according to Rizzo (2010) a photovoltaic panel could provide significant energy to contribute 20-30 % of the required energy during typical daily urban driving. Some manufacturers have applied solar panels on the roof of the car that provide ventilation in the interior when the car is parked (Presting and König

2003). The use of solar energy when parked could be improved with the use of moving panels that adjust according to the movement of the sun with gains of 46 % at low latitudes and 78 % at high (Rizzo 2010). This could be rather helpful especially as the electrification and hybridisation of the fleet progresses (Coraggio et al. 2010).

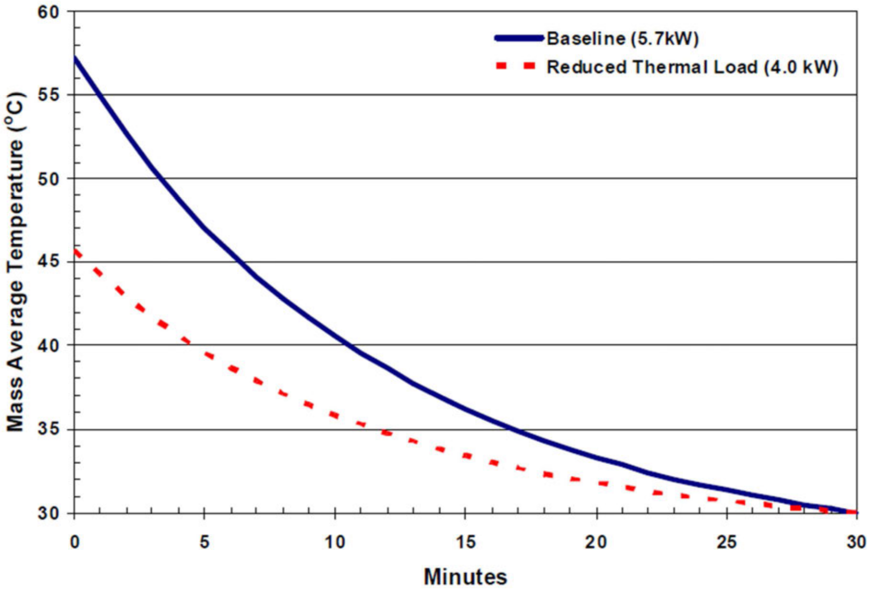


Figure 3-6: Cool down curves for a baseline and a vehicle with thermal reflective systems (Rugh et al. 2007)

3.2.3 Heating systems

The operation of cabin heating systems indirectly affects the use of A/C systems under cold weather conditions. Recent improvements in engine fuel efficiency resulted in a drawback as the lower engine heat rejection to the engine coolant reduced the performance of the heating systems, which in turn led to an increase in electric power demand (Feuerecker et al. 2005). As a result, auxiliary heating systems that counteract this effect have become necessary. Such systems may require an additional 400-2 000 W (Hoffmann 2011) of electric power during their operation. This can have a major impact on fuel consumption as an increase of 600 W can result, according to Nikolian et al. (2012), in fuel consumption increases of 5-10 %. In certain cases the use of A/C systems for heating up the cabin instead of electrical heaters is promoted by vehicle OEMs.

The performance and efficiency of various auxiliary heating systems was examined by Feuerecker et al. (2005). In their study they assessed the effectiveness of the following systems for various outside temperatures:

- Positive Thermal Coefficient (PTC) (18) — heater
- Fuel-fired heater
- Dissipative heating system

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(18) PTC material is named for its positive thermal coefficient of resistance (i.e. resistance increases upon heating). These materials can become extremely resistive above a composition-dependent threshold temperature. This behaviour causes the material to act as its own thermostat, since current passes when it is cool, and does not when it is hot.

- Air/air heat pump
- Coolant/air heat pump

The extra specific fuel consumption is presented in Figure 3-7. They concluded that the use of additional heating systems for cars in the city of Frankfurt results in an increase of between 0.15 l/100 km and 0.25 l/100 km, which corresponds to 2.6 % and 4.4 % respectively for an average fuel consumption of 5.5 l/100km.

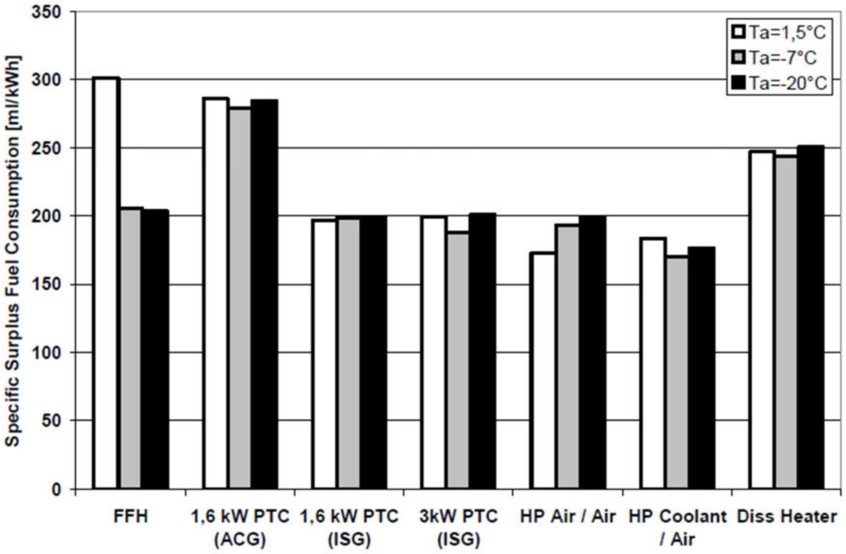

Figure 3-7: Specific surplus fuel of auxiliary heating systems for different outside temperatures. FFH: Fuel Fired Heater, HP: Heat Pump, ACG: Air Cooled Generator, ISG: Integrated Starter Generator (Feuerecker et al. 2005)

3.3. Steering assist systems

Steering assist systems contribute to driving safety and comfort, but they require an additional energy supply, which in turn leads to increased fuel consumption. Steering action is considered rare compared to the total vehicle operating time. According to Sonchal et al. (2012a) for a typical highway travel, the power steering assisted system remains idle for about 76 % of the time. However, according to ECMT (2005) electrical power steering increases fuel consumption by a measurable 2-3 %.

Steering assist systems are distinguished in the following categories (Wellenzohn 2008):

- Hydraulic power assisted steering (HPAS);
- Electro-hydraulic power assisted steering (EHPAS);
- Electric power assisted steering (EPAS).

HPAS has been the main power assisting system for several years, but since it is constantly powered by the combustion engine belt drive, even when in standby, it is a significant consumer of energy. Because of the lower power needs EHPS and EPS systems are considered suitable for small and medium-sized cars (Pfeffer et al. 2005). In recent years there has been an effort to implement power-on-demand type of systems, which lead to the evolution of EHPAS, a partially-on-demand system, and EPAS (Wellenzohn 2008). In EHPAS the hydraulic pump is driven by a constantly operating electric motor, which has a lower engine speed than the combustion engine resulting in lower power demand. On the other hand, in EPAS, steering assistance comes directly from an electric motor, which is only activated when power assistance is required resulting in lower energy consumption (Pfeffer et al. 2005). In terms of required power HPAS demands ~ 270 W, EHPAS ~ 38 W and EPS ~ 18 W based on the simulations and measurements of Lin et al. (2011).

An indicative quantification of the extra fuel consumption demand imposed by each of the three systems is presented in Figure 3-8 (See Table 14-2 in Annex) as adapted from Wellenzohn (2008).

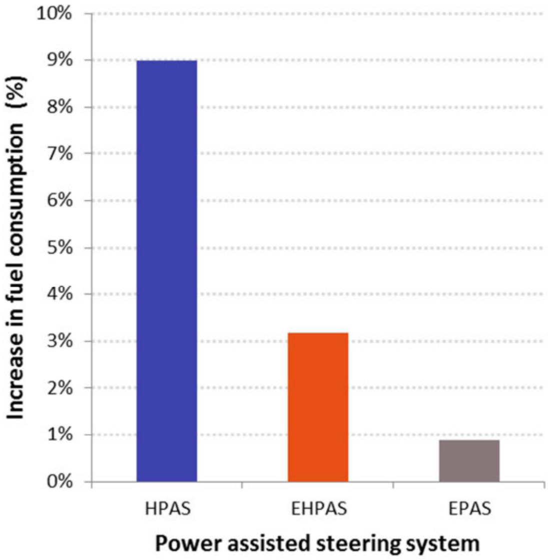

Figure 3-8: Increase in fuel consumption with the use of various power assisted steering systems (adapted from Wellenzohn (2008))

As HPAS is the most fuel-consuming system Sonchal et al. (2012b) suggested the use of Energy Efficient Hydraulic Power Assisted Steering System (E^2HPAS), where the HPAS pump is disconnected by an electromagnetic clutch when steering is not needed. The authors measured on-road and NEDC fuel consumption comparing these systems. The on-road measurements show a decrease of 5 % and 4.1 % for highway and urban driving respectively compared to normal use of the HPAS system. The overall decrease in consumption for the NEDC was 3.9 %, where the decrease was higher in the UDC than the EUDC, 4.8 % and 2.7 % accordingly.

The evolution of modern and sophisticated systems like parking, lane keeping and traffic jam assistance, side wind compensation and collision avoidance is expected to increase the energy requirements from steering assist systems in the future. Their effect on fuel consumption is therefore likely to become more significant.

According to the data collected in this study the operation of steering assist systems can contribute by up to 4.5 % to the in use fuel consumption with an average estimate for modern systems being in the order of 1-2 %. Part of this extra fuel consumption is probably captured also during the certification test despite the lack of actual steering. However it is possible that for electrically driven steering assist systems this extra fuel consumption is not captured during the certification test as the standard practice is to run the NEDC cycle with fully charged battery, a condition that may cause the suspension of the operation of the vehicle's alternator. No specific study was found that quantifies the contribution of the steering assist system to the certified fuel consumption test. Further investigation is necessary for providing more accurate estimates.

3.4. Other vehicle auxiliaries

This paragraph investigates other vehicle-related auxiliaries whose operation may not affect the certification test or may have a smaller impact compared to real-world operation. Typical examples in this category are components such as lights, pumps or the ventilator which require additional electric energy to operate and hence result in increased fuel consumption and CO_2 emissions. The operation of systems like engine and vehicle control units, fuel pumps and injection systems (ADL 2006), various sensors (gas, speed, temperature, force and torque, etc.) (Reif and Dietsche 2011) affects fuel consumption under any driving condition but it is very difficult to quantify their impact on real driving compared to the certification test.

Johnson (2002) has found that the use of accessories can increase fuel consumption by 2.8 %, while other recent research found that a vehicle with all electrical systems switched on can present an increase in consumption of up to 16 % (Dings 2013).

Huhn (2008) found in his research regarding lighting equipment that complete lighting functions (19) require 144 W, which leads to an increased fuel consumption of 0.14 l/100 km. Older lighting equipment technology used during the 1980s led to an increase between 0.18 and 0.28 l/100 km. The use of LED headlamps can decrease the demand, as they are more efficient. Additionally, the author identifies that the use of daytime running lights increases fuel consumption by 0.28 l/100 km, which was the main argument against the mandatory use of such technology.

The electrical power demand of several auxiliary systems were quantified in a study by ADL (2006) the results of which are summarised in Figure 3-9 for a typical American car. In addition, Figure 3-10 presents the power requirements of auxiliaries, whose power needs are not stable but change over time and driving conditions.

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(19) Xenon headlamps, front position bulbs, rear LED lamps, licence plate bulbs and interior lights.

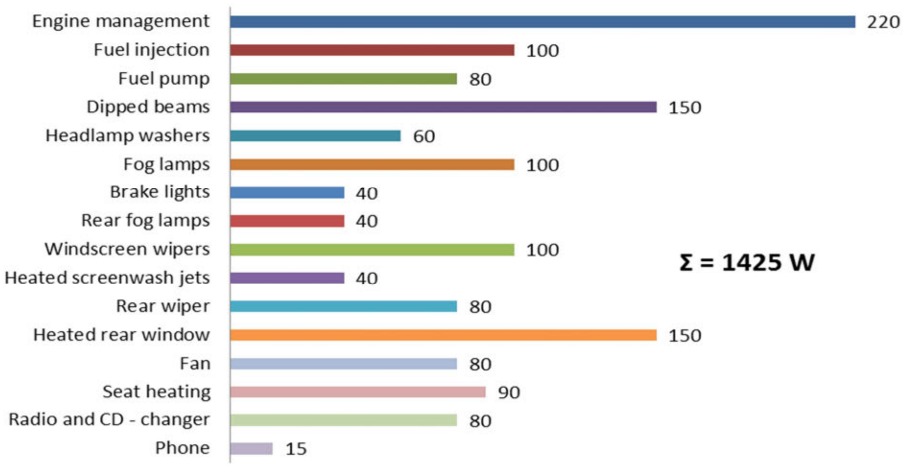

Figure 3-9: Maximum power demand of auxiliary systems (ADL (2006))

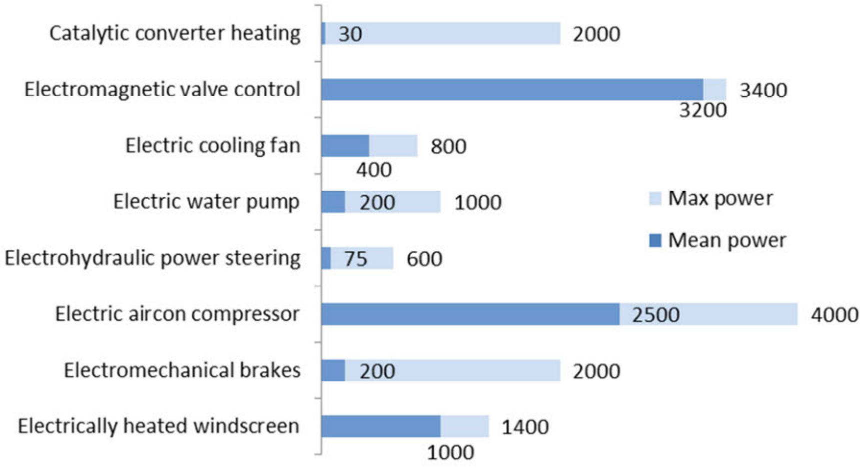

Figure 3-10: Power demand of auxiliary systems with varying power requirements (ADL (2006))

Dudenhöffer and John (2009) have pointed out the significance of the various auxiliaries on fuel consumption for the European customer. They provided a list with the power needs and the potential increase in fuel consumption of the auxiliaries, which is presented in Figure 3-11 (See Table 14-4 in Annex). A/C is presented for comparative reasons to the other electric energy consumers as it accounts for 1 500 W of required power or 1.5 l/100 km increase in fuel consumption. The other auxiliaries require a total of 3 305 W or 3.3 l/100 km. Based on these results in a rainy, winter and night scenario (20) a car would consume 1.5 l/100 km more fuel, an increase of 26 % compared to the average European car.

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(20) Use of headlights, windscreen wiper, rear window heating and wiper and electrical booster heater is assumed.

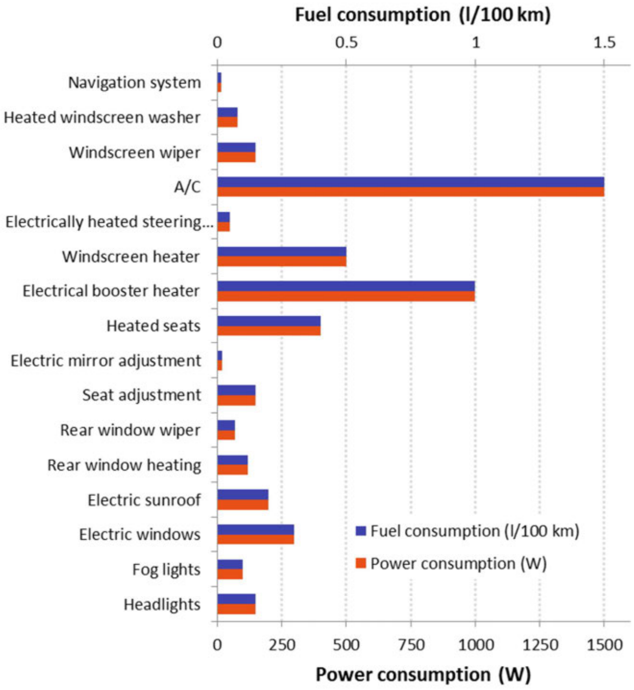


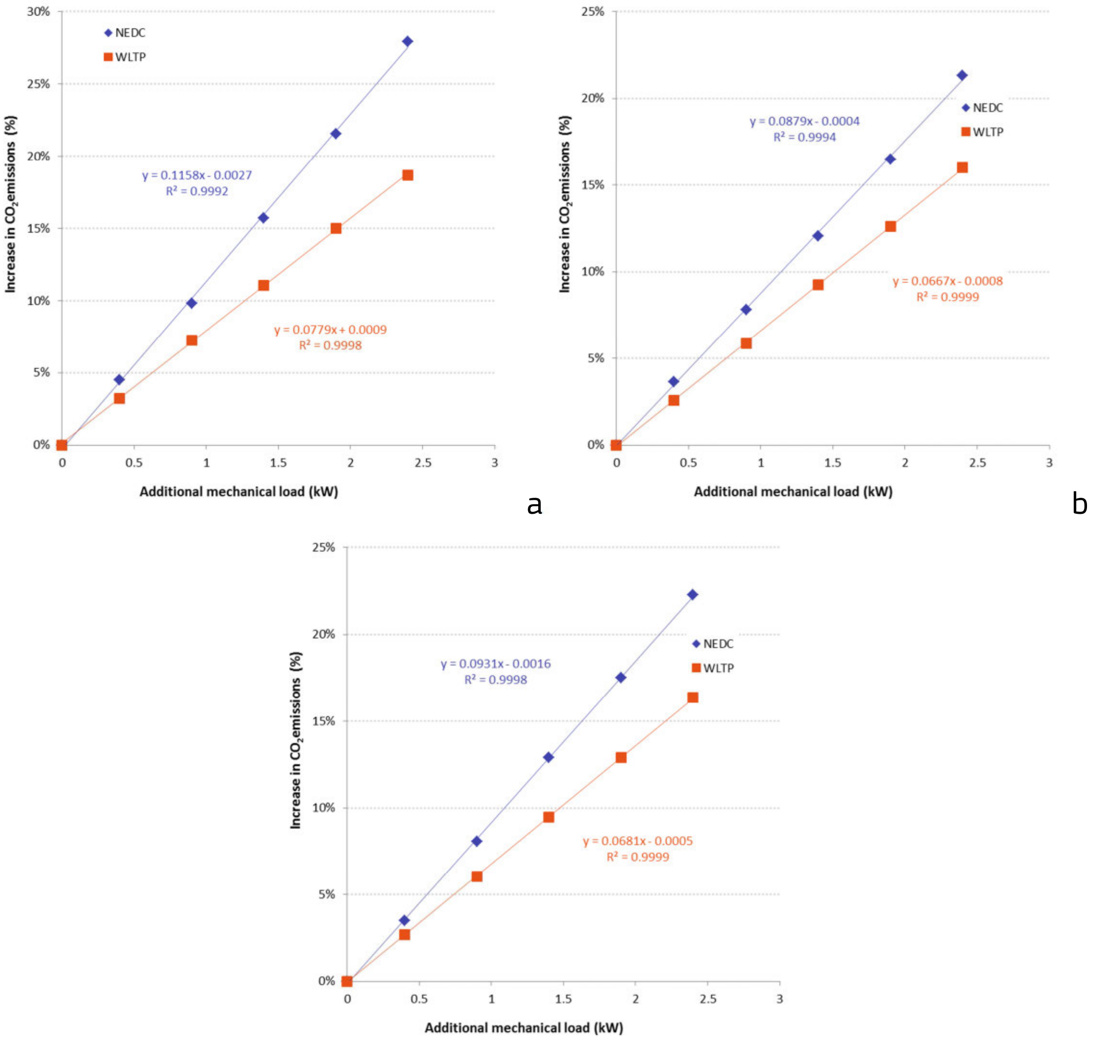
Figure 3-11: Power consumption and fuel consumption increase due to various auxiliaries (Dudenhöffer and John 2009)

3.5. Simulation scenario and results

In a simulation scenario the vehicle was tested under different mechanical and electrical loads in order to mimic the energy needs of the various auxiliaries.

In the first case, the energy demands of the mechanical auxiliaries were tested, although there would be only a few components in modern cars that require additional mechanical energy. The additional mechanical loads correspond to an initial value of 0.4 kW which is then increased stepwise by 0.5 kW to 2.4 kW.
The results are shown in Figure 3-12.

The second case refers to the electrical energy demand, which is increasing in modern vehicles. It was difficult to find robust experimental data regarding the electrical power demand of specific components correlated to other factors like A/C and temperature. For the latter it would be interesting to see the effect on CO_2 emissions over the certification cycle, as an increased ambient temperature leads to reduced cold start emissions, but also to higher emissions from A/C usage.



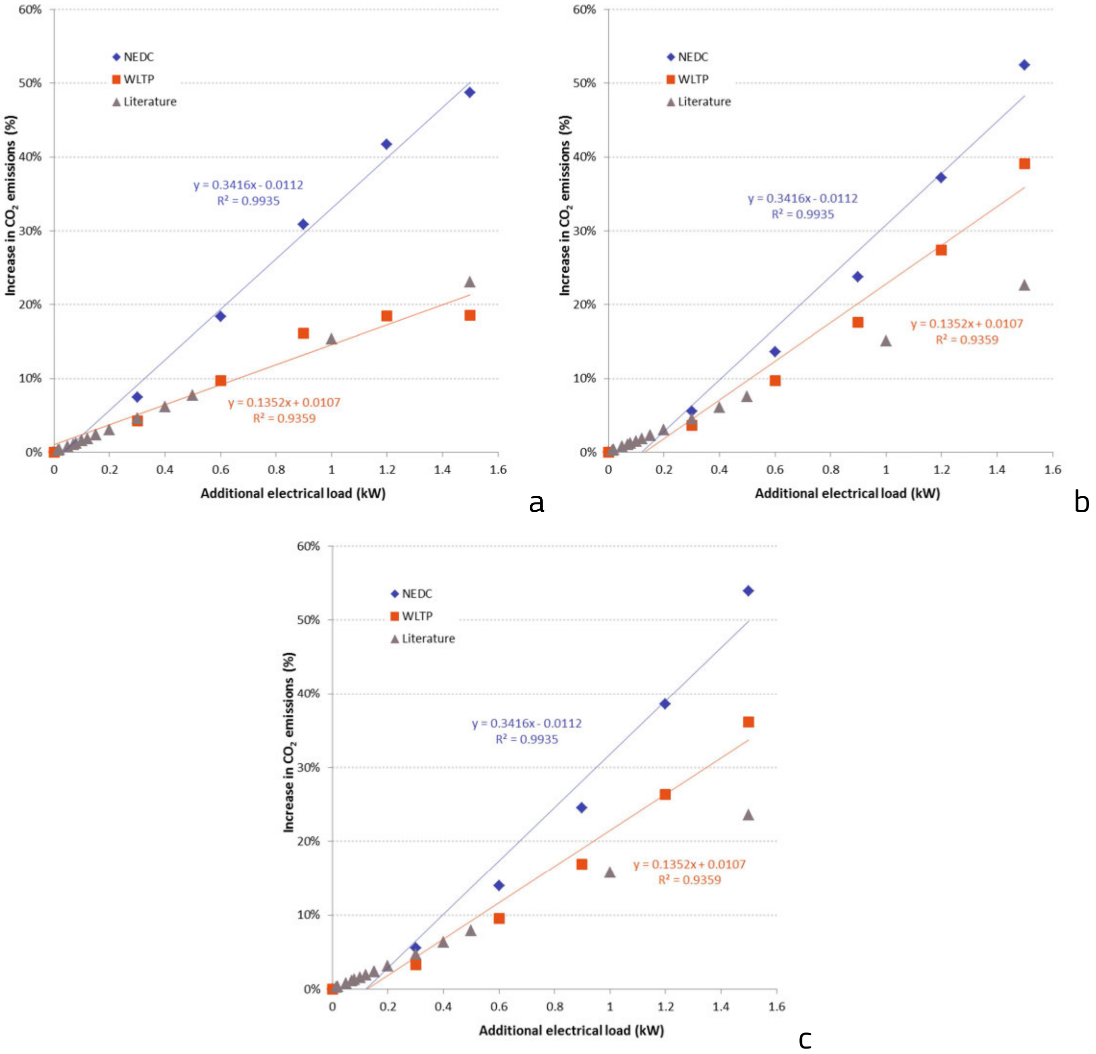
a

b

Figure 3-12: Increase in CO_2 emissions for additional mechanical loads for a petrol NA (a), a petrol turbo (b) and a diesel (c) vehicle

The electrical loads tested in this context correspond initially to 0.3 kW and are then increased stepwise by 0.3 kW to 1.5 kW ([21]). The effect of the additional electrical loads on CO_2 emissions is shown in Figure 3-13. The values regarding the electrical loads by Dudenhöffer and John (2009) were also included and are indicated in the charts as 'Literature'. The effect on CO_2 emissions is shown in percentile change with respect to the baseline emissions as this was a common way of presenting such results in literature. This representation offers also a means for comparison with the effect of other factors presented in the current work.

([21]) It should be noted that for the operation of the alternator a fixed efficiency of 67 % was assumed while the efficiency of the battery and the remaining electrical system was fixed to 95 %. Therefore in terms of engine load the assumed electrical loads are multiplied by a factor of 1.57. The presence of a brake energy recuperation system was assumed in all cases.



a b c

Figure 3-13 Increase in CO_2 emissions for additional electrical loads for a petrol NA (a), a petrol turbo (b) and a diesel (c) vehicle

3.6. Overview

The sources reviewed regarding the quantification of the impact of auxiliary systems on fuel consumption provide mostly information about increases in electrical power demand which subsequently increase fuel consumption.

Most research regarding electrical systems is targeted on the use of A/C. A sufficient amount of sources was found quantifying this effect and additionally, the literature was rich in methodologies for retrieving experimental and real-world data and for proper A/C operation modelling. Several discussions in user forums and other sites were also found on the internet demonstrating a wide public concern about this subject. The main issue of concern seems to be whether A/C or opening the windows is a more fuel-efficient practice during everyday driving, a topic which is further discussed in later chapters.

Power assisted steering systems increase fuel consumption depending on the system used. Few studies were found quantifying sufficiently this effect, although there were enough journal papers supporting this claim. The most power-demanding system to the least demanding is hydraulic power assisted steering, electro-hydraulic power assisted steering and electric power assisted steering.

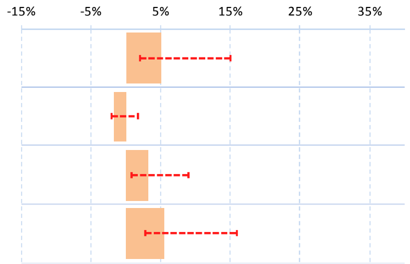
The results of the simulation show that there is a significant increase in CO_2 emissions for additional mechanical and electrical loads. An additional mechanical load of 2.4 kW leads to an increase on average of 24 % for NEDC and 17 % for WLTP. An electrical load of 0.6 kW leads to an increase of about 15 % for NEDC and for WLTP of 9.6 %. The WLTP values are closer to the ones indicated by the literature review.

The simulation results also show that the effect of an extra electrical load is lower in the case of a petrol NA. This could be attributed to the fact that the petrol NA engine has the lowest power of all the options simulated, and therefore is operating during the cycle close to the maximum available power, which means in turn that it has a better overall efficiency over the cycle.

To account for the use of auxiliaries, their usage factor is also required. It was difficult to find information on the real-world use of these auxiliaries except for those provided by the Technical Guidelines of the European Commission (2013). These are normally used for the approval of innovative technologies (so-called ‘eco-innovations’) as part of the CO_2 emissions regulations.

In conclusion, a summary of the average values (JRC estimations) reflecting the impact of auxiliary systems, based on the collected literature data, is presented in Figure 3-14.

Category	Factor		Literature median value	Sources No.
Auxiliary systems	Air conditioning	Increased electrical supply is required	5.0%	10
		Improved MAC systems, EV HVAC - heat pump, active seat ventilation, solar reflective paint, solar control glazing, solar roofs	-1.7%	8
	Steering assist systems	Hydraulic Power Assisted Steering, Electro - Hydraylic Power Assisted Steering, Electric Power Assisted Steering. Improved steering pump	3.2%	3
	Other vehicle auxiliaries	Engine management, fuel injection, fog lamps, brake lights, wipers, dipped beams, brake assist, heated windscreen, fan, etc	5.5%	6



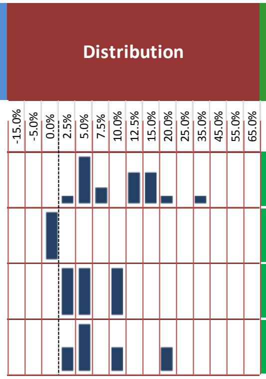


Figure 3-14: Summary table of the effect of auxiliary systems on fuel consumption. Error bars represent minimum–maximum values reported.

4. Aerodynamics

4.1. About vehicle aerodynamics

Vehicle aerodynamic characteristics are one of the main factors influencing fuel consumption in high-speed driving conditions (Hucho and Sovran 1993, Crolla 2009). Aerodynamic resistance is expressed as a function of the cube of vehicle speed and proportional to the product of aerodynamic drag coefficient (C_w), frontal area (A) and air density. In layman's terms, aerodynamics refers to the shape and design of the car and its projected frontal area. The aerodynamic drag coefficient is affected by the design of the car. Increases in the $C_w \times A$ product (henceforward referred to as drag) translate directly into increased aerodynamic resistance, which in turn lead to decreased fuel economy and higher CO_2 emissions (Fontaras et al. 2007).

Improved aerodynamic characteristics reduce the aerodynamic drag coefficient and increase vehicle stability by alleviating lift and side forces (Crolla 2009). Improved design and more sophisticated manufacturing techniques led to the reduction of vehicle drag coefficients in the past decades. Meanwhile, a steady increase in vehicle dimensions has offset much of these benefits as the frontal area of the vehicles increased (Fontaras and Dilara 2012).

Not directly related to the aerodynamic design of the vehicle but influencing fuel consumption is the air density which varies depending on altitude (the higher the driving altitude the lower air density) and ambient conditions. The effect of altitude might be measurable as density is consistently lower at higher altitudes while it is very difficult to evaluate the influence of the yearly weather fluctuations on average air density and subsequently on vehicle fuel consumption. Ambient wind which is almost always present and affected by the variation of the landscape along the road has an impact on aerodynamic resistance (Hucho and Sovran 1993). The effect of pressure and other ambient conditions is further examined in Chapter 5.

Aerodynamic resistance is also affected by various vehicle add-ons and different shape configurations (Chowdhury et al. 2012) which are not necessarily captured by the current certification procedure. Even small modifications can affect air drag leading to measureable changes in fuel consumption. It is estimated that an increase in aerodynamic drag between 10 to 20 % can result in a 2-4 % increase of fuel consumption in highway operation (ECMT 2005). To improve the vehicle's aerodynamic characteristics and performance, OEMs and individual drivers may attach spoilers and vortex generators (VG) or other devices on the vehicles. A combination of a spoiler with VGs could result in a reduction in C_w of 4.35 % compared to a reference vehicle (Bansal 2014). In a test in which the vehicle had folded side mirrors, wheel caps taped closed and antenna and windscreen blades removed, air drag was found to have decreased by 4 % (Van Mensch et al. 2014). Fontaras and Samaras (2010) calculated that reductions of 5 % and 10 % in aerodynamic drag could lead to a decrease of CO_2 emissions for NEDC from 0.6-1.2 % and 1.2-2.4 % respectively. It is therefore expected that OEMs currently choose to base their type approval test on the vehicle variant that presents the lowest resistance possible.

This review is focused on customers' behaviour that affects the frontal area and the shape of the vehicle. It was found that the majority of sources address the installation of roof add-ons, the use of the roof rack which increases the drag *(C_w x A)* and the addition of spoilers which claim to decrease (22) the aerodynamic resistance factor C_w.

4.2. Roof add-ons and modifications

The components most frequently mentioned in literature affecting aerodynamics are roof racks. Roof racks usually serve as a basis for installing a roof box (luggage box, ski boxes or for other equipment) but can be also found as a stand-alone component used for carrying particular objects. Lenner (1998) has found that a roof rack increases fuel consumption between 1-3 % for a speed range of 70-90 km/h (See Table 14-6 in Annex). The addition of roof boxes on roof racks directly increases vehicle frontal area (which normally ranges from 0.22 to 0.45 m^2 according to Halfords (2014) and also increases the aerodynamic drag coefficient. The aerodynamic effect of roof boxes is further examined in paragraph 4.3. Various items, like sirens and advertising signs can also be attached to the car, increasing both the frontal area and drag coefficient, increasing aerodynamic resistances and fuel consumption. The effect of various add-ons is presented in Table 4-1.

Table 4-1: Examples of various add-ons and their effect (Chowdhury et al. 2012)

Add-ons	Increase in drag coefficient (C_w) (%)	Increase in projected frontal area over the baseline (%)	Increase in fuel consumption (JRC estimations) (%)
Advertising sign	7.2	0.8	1.3
Taxi sign	5.1	2.0	0.9
Roof rack	20.4	1.2	3.7
Roof rack with ladder	24.0	2.5	4.3
Barrel	33.1	4.9	6.0

The papers and reports reviewed did not provide enough information to cover in full detail the effects of these add-ons individually. Further investigation of the topic is therefore necessary.

4.3. Roof box (aerodynamics)

A roof box directly increases the air drag of the vehicle, leading to an increase in fuel consumption and CO_2 emissions. The average increase of the frontal area caused by a roof box is estimated at 0.37 m^2 — based on the available model data obtained from Halfords (2014) — while the increase caused to the air drag coefficient is very difficult to quantify. It is important to note that the deterioration in fuel consumption takes place even when the box is empty so the unnecessary use of boxes should be avoided. In the Artemis sub-cycle at 120 km/h a non-laden roof rack (EcoDrive 2011) was found to increase fuel consumption by 7.5 % on average. Apart from the effect on aerodynamics, the additional average weight of the roof box itself is estimated at 15 kg contributing also to a marginal

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(22) Vehicle aerodynamics can be influenced by a series of factors. Retrofit systems sold for improving aerodynamic characteristics might have contrary results if they are not designed appropriately for the characteristics of a specific vehicle and if installed in the wrong way.

increase in fuel consumption. The effect of the extra vehicle mass of a loaded roof box is examined in more detail in Chapter 8, along with the effect of the total vehicle mass.

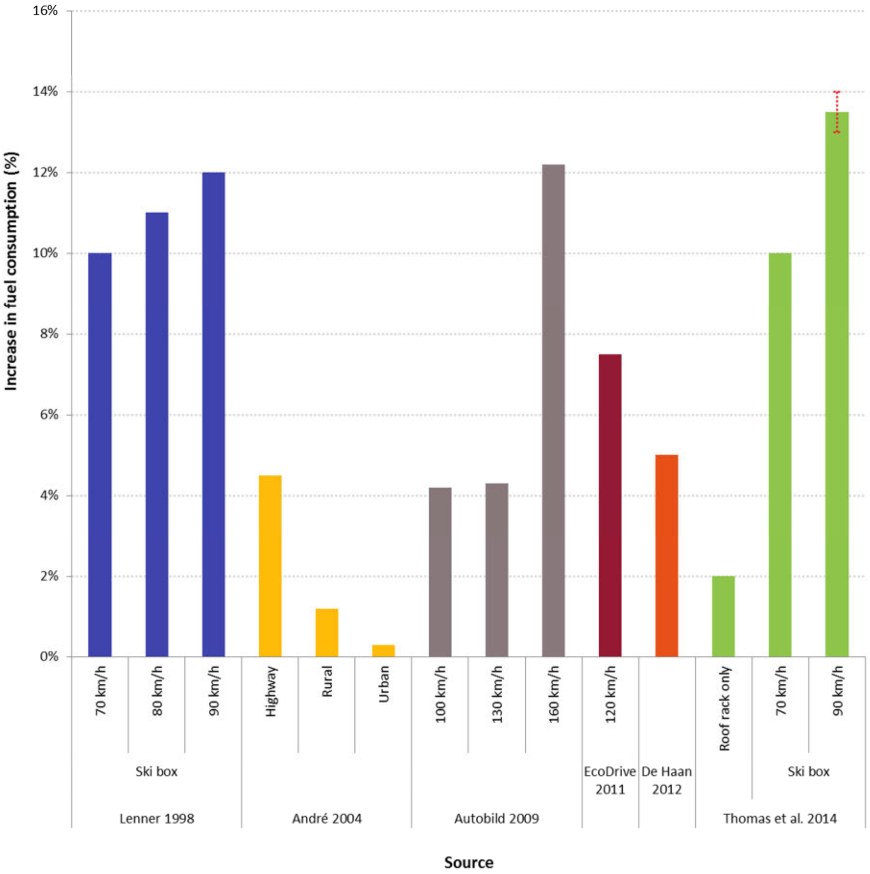

Figure 4-1: Percentage increase in fuel consumption for an unladen roof box ([23])

Lenner (1998) used a common commercial ski-box with a frontal area of 0.25 m^2 and measured fuel consumption at speeds of 70, 80 and 90 km/h and found an increase of 10 %, 11 % and 12 % accordingly (See Table 14-6 in Annex for more details).

A summary of the findings is presented in Figure 4-1 (for more details see Table 14-5 in Annex).

4.4. Open windows

Open windows affect the normal flow of the air around the vehicle influencing its aerodynamic resistance. The range and magnitude of this influence depends on the vehicle's shape, the average speed and how much and which windows are open. The data collected on the issue during this analysis were scarce and insufficient for drawing a solid conclusion. The main source found was a US study by Thomas et al. (2014) that estimated the increase in fuel consumption for a speed range from 64 to 129 km/h (40 to 80 mph) with an 8 km/h interval (5 mph). They tested a Toyota Corolla and a Ford Explorer with all windows open and the findings are presented in Figure 4-2 and Figure 4-3 for each vehicle respectively.

([23]) Different vehicles and testing conditions were used in each study.

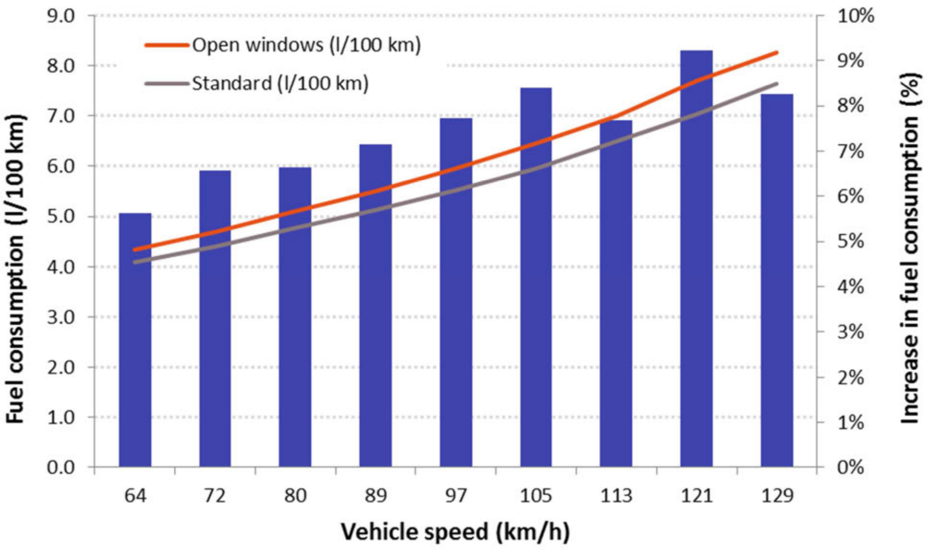

Figure 4-2: Increase in fuel consumption for various speeds for a Toyota Corolla with all windows open, based on an American study by Thomas et al. (2014). Adapted chart, bars correspond to percentile increase in fuel consumption. Original units, US MPG and miles/hour were converted to l/100 km and km/h.

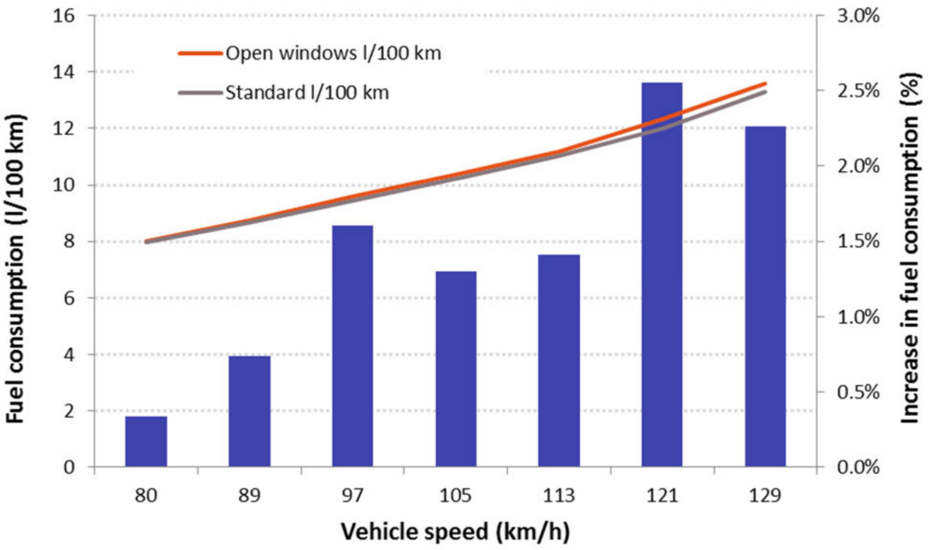

Figure 4-3: Increase in fuel consumption for various speeds for a Ford Explorer with all windows open, based on an American study by Thomas et al. (2014). Adapted chart, bars correspond to percentile increase in fuel consumption. Original units, US MPG and miles/hour were converted to l/100 km and km/h.

A question that it is often raised is whether open windows or A/C systems lead to higher fuel consumptions at high speeds. No clear answer can be drawn from the existing data, however OEAMTC (2012) claims that for speeds up to 90 km/h the impact of open windows on fuel consumption is lower than the use of A/C. Auto Alliance (n.d.) in their EcoDriver's manual suggests that windows should be open up to the speed of 65 km/h.

4.5. Wind conditions

Ambient winds are almost always present and affect the aerodynamics of the car. Wind direction tends to change during on-road driving due to weather conditions, the varying landscape or vehicle turning. Wind perpendicular to the car's motion is called crosswind and apart from prevailing ambient winds it can be caused by another passing vehicle. Crosswinds result in an asymmetric flow around the vehicle affecting drag, lift and pitching moment that can cause instability (Gajendra Singh et al. 2009). As the vehicle turns or as the velocity of crosswinds becomes higher, the angle between the direction of the apparent wind ([24]) and that of the vehicle speed (yaw angle) changes and the car exposes a larger area to the wind, than its actual frontal area (Hucho and Sovran 1993). This may also result in increased aerodynamic resistance particularly in the case of larger square-shaped vehicles like SUVs or trucks. In real-world conditions wind is affected by roadside objects and other vehicles that cause a non-uniform airflow and turbulence, which deviate from the ideal conditions found in the laboratory (Lawson et al. 2007). Landström et al. (2010) identify that despite the effect of crosswinds, yaw angle and speed, the majority of published studies examine aerodynamics at zero yaw angle conditions.

Gajendra Singh et al. (2009) have examined the impact of crosswind angle and velocity on the drag coefficient. Their results are presented in Figure 4-4 and Figure 4-5.

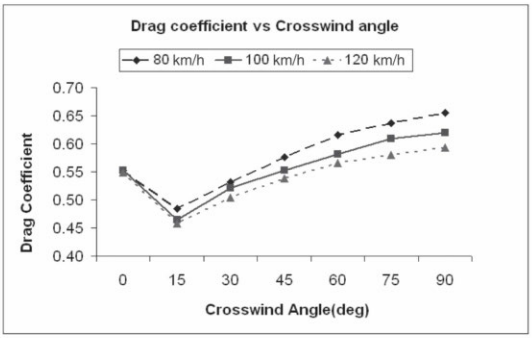

Figure 4-4: Variation of drag coefficient according to crosswind angle, for crosswind speed of 7 m/s from Gajendra Singh et al. (2009)

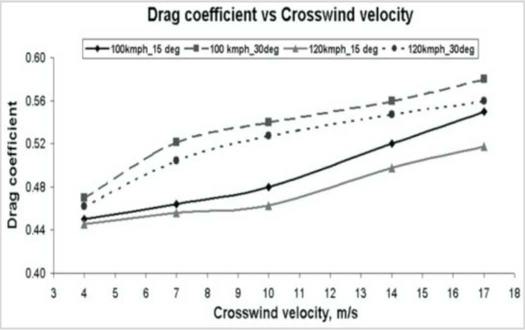

Figure 4-5: Variation of drag coefficient according to crosswind velocity for angles of 15° and 30° from Gajendra Singh et al. (2009)

The effect of crosswind under different yaw conditions on the aerodynamics of a car was examined also by Landström et al. (2010) who also took into consideration the effect of the rotating wheels and air inlets. Figure 4-6 presents the difference in the drag coefficient for various yaw angle values for four car configurations. The authors observed a significant increase in drag in yaw angles between 8 ° and 18 ° and they indicated a gap in current knowledge on the subject.

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[24] The wind experienced by a moving object is the sum of the true wind and the head wind caused by vehicle's motion

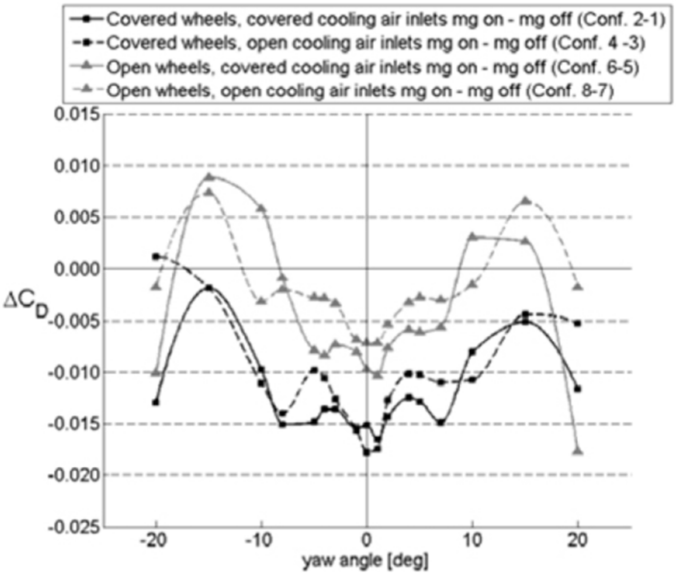


Figure 4-6: Difference in aerodynamic coefficient for various yaw angle values (Landström et al. 2010)

At the type approval test an increase of 10 % in air drag results in a 2 % average increase of CO_2. (Figure 4-7). It is therefore concluded that wind conditions can have a measurable and possibly significant impact on the in-use fuel consumption and CO_2 emissions, increasing the gap between reported values and the consumption experienced by the drivers. However, further data and analysis is necessary for accurately quantifying these effects.

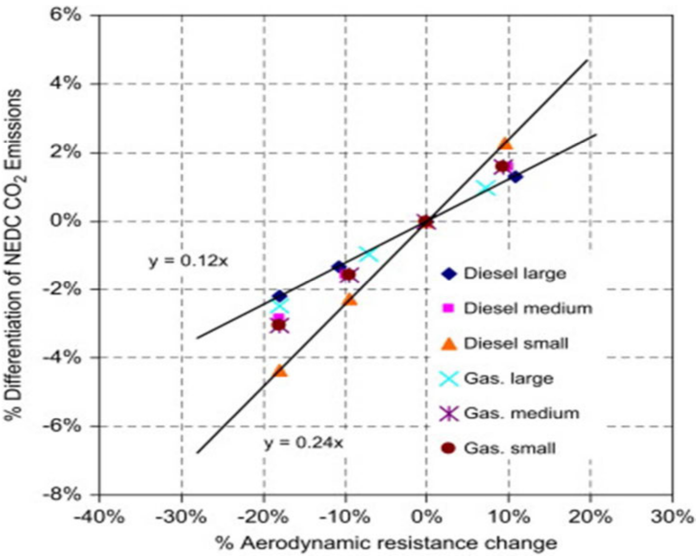


Figure 4-7: Variations in CO_2 emissions according to the variations of aerodynamic resistance (Fontaras and Samaras 2010)

4.6. Improvements

The aerodynamic coefficient can be improved mainly by the addition of appropriately designed spoilers (Bansal 2014). Spoilers improve air flow around the vehicle as they increase the minimum pressure around the surface of the vehicle and reduce the formation of vortices, which contribute to aerodynamic drag. In Table 14-9 in the Annex are presented values comparing frontal air pressure for standard car modifications and with a use of spoilers. The aerodynamic coefficient is reduced as shown in Table 4-2, with the use of vortex generators. It should be noted that apart from the reduction in the aerodynamic coefficient a significant decrease in lift coefficient is reported.

Table 4-2: Drag reduction with the use of various attachments (summary from Sharma (2014), Bansal (2014) and JRC estimates)

Configuration	Drag coefficient	Reduction from baseline (%)	FC reduction (%) (Initial JRC estimation)	
			Petrol	Diesel
Baseline	0.35	0	0.0	0.0
Spoiler	0.34	2.0	0.2	0.5
VG	0.35	1.15	0.1	0.3
Spoiler with VGs	0.34	4.35	0.5	1.0

4.7. Simulations

Using dedicated simulation run we attempt an investigation of the effect of various shape modifications that affect the frontal area and the aerodynamic coefficient. Some common shape modifications are a taxi sign, police siren and roof box, as well as the use of a spoiler that is considered an improvement on the aerodynamic design of the vehicle. The simulated effect of these modifications is shown in Table 4-3.

Table 4-3: Effect of aerodynamic modifications on aerodynamic coefficient and frontal area (Chowdhury et al. 2012, Bansal 2014)

Modification	Effect on aerodynamic coefficient (%)	Effect on frontal area (%)
Taxi sign	5.1	2
Police siren	19.3	0.9
Barrel	33.1	4.9
Roof box	10	14.8
Spoiler	− 2	0

The results of the tests are presented in Figure 4-8, Figure 4-9 and Figure 4-10.

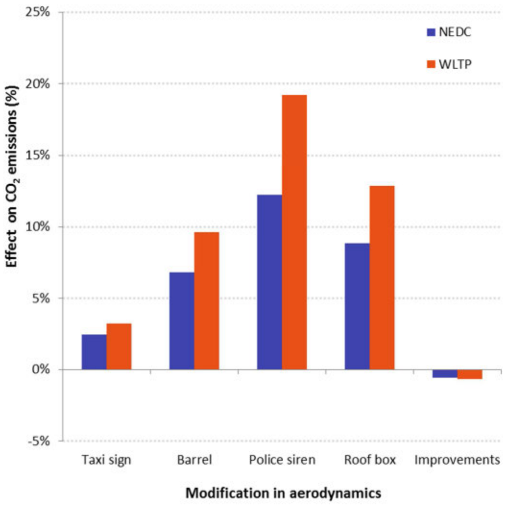


Figure 4-8: Effect on CO_2 emissions of various shape modifications for a petrol NA vehicle

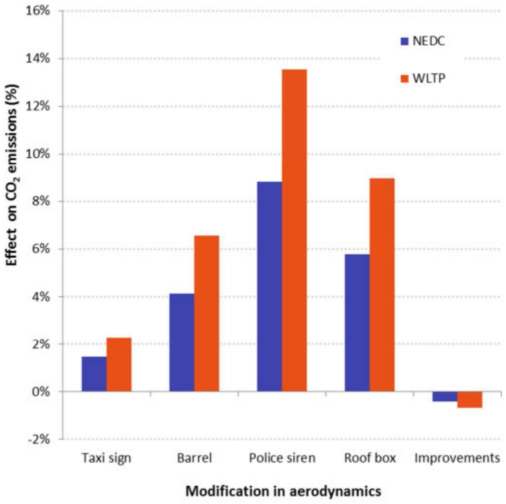


Figure 4-9: Effect on CO_2 emissions of various shape modifications for a petrol turbo vehicle

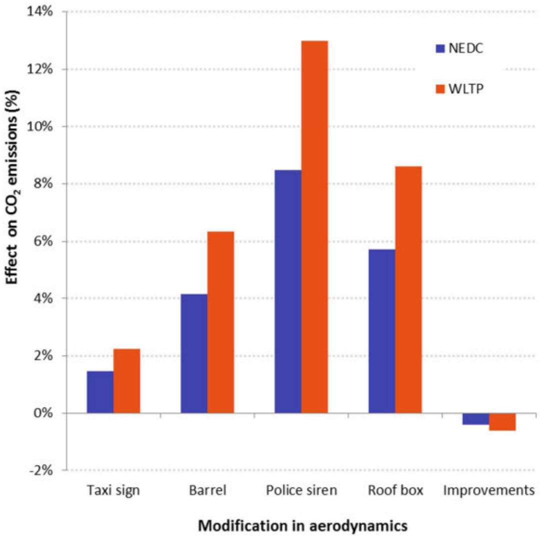
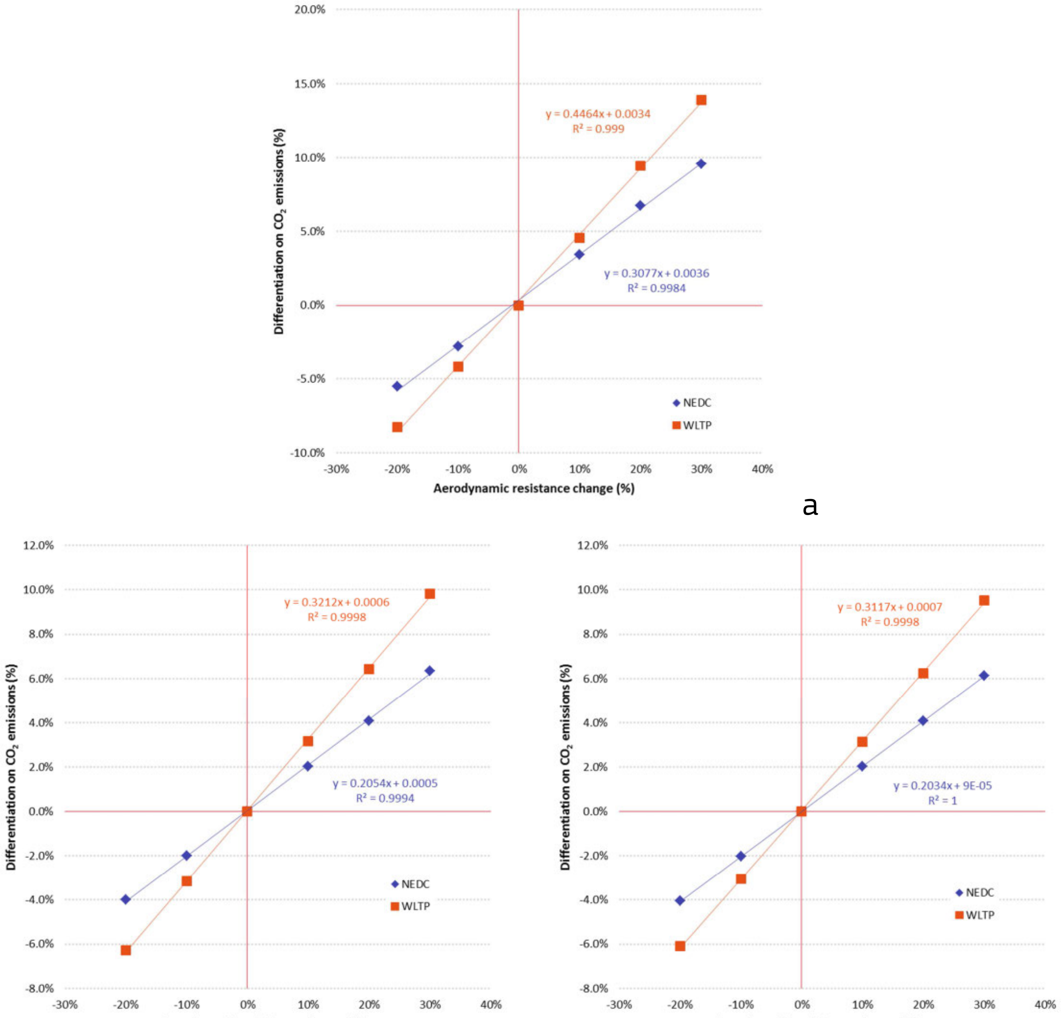


Figure 4-10: Effect on CO_2 emissions of various shape modifications for a diesel vehicle

The effect of altering the aerodynamic resistance in steps of 10 % from – 20 % to 40 % was also simulated in order to identify a trend in CO_2 emissions over the tested vehicles. The results are presented in Figure 4-11.



a

b

c

Figure 4-11: Aerodynamic resistance change and differentiation in CO_2 emissions for a petrol NA vehicle, a petrol turbo, a diesel vehicle

4.8. Overview

A first important finding is that despite the high influence of aerodynamics on vehicle resistance and fuel consumption few studies actually quantify in a comparable and consistent way the effect of aerodynamic coefficient variation on fuel consumption during actual operating conditions.

The studies regarding roof add-ons, like police sirens and signs, were not sufficient to quantify safely their effect on fuel consumption or on resistances. The majority of the studies dealt with the use of roof boxes, for which the average increase was 6.4 %. Regarding the various add-ons, the simulation results show an average increase in fuel consumption of 5.6 % for NEDC and 8.5 % for WLTP. For the roof box only the increase was 6.5 % and 9.7 % respectively. The difference between the two cycles is attributed to the higher speed of the WLTP, which leads to a significant increase in aerodynamic resistance.

The literature review on roof boxes was rather rich and the effect was quantified and accounts for about a 6.4 % increase in fuel consumption for a speed range of 70-120 km/h. These studies usually provided estimations of the impact over various speeds, providing a better view of roof box impact for different operating conditions. The results of the simulation show an increase of 6.5 % in emissions in the NEDC and 9.7 % in the WLTP. Over the EUDC an increase of 10.2 % was found, while over the high and extra high sub-cycles of the WLTP it reached 12.1 %.

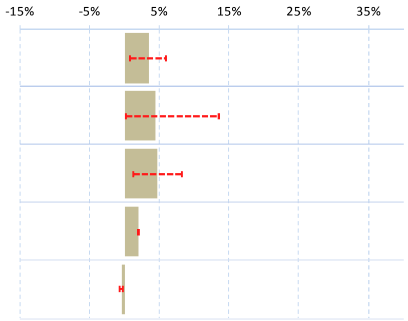
The use of spoilers which improve the aerodynamic performance of the car is adequately documented and data are available regarding their effect on the aerodynamic drag coefficient and the air pressure influencing the car. According to literature, the use of spoilers can reduce fuel consumption by 0.4 %. The simulation results are in accordance with the literature findings as they estimated a 0.4 % reduction for NEDC and 0.6 % of the WLTP. In general, improvements in the aerodynamic design can provide significant benefits. A decrease of 10 % in the aerodynamic resistance can lead to 2.2 % and 2.6 % less emissions for NEDC and WLTP respectively.

The effect of open windows on fuel consumption was very difficult to assess as there are very few studies actually quantifying it. A US study (Thomas et al. 2014) has been the main source of data for various different operating speeds. An online search showed that the public is particularly concerned about choosing whether to open windows or operate the A/C, and the question which is more fuel efficient at high speeds appears in several discussions. The prevailing opinion is that at low speeds (less than 60-80 km/h) it is more fuel efficient to drive with the windows open, while at higher speeds switching on the A/C is more efficient. Some new observations claim however that open windows are more fuel efficient even at higher speeds and this opinion has started spreading through the internet. It is expected that a car with proper aerodynamic design and inefficient A/C could have a lower fuel consumption with windows open at high speeds than with the A/C switched on and closed windows. On the contrary, a car with high aerodynamic drag and highly efficient A/C could have better consumption with A/C than with open windows at high speeds. In order to reach a solid conclusion additional scientific evidence is necessary.

The effect on CO_2 emissions of side winds and open windows was difficult to emulate in this simulation scenario. Side winds are related to the intensity and the direction of the blowing wind and it was difficult to make significant assumptions about these characteristics. The angle of the side winds would affect the frontal or the rear and the lateral area of the vehicle increasing the total vehicle area where air pressure is applied. Also the intensity of the side winds should be added to the relative air speed experienced by the vehicle, which was difficult to incorporate in the model. Opening the windows causes alterations in the air flow around the vehicle that could not be taken into consideration in the current model. Since in both cases the air drag is affected some simulation runs were carried out for different air drag values and the provided results show a linear trend between aerodynamic resistance change and CO_2 emissions. An increase of 30 % in air drag causes an emissions increase of 7 % for NEDC and 10.6 % for WLTP. On the other hand, a decrease of 10 % in aerodynamic resistance — this could be in the case of a tailwind — would decrease CO_2 emissions by 2.2 % and 3.3 % respectively.

A summary of the average values (JRC estimations) based on the collected literature data is presented in Figure 4-12.

Category	Factor		Literature median value	Sources No.
Aerodynamics	Roof add - ons and modifications	Various add - ons that are attached to the roof, except for a roof box	**3.6%**	2
	Roof racks / boxes (air drag increase)	Effect on fuel consumption with the addition of an un - laden roof box. Increased aerodynamic resistance	**4.5%**	5
	Open windows	At a speed of 130 km/h, based mainly on an american study	**4.8%**	3
	Sidewinds effect	Change in aerodynamic drag and frontal area, depends on wind velocity and angle. Results for 10% air drag increase (caused from 15o to 30o yaw angle or from 4 - 8 m/s wind velocity)	**2.0%**	5
	Improvements	Spoilers, vortex generators	**-0.4%**	3



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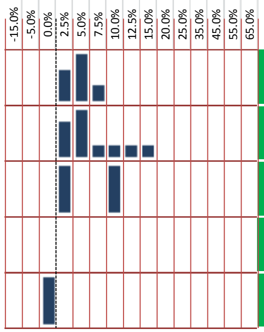

Figure 4-12: Summary table of the effect of aerodynamics on fuel consumption. Error bars represent minimum–maximum values reported.

5. Weather conditions

5.1. About weather conditions

By weather conditions we refer to all factors associated with meteorological phenomena that can have a direct or indirect influence on vehicle fuel consumption. The present certification test is performed at fixed temperature, pressure and humidity (25), conditions which do not reflect weather variations that a driver experiences throughout the year. These also depend on the geographical location. Therefore a measurable contribution of weather variations to the shortfall between certification fuel consumption and real-world performance is expected. Karlsson (2012) identified three categories that appear to have the largest impact on the fuel consumption and CO_2 emissions of passenger cars: wind, temperature and altitude (ambient pressure). Weather conditions such as rain, snow or fog can also have an important impact on fuel consumption in principle by affecting the way the vehicle is driven and secondly by influencing resistances, the operation of auxiliary units or the engine.

The weather conditions examined in this chapter are precipitation (rain or snow) and temperature. The effect of wind has been examined in Chapter 4. Rain and snow can affect fuel consumption by forcing the driver to reduce speed or drive in a non-regular way, but they also change the road surface characteristics, which is directly connected to rolling resistance and vehicle grip. The use of wipers and/or lights during rain, snow or fog is not taken into consideration in this chapter as it has been examined along with other electric systems in Chapter 3.

It should be taken into consideration that ambient conditions are not stable and may vary substantially depending on geographical location, weather pattern, and yearly seasons. This fact makes it difficult to summarise their influence on fuel consumption in a few averaged figures. Reliable quantifications call for use of more detailed models.

5.2. Rain–snow

As mentioned above rain and snow influence fuel consumption in multiple ways. Since it is very difficult to assess changes in driving behaviour and style imposed by weather it was chosen to focus on the factors which affect vehicle resistances that are easier to quantify.

Rain and snow affect the grip and the rolling resistance of the vehicle as they change the characteristics of the road surface. Rain creates a layer of water that the wheels have to overcome. According to Karlsson (2012) for water depths of 1, 2 and 4 mm the overall increase in fuel consumption was 30 %, 90 % and 80 % respectively. The author explains the fact that the increase in fuel consumption is higher for 2 mm than 4 mm because of the reduced speed of the vehicle at the 4 mm depth, which is caused by the increased amount of rain and reduced visibility. A US study regarding heavy duty vehicles (HDV) also indicates that fuel consumption increases (Cummins n.d.) with rain (26).

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(25) Although we were not able to retrieve scientific references on the impact of humidity on CO_2 emissions a study by Lindhjem et al. (2004) describes a direct impact of this which affects NOx emissions.

(26) Fuel economy decreased according to the study by 0.2-0.3 MPG (0.9-0.13 km/l), however comparisons between HDVs and PCs are

Snow and ice can increase fuel consumption. The wheels can slip on the road, wasting energy as they have reduced grip, while driving speeds are significantly lower than normal. Additionally, some cars use four wheel drive for better grip, which results in higher fuel consumption (DOE — EPA 2014c).

It hasn't been possible to locate adequate quantitative scientific information on the effect of rain and snow on fuel consumption, but the public seems rather concerned about this. For comparison, a search in Google scholar provided poor results, which were mainly irrelevant to the subject, while a standard Google search with the same keywords returned a plethora of results. Most of these results were forum discussions and the prevailing opinion is that fuel consumption is increased due to the fact that the wheels have to push through the layer of the water on the road surface, followed by the effect of the increased humidity in the air, the use of wipers and lights. All of these points are considered valid from an engineering point of view but still it is very difficult to quantify their absolute impact on CO_2.

5.3. Ambient temperature

Ambient temperature influences a variety of factors, such as tyres (EAPA — Eurobitum 2004, TRB 2006), motor oil viscosity during cold start conditions (Dössegger 2013), cold start engine operation and management, all affecting fuel consumption (Joumard et al. 2006, Mock et al. 2012). After the warm up of the catalyst, engine block, lubricant and coolant water, the effect of ambient temperature is mitigated (Li et al. 2010, Lohsse-Busch et al. 2013). The Type Approval test foresees a starting temperature range between 20-30 °C, with most tests performed at 25 °C, which is not representative for most cases of real-world operation (Dings 2013). Starting temperatures lower than 20 °C can increase CO_2 emissions by up to 6 % (Mock et al. 2012), while within the range of the test from 20 to 29 °C the difference can surpass 2 % (Dings 2013).

Climatic data for the region of Milan, obtained from (ECA&D 2014), suggest an autumn and spring temperature of 14 ± 4 °C, a range that is considered representative of the European average. For this range, fuel consumption varies roughly by 2 % (Joumard et al. 2009). Ligterink and Eijik (2014) have observed a difference in fuel consumption from the change of season. They claim a decrease of 2-3 % in fuel consumption for an increase of 10 °C in air temperature.

Low ambient temperature significantly affects cold start consumption, as extra fuel is required to warm up the engine and overcome the increased friction. (Weilenmann et al. 2009). Weilenmann et al. (2009) have tested several Euro–4 petrol and diesel vehicles at temperatures of – 20, – 7 and 23 °C. Their results are presented in Figure 5-1.

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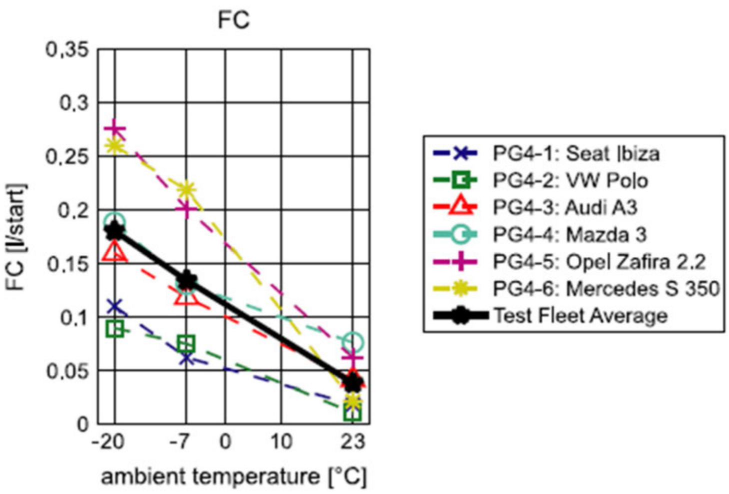


Figure 5-1: Cold start emissions as a function of ambient temperature for petrol cars (Weilenmann et al. 2009)

Additionally, ambient temperature can influence to a greater or lesser extent all kinds of external resistances acting on the vehicle. As mentioned previously, low ambient temperature results in increased air density and higher aerodynamic resistances (Fontaras and Dilara 2012), while increased air temperature decreases aerodynamic resistance (Ligterink and Eijik 2014). The tyre condition is also affected by the increased temperature, as the contained air pressure, the stiffness and the hysteresis of the rubber all change, which subsequently results in a lower rolling resistance (Snyder 1977, TRB 2006). Lower temperature leads to greater heat losses and tyre friction, increasing fuel consumption by 0.2 % per °C decrease. As temperature decreases, this discrepancy increases as well, so from 0 °C to – 20 °C fuel consumption increases 0.5 % per °C (ECMT 2005).

Dardiotis et al. (2013) measured NEDC fuel consumption and CO_2 emissions of eight petrol and five diesel cars at temperatures of 22 °C and – 7 °C. The results show a significant increase in fuel consumption and emissions over the UDC sub-cycle compared to the EUDC sub-cycle, at the lower temperature with a greater impact on diesel vehicles than petrol. Their results are presented in Figure 5-2 and Figure 5-3.

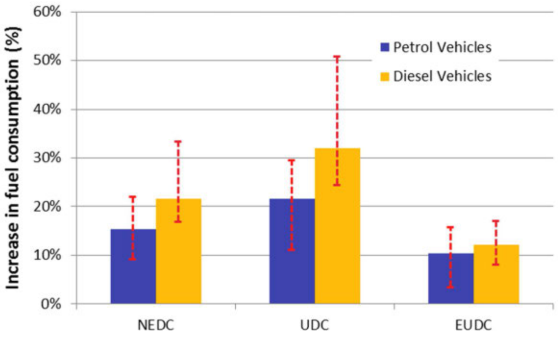


Figure 5-2: Fuel consumption increase compared from 22 °C to – 7 °C for petrol and diesel vehicles (Dardiotis et al. 2013)

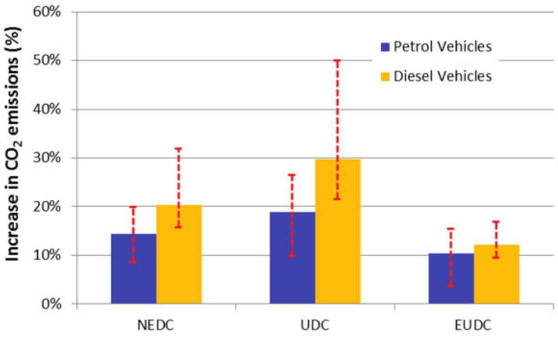


Figure 5-3: CO_2 emissions increase compared from 22 °C to – 7 °C for petrol and diesel vehicles (Dardiotis et al. 2013)

The type of the engine, multi-point spark ignition (MPI-SI) or direct injection spark ignition (DISI), influences consumption over different ambient temperatures. Bielaczyc et al. (2013b) tested vehicles over NEDC for temperatures of 25 °C and –7 °C and have divided the results at – 7 °C by those at 25 °C to get a dimensionless deterioration factor. If the quotient is higher than one, then an increase in consumption occurs, otherwise a decrease. Their results are presented in Table 5-1.

Table 5-1: Deterioration factor for – 7°C and 25 °C for Multi Point Injection and Direct Injection Spark Ignition engine types (Bielaczyc et al. 2013b)

Cycle phase	Engine type	
	MPI	DISI
UDC	1.28	1.22
EUDC	1.14	1.12
NEDC	1.21	1.16

It is observed that in all cases fuel consumption increases for the lower temperature (– 7 °C) with an overall NEDC increase of 21 % for SI-MPI and 16 % for DISI.

Temperature can have a more significant impact on the fuel consumption of hybrid electric vehicles because battery capacity is highly affected by temperature conditions (Alvarez and Weilenmann 2012). A Canadian study by Christenson et al. (2007) tested a conventional petrol vehicle (Smart Car) and three hybrids at temperatures of – 8 °C and 20 °C. The deterioration factor of their findings is shown in Table 5-2.

Table 5-2: Deterioration factor for – 18 °C and 20 °C for three hybrids and a conventional car (Christenson et al. 2007).

Cycle	Smart car (2002)	Toyota Prius (2004)	Ford Escape (2005)	Honda Civic (2003)	Honda Insight (2000)
City cycle (LA4)	1.23	2.07	1.56	1.56	1.56
Unified cycle (LA92)	1.19	1.77	1.31	1.44	1.38

The increase in consumption for the hybrids in this case varies from 56 % to 107 % for the city cycle and from 31 % to 77 % in the unified cycle, while the discrepancy for the conventional car is lower at 23 % and 19 % respectively.

For temperatures of – 6.7 °C (20 °F) an American study on the effect of the cold start in the urban cycle has found an increase between 15 % and 20 % for conventional vehicles and between 20 % and 37 % for hybrids, whereas for 22 °C (72 °F) the increase was from 6 % to 12 % and 6 % to 20 % respectively (Lohsse-Busch et al. 2013).

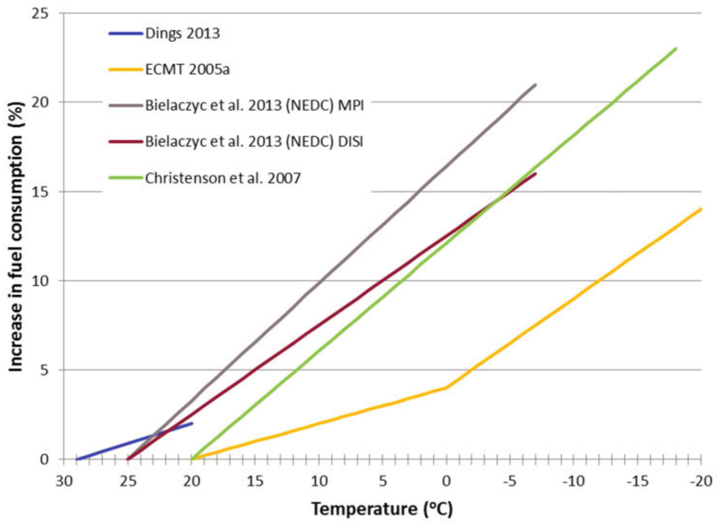


Figure 5-4: Percentage increase in fuel consumption related to decreasing temperature

Figure 5-4 presents a summary of the values found in literature. The chart was produced based on minimum and maximum values provided or per centigrade change for a specific range of temperatures (See also Table 14-10 in Annex).

A JRC (2014) analysis based on internal data was conducted to measure the effect of the cold start on fuel consumption and emissions. The 16 vehicles tested were both petrol and diesel. The starting test temperature was ~ 20 °C and the measured factors were compared to the values of the engine's optimum operational temperatures (~ 90 °C). The measurements of vehicles at – 7 °C included in the chart were provided by the supplementary data of Dardiotis et al. (2013) and (Dardiotis et al. 2015). The results are shown in Figure 5-5.

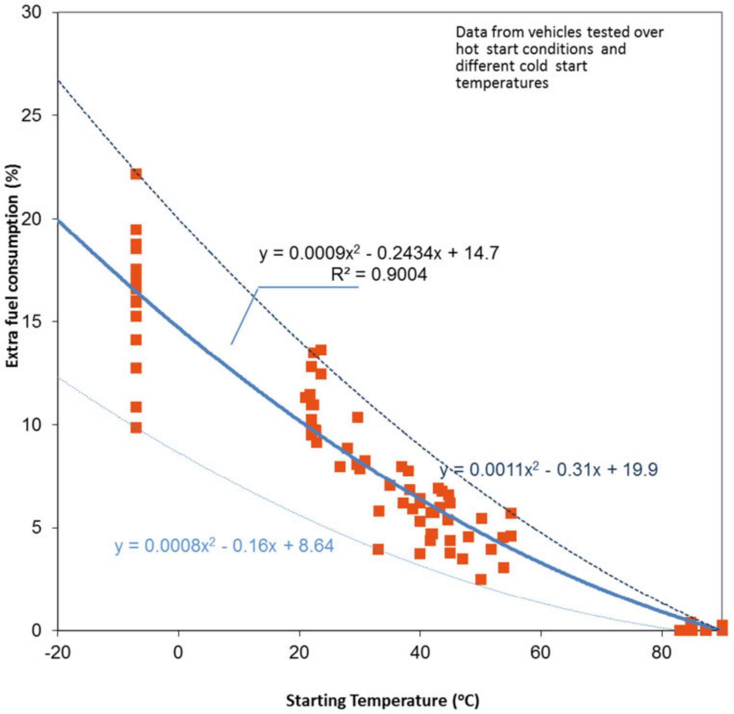


Figure 5-5: Increase in fuel consumption of cold start compared to hot start conditions for NEDC. Upper–lower trendlines indicate maximum–minimum value trend

5.4. Simulations

In this scenario the effect on fuel consumption and CO_2 emissions for – 7, 14 and 20 °C is simulated and compared to the baseline scenario. It should be noted that the assumed certification test temperature for the NEDC is 25 °C and for the WLTP is 23 °C. Figure 5-6 shows the data from Figure 5-5 adapted to include the simulation results. It is observed that the simulation values fall within the minimum and maximum limits found in the literature review.

The average CO_2 emissions increase for the different test temperatures compared to the hot start for all simulated cars is shown in Table 5-3.**Error! Reference source not found.**

Table 5-3: Average increase in CO_2 emissions for different simulated test temperatures for all test vehicles compared to hot start.

Temperature °C	NEDC	WLTP
– 7	19.8 %	6.7 %
14	11.5 %	4.5 %
20	10.2 %	3.9 %
50	3.8 %	1.4 %

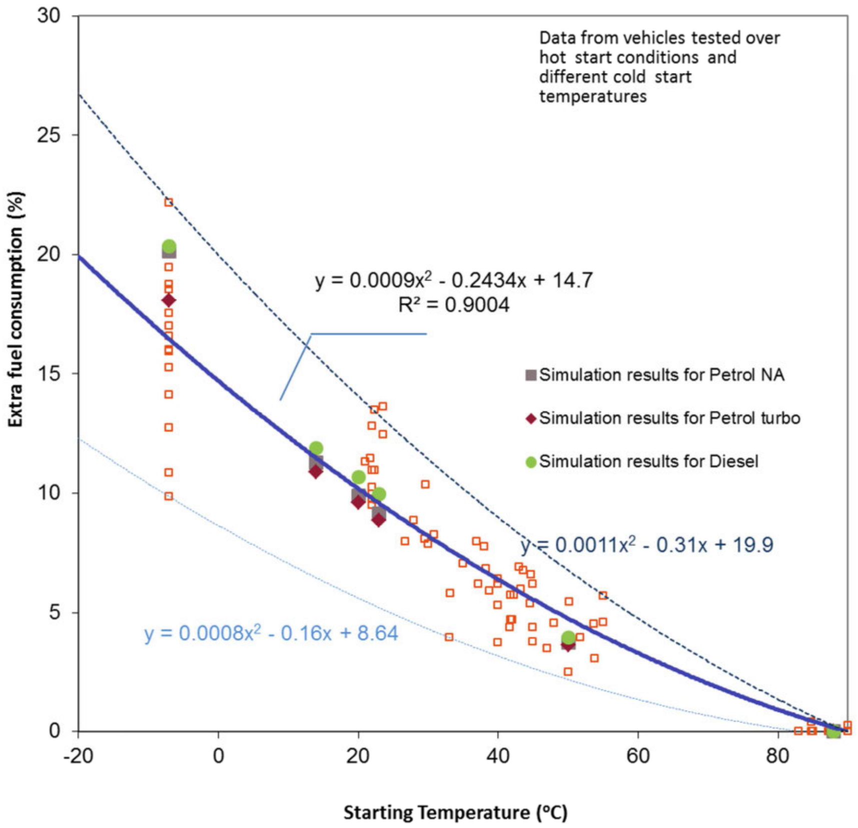


Figure 5-6: Effect of ambient temperature on fuel consumption compared to the values found in the literature review for a petrol and a diesel vehicle for NEDC

5.5. Overview

The effect of weather conditions is generally not sufficiently quantified in literature, except for temperature. There is a lack of studies regarding rain, snow and precipitation in general while, as stated in Section 5.2, this is of major interest to the public.

The majority of studies regarding ambient conditions refer to ambient temperature and its impact on cold start. Sufficient results were retrieved that make it possible to quantify the temperature cold start effect. The public appears to be aware that low temperatures increase fuel consumption, as in many discussions the subject is explained adequately. People living in colder climates seem more concerned about this matter, as expected, as they experience much higher fuel consumption than type approval values, according to several forum discussions. Additionally, people are concerned about the efficiency of winter–summer diesel mixtures and the effect of winter tyres which are not relevant to cold start but are indirectly linked to the prevailing ambient temperature in each geographic area.

The increase in fuel consumption ranges from 9.8 % to 22.1 % for NEDC compared to a hot start, based on the results from the literature review (ambient temperature). The simulation results show a significant increase in CO_2 emissions especially in colder temperatures. The increase at – 7 °C is in the order of 20 % for the NEDC and 5 % for the WLTP compared to a hot start. According to the data from literature, at 14 °C the increase in fuel consumption due to cold start is between 6.6 % and 15.8 % for NEDC compared to the hot start. Simulations showed that cold start extra fuel consumption at 14 °C was about 11.3 % and 3.4 % respectively for NEDC and WLTP.

Unfortunately, due to lack of literature data it is difficult to identify and quantify properly the parameters regarding rain and snow. Further investigation is required in this field, as the majority of the studies found relate to the grip and driving properties of the tyres.

Figure 5-7 presents a summary of the average values (JRC estimations) based on the collected literature data.

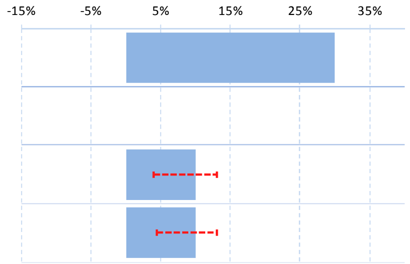
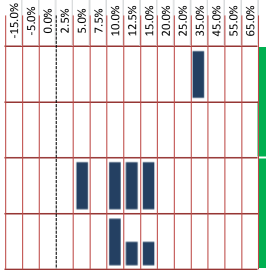
Category	Factor		Literature median value		Distribution	Sources No.
Weather conditions	Rain	Wheels have to push through water. Increase for 1 mm of water depth on road surface	**30.0%**			3
	Snow/Ice	Decreased tire grip, wasting energy. Lower than normal driving speeds. Decreased tire pressure	Qualitative data			
	Temperature, the type approval test current range is 20 - 29 oC	0 °C compared to 20 °C	**10.0%**			15
		-20 °C compared to 0 °C	**10.0%**			

Figure 5-7: Summary table of the effect of ambient conditions on fuel consumption. Error bars represent minimum–maximum values reported.

6. Driving behaviour

6.1. About driving behaviour

Driving behaviour refers to the personal driving style of a driver and is characterised by instantaneous and average speed, acceleration and choice of gears (Brundell-Freij and Ericsson 2005). Driving behaviour may depend on the personal character, age and gender of the driver (Brundell-Freij and Ericsson 2005, Schipper 2011), as well as on external factors like street type, type of journey, weather and traffic conditions (Ericsson 2000). Aggressive driving is known to increase fuel consumption and CO_2 emissions (Ericsson 2000, Hill 2011, Schipper 2011), while driver training leads to decreased fuel consumption (ECMT 2005, Beusen et al. 2009, Barkenbus 2010). The factors affecting fuel consumption which relate to driving behaviour as reported by ECMT (2005) are summarised below:

- Gear change
- Acceleration and deceleration patterns
- Driving at high speeds
- Unnecessary idling.

In the following paragraphs the effect of driving behaviour on the following parameters is investigated:

- Aggressive driving — this focuses on the effect of high acceleration, deceleration, braking and speed.
- Trip planning — this affects fuel consumption, as it affects the number of cold starts, stops and average speed.
- Driving mode — many modern cars offer different driving modes that adjust the powertrain management and gearshifting in cases of vehicles equipped with automatic gearboxes according to the desired performance.
- Eco-driving — this refers to driver training and the use of driver aids which help to reduce fuel consumption by influencing the abovementioned factors.

The impact of vehicle speed on emissions is also discussed in Section 9.4 which addresses traffic conditions. Figure 9-6 in this paragraph presents in charts the variations of emissions according to speed. There was no simulation scenario for this factor, as this study focuses mainly on the type approval cycles.

6.2. Aggressive driving

Aggressive driving, which is characterised mainly by high acceleration and deceleration, intense braking and high maximum speed, leads to increased fuel consumption and CO_2

emissions (Ericsson 2000, Schipper 2011, EPA 2014b). André and Pronello (1997) claim that maximum speed is the factor with the highest influence on fuel consumption. Figure 6-1 summarises the values collected regarding the effect of aggressive driving on fuel consumption (See Table 14-11, Table 14-12 and Table 14-13 in Annex).

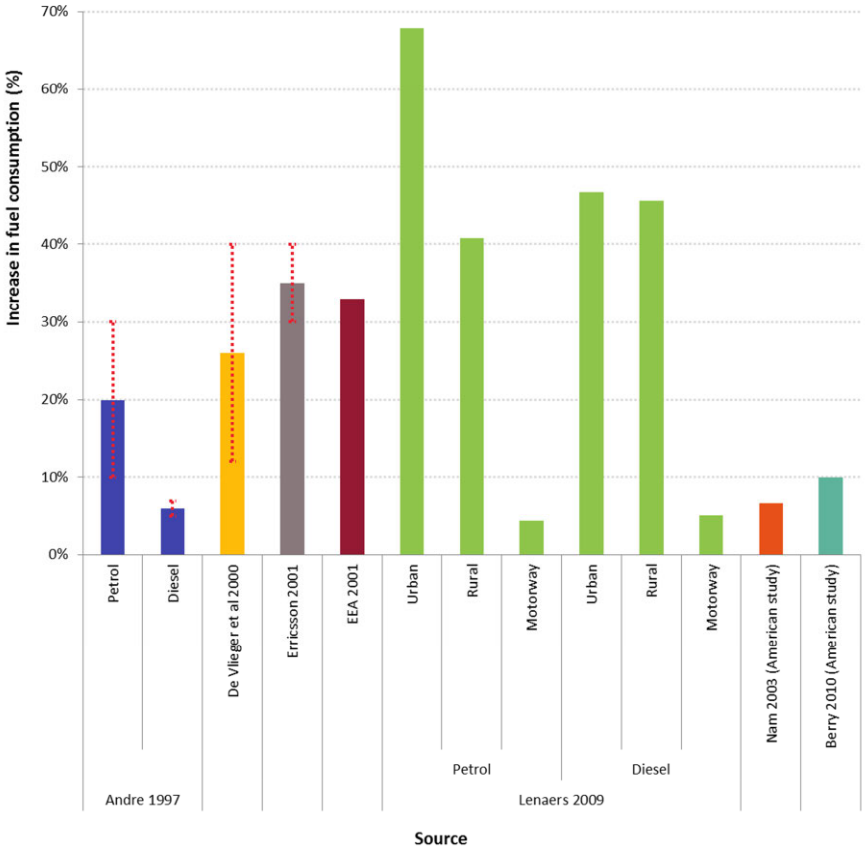


Figure 6-1: Increase in fuel consumption for aggressive driving compared to normal driving. Error bars correspond to minimum–maximum observed values.

It has to be mentioned that is quite difficult to define actual average driving behaviour which can be used as reference. Considering the average value of the results presented in Figure 6-1 it has been estimated that fuel consumption for aggressive driving can increase up to about 25 % in European conditions. The difference between the EU and the US shown in Figure 6-1 could be traced back to the fact that cars in the United States exhibit higher fuel consumption compared to their European counterparts. This means that the baseline fuel consumption is already higher in the US so the relative penalty in fuel introduced by driving more aggressively is lower, an explanation supported also by Dössegger (Dössegger 2013).

An interesting observation was found in a Canadian study by Gao and D. (2007) where over three driving patterns, urban, aggressive driving and highway test, the highest consumption occurred in the urban test. This observation was attributed to the influence of idle consumption, because of the start and stops and to frequent accelerations in urban conditions. On the other hand aggressive driving had minimal idling and extreme accelerations, while the highway test delivered the lowest results because of the minimal idling and accelerations and high average speed. Their results are summarised in Figure

6-2. It is expected that modern vehicles equipped with start–stop systems do not suffer as much from frequent stops hence an aggressive, highly transient speed profile will lead to comparable, if not higher, fuel consumption as the urban test.

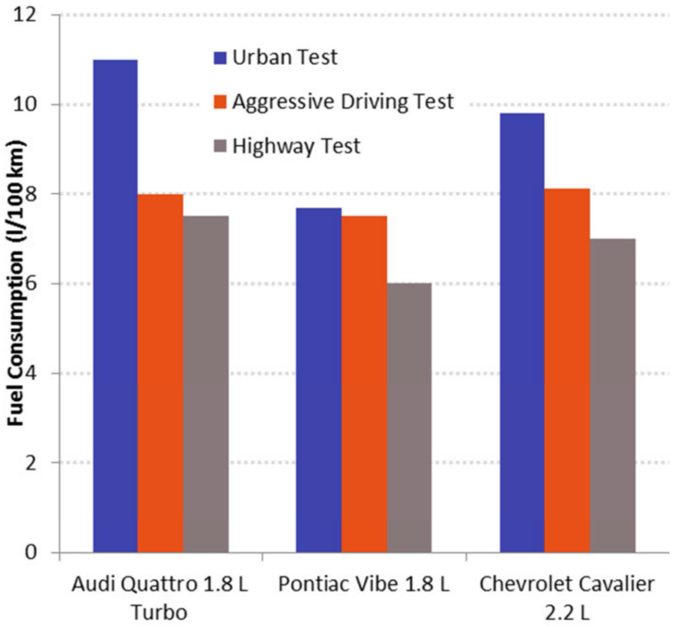


Figure 6-2: Vehicle fuel consumption compared to different driving patterns (adapted from Gao and D. (2007)).

6.3. Driving mode

Some cars offer built-in driving modes for achieving more dynamic performance or reduced fuel consumption. These modes can adjust engine tuning, gear shifting in the case of automatic gearboxes, perform suspension adjustment and engage four wheel drive when necessary. Information provided by Dena (2013), although not directly connected to driving modes, states that a four wheel drive vehicle can have an increased fuel consumption by 0.5 l/100 km, while automatic transmission could consume up to 0.7 l/100 km more compared to manual. It is unclear if the use of specific modes can counterbalance increases in fuel consumption introduced by specific technologies or components (e.g. using an automatic gearbox with eco function instead of a manual one).

A web search in manufacturers' websites about these technologies revealed three general types of modes that are used the most, even though every manufacturer uses different commercial names to describe them:

- Eco, for reducing fuel consumption;
- Normal which is the baseline operation of the car;
- Sport, for better performance, which is expected to be the most fuel consuming mode.

The ECO PRO Mode of BMW (2014a) provides, according to the manufacturer, up to 20 % better fuel consumption by using pedal and gear recognition, brake energy regeneration, optimising shifting and A/C temperature control, while providing additional information for more efficient driving. The same manufacturer offers a 'sport' mode option, where the car is adjusted to a more dynamic style, while the engine is more responsive and the suspension is stiffer (BMW 2014b).

Similarly the 'Sport' mode option for a Toyota Corolla leads to faster acceleration by increasing throttle response, higher gear shifting, more performance-oriented RPM and adjusted electric power steering assist for sportier feeling as stated by Toyota (2014a).

For information, is also mentioned that recently some new generation hybrid cars offer the option to use the vehicle in an all-electric mode (EV). Manufacturers encourage the use of this mode for a short distance at low speeds, in traffic, in closed spaces like garages and to decrease noise late at night (Toyota 2013, Honda 2014).

According to VW (2014) the 'eco' mode in their vehicles leads to more environmentally friendly driving with less emissions and lower fuel consumption by optimising engine, gearbox and A/C performance. The decrease is not specified quantitative by the manufacturer. On the other hand the sport mode results in faster accelerations and better steering response.

It was not possible to find an extensive study regarding these modes, as there is no common definition for the terms and every manufacturer uses its own settings. The only source that provided some information, even though not strictly scientific, was the website Cars.com (2014), where the multimode function of the cars is discussed. The authors claim to have observed up to 11 % increase in fuel consumption for the 'sport' mode, while they provide some information about how EPA rates these cars in the United States. According to the authors of Cars.com (2014) the procedure (27) is complex, but could be summarised as follows: when the car returns to a particular mode every time the engine is turned on, then this mode is used for the TA test. If it doesn't, then an average value is extracted from all the available modes.

6.4. Eco-driving

Proper driver training leads to improved fuel economy and consists of optimal gear shifting, maintaining steady speeds, anticipation of movement and traffic, smooth deceleration and stopping (ECMT 2005, Joumard et al. 2006). Also, it was found that the use of fuel-saving accessories like the gear shift indicator can contribute to decreasing consumption (Fontaras et al. 2008, Dings 2013). The website of the Natural Resources of the Government of Canada (NRCAN 2013) shows in a chart (Figure 6-3) five fuel efficient driving techniques compared to an average driving style. These techniques include gentle accelerations, coast down decelerations, maintaining a steady speed and avoidance of high speeds which in essence summarise the main principles of eco-driving.

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(27) We have not managed to locate the original EPA document.

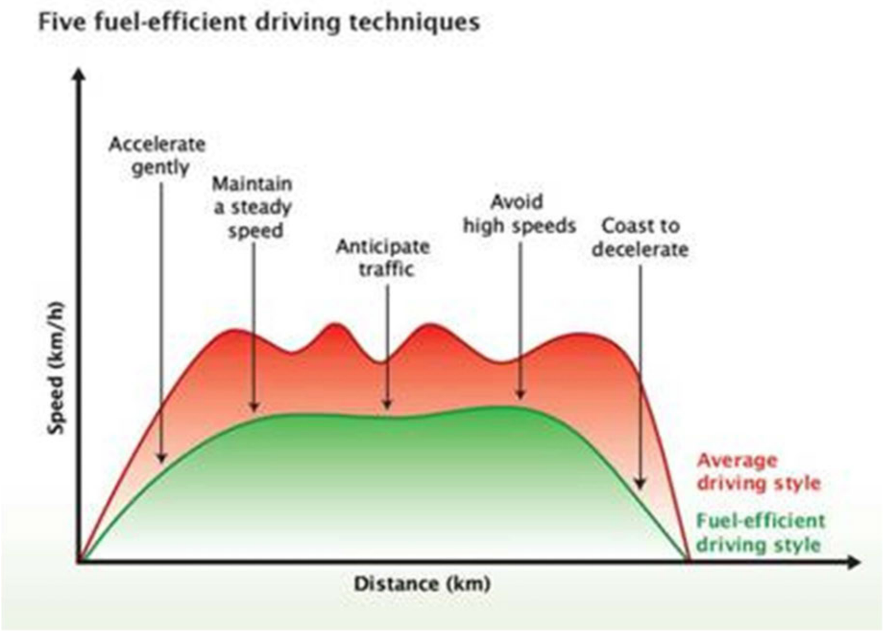

Figure 6-3: Fuel efficient technics compared to average driving style (NRCAN 2013)

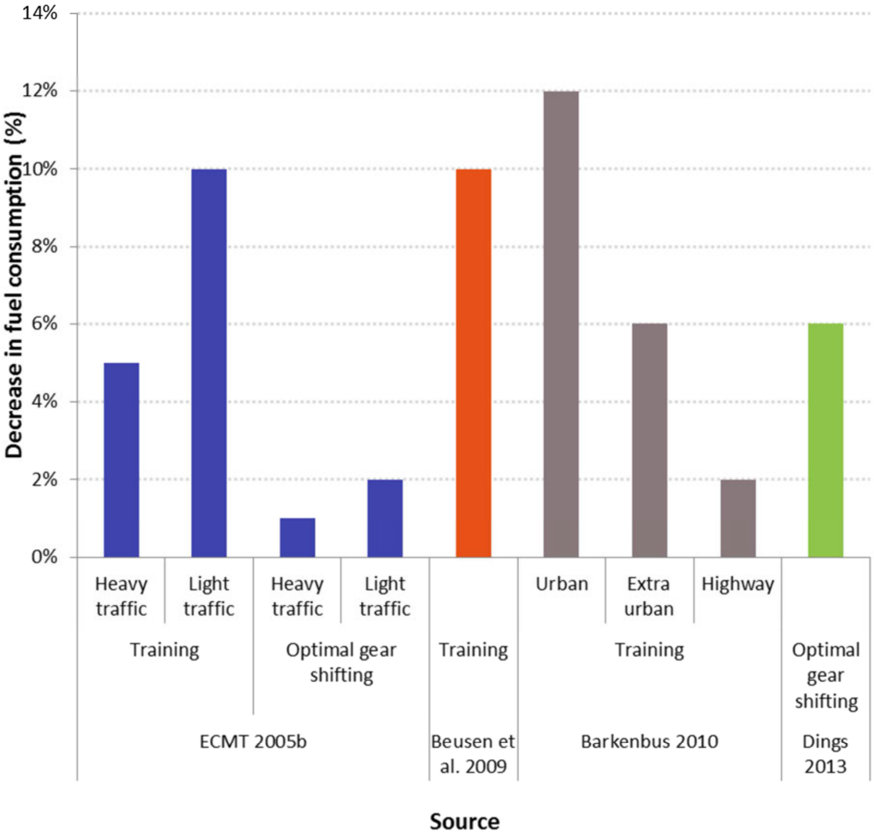

Figure 6-4: Decrease in fuel consumption for eco-driving compared to normal driving

Figure 6-4 presents a summary of the effectiveness of two driving strategies. One strategy is simply an optimal gear shifting, while the other one labelled as training consists of more elements like smooth accelerations and decelerations, braking and traffic anticipation.

Varnhagen and Korthaus (2010) suggest that the improved navigation systems and intelligent use of navigation data is expected to improve the efficiency of eco-driving strategies (See Table 14-14 in Annex). As the NEDC is comprised of smooth accelerations and decelerations it could be assumed that the use of eco-driving strategies in real-world conditions approach this kind of profile.

6.5. Overview

Several studies are available regarding the impact of driving style on fuel consumption. A number of studies are also available regarding driver training and auxiliary systems that can help achieve more fuel-efficient driving. It is interesting that in the case of the aggressive driving the average publishing year is 2005 with a standard deviation of 5.4 years, while the average publishing year for fuel efficient driving is 2009 with a standard deviation of 2.9 years. This indicates a rising concern in this matter possibly originating from the significant increase in fuel prices that occurred in the decade 2004-2014 and potentially also from policies adopted in Europe for reducing passenger car CO_2 emissions, such as the integrated approach. The general public is also concerned about increased fuel consumption associated with aggressive driving and the discussions retrieved from an online search were almost always accompanied by tips for more fuel-efficient driving practices. The search key-word ‘fuel efficient driving’ returned a plethora of magazine articles and forums.

Regarding the metrics, aggressive driving is reported to increase fuel consumption dramatically by up to 24 %, while eco-driving is reported to provide benefits in the order of 6-8 % compared to standard real-world operation with certain sources raising this figure up to 30 % (28).

The effect of the trip type on fuel consumption is more related to the average speed, the warm-up phase and cold operation period. For the same total trip time, multiple short trips would result in an increased number of cold or semi-warm starts compared to fewer and longer trips. In this case, better commuting planning can result in decreased total fuel consumption. Various scientific sources regarding this effect are available although it is very difficult to accurately quantify the effect due to the large number of influencing factors and the associated variability of the observed fuel consumption increase. The major issue is the cold start, which was investigated in Section 5.3.

It was difficult to find information regarding driving modes, as the majority of searches returned results from the OEMs where benefits of the various modes are advertised but not quantified or scientifically demonstrated. The mode usually labelled as ‘Eco’ was promoted as being more fuel efficient, while the ‘Sport’ mode was promoted for its performance. The discussions between the users of such modes not only provide information about the performance of these modes, but also about the way drivers use them. Several users seemed uninformed about the proper use of different modes, while a

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(28) As mentioned, aggressive driving may increase emissions by 24 %. So the overall variation range in CO_2 emissions that can be attributed to driving behaviour appears to be indeed in the order of 30 %. Of course it is extremely difficult to define the ‘standard’ driving style which serves as reference for such calculations. It is expected that as drivers become more concerned about fuel consumption and as driver aids such as gear shift indicators proliferate the average driver behaviour should become more fuel efficient.

rough estimation based on the opinions expressed is that many drivers use just only one mode, usually the ‘Sport’ mode. The latter reveals one of the underlying problems, as this mode normally leads to higher CO_2 emissions while it also increases the shortfall between certified and real-world emissions, as these vehicles are probably type-approved using the most fuel efficient mode. Further investigation is very important in order to understand customer behaviour in this context.

Figure 6-5 presents a summary of the average values based on the collected literature data.

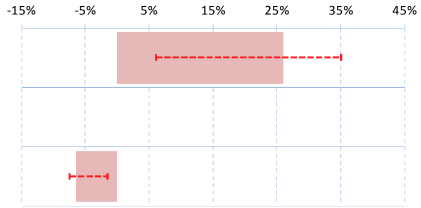
Category	Factor		Literature median value		Distribution	Sources No.
Driving behaviour/style	Aggressive driving	High acceleration and deceleration, braking and maximum speed	**26.0%**			10
	Driving mode	Consumption varies according to Eco or Sport mode. Non scientific research claims increase up to 11% for Sport mode	**Qualitative data**			6
	Eco - driving	Optimal gear shifting, smooth accelerations and decelerations, steady speed maintenance, anticipation of movement and traffic, Green - Light Optimal Speed Advisory (GLOSA)	**-6.5%**			6

Figure 6-5: Summary table of the effect of driving behaviour/style on fuel consumption. Error bars represent minimum–maximum values reported.

7. Vehicle condition

7.1. About vehicle condition

Vehicle condition refers to the general condition of the vehicle in terms of maintenance and natural wear. Several factors were found that can affect fuel consumption, with the most important being lubricants and the type and condition of tyres, with the latter directly affecting rolling resistance (29). It should be noted that the paragraph regarding lubricants deals mainly with the decrease in fuel consumption with the use of low viscosity lubricants. Similarly, for tyres, the benefits of low-rolling resistance tyres were investigated compared to standard tyres and the effect of low pressure and poor maintenance. Additionally, the effect on fuel consumption of other parameters that are checked during the programmed annual maintenance of a car was examined. The latter findings are described in the paragraph 'Other'.

7.2. Friction and lubricants

It is estimated that up to 25 % of fuel energy spent during the certification test is consumed to overcome the friction of the car's components, which refers to the engine, transmission and brakes (Holmberg et al. 2012). A significant part of the energy is lost to the exhaust emissions and heating dissipated through conduction and finally, about 22 % of the total fuel energy is actually used to move the vehicle (Holmberg et al. 2012). These authors estimated that a passenger car consumes on average 340 l of fuel annually to overcome friction for an average mileage of 13 000 km. Their projection for the future is that, with the use of new friction reduction technologies, friction losses can be reduced in the short term by 18 % and in the long term by 61 %, resulting in significant savings and reduced CO_2 emissions. The most common technology option for reducing friction in the vehicle's mechanical parts is the use of lubricants with lower viscosity.

Viscosity is an important factor for achieving good lubrication. A lubricant's viscosity must present the following characteristics:

- Should be low enough for the lubricant to flow to the parts that need it, providing the necessary protection;
- Should be high enough for the lubricant to form a protective film between the surfaces it is supposed to protect from contact. This lubrication film must have the appropriate properties to withstand the loads and pressures occurring between the surfaces.

When viscosity is lower than necessary, the film formed by the lubricant won't provide sufficient protection of the moving parts. This can result in problems such as increased friction and wear, as well as increased heating and oxidation. When viscosity is higher than necessary problems may occur too. Inadequate flow could lead to increased drag and friction leading to higher operating temperatures and energy consumption. Low viscosity

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(29) Rolling resistance refers to the energy loss in the tyre due to the deformation of the contact area and the damping properties of the rubber (Crolla 2009). EU Regulation 1222/2009 has introduced label categories for tyres based on the rolling resistance and is discussed in Chapter 7.3 Tyres.

lubricants (LVL) are lubricants which provide the benefits of lower viscosity while maintaining their ability to sufficiently protect the mechanical parts of the vehicle. Therefore the characterisation of a lubricant as low viscosity or energy efficient has to take place considering the type, characteristics and the operation of the respective mechanical component.

According to the literature review the use of low friction motor oil decreases fuel consumption (European Commission 2006, Dena 2009, EcoDrive 2010b, UBA 2010, VW 2010b, Holmberg et al. 2012, AGVS 2013), while the effect seems to be greater in the urban cycle than in the suburban one (Dena 2009). An average improvement in fuel economy is estimated at about 4 %, while alternating motor oil of higher and lower viscosity between summer and winter seasons could also contribute to decreased fuel consumption (IEA 2005).
Figure 7-1 presents the improvement in consumption for low viscosity motor oil, based on the values found in the literature review (See Table 14-15 and Table 14-16 in Annex).

Motor oil viscosity is inversely dependent on temperature: the higher the temperature, the lower the viscosity. Proper lubrication occurs at operating temperatures of 90 °C, which for a cold start in the case of the NEDC cycle is reached at the end of the test (1 180 s), while it could take longer in congested traffic (Andrews et al. 2007). According to the same study, a hot start results in 10 % lower fuel consumption compared to a cold start and in the NEDC.

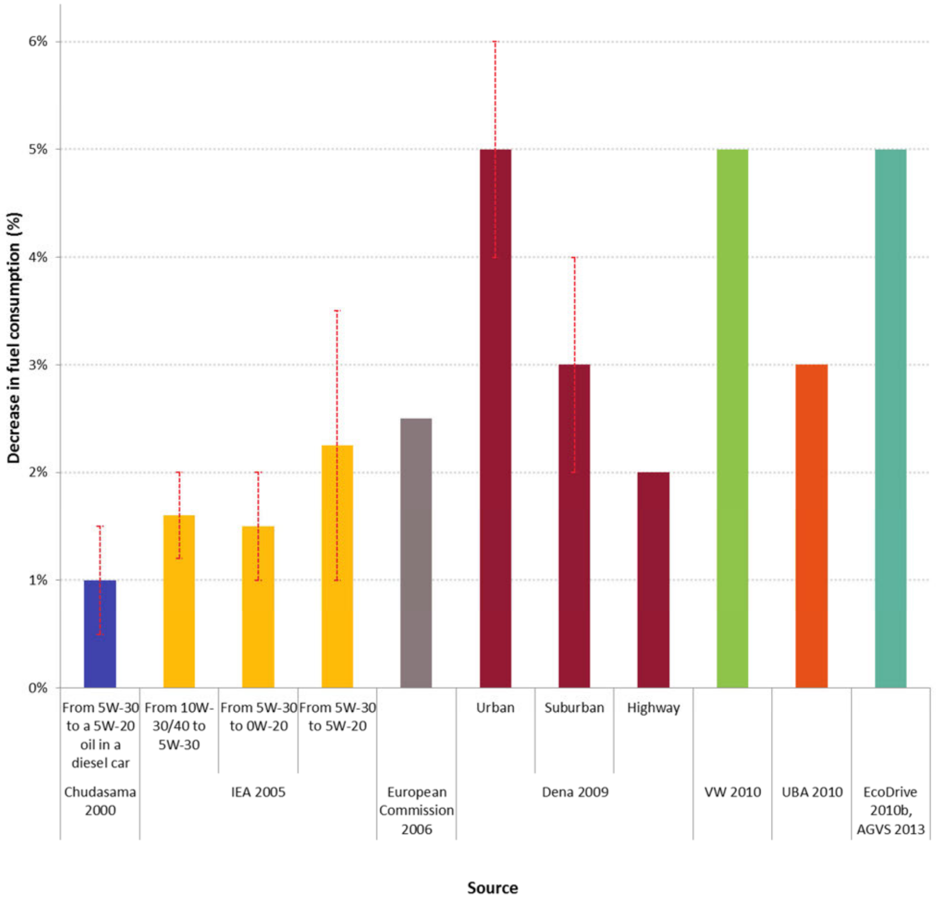

Figure 7-1: Decrease in fuel consumption by switching to lower viscosity motor oil

An earlier study related to the cold start effect showed that it is bigger for short journeys (André 1989). According to a survey conducted by the author for six daily journeys, 26 % of them are less than 1 km and 52 % do not exceed 3 km. The study also found that oil temperature in 18 % of the cases did not exceed 30 °C.

Figure 7-2 shows the relation between motor oil temperature and viscosity for new and used petroleum based oil (15 W-50) and synthetic oil (5 W-20).

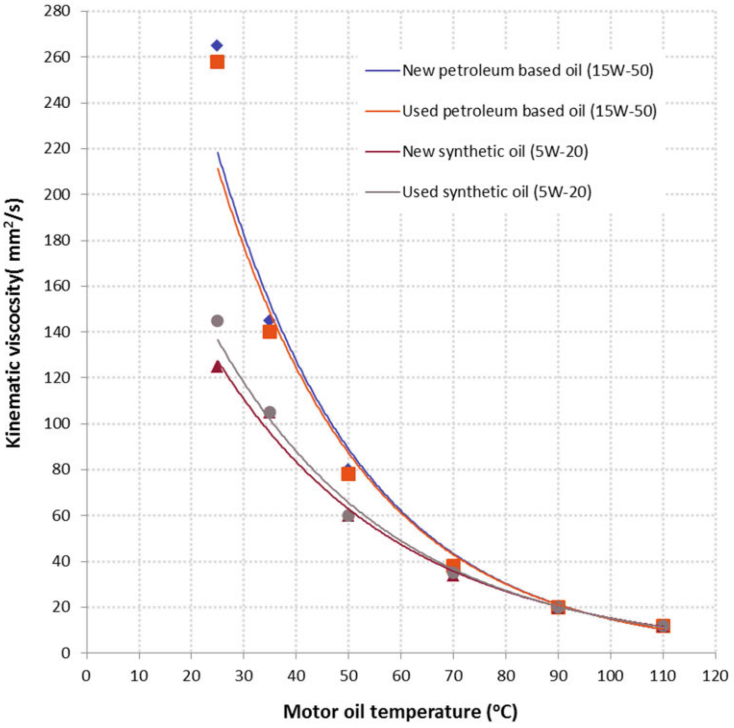

Figure 7-2: Relation between motor oil temperature and viscosity adapted from Andrews et al. (2007)

Honda et al. (2014) state that for a 5 W-30 oil at 30 °C fuel consumption is 20 % higher than at 80 °C. This effect is alleviated through the use of low viscosity oil of grade HTHS 1.7 (High Temperature High Shear Viscosity Oils). The properties of the latter can be improved further at higher temperature with the addition of MoDTC (molybdenum dithiocarbamates) friction modifier as it is shown in Figure 7-3.

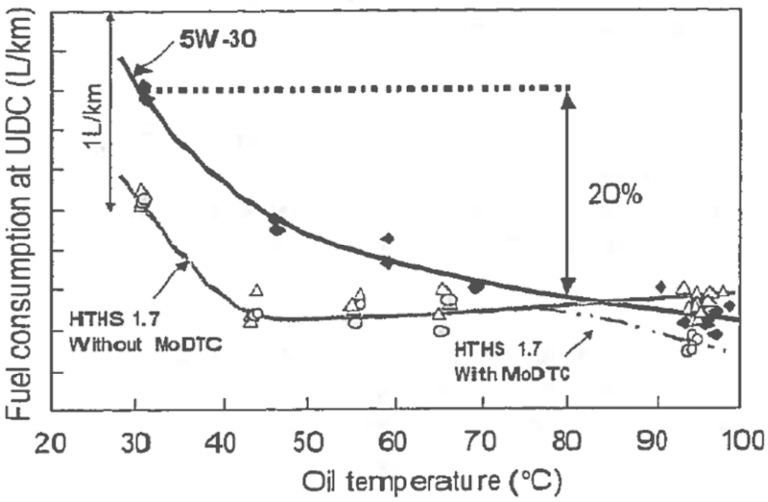

Figure 7-3: Effect of oil temperature on fuel consumption (Honda et al. 2014)

Figure 7-4 illustrates the results of a study by Hawley et al. 2010 where the authors associate kinematic viscosity of the engine lubricant and fuel consumption for NEDC for 25 and – 7 °C ambient temperature.

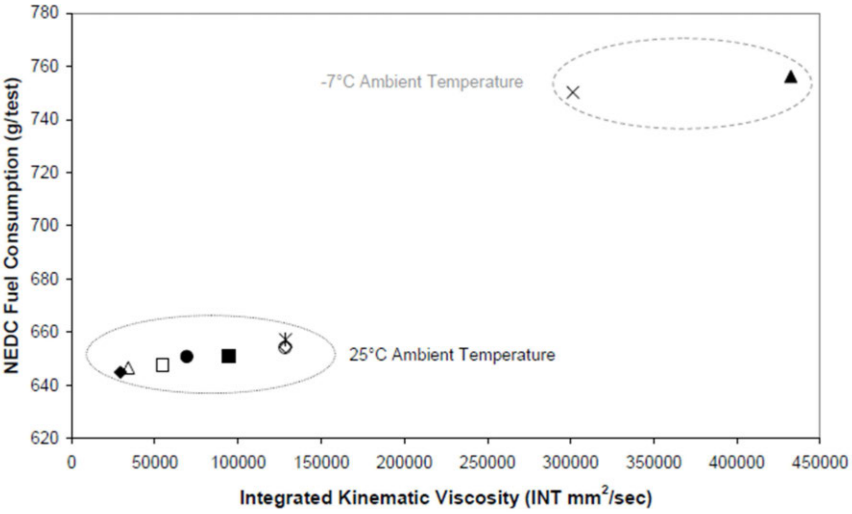

Figure 7-4: Correlation between kinematic viscosity and NEDC fuel consumption (Hawley et al. 2010)

It is expected that for the certification test, vehicle OEMs are using the most appropriate and fuel efficient lubricants exploiting any potential CO_2 benefit (30).

The same practice is advisable for in-use operation but cannot be guaranteed. It is up to the driver or the car owner to follow the manufacturer's suggestion regarding the timely replacement of engine lubricant or the use of more fuel efficient ones. It is expected that at least during the validity period of the vehicle's warranty the majority of cars undergo the advised maintenance on a regular basis which should include the appropriate lubricant change. The criteria influencing the selection of lubricant grade and type by the end user are neither clear nor is the level of awareness regarding the benefits of fuel efficient

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(30) There are online sources claiming that the use of inappropriate lubricants with very low viscosity is another practice employed by OEMs in order to reduce certified CO_2 emissions. No official or scientific evidence was found to support this. Such practices are against the spirit of law and can potentially damage the components of the vehicle being tested.

lubricants. It is estimated that in the case of older vehicles the situation possibly worsens, broadening the gap between certification and actual fuel consumption, as owners tend to be less meticulous about the car's condition and possibly less willing to invest in more expensive fuel efficient lubricants or other replacement parts.

7.3. Tyres

Tyre type and size influence rolling resistance, greatly affecting fuel consumption especially at low speeds (Crolla 2009). European (Regulation (EC) No 1222/2009) lays down a scale of energy efficiency classes based on the rolling resistance coefficient (RRC). The classes range from A being the most efficient to G the least efficient, while the RRC is measured in kg/t (dimensionless quantity). For a passenger car, category A tyres have a RRC of less than 6.5, while a category G tyre has a RRC of more than 12.1, so the variation in RRC can reach 90 %. Such a difference in RRC according to Goodyear (2014) could result in a consumption increase of 7.5 %. Tyre categories with their percentage difference from class to class (upper values used) are presented in Table 7-1 (See also Table 14-17 in Annex). According to Regulation No 117 (Regulation (UN) No 11 2011) the value of rolling resistance should not exceed 12 kg/t for all-season tyres and 13 kg/t for snow tyres.

Maximum RRC limits are foreseen for passenger car tyres sold in Europe post-2016. The value of rolling resistance should not exceed 12 kg/t for all–season tyres and 13 kg/t for snow tyres from November 2016 and 10.5 kg/t and 11.5 kg/t respectively from November 2018. It is estimated, based on tyre sales, that the average RRC of the tyres sold in the EU was 9.25 kg/t (class E tyres) in 2015 presenting an improvement compared to 2013 (9.5 kg/t) due to the introduction of the labelling scheme.

Table 7-1: Tyre categories according to Regulation (EC) No 1222/2009 (2009) and percentile difference

RRC in kg/t	Energy efficiency class	Difference in mean RRC
RRC ≤ 6.5	A	18 %
6.6 ≤ RRC ≤ 7.7	B	17 %
7.8 ≤ RRC ≤ 9.0	C	17 %
9.1 ≤ RRC ≤ 10.5	E	14 %
10.6 ≤ RRC ≤ 12.0	F	N/A
12.1 ≤ RRC	G	

Currently, the tyres sold with the vehicle are not necessarily of the same class as the tyres which were fitted during certification (31). This situation directly creates a discrepancy between the certified and the in-use fuel consumption. However this is expected to improve with the introduction of the WLTP which stipulates that a vehicle shall be measured with the best and worst-case tyres and when the same vehicle is sold with tyres belonging to an intermediate RRC class the fuel consumption shall be corrected accordingly via linear interpolation.

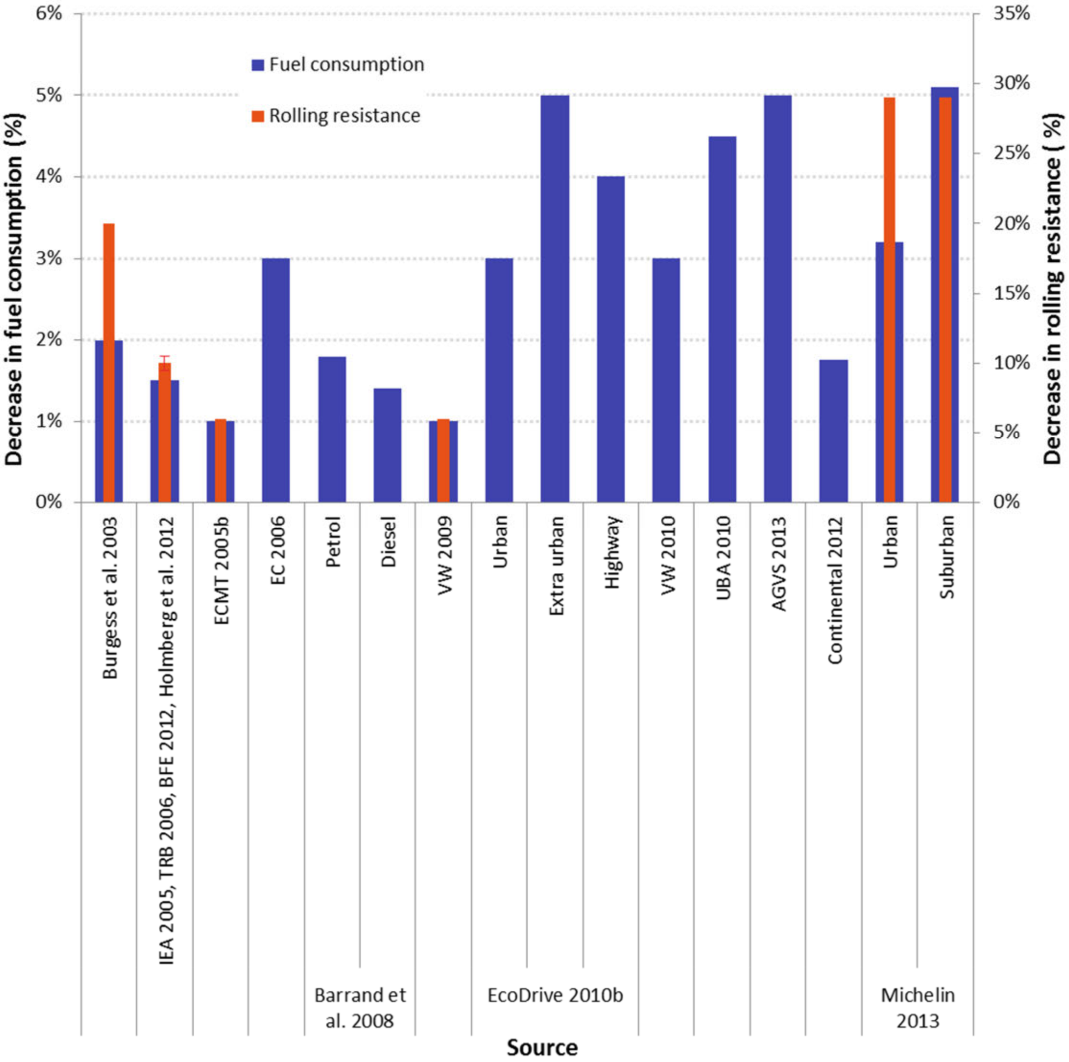

Figure 7-5: Decrease in fuel consumption, with the use of lower resistance tyres

In addition to the difference between the RRC of the tyres used for certification and those actually installed on the vehicles, additional fuel consumption can occur during regular vehicle operation due to a number of factors such as improper maintenance, low tyre

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(31) According to Regulation (UN) No 83 (2011). 'Addendum 82: Regulation No 83. Uniform provisions concerning the approval of vehicles with regard to the emission of pollutants according to engine fuel requirements. E/ECE/324/Rev.1/Add.82/Rev.4–E/ECE/TRANS/505/Rev.1/Add.82/Rev.4.' the vehicle during coast down shall be equipped with the widest tyre. If more than three tyre sizes are available, the second widest shall be chosen. In general, the wider a tyre, the higher its rolling resistance. Nevertheless this does not necessarily define the energy class of a tyre, so the widest class A tyre can be chosen while a vehicle is sold with a narrower tyre of a lower energy class.

pressure, temperature and tyre wear. A typical example is the replacement of tyres, where moving to tyres of lower RRC class may have a significant impact on consumption and CO_2 emissions. An increase of 20 % in rolling resistance, which corresponds to a change of up to two categories can increase fuel consumption by 2 % (Mellios 2011). Similarly, important benefits can occur by replacing 'black' tyres with 'green' ones which decrease rolling resistance by approximately 40 % (Michelin 2013). This replacement could, according to the author, reduce fuel consumption on average by 4 %. In-house calculations based on the available literature values show that replacing high rolling resistance tyres with low resistance ones could decrease fuel consumption on average by 2.1 %. Figure 7-5 presents the impact on fuel consumption according to literature (See Table 14-18 in Annex).

In addition to tyre category and characteristics, tyre condition and maintenance can also significantly influence the RRC. While tyre wear may reduce the RRC it is also associated with loss in grip and other undesirable characteristics which can make tyres unsafe and dangerous to use. It is extremely difficult to assess these influences on fuel consumption and such practices should be avoided for safety reasons. Tyre wear control is part of the mandatory technical inspection done in European cars on a biannual basis.

Winter tyres, which are mandatory during winter season in some countries (e.g. Germany (The AA 2014)) also present higher RRC compared to regular tyres and subsequently lead to a certain increase in fuel consumption (Continental 2012). However, they are designed as such for safety reasons and thus their use shouldn't be questioned. It is expected that winter tyre RRC will improve with time as does RRC of regular tyres.

The most important aspect of proper tyre maintenance is tyre pressure control. All tyres have a designated operating pressure. As demonstrated in Figure 7-6 (Michelin 2013) tyre rolling resistance is not linearly linked to tyre pressure, with deflations of 0.3 bar causing increases in rolling resistance of 6 % while deflations of 1 bar result in a 30 % increase in rolling resistance. Many online sites mention tyre over inflation as a practice to reduce rolling resistance. In fact as demonstrated in Figure 7-6 an over inflation of 1 bar can reduce rolling resistance by approximately 20 %. However it should be made clear that operating a tyre outside the manufacturer's specifications is likely to have deteriorating effects on other tyre characteristics such as grip, noise and durability, compromising safety.

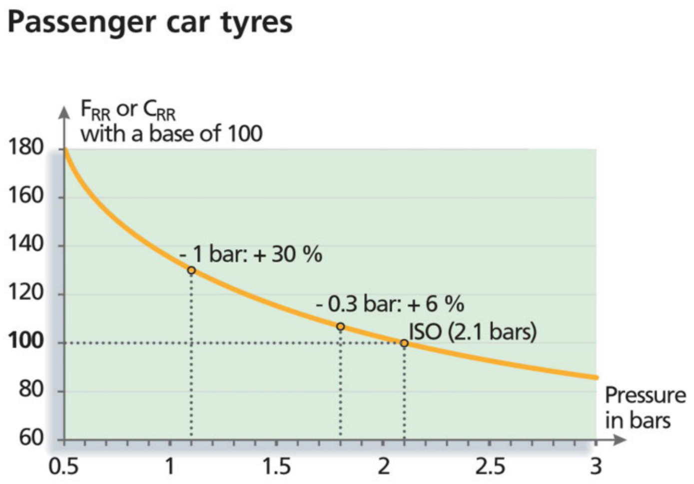

Figure 7-6 Evolution of tyre rolling resistance as a function of tyre pressure. Base rolling resistance equals 100, measured at 2.1 bar according to ISO 8767 (Michelin 2013).

Ageing, accumulated mileage and temperature variations can lead to pressure losses. Low tyre pressure results in higher rolling resistance (ECMT 2005, ADAC 2012c), which directly increases fuel consumption (EAPA — Eurobitum 2004, TRB 2006). A US study by Pearce and Hanlon (2007) suggests that an average under-inflation of 2.639 psi (0.18 bar) results in a decrease of 0.16-0.22 MPG (0.07 0.09 km/l) in a city and 0.22-0.29 MPG (0.09-0.12 km/l) on a highway. A more recent study by Thomas et al. (2014) examined the effect of low tyre pressure on fuel consumption over constant speed conditions in a range between 64 and 129 km/h (40 to 80 mph) with an 8 km/h interval (5 mph). The results are presented in Figure 7-7, where the original units of MPG were converted into l/100 km (See Table 14-20 in Annex). Regular pressure checks of tyre pressure can lead to measurable improvements in fuel consumption. Figure 7-8 presents a summary of the effects of tyre pressure on fuel consumption based on the collected literature sources (See Table 14-19 in Annex).

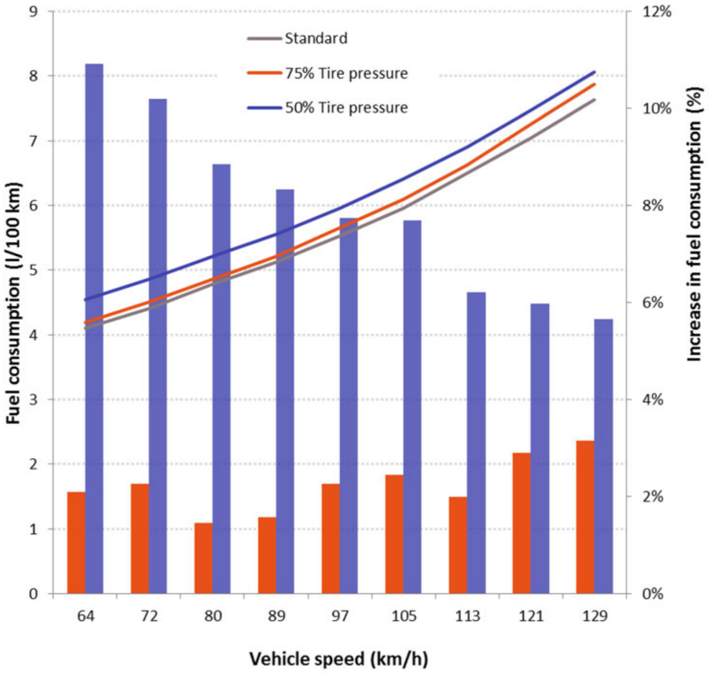

Figure 7-7: Increase in fuel consumption for various speeds, for 75 % and 50 % of the recommended tyre pressure, based on an American study by Thomas et al. (2014). Adapted chart, bars correspond to percentile increase according to colour. Original units, US MPG and miles/hour were converted to l/100 km and km/h.

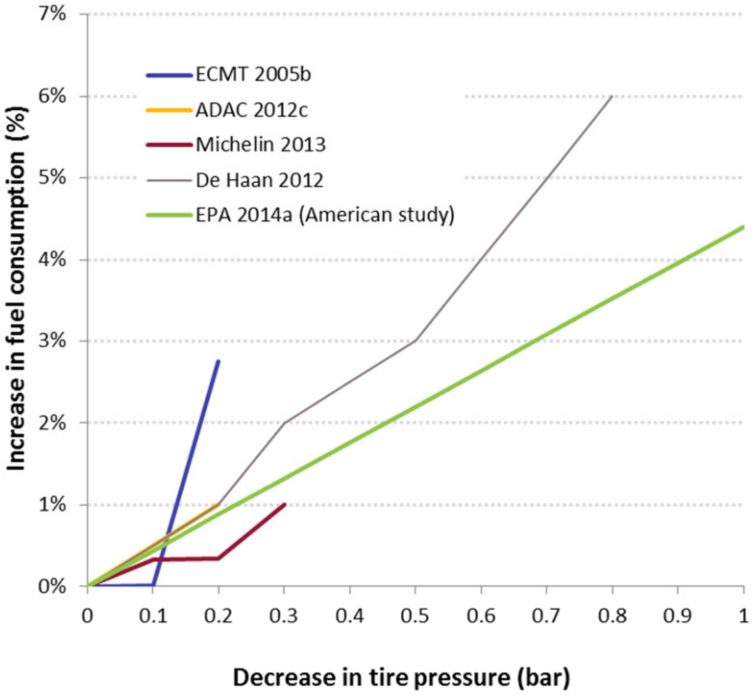

Figure 7-8: Effect of lowered tyre pressure on fuel consumption

As in the case of lubricants, it is difficult to assess customers' attitudes as regards energy-efficient tyres or appropriate tyre maintenance. For the first 3 years of a vehicle's life OEM tyres are usually installed. This initial tyre selection is considered very important as many users tend to keep the original tyre type. Until a vehicle is retired, three to five sets of tyres are replaced making the tyre aftermarket and the replacement of tyres very important with respect to environmental performance. Providing sufficient and accurate information regarding their benefits is very important for promoting fuel-efficient tyres. Similarly, it is essential that drivers are aware of the benefits associated with proper tyre maintenance.

Tyres in current certification test

Under the NEDC at Euro 6 standards, the widest tyre should be chosen for the testing among all those that can be fitted on a given vehicle. If there are more than three tyre sizes, the second worst tyre should be selected. Under the new WLTP, for individual vehicles in vehicle interpolation family, the CO_2 interpolation method shall be based on the real RRC values for the tyres fitted to those individual vehicles (UNECE 2015). Looking only at procedural definitions NEDC might seem more stringent compared to WLTP concerning the tyre selection. However, the prescription of the tyre width in NEDC does not necessarily imply the worst RRC, because RRC does not depend only on tyre width, thus for the type-approval of a vehicle the widest tyre could be selected with a relatively low RRC, while the other vehicle of the same CO_2 family might be put on the market with worse RRC tyres. With WLTP these flexibilities will be eliminated and CO_2 emission results will increase.

As mentioned, another important element for the RRC is the tyre pressure. In NEDC there was no prescription concerning the tyre pressure, thus the common practice was to inflate the tyre up to the maximum pressure for which it had been designed, obtaining an advantage on the RRC. In real life it is not a common habit to keep the tyre pressure always to the highest possible level, on the contrary it often happens that the actual tyre pressure during normal duty of the vehicle is even below the minimum pressure value of the tyre. In order to take in account this 'real-life' aspect of the tyre pressure, the WLTP prescribes that the type-approval tests (on both TMH and TML) are carried out with the tyre pressure set at the minimum of its range. These particularities of the type approval procedures have been taken into account when formulating the scenarios of Chapter 11.2.

Concerning the impact of tyre tread depth on rolling resistance, the higher the depth, the higher the RRC is. The WLTP standard for the minimum tyre tread depth is more stringent (80-100 %) than under NEDC (50-90 %). We can assume an average tyre tread increase of 2 mm over WLTP compared to the NEDC with the effect of 0.1 kg/tonne per mm. Consequently, the corresponding increase in the RRC of 0.2 kg/tonne leads to an approximately 0.3 % increase in CO_2 emissions over the WLTP.

7.4. Other

In addition to tyres and lubricants, several other parameters were investigated that are related to regular vehicle maintenance. The effect of misaligned wheels, suspension losses and clogged air filters was examined.

Misaligned wheels can also increase fuel consumption (ECMT 2005, Hill 2011, Michelin 2014) in passenger cars by up 3 % for a 2 mm misalignment (Ahn 1998), while in other cases it is suggested that this figure can rise by up to 30 % (Pedders n.d.). Only a few studies were found quantifying this effect. However, on this topic there are several studies for heavy duty vehicles, where the impact seems to be greater.

Suspension can affect fuel consumption (EAPA — Eurobitum 2004), as suspension losses make about 23.2-39.5 % of those related to the rolling resistance (Soliman et al. 2013). Unfortunately, it was difficult to find additional citations quantifying the effect for light duty vehicles.

Clogged air filters were found to increase fuel consumption in old carburetted cars by 2 to 6 %, but there was no information on similar effects occurring on modern fuel injection spark ignition cars; presumably the effect is much lower or zero as fuel injection in modern cars is adapted to ensure correct mixture. These values are in accordance with an older report (ECMT 2005), which states that fuel consumption is increased by up to 6 % for older cars. This case, for old carburetted cars, is also verified by the U.S. Department of Energy — U.S. Environmental Protection Agency (DOE — EPA 2014d) and presented on their fuel economy website. Thomas et al. (2013) tested two turbocharged vehicles with clean and clogged air filters. Figure 7-9 and Figure 7-10 show their results over the FTP test cycle. The authors did not notice a significant change. According to Norman et al. (2009) there should be further research on this topic on compression ignition engines, while they point out that the greatest effect of a clogged air filter is a decrease in maximum power and acceleration.

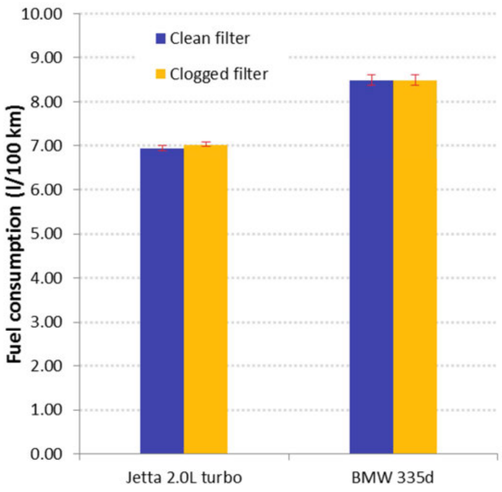

Figure 7-9: Effect on fuel consumption depending on filter condition over FTP test cycle (Thomas et al. 2013)

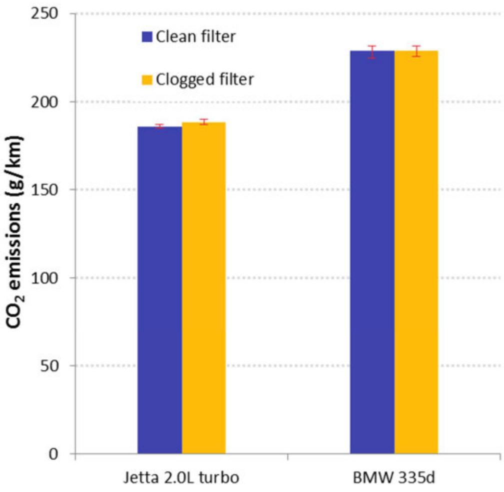

Figure 7-10: Effect on CO_2 emissions depending on filter condition over FTP test cycle (Thomas et al. 2013)

7.5. Simulation scenario and results

7.5.1 Engine oil

The cases tested by means of simulation address the effect of engine oil and rolling resistance on CO_2 emissions. The engine oil used for the baseline scenario is SAE 5 W-30 for the petrol vehicles and SAE 10 W-40 for the diesel. The values used in the simulation represent the kinematic viscosity at 40 and 100 °C oil temperature and are shown in Table 7-2.

Table 7-2: Kinematic viscosity of the motor oils used in the simulation

Kinematic viscosity (mm^2/s)	Engine oil grade	Temperature	
		40 °C	100 °C
	SAE 5W-30 (Petrol baseline)	63.2	10.5
	SAE 10W-40 (Diesel baseline)	93.3	14.6
	SAE 0W-20	44.8	8.7
	SAE 5W-20	45.2	8.4
	SAE 5W-40	90.9	14.4
	SAE 10W-30	69.0	11.0

The simulation results for the various engine oil grades are shown in Figure 7-11.

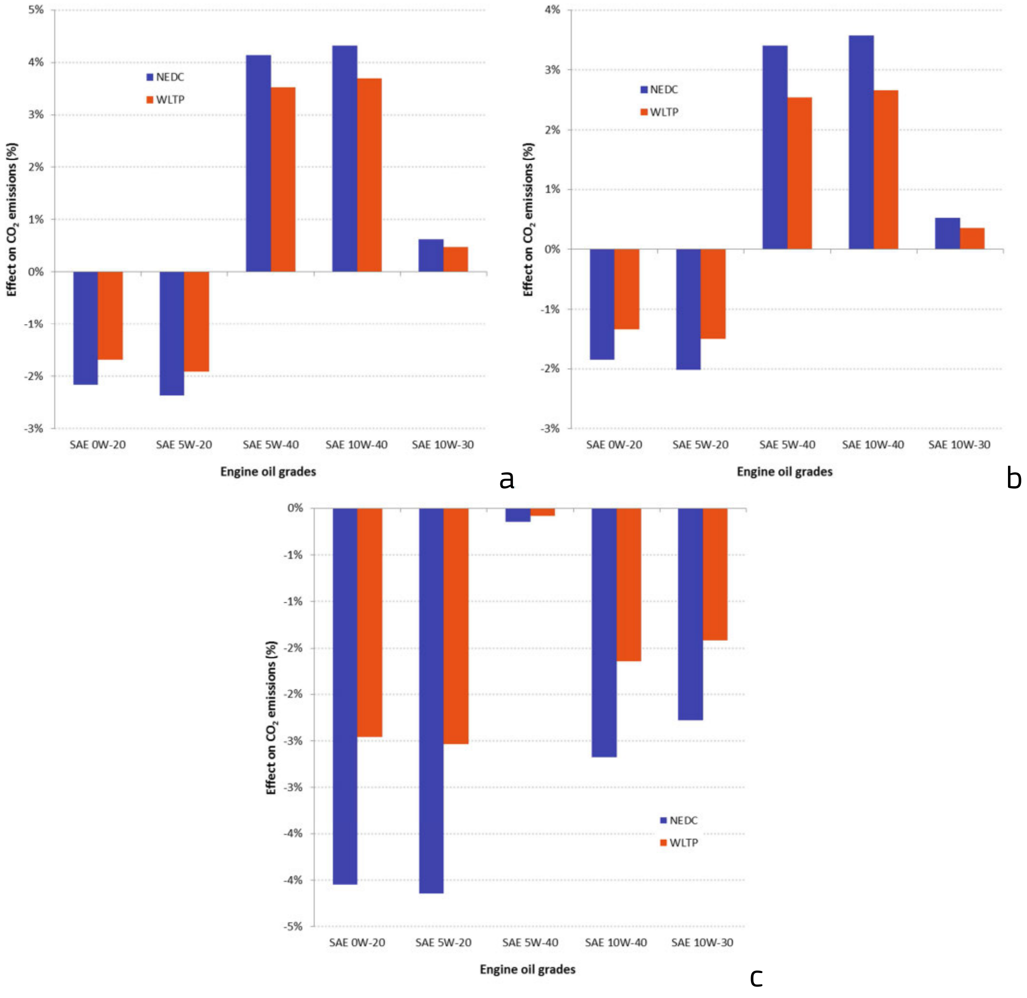

Figure 7-11: Effect of engine oil on CO_2 emissions for a petrol NA (a), a petrol turbocharged (b) (Baseline SAE 5 W-30), and a diesel vehicle (c) (Baseline SAE 10W-40)

7.5.2 Tyres

The effect of rolling resistance was tested stepwise with 10 % increments from -40 % to 20 % applied to the baseline. This range covers all of the tyre energy efficiency classes. The results are presented in Figure 7-12 with absolute rolling resistance values at the upper limit of each energy efficiency class.

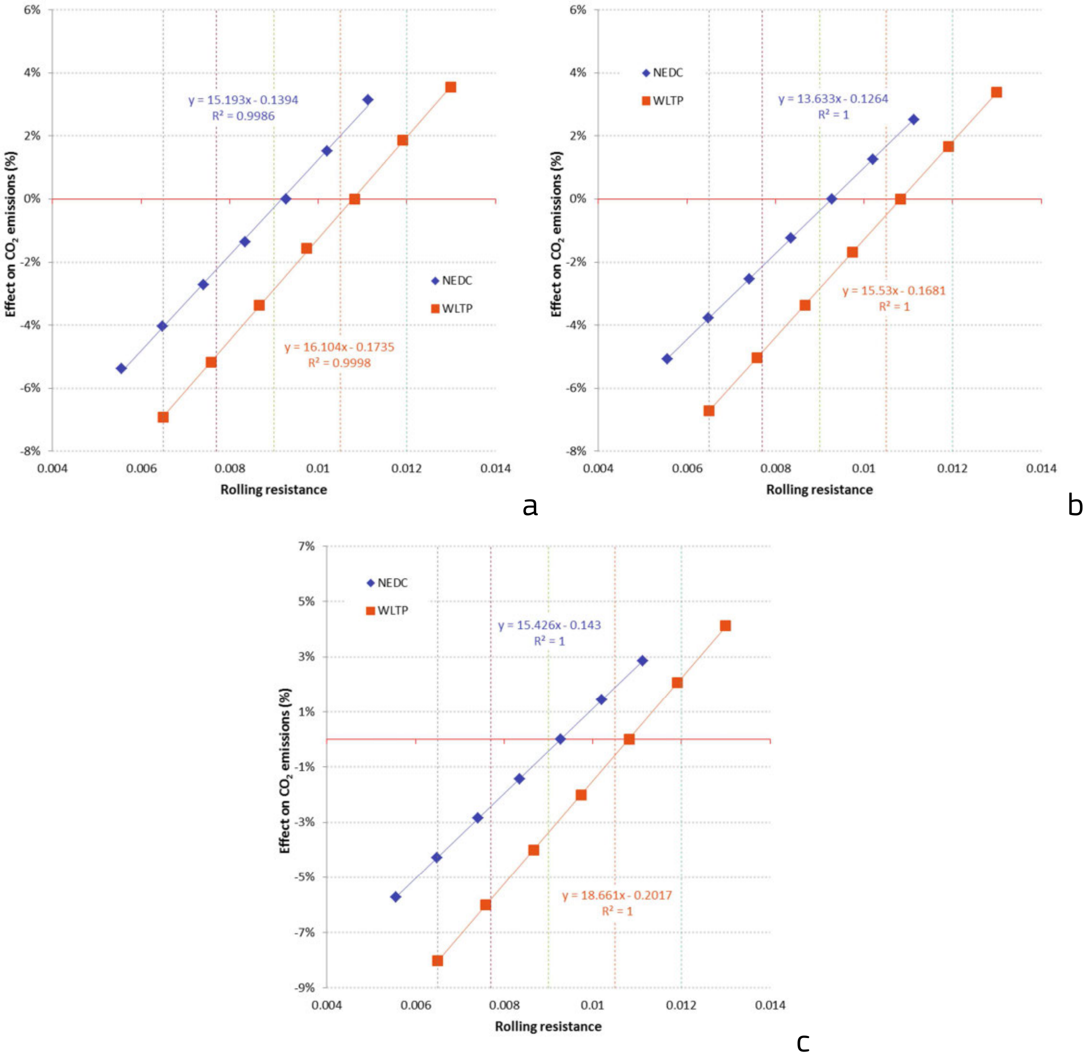

Figure 7-12: Effect of rolling resistance coefficient on CO_2 emissions for a petrol NA (a), petrol turbocharged (b) and diesel (c) vehicle

Charts are also included for each vehicle where the differentiation in rolling resistance is expressed in a percentage change over the baseline scenario. The results are shown in Figure 7-13.

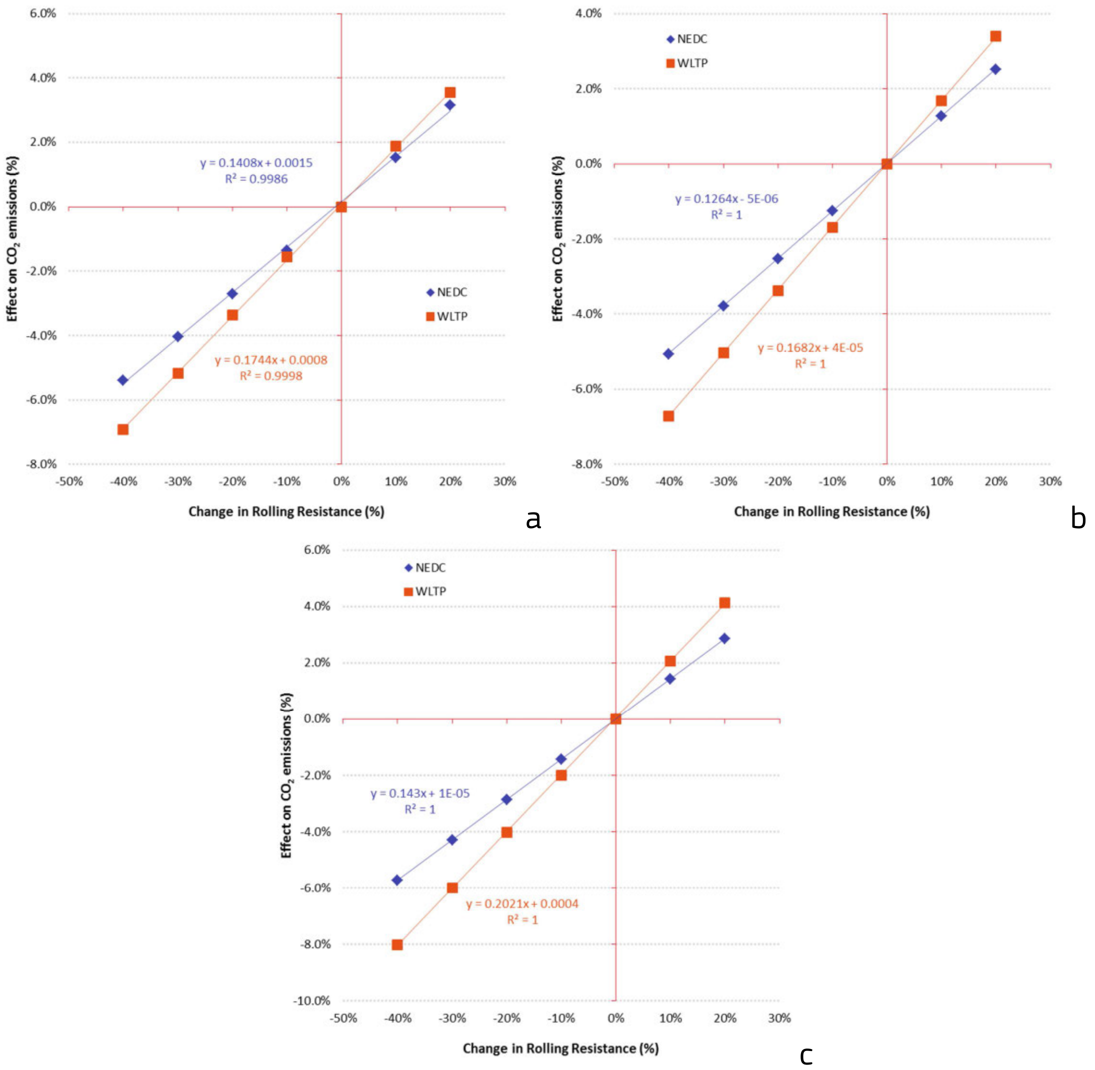

Figure 7-13: Effect of change in rolling resistance coefficient on CO_2 emissions for a petrol NA (a), petrol turbocharged (b) and diesel (c) vehicle

7.6. Discussion — Overview

The effect of lubricants on fuel consumption was quantified based on a significant number of sources and is described in detail. Several OEM sites address the subject (VW 2010a). According to literature, the use of low viscosity oil can provide benefits in fuel consumption of 3.8 % on average.

The simulation results have also shown a significant effect on CO_2 emissions related to the viscosity of the oil. Changes in engine oil viscosity result in a change in emissions on a range from – 2.8 % to 3.2 % for NEDC for petrol vehicles and up to –4.1 % for diesel (32). For WLTP, petrol cars can benefit by up to 1.9 % lower emissions for low viscosity oils, while the corresponding value for diesel is 2.5 %. Higher viscosity engine oils can increase CO_2 emissions by up to 3.7 % in petrol vehicles.

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(32) The baseline engine oil for diesel was the thickest of all, so all the other oils provided lower CO_2 emissions. For this reason we did not provide the upper limit.

Several sources focus on the influence of tyres on fuel consumption, as tyre type labelling is mandatory under EU legislation. There appears to be sufficient information for the public regarding the performance of different tyre types and in some cases not only the tyre class is provided but also the absolute RRC value. Magazines and manufacturers' sites provide information and hints for lower fuel consumption with the use of 'green' low rolling resistance tyres. A lot of public informative material was found presenting the advantages and the disadvantages of winter and all-season tyres. Tyre pressure effect on fuel consumption is examined thoroughly in literature and there are also a lot of online discussions in this context. According to literature, a decrease of 10 % to 20 % in rolling resistance would result in 2.1 % lower fuel consumption.

The simulation results regarding tyres have shown that lowering the rolling resistance by 10 % to 20 % can decrease CO_2 emissions by 1.4 % to 2.8 % for NEDC and by 1.8 % to 3.7 % for WLTP. An improvement of two energy efficiency classes, which is 30 % lower rolling resistance, results for all vehicles in a decrease of CO_2 emissions of – 4.1 % over NEDC and – 5.6 % for WLTP. On the contrary, an increase of 20 % of the rolling resistance would result in additional 2.8 % CO_2 emissions for NEDC and 3.8 % for WLTP.

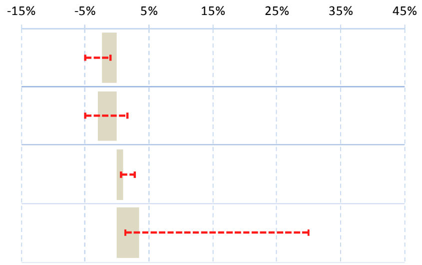
It was not possible to identify studies regarding misaligned wheels and for this reason the topic was not analysed further. The majority of the online investigations returned results for systems and methods for the improvement of wheel alignment. At the same time, some studies were identified addressing heavy duty vehicles and how misalignment affects fuel consumption. Public concern around this issue appears to be mainly focused on maintenance cost, damage to the car, tyre wear and driving safety.

It was also not possible to find significant information regarding suspension and suspension losses and quantify its effect on CO_2 adequately. The majority of the searches returned guidelines about vehicle tweaking for better performance and handling. These could have an effect on fuel consumption, whether positive or negative, but it requires further investigation.

It was found that the condition of air filters has mainly a significant impact on older cars with a carburettor. Further research is necessary for modern cars for all engine types and fuels.

A summary based on the values found from the literature review is presented in Figure 7-14.

Category	Factor		Literature median value	Distribution	Sources No.
Vehicle condition	Lubrication	Use of low viscosity motor oil results in lower internal friction	-2.4%		13
	Tires	Low resistance tires by 10 - 20%	-3.0%		19
		Lower tire pressure by 0.2 bar	1.0%		
	Other	Clogged air filters, misaligned wheels, poorly tuned engine	3.5%		5



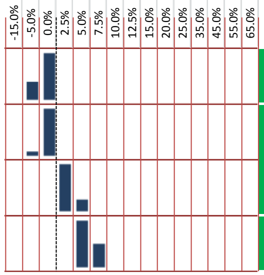


Figure 7-14: Summary table of the effect of vehicle condition on fuel consumption. Error bars represent minimum–maximum values reported.

8. Operating mass

8.1. About operating mass

The operating mass of a vehicle consists of the mass of: (i) the empty vehicle, (ii) the fuel in the tank, and (iii) the passengers and equipment. An increase in the operating mass increases fuel consumption, as more power is needed to move the extra load (Crolla 2009, Bishop et al. 2014) while the rolling resistance is also affected proportionally (Van Mensch et al. 2014). In this chapter, in addition to the operating mass, the case of trailer towing, the influence of the extra mass resulting from roof boxes (33) and the effect of additional passengers (occupancy rates) are also investigated.

In the NEDC test procedure the mass of the vehicle used for road load measurement is equal to kerb mass + 100 kg and this usually represents a best-case scenario with respect to the actual mass of the vehicles belonging to a given vehicle family. In WLTP the measurement of road load parameters must be carried out either in a worst-load case condition for a given vehicle family (TMH), or can be completed by a second set of measurements best-load case scenario (TML) that, together with the high-load one, set the boundary limits of the road load parameters for the vehicle family. In both cases (TML and TMH) the mass of the vehicle is higher than the equivalent NEDC mass, so the expected impact on CO_2 emission is toward higher values.

8.2. Vehicle mass

Operating mass contributes to the discrepancy between certified and real operation fuel consumption as it is usually higher than the vehicle mass set during the current vehicle certification. For current type approval purposes the concept of reference mass is introduced. It equals the empty vehicle mass with an additional 100 kg to account for the driver and fuel. The reference mass is considered by definition lower than the operating mass as it doesn't take into account the weight of additional passengers, equipment transported or variations of the vehicle mass caused by extra components and accessories and different levels of equipment. In addition, the NEDC reference mass is linked to specific tiers (inertia classes) which define the vehicle inertia that is actually simulated during the certification test. The latter lead to a non-continuous distribution of vehicle mass contrary to what happens in reality where mass is a continuous quantity.

The introduction of the WLTP is expected to address this issue as vehicle mass will have continuous values and new definitions of test mass are foreseen as described in paragraph 2.2.1. Further to this, the test will be performed for the minimum and maximum possible masses (test mass low and test mass high) that a vehicle might present, depending on the equipment installed when it is sold. Fuel consumption for the same vehicle with intermediate mass configurations shall be calculated through linear interpolation based on the measured values.

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(33) Also examined previously in Chapter 4 with respect to its effect on aerodynamic resistances.

With respect to the effect of mass in real-world driving, an additional 100 kg is reported to increase fuel consumption by an average 7 % for a medium-sized car of 1 500 kg (FORUM Umweltbildung 2008). In absolute numbers, an additional 100 kg load can cause an increase from 0.3 to 0.5 l/100km (EcoDrive 2010b, VW 2010b, VDA 2011, ADAC 2012a, Löhrer 2013). Figure 8-1 presents the effect of vehicle weight on fuel consumption, according to the values found in the literature review (See Table 14-21 in Annex).

At this point it should be noted that not all literature sources make clear reference to the reference vehicle mass considered during the measurements or the calculations. In most cases discrete mass increases are reported together with their effect on CO_2 emissions. These discrete increases make sense for passenger cars where the vehicle is used for transporting passengers rather than goods. It is therefore understandable why the extra 100 kg mass is considered by many researchers as this usually reflects the transport of an extra passenger and his equipment or in the case of the European certification test the shift from one inertia class to the next which in most cases signifies an increase of 120 kg. Where the respective information was available and in the simulations performed we try to demonstrate the effect of mass increase as a continuous quantity.

In real life, the factor causing the greatest variation in vehicle weight is the number of passengers, also referred to as the occupancy rate. Because of its particularity (34), occupancy rate is examined separately. Average passenger weight is estimated at 75 kg, while additional equipment or luggage weight varies depending on the purpose of the trip. It can range from a few kg for everyday use to more than a hundred kg for long distance trips. The average occupancy rate in the EU-15 is 1.6 (EEA 2010a), resulting in an additional mass (above that assumed in the NEDC) of 45 kg. At the same time, 5-10 kg of equipment should be also accounted for, leading to an extra load of 50-60 kg that is not taken into consideration in the certification test. Considering an average 7 % increase per 100 kg as shown in Figure 8-1 can result in an increase of 4 % in fuel consumption.

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(34) Higher occupancy rates increase CO_2 but are overall beneficial for the environment.

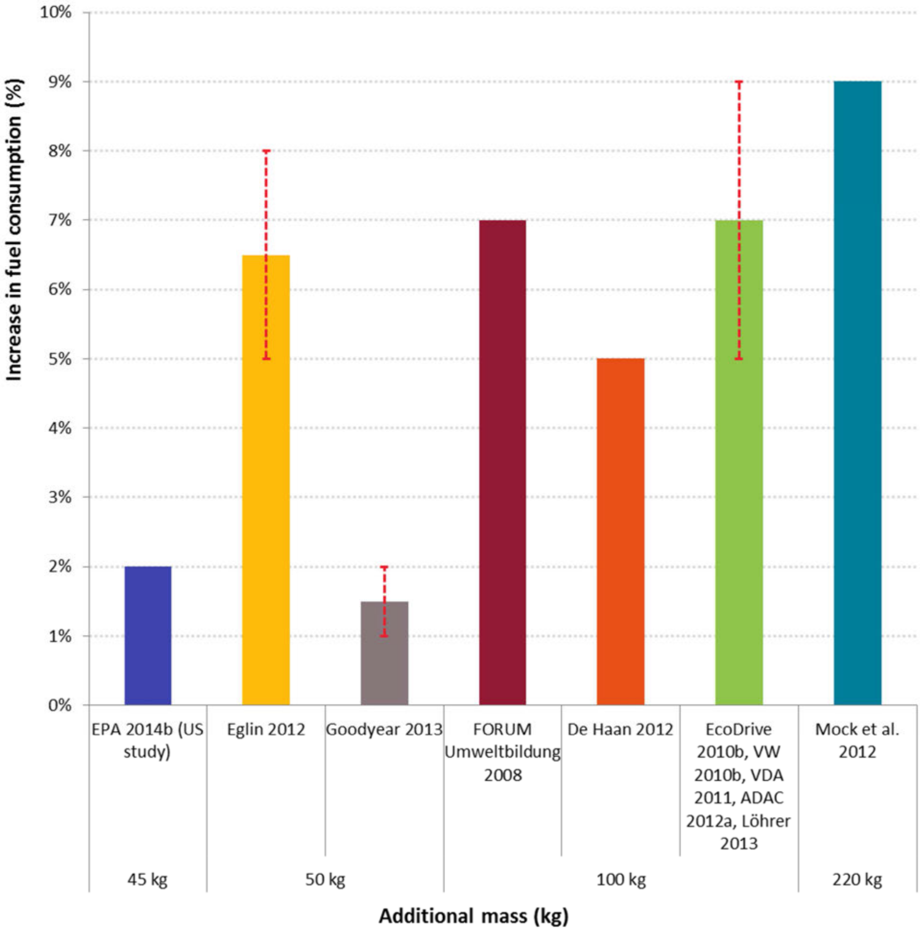

Figure 8-1: Increase in fuel consumption due to additional mass as reported in different sources

8.3. Trailer towing

Trailer towing influences several factors which increase fuel consumption. Vehicle mass is increased due to the additional weight of the trailer and its load, while the extra wheels introduce additional rolling resistances. Vehicle aerodynamic resistances are also influenced and the driving style is usually adjusted to the new conditions. In general, towing causes a reduction in vehicle speed and leads to a milder driving. The reduced speed partly counterbalances the effect of deteriorated aerodynamics. Finally, additional energy is needed for lights and other trailer accessories. The decrease in fuel economy due to towing is pointed out by the U.S Department of Energy (2014d).

The increase in fuel consumption due to towing was examined in a study conducted by Lenner (1998) in which he tested a passenger car towing an unloaded trailer and the same trailer loaded at 60 % of full load capacity (35). Tests were carried out at speeds ranging from 70 to 90 km/h. The mass of the vehicle was 1 408 kg with a 2.15 m^2 frontal area and the trailer had a length of 4.3 m and a width of 2.2 m. The height of the trailer was minimal and its frontal area was fully within the frontal area of the vehicle, so any effect on aerodynamic resistances is expected to be limited. The results of that study are

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(35) The total weight of the empty trailer was 310 kg and 564 kg including the 60 % capacity load.

presented in Table 8-1. Thomas et al. (2014) realised an experiment with an SUV (4.0L V6 engine, 2 268 kg, 2.53 m^2 frontal area) towing a trailer of 1 588 kg total weight, length of 3.66 m, width of 1.83 m and height of 1.83 m. The frontal area was increased by 37 % (to 3.47 m^2) when towing. The results for various speeds ranging from 80 to 129 km/h are presented in Figure 8-2.

Table 8-1: Increase in fuel consumption for towing an unloaded trailer (Lenner 1998)

Speed (km/h)	Reference	Trailer		Loaded trailer	
	Fuel consumption (l/100km)	Fuel consumption (l/100km)	Increase	Fuel consumption (l/100km)	Increase
70	6.96	9.24	32.8 %	9.52	36.8 %
80	7.37	10.06	36.5 %	10.16	37.9 %
90	7.87	11.25	42.9 %	11.41	45.0 %

8.4. Roof box (mass increase)

The effect of a roof box on fuel consumption due to its influence on aerodynamics was examined in Chapter 4. When a roof box is laden, the additional mass affects fuel consumption accordingly. The average empty weight of a roof box is about 15 kg. An average maximum load of 60 kg would result in additional 75 kg (5.5 % mass increase for a vehicle with 1 360 kg mass), which is considered the weight of the average passenger. According to the values presented in Table 14-21, this increase for an average European vehicle can increase consumption and CO_2 emissions between by 2 to 5 %. Regarding the combined effect of weight and aerodynamic resistances increase, it was estimated that consumption can increase by 15 % on average for speeds higher than 100 km/h. More details are provided in Figure 8-3 (See Table 14-22 in Annex).

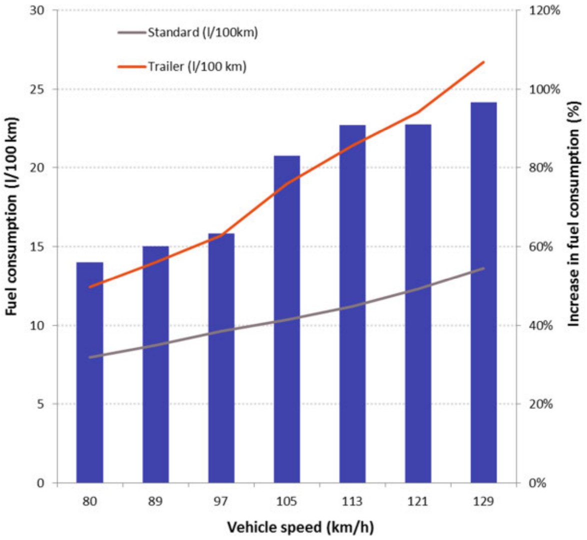

Figure 8-2: Increase in fuel consumption for towing a trailer for various speeds, based on an American study by Thomas et al. (2014). Adapted chart, bars correspond to percentage increase. Original units, US MPG and miles/hour were converted to l/100 km and km/h.

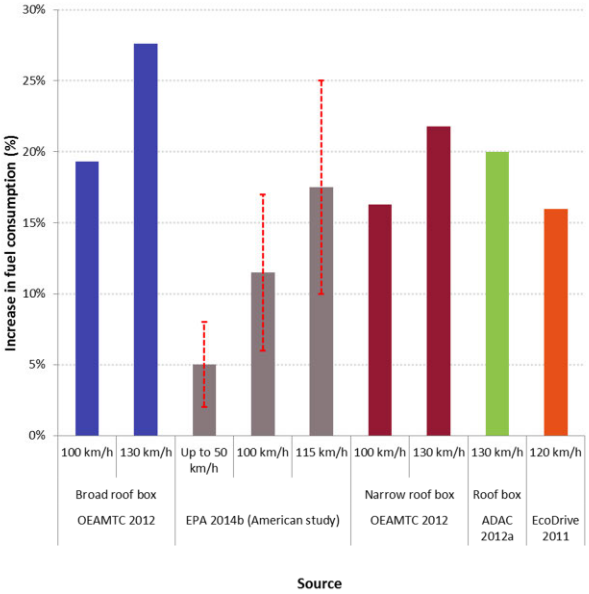

Figure 8-3: Increase in fuel consumption because of laden roof box (influence on both mass and aerodynamics considered). Different vehicle configurations considered in each study.

As the roof box is placed on the top of the car, the centre of gravity of the vehicle is raised raising the question of its effect on consumption in addition to stability. It should be noted that no studies investigating this effect were found.

8.5. Occupancy rates

Occupancy rate is defined as the number of occupants per vehicle, including the driver. As mentioned previously the addition of an extra passenger and his luggage can cause an increase of about 5-7 % compared to the certification value. CO_2 emissions can be divided by the total passengers in order to find the CO_2 emissions per passenger which is a commonly used metric to assess the environmental impact of different passenger transport modes. A high occupancy rate is desirable, as although it increases the operating mass of the vehicle and therefore the fuel consumption, the CO_2 emissions per passenger transported are reduced. In this chapter the occupancy rates of various means of transportation were found and compared.

The average occupancy rate of passenger cars has decreased from 1.75 in 1980 to 1.6 in 2003 in three selected European countries as shown in Figure 8-4 (EEA 2006), while the data provided by IEA in 2005 was 1.37 for urban vehicle occupancy and 1.15 for commuting vehicle occupancy (IEA 2005). The average occupancy rate for passengers cars in 2008 was 1.8 and 1.6 for the EU-12 and EU-15 countries respectively (EEA 2010b, EEA 2010a). Given the rate of decrease, one would expect even lower values at present. On the other hand, the promotion of car-pooling, car sharing websites and the economic crisis may have modified this trend. However, it was not possible to retrieve more up-to-date information regarding occupancy rate at European level (36).

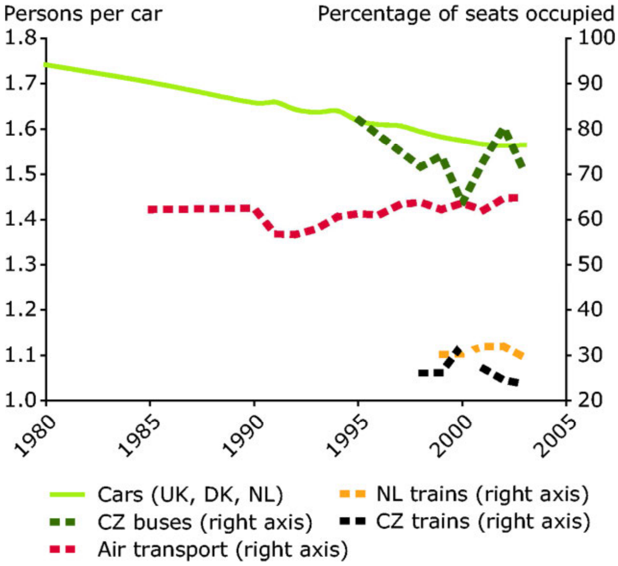

Figure 8-4: Occupancy rates for various media of transportation (EEA 2006).

An overview of passenger car occupancy rates between 2004 and 2008 in different European countries is shown in Figure 8-5 (EEA 2010a).

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(36) The Eurostat website states that the occupancy rate indicator is discontinued, thus no further assessments are produced.

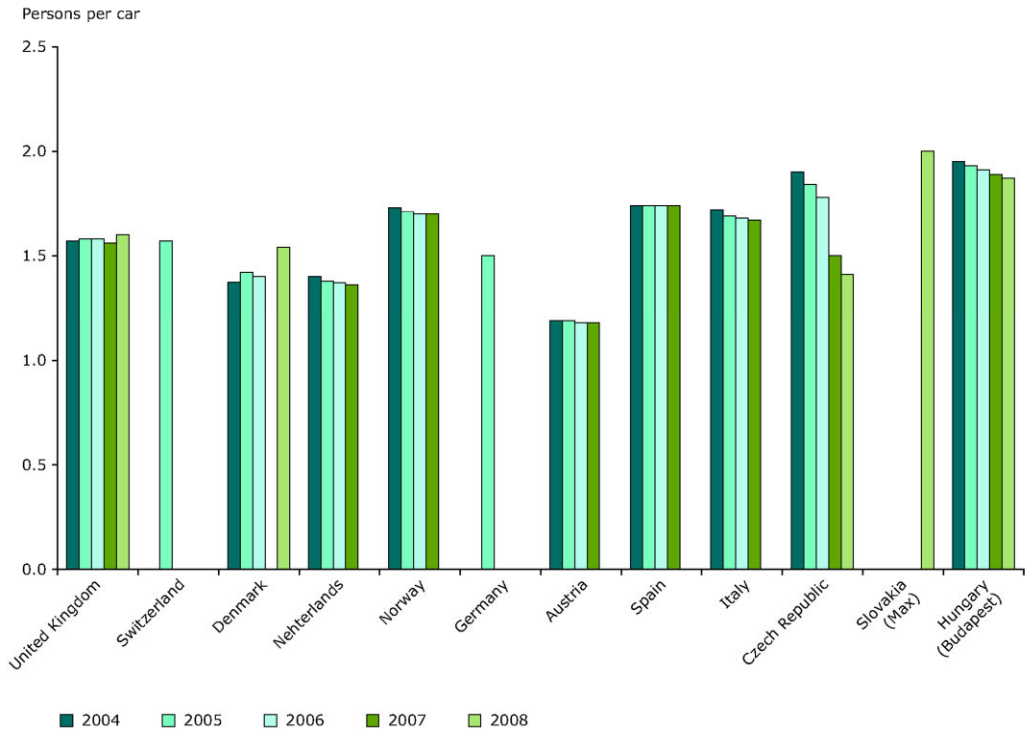

Figure 8-5: Passenger car occupancy rates for various European countries between 2004 and 2008 (EEA 2010a)

As discussed previously, assuming an occupancy rate of 1.7, passengers would increase the mass of an average passenger car (1 360 kg) by 3.8 %. As will be demonstrated in the simulations section this mass increase would result in a CO_2 emissions increase over NEDC of about 1.5%, or about 1.8 g/km for vehicle certified at 125 g/km.

8.6. Simulations

The operating mass of the vehicle in this case is the mass of the vehicle plus the additional mass that it can carry, which is the weight of the passengers, luggage and cargo. The vehicle masses considered in the reference case were the following.

It should be noted that the increase of mass has a direct impact on rolling resistances. The latter effect has been taken into account in all simulations presented here by keeping the original tyre rolling resistance coefficient constant and modifying rolling resistances according to the changes in vehicle weight.

Table 8-2 Baseline vehicle masses assumed in the simulations

Vehicle	**Assumptions made in calculations**	
	NEDC Inertia Class (kg)	WLTP Mass (kg)
Petrol NA	1 130	1 315
Petrol turbo	1 360	1 540
Diesel	1 470	1 730

The following scenarios were considered for investigating the impact of the increase in vehicle mass, the number of passengers (occupancy rates), towing a trailer and a laden roof box and compared to the reference case.

- ***Vehicle mass***: An additional mass of 50, 100 and 220 kg was simulated, as it was found in the literature review (De Haan 2012, Mock et al. 2012, Goodyear 2013). The CO_2 emissions were also tested for additional 300 kg in order to better estimate a trend according to the increase of mass.

- ***Number of passengers (occupancy rates):*** The number of passengers increases the operational mass of the vehicle, but this is more complex than just a simple mass increase. Since all the passengers have a fulfilled need for transportation, you need to determine the CO_2 emissions per passenger. Although this is beyond the purpose of this study, it enables comparisons with other means of transportation.

- ***Towing***: Towing a trailer affects several factors like mass, frontal area, air drag and driving behaviour. For the purpose of the simulation, the parameters related to the mass, frontal area and air drag have been altered over two scenarios. In these scenarios, the trailer is tested unloaded and loaded by 60 % of its maximum load. The characteristics of the trailer are based on two studies (Lenner 1998, Thomas et al. 2014) found in the literature review and are presented in Table 8-3.

- ***Laden roof box:*** The effect of the roof box on aerodynamics is described in the section 'Aerodynamics', where for the mass increase only the additional mass of the roof box itself was considered. Here a laden roof box with a total mass of 75 kg is simulated. Simulations take into account an increase in frontal area of 0.37 m^2 and an increase in aerodynamic coefficient of 1 % to account for the aerodynamic effect of the roof-box.

Table 8-3: Characteristics of trailer

Characteristic	Value
Extra mass unloaded (kg)	310
Extra mass loaded (kg)	560
Aerodynamic coefficient	0.55
Frontal area (m^2)	3.47
Additional frontal area over the baseline considered in simulations (m^2)	0.97

8.6.1 Vehicle mass

The CO_2 emissions are correlated linearly to the vehicle mass as it was found in the simulation results. Figure 8-6, Figure 8-7 and Figure 8-8 show the results for the petrol and the diesel vehicles respectively.

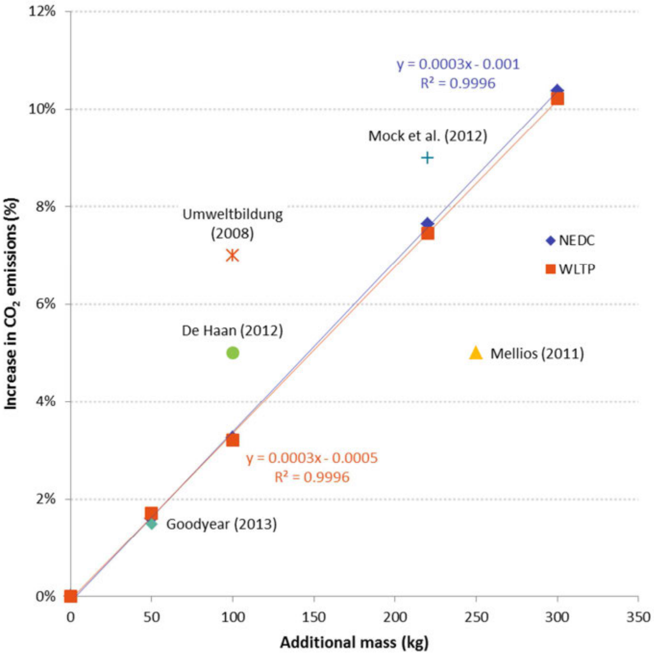

Figure 8-6: Effect of additional mass on CO_2 emissions for a petrol NA vehicle (NEDC: 1 130 kg, WLTP: 1 315 kg).

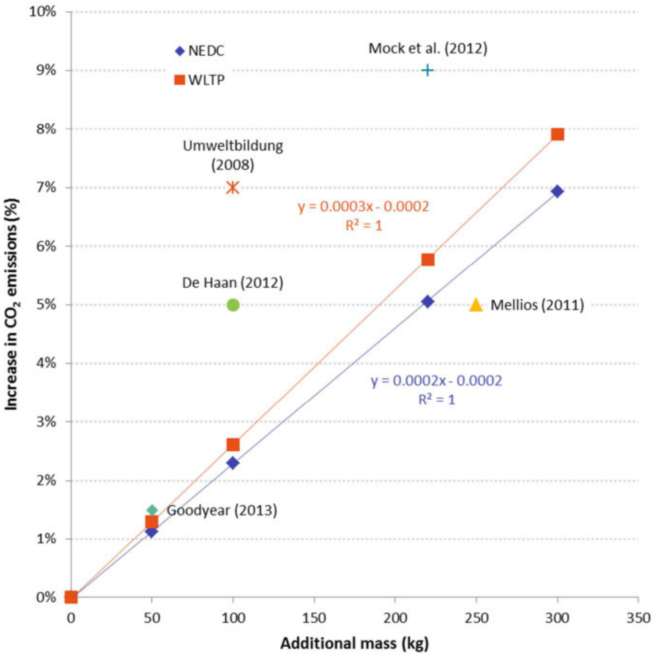

Figure 8-7: Effect of additional mass on CO_2 emissions for an average petrol turbo vehicle (NEDC: 1 360 kg, WLTP: 1 540 kg)

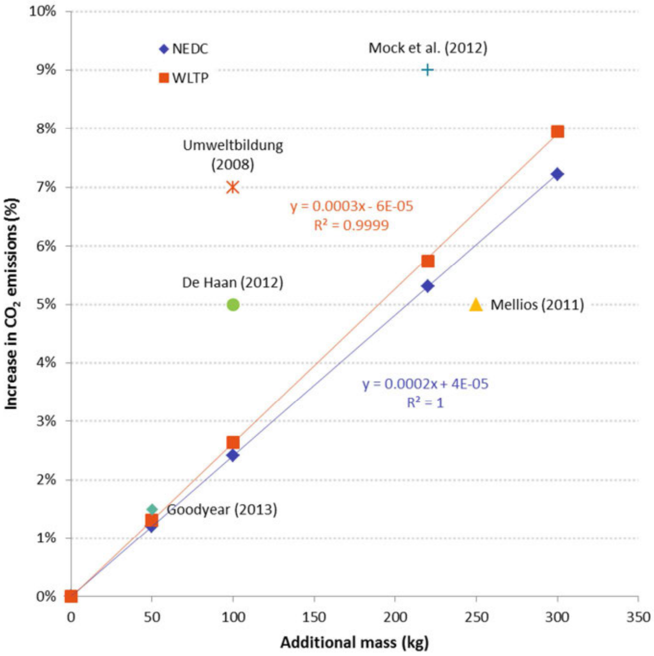

Figure 8-8: Effect of additional mass on CO_2 emissions for an average diesel vehicle (NEDC: 1 470 kg, WLTP: 1 730 kg).

Additionally, the effect on CO_2 emissions as a % change of mass is presented for the simulated vehicles. The results are shown in Figure 8-9, Figure 8-10 and Figure 8-11.

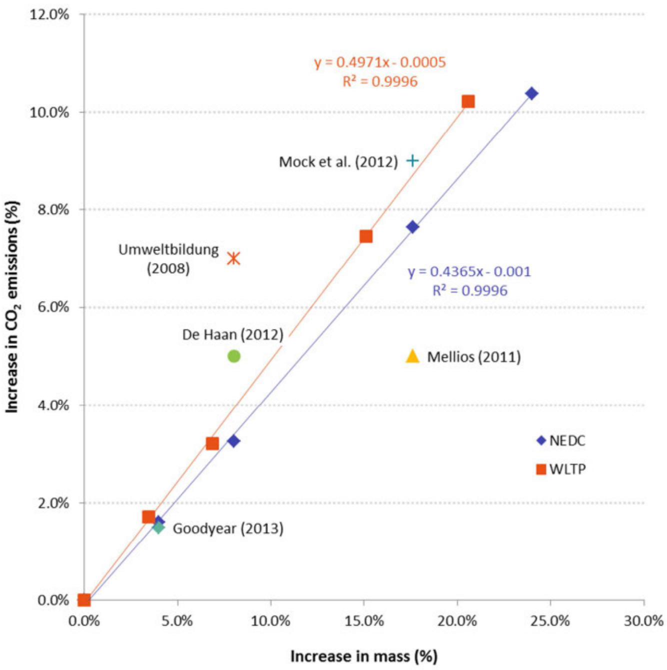

Figure 8-9: Effect on CO_2 emissions as a percentage change of mass for a petrol NA vehicle

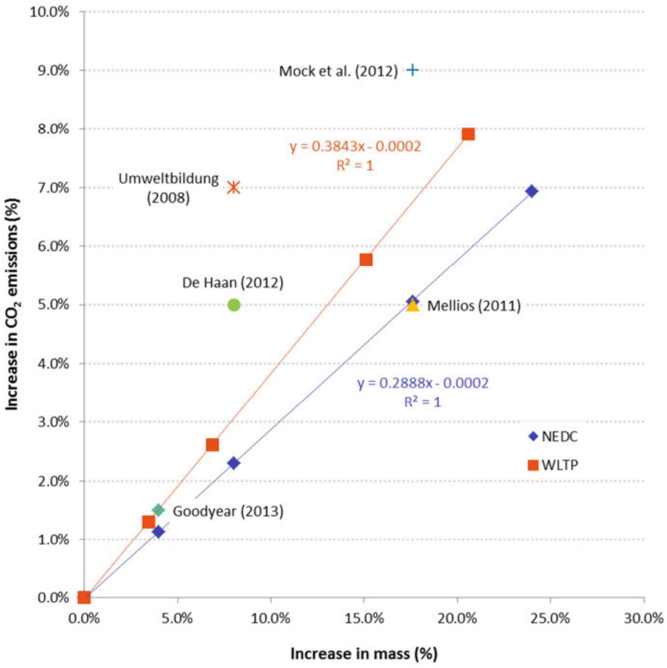

Figure 8-10: Effect on CO_2 emissions as a percentage change of mass for a petrol turbo vehicle

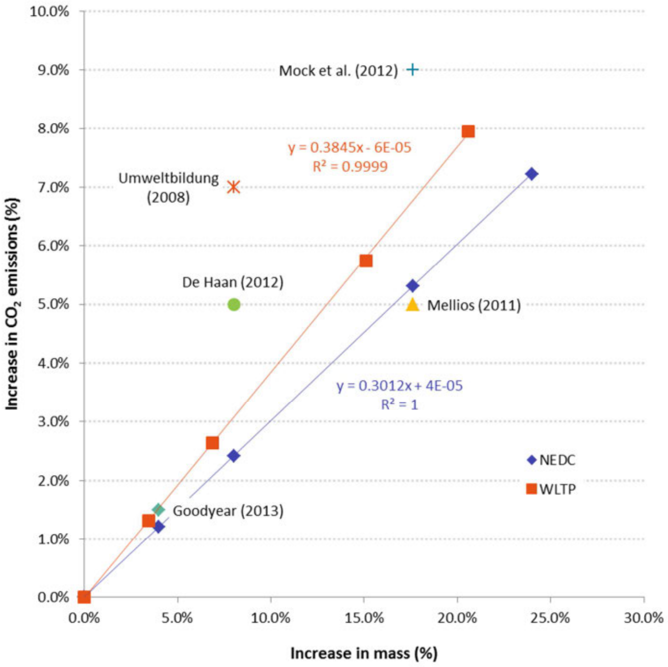

Figure 8-11: Effect on CO_2 emissions as a percentage change of mass for a diesel vehicle

8.6.2 Occupancy rates

In this paragraph the CO_2 emissions per passenger are presented. A declining trend is observed, although the effect is somewhat offset by the mass increase as shown in Figure 8-12, Figure 8-13 and Figure 8-14. The mass of each passenger is estimated at 75 kg. One passenger is considered to be the driver and his weight is included in all the simulation results of the present study.

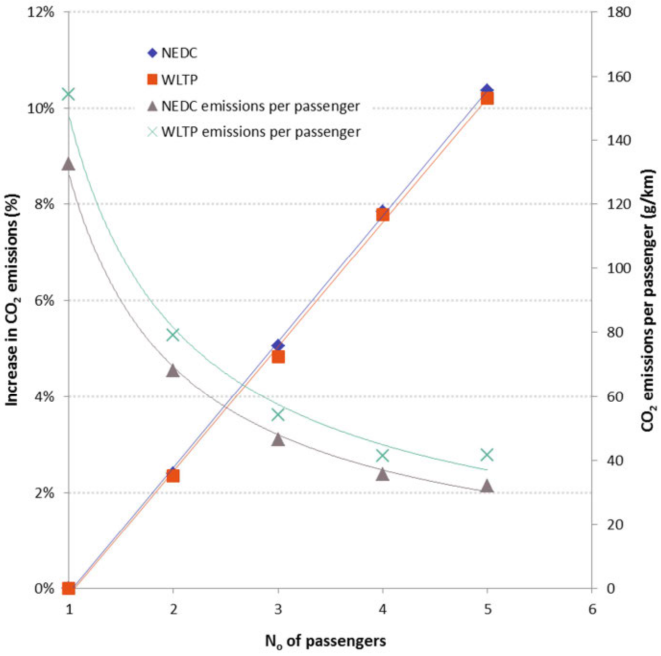

Figure 8-12: CO_2 increase and CO_2 emissions per passenger for a petrol NA vehicle

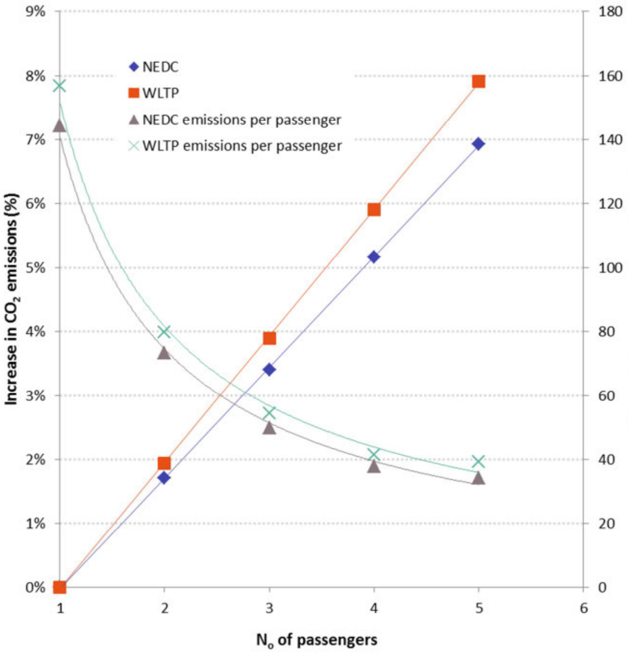

Figure 8-13: CO_2 increase and CO_2 emissions per passenger for a petrol turbo vehicle

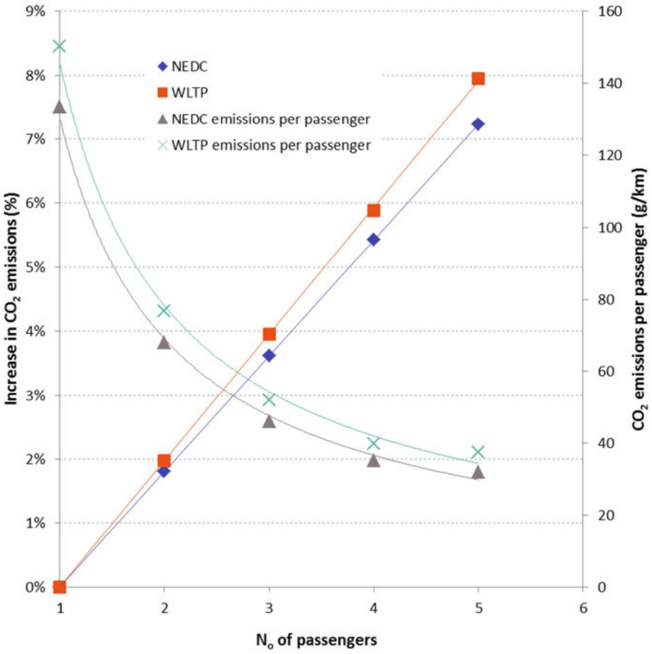

Figure 8-14: CO_2 increase and CO_2 emissions per passenger for a diesel vehicle

8.6.3 Towing

The simulation of trailer towing confirms an increase in CO_2 emissions, as expected. This case is subject to the combined effect of several factors. Here the effect of increased mass and air drag is shown in Figure 8-15. The values found in literature are also shown (Lenner (1998)).

The chart in Figure 8-16 shows the relationship between the increase in CO_2 emissions with the average speed of the WLTP sub-cycles for the unloaded and the loaded trailer (150 kg difference). The average increase for all three vehicles simulated was considered. The WLTP was chosen as it is considered more representative of real-world conditions and offer a larger speed range than the NEDC sub-cycles.

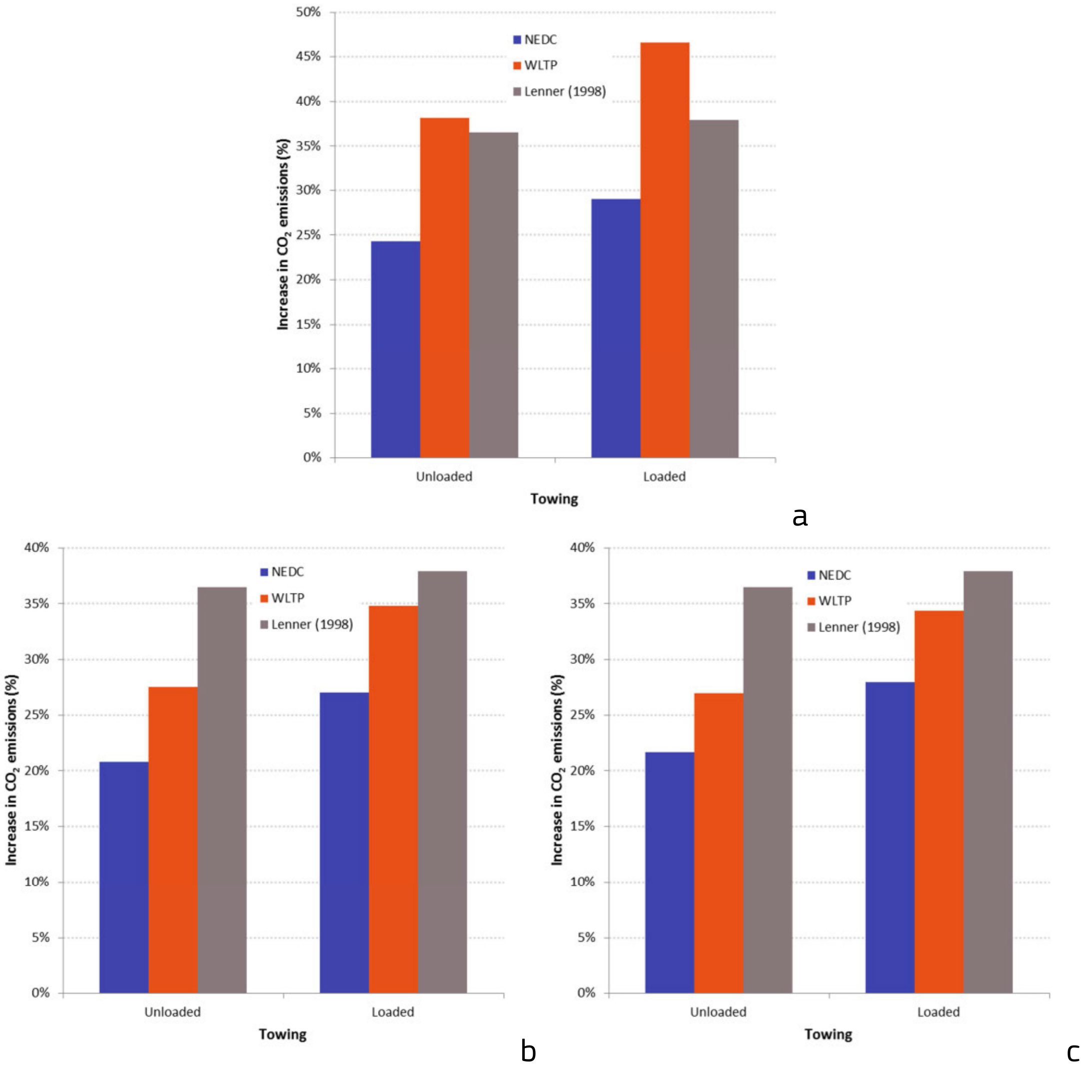

Figure 8-15: Effect of towing a trailer on CO_2 emissions for a petrol NA vehicle (a), petrol turbo vehicle (b) and a diesel vehicle (c)

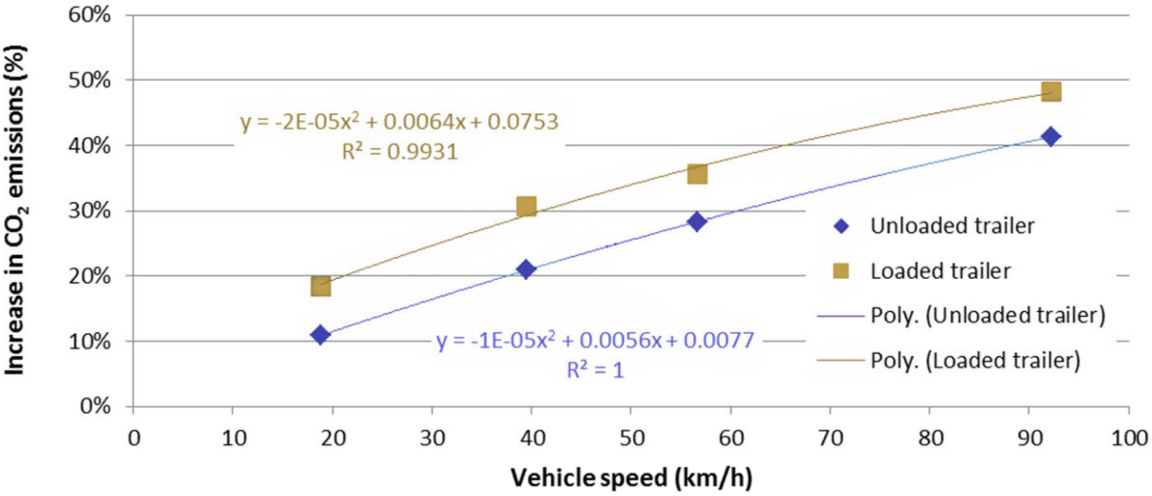

Figure 8-16: Correlation of vehicle speed and the increase in CO_2 emissions (average value derived from the simulations of the three vehicles) for towing a trailer

8.6.4 Laden roof box

The results of the simulation of a laden roof box, showing the combined effect of mass and air drag, are shown in Figure 8-17.

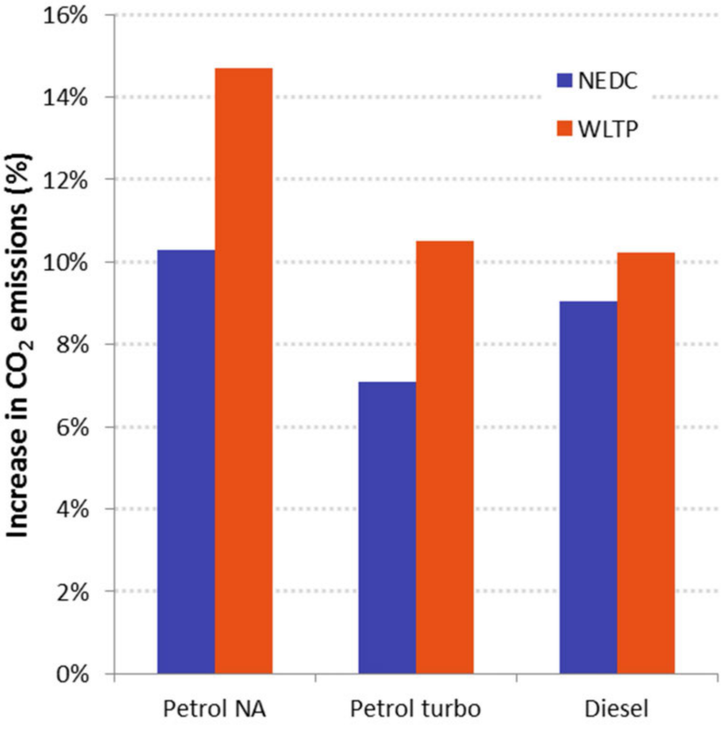

Figure 8-17: Effect of a laden roof box on CO_2 emissions for all vehicles

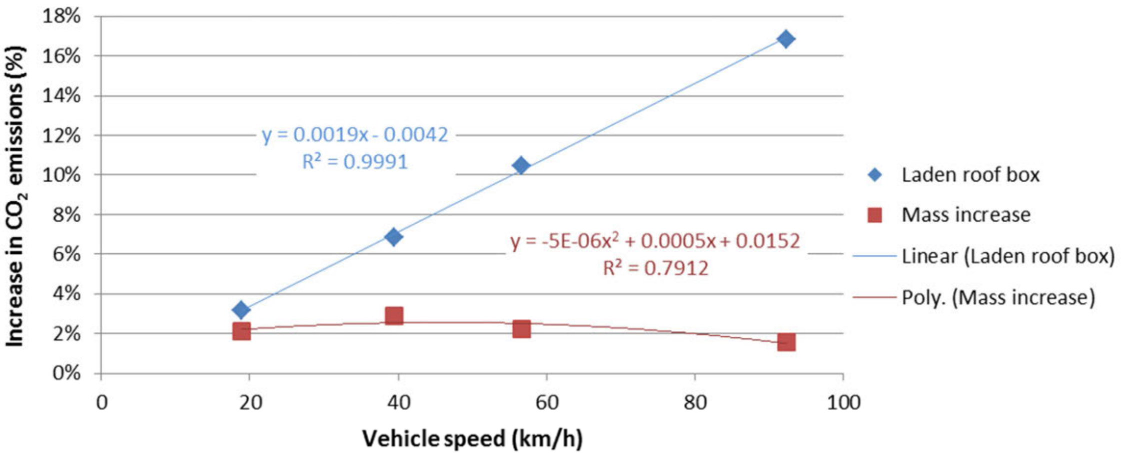

Figure 8-18: Relationship of average (37) CO_2 emissions increase due to laden roof box and impact of the mass increase alone with the average speed of the WLTP sub-cycles

Figure 8-18 presents two series of results. The 'laden roof box' series demonstrates the combined impact of mass and aerodynamic resistance, as average increase in CO_2 emissions (average of all three vehicles simulated) correlated with the average speed of the WLTP sub-cycles. The 'mass increase' series demonstrates only the effect of vehicle mass increase without considering changes in the aerodynamic components. As expected at low speed ranges the CO_2 increases can be attributed mostly to the increase of vehicle mass while the aerodynamic effect of the roof box becomes prominent at high speeds causing a rise in CO_2 emissions of 15 % in the Extra High speed sub-cycle.

8.6.5 Aerodynamic drag and vehicle mass combination

The effect of aerodynamic drag and vehicle mass on CO_2 emissions has been already investigated individually. It is of relevance to study the combined effect, since the two are major factors affecting emissions. For this reason, the vehicles simulated have been simulated with different aerodynamic coefficient values and masses. The vehicle mass was varied by 50, 100, 200, 300 and 500 kg and the aerodynamic coefficient was varied by – 10 %, 10 %, 20 % and 30 %. All combinations of the abovementioned cases were simulated. The simulations were carried out for WLTP and are presented in Figure 8-19, Figure 8-20 and Figure 8-21. For facilitating comparability all axes are set to show % changes and not absolute quantities.

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(37) Average values retrieved from the simulations of the three vehicles.

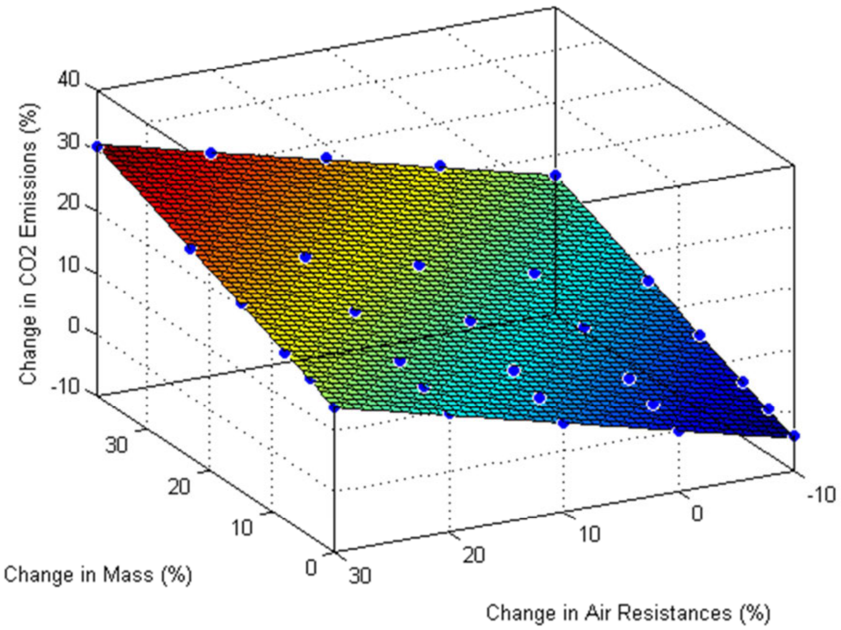

Figure 8-19: Combined effect of change of mass and air resistance on CO_2 emissions for a petrol NA vehicle

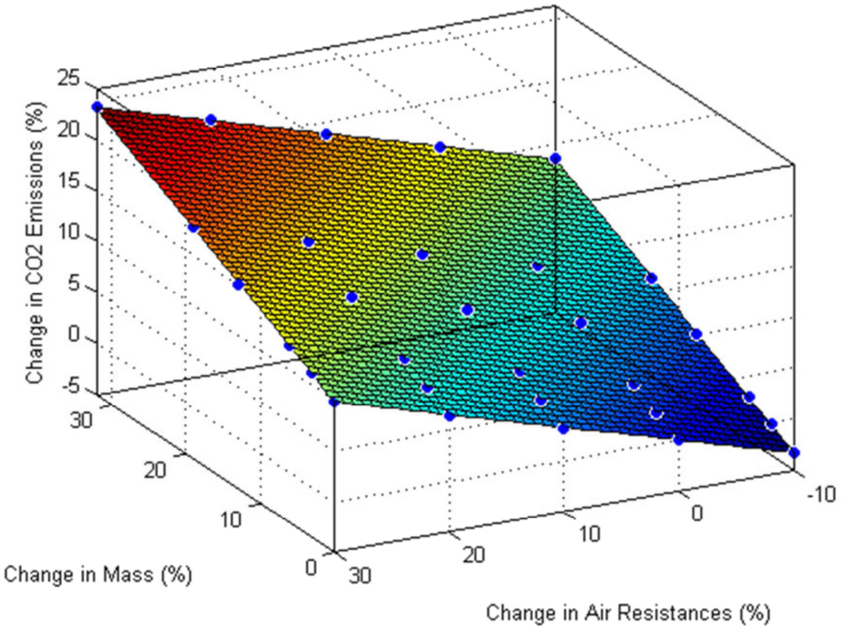

Figure 8-20: Combined effect of change of mass and air resistance on CO_2 emissions for a petrol turbo vehicle

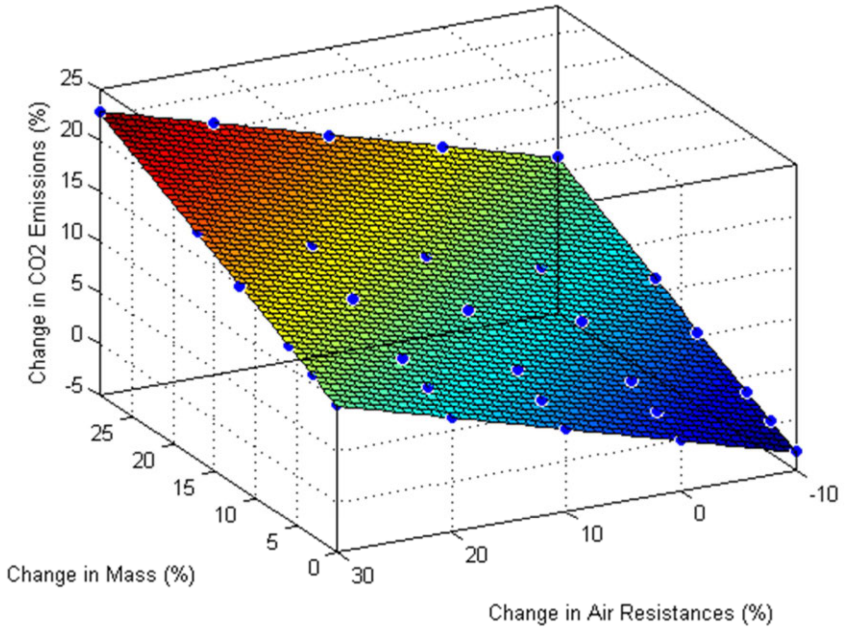

Figure 8-21: Combined effect of change of mass and air resistance on CO_2 emissions for a diesel vehicle

It is observed that both mass and air resistance changes are linearly related to the changes in CO_2 emissions. Using regression a simple polyonym was fitted to the simulated datasets (Equation 9-1).

Equation 8-1: Formula of the air resistances and mass changes correlated to CO_2 emissions for all vehicles

$$f(x,y) = p00 + p10 \times Change\ in\ Air\ Resistance\ (\ \%) + p01 \times Change\ in\ mass\ (\%)$$

Table 8-4: Coefficients with 95 % confidence bounds for Equation 8-1 according to vehicle type

Coefficient	Petrol NA	Petrol turbo	Diesel
p00	0.001194 (– 0.1462, 0.1439)	0.01043 (– 0.06861, 0.08947)	0.06168 (– 0.1458, 0.02249)
P10	0.459 (0.4529, 0.4651)	0.3248 (0.3214, 0.3281)	0.3127 (0.3091, 0.3162)
P01	0.455 (0.4483, 0.4618)	0.4177 (0.4133, 0.4221)	0.4631 (0.458, 0.4683)

8.7. Overview

A number of literature sources describing the effect of increased mass on fuel consumption were reviewed. The findings mostly refer to real-world performance. On average, 100 kg of additional mass is reported to increase fuel consumption by an average 5.5 %. This percentage appears to be on the high side compared to the simulation results in which the WLTP (test mass high configuration) fuel consumption increased by a factor of 2.5-3.5 % for the same increase in vehicle mass (100 kg). The respective increase for NEDC was in the order of 2.5 %. The results for an additional 300 kg are 7.9 % and 8.5 % respectively for NEDC and WLTP.

The effect of towing on fuel consumption is not examined thoroughly in literature, although it seems to be of major concern to the public. Many websites and discussions provide advice for proper towing in terms of driving safety and fuel economy. However, only a small number of scientific sources address this issue. The few results found have shown increases in the order of 30-40 % in fuel consumption depending on the trailer characteristics. The simulation results have shown an average increase of 22 % for NEDC and about % for WLTP for an unloaded trailer, with these figures containing also the effect of additional aerodynamic resistances. For a trailer loaded with an extra 150 kg, the results were 28 % and 37 % respectively. It is also interesting to present the results of the high-speed sub-cycles, where due to the aerodynamic resistance the CO_2 emissions increase significantly.

A significant number of studies have been identified addressing the effect of a laden roof box and quantifying its impact on fuel consumption. These literature results show an average increase of 17.2 %. In simulation, the use of a laden roof box increased CO_2 emissions by 8.9 % and 11.3 % for NEDC and WLTP respectively. For the EUDC, the average increase was 13 %. For the High and Extra High sub-cycles of the WLTP the effect was 10.5 % and 16.8 % respectively. Comparing a laden roof box with the same increase in mass, but without the aerodynamic effect, the difference in CO_2 emissions is about 15 % at the Extra High part of the WLTP. Since roof boxes are mainly used for long-distance trips, the Extra High part of the WLTP is considered as a more representative usage condition.

On the issue of occupancy rate a significant amount of data and studies have been identified, with 2010 being the average year of publication. Only data for certain European countries was found and in some cases only for a very limited number of years. The latest EU-wide results show occupancy rates for 2008 and a clear decreasing trend until then. After 2008, the occupancy trend could be different due to the impact of the financial crisis on the public and the rising price of fuel (until 2014). A regular Google search with the same keywords used with Google scholar (e.g. occupancy rates fuel consumption), did not provide sufficient results. The keyword ‘car-pooling’ yielded however a plethora of results, ranging from smart phone applications to find car-pooling to sites and forums explaining how it works and how local offers can be found. The simulation results show that high occupancy rates seem to counterbalance the increased emissions due to the additional weight when emissions are approached on a per passenger basis. It was found that the CO_2 per passenger is decreased by around 73.6 % for the NEDC and 73.5 % for the WLTP for a car with four passengers including the driver compared to just the driver.

Finally, using simulations, the combined effect of mass and aerodynamic resistance was investigated. Both of them can be affected by proper vehicle design and the choices of the driver. In the latter case proper decisions on the manner of transportation of people and cargo could significantly reduce emissions. As for mass, its reduction could be achieved by removing unnecessary weight before the trip. Higher occupancy rates reduce the CO_2 emissions per passenger. Regarding aerodynamic resistance, the choice of how to transport cargo (e.g. car boot, roof rack/box, trailer, etc.) can have a significant impact on emissions that the driver should take into consideration.

A summary in Figure 8-22 is presented based on values found in literature.

Category	Factor		Literature median value	Distribution	Sources No.
Operational mass	Vehicle mass	Increased mass by 100 kg	5.8%		17
	Trailer towing	Affects weight, rolling resistance, aerodynamics and driving behavior	37.9%		3
	Roof racks / boxes (mass increase)	Fuel consumption increases as speed increases	19.7%		5

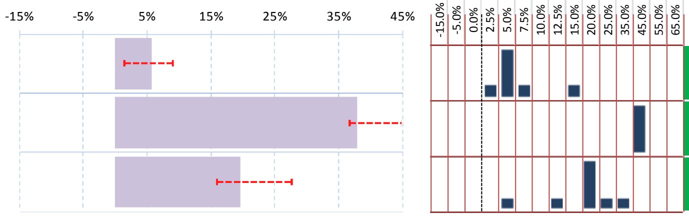

Figure 8-22: Summary table of the effect of operational mass on fuel consumption. Error bars represent minimum–maximum values reported.

9. Road (morphology, surface, traffic)

9.1. About road condition

The term road condition refers to the road morphology, road surface, road shape and traffic conditions. All of them can impact real-world CO_2 emissions to a greater or lesser extent but none of them is actually reflected in the current certification test. NEDC is known to be non-representative of real-world traffic conditions while it would be extremely difficult to take into account most of the other factors (e.g. road surface) in a single test cycle. The forthcoming WLTP is expected to address to a certain extent the issue of a non-realistic speed profiles or traffic conditions as the WLTP cycle was produced from real-world speed profiles and is subdivided in four different phases reflecting traffic conditions at different average speeds. It would be very difficult and possibly unrealistic to include the rest of the road-related factors in a laboratory test as it would greatly increase the variability of the results.

Road morphology means the geomorphological characteristics of the road. The characteristics that have an effect on fuel consumption are altitude, road shape, road surface and grade. At higher altitude, air density is lower thus aerodynamic resistance is also lower. By contrast, in a mountainous landscape cornering and road grades would increase. Road grade affects fuel consumption as the vehicle requires more power to move on a road with a positive grade than on a flat one, while the contrary is true for a road with a negative grade. Nevertheless, travelling up and down the same hill will result in a higher mean fuel consumption compared to travelling the same road under the same conditions at zero gradient.

Very little data is available regarding road shape and cornering and the topic requires further investigation. There are however studies which examine the effect of cornering on aerodynamic drag as yaw angle changes but they do not provide solid conclusions with regard to the impact on fuel consumption.

The road surface is examined in terms of structural condition and construction material. The structural condition of the road surface is described by the roughness and the texture. The roughness of the road is the vertical deviation of the intended longitudinal profile of the surface (LGAM n.d.) and is measured by means of the International Roughness Index (IRI) (38). Texture is the deviation from a planar surface and plays a role in road surface friction resistance and affects the braking of vehicles (DPLTI 2013). The construction materials of the road surface, also denoted as pavement, investigated in this study were asphalt and cement.

Traffic refers to the number of vehicles that occupy the road at a given time which together with the road size and speed limits determine vehicle speed profile. Heavy traffic can result in congestion and completely alter operating conditions in a given road. This

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(38) IRI, according to Pavement Interactive. (2007). 'Roughness.' Retrieved 11/08/2014, 2014, from http://www.pavementinteractive.org/article/roughness/#footnote-1. is based on the average rectified slope (ARS), which is a filtered ratio of a standard vehicle's accumulated suspension motion (in mm, inches, etc.) divided by the distance travelled by the vehicle during the measurement (km, mi, etc.). IRI is then equal to ARS multiplied by 1 000.

results in undesired accelerations and decelerations and starts and stops which eventually increase fuel consumption (Spalding 2008). Several studies were found where fuel consumption was measured over the same route during normal traffic and congestion and afterwards they were compared.

9.2. Road morphology

9.2.1 Altitude

An increase in altitude is generally reported to decrease fuel consumption (Dings 2013), as lower atmospheric pressure leads to reduced air drag (Van Mensch et al. 2014). At increased altitude, air density, oxygen concentration and aerodynamic resistance all decrease. The decrease in aerodynamic resistance affects all vehicles in the same way. Vehicles equipped with engines that operate in stoichiometric conditions may also be affected, particularly if the air–fuel ratio control is done by means of throttling. Lower air densities lead to a wider throttle opening, for charging the engine with the same amount of air, resulting in lower pumping losses, leading in turn to decreased fuel consumption.

It was found by Zervas (2011) that a high altitude can result in decreased fuel consumption by up to 3.5 % compared to the NEDC and 2.6 % on FTP, while an increase of 6.2 % was found for highway operation. The author states that further investigation is needed to answer this discrepancy. Another study has found a decrease of fuel consumption of around 4-5 % for test tracks at high altitude and warm weather (Dings 2013). DriverSide (n.d.) suggests however that because of the lower amount of oxygen at higher altitudes, fuel consumption is increased as the driver has to press the throttle more in order to maintain the same speed, while turbocharged vehicles do not face these problems. The observation may stand true but for engine operating conditions close to full load where the throttle is almost wide open. In such cases the occurring reduction in engine power due to the lower volumetric efficiency may result in enrichments introduced to compensate the power deficit. This could be a possible explanation to the observations of Zervas (2011) that fuel consumption is increased in highway operation.

9.2.2 Road grade

A car that is driven uphill requires more power to overcome gravity (referred to also as weight resistances) than one that is on a flat road, while a car that is going downhill requires less. Road grade has an important effect on vehicle CO_2 emissions.

Wyatt et al. (2014) performed measurements and simulations on a passenger car, investigating the effect of grade on CO_2 and testing the CO_2 emissions sensitivity. They identified the need for testing CO_2 emissions in conditions where the road grade varies. The study shows that in order to accurately estimate vehicle CO_2 exhaust emissions at a micro-scale in real-world conditions, a representative road grade profile for each second of the test data is needed. The research shows also that failing to account for even a relatively modest road grade, when modelling micro-scale vehicle emission, could potentially result in highly inaccurate estimates of real-world emission. Transport management and urban planning projects should be incorporating road grade into their analysis where prediction of vehicle emissions is required.

Park and Rakha (2005) found that for a 1 % increase in roadway grade, fuel consumption increases by 9 %, while a decrease in roadway grade can provide significant savings.

Boriboonsomsin and Barth (2008) measured real-world CO_2 emissions for two different routes for the same destination for a passenger car. One route was flat, while the other one had uphill and downhill sections. They found that fuel consumption is increased by 15-20 % for the hilly route and it is linearly related to gradient for a range between – 2 % and 2 %. Their results are presented in Figure 9-1, with the average grade for the hilly route being 4 % with a maximum of 6 %.

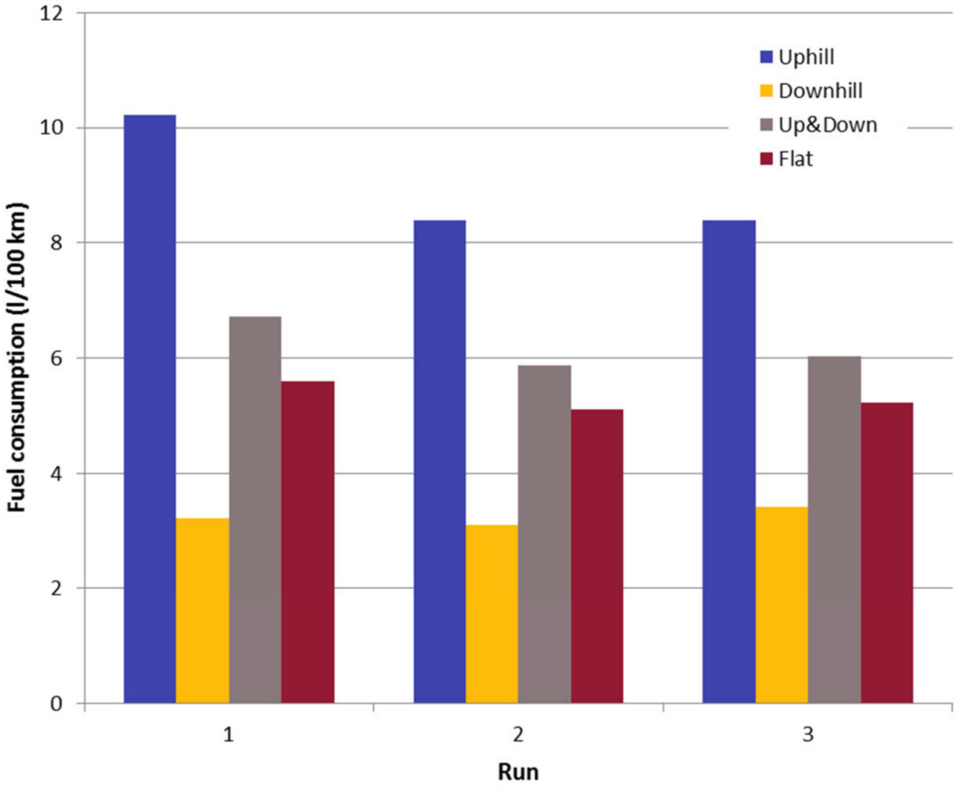


Figure 9-1: Fuel consumption for different routes according to road grade (Boriboonsomsin and Barth 2008)

9.3. Road surface

Road surface is examined with respect to structure and materials and a short description of the structure properties (texture and roughness) is given in the following paragraphs.

9.3.1 *Roughness*

Roughness depends on the construction and the condition of the road and is used as an indicator for maintenance. Rough roads limit maximum speed, while causing discomfort to the passengers (MnDOT 2007, Green 2013). The various types of pavements for different uses graded in IRI are presented in Figure 9-2.

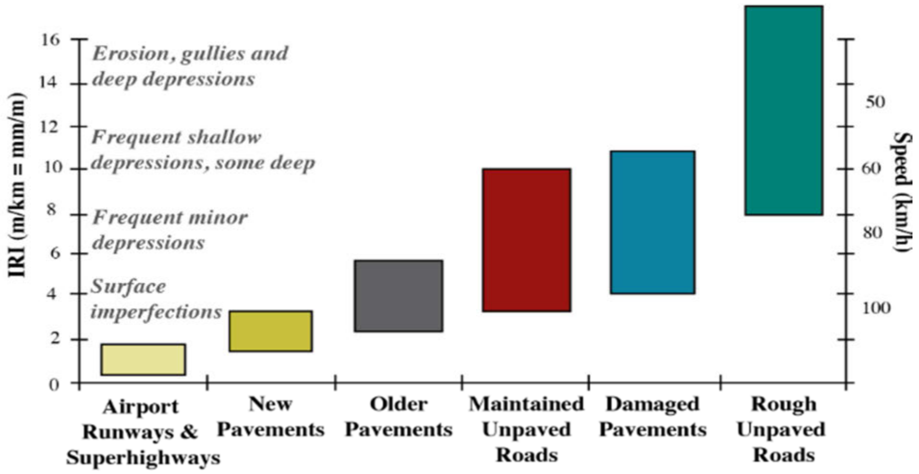


Figure 9-2: Types of road and top speed according to road roughness (Green 2013)

Fuel consumption is proportionally affected by road roughness, because it poses a resistance to the vehicle's movement and increases as IRI increases. This is presented in Figure 9-3, from Green (2013).

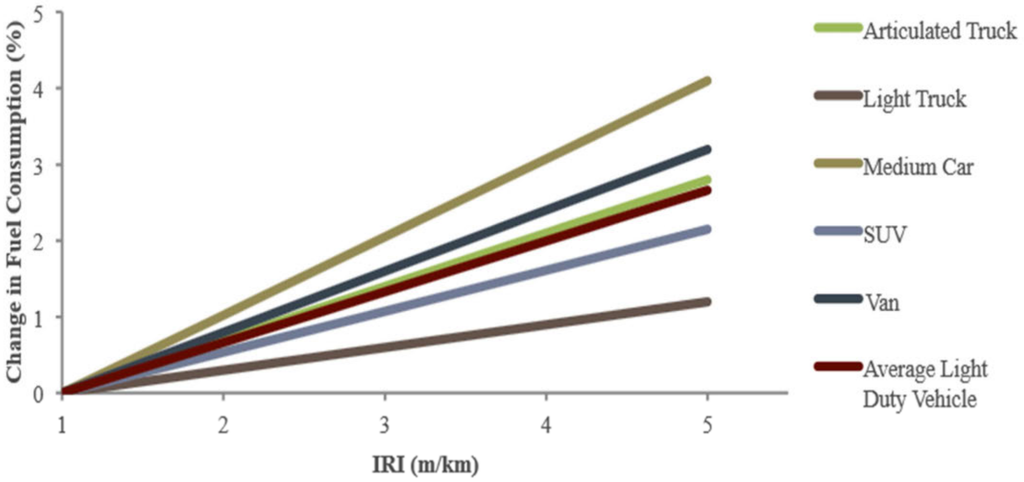


Figure 9-3: Effect of pavement roughness on fuel consumption according to type of the vehicle (Green 2013).

9.3.2 Texture

Texture is the deviation from a planar surface and plays a part in road surface friction resistance and assists in the braking of vehicles (DPLTI 2013). Road texture is defined based on its wavelength and its effect varies according to its size. The smaller the wavelength the more the effects are beneficial, like better friction and noise reduction. As it increases, rolling resistance is affected negatively, noise becomes louder, discomfort is caused to the passengers and the vehicle is subject to wear. Figure 9-4 shows the expected effects according to the wavelength.

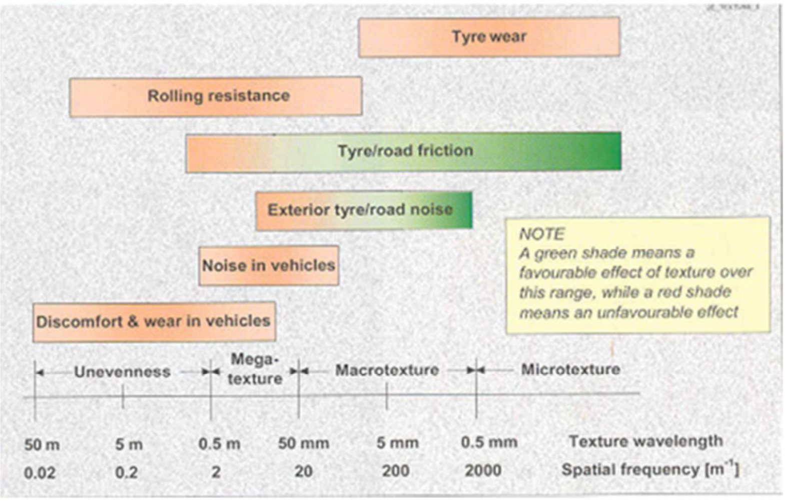


Figure 9-4: Effect of texture according to wavelength (DPLTI 2013)

The authors of EAPA — Eurobitum (2004) have noticed that significant changes within a texture category (as shown in Figure 9-4) could result in an increased fuel consumption by 5 to 10 %.

9.3.3 Materials

The authors of (EAPA — Eurobitum 2004) have not noticed a statistically significant difference in fuel consumption between asphalt and cement pavements. On the contrary, a study conducted in the US found that for urban driving speeds of less than 50 km/h fuel consumption is higher by 4 % on asphalt pavements than on concrete (Ardekani and Sumitsawan 2010). Their results are presented in Figure 9-5 (Table 14-24 in Annex).

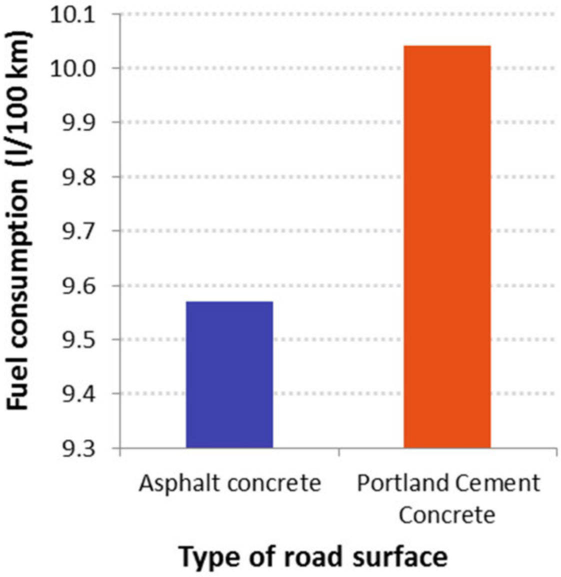


Figure 9-5: Average fuel consumption for cement and asphalt road surface for speeds under 50 km/h (adapted from Ardekani and Sumitsawan (2010))

9.3.4 Case studies

The authors of EAPA — Eurobitum (2004) examined two case studies, in Sweden and the Netherlands. The road roughness is evaluated based on a scale for microtexture from 0 being the smoothest to 9 the harshest. Detailed data can be found in Table 9-1 and Table 9-2.

Table 9-1: Texture type and fuel consumption for different pavement types for a Volvo passenger car (adapted from EAPA — Eurobitum (2004))

Type of asphalt	Micro scale 0-9	Fuel consumption (l/100 km)			Fuel consumption relative to dense asphalt concrete 0/16 (%)		
		50 km/h	60 km/h	70 km/h	50 km/h	60 km/h	70 km/h
Dense asphalt 0/8	6	6.95	6.76	7.36	– 2.66 %	– 2.31 %	0.55 %
Dense asphalt 0/16	3	7.14	6.92	7.32	0.00 %	0.00 %	0.00 %
Cement concrete 0/25	2	7.2	7.1	7.56	0.84 %	2.60 %	3.28 %
Surface Dressing 4/8	7	6.96	7.01	7.81	– 2.52 %	1.30 %	6.69 %
Surface Dressing 12/16	6	7.08	7.25	7.88	– 0.84 %	4.77 %	7.65 %

Table 9-2: Fuel consumption at 90 km/h compared to dense asphalt concrete 0/16, for a Volvo 70 passenger car from EAPA — Eurobitum (2004).

Road surface type	Fuel consumption relative to dense asphalt concrete 0/16 (%)
Dense asphalt concrete 0/16	0
Porous asphalt 6/16	– 0.0 (± 3.5)
Stone mastic asphalt 0/6	+ 3.4 (± 3.6)
Double-layered porous asphalt 4/8 + 11/16 (new road surface; bitumen film still present)	+ 1.2 (± 3.3)
Cement concrete, broomed transversely	+ 0.4 (± 3.4)
Cement concrete treated with a surface epoxy durop	+ 2.7 (± 4.5)
Brick-layered pavement	+ 5.3 (± 6.6)

The literature review on the condition of the road surface found that the majority of the studies are concerned with the life-cycle carbon emissions occurring from roads, from construction and maintenance to vehicle emissions for a certain period of time (EAPA — Eurobitum 2004, Green 2013).

9.4. Traffic conditions

Traffic conditions affect fuel consumption in several ways. Primarily this is by affecting the average speed of the trip, by limiting or increasing transient operation (accelerations-decelerations) or by causing in congested conditions more start–stop incidents than usual (Greenwood 2003, Spalding 2008). The latter specifically applies if the vehicle does not feature any start and stop technology (Fonseca et al. 2011, Dings 2013). A typical example of the effect of average speed/traffic conditions on CO_2 emissions can be found in Figure 9-6 (Fontaras et al. 2014a). The continuous lines demonstrate the predictions of two commonly used emission inventorying tools in Europe (Copert & Handbook) while the dots and the corresponding error bars demonstrate the average experimental results and their standard deviation respectively. These were obtained during an experimental campaign from various Euro 5 vehicles over different driving cycles (NEDC, Artemis, WMTC). As shown, trips with very low average speed (< 20 km/h) present the highest CO_2 emissions while the optimal trip speed appears to be in the range of 50 to 80 km/h.

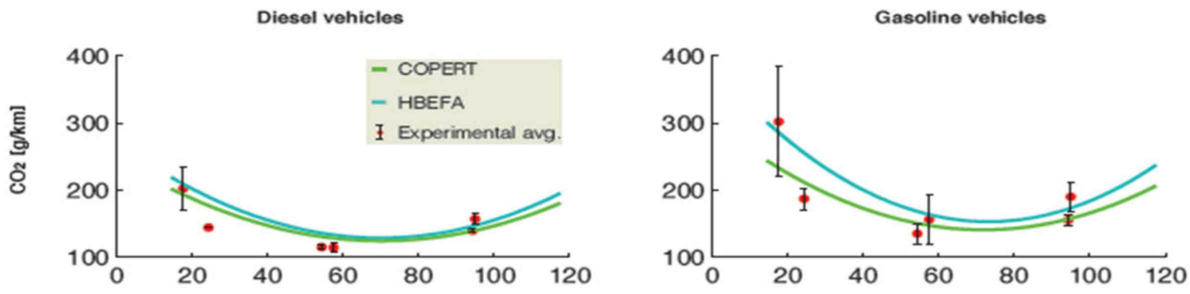


Figure 9-6 Impact of average driving speed on CO_2 emissions of Euro 5 vehicles (Fontaras et al. 2014a)

Congestion is in general considered to be the traffic condition leading to the highest fuel consumption (expressed on a per km basis), and can result in up to 40 % higher fuel consumptions than those regularly experienced (De Vlieger et al. 2000). Two studies were found in which two routes where selected and were driven twice: one in peak traffic hours and one in normal driving conditions. The results are presented in Figure 9-7 (See Table 14-25 in the Annex). The case may be reversed for hybrid vehicles where the contribution of the electrical system during urban driving conditions offers significant fuel consumption reductions (Fontaras et al. 2008). It is interesting to note that in certain cases of motorway driving, some level of congestion may reduce the fuel consumption as they force the driver to keep to a lower speed and to adapt the driving to the trajectory of the lead vehicle limiting the variability of fuel consumption with driving.

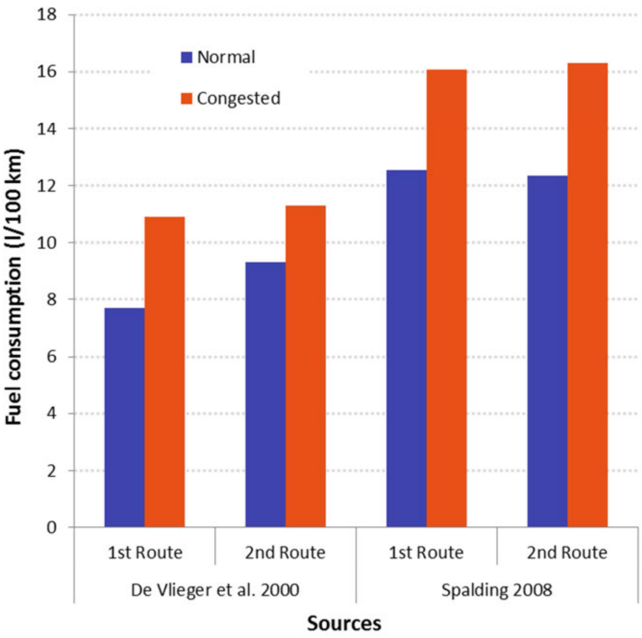


Figure 9-7: Fuel consumption for normal and congested routes (adapted from De Vlieger et al. (2000) and Spalding (2008))

The average increase in fuel consumption for congested roads calculated from all cases examined is about 26 %.

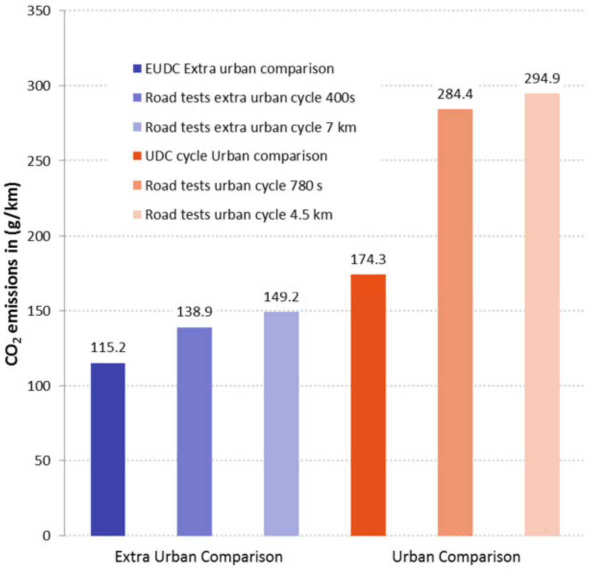


Figure 9-8: Increase in emissions for urban and extra urban routes compared to UDC and EUDC respectively (Merkisz et al. 2010)

Another study examined the type approval test results compared to real-world driving and traffic conditions by performing a measurement with PEMS on an urban and an extra-urban route. The results showed an increase in CO_2 emissions between 63-69 % in the urban cycle and 21-30 % in the extra-urban (Merkisz et al. 2010). Figure 9-8 provides an illustrative demonstration of these results. Of course in this case other factors may contribute to the increases such as the road grade, environmental conditions and the vehicle configuration compared to the original certification procedure, so it is impossible to distinguish the actual contribution of traffic conditions.

Finally, the psychological effect of congestion on drivers should be taken into consideration, as it was found that a significant percentage of drivers experience increased stress levels, anger, decreased concentration performance and sleep disorders (Caldow 2008). This could have an impact on driving behaviour and safety. In addition, independently from fuel consumption, lowering vehicle speed generates significant societal costs in terms of higher time losses and reduction in the overall productivity.

9.5. Trip distance, duration and number of sub-trips (trip type)

A trip is characterised by the distance travelled, its duration and the number of sub-trips it includes. Generally, very short-distance trips tend to exhibit higher fuel consumption compared to medium-distance ones. This is mainly attributed to the high influence of temperature and non-stabilised operation of various components (engine, gearbox, tyres, etc.). Over a trip similar to the certification cycle (NEDC) the initial cold start is estimated to increase emissions by 10 % (Mellios 2011), a percentage which becomes higher for shorter distance trips (NEDC: 11 km, 20 minutes) and lower loads (NEDC mean speed: 33 km/h). Thus an increased frequency of short urban trips, typical in European cities, can result in significant extra fuel consumption compared to the reported value, as most of these trips are realised with the vehicle non thermally stabilised. The engine under such conditions does not reach normal operational temperature, while the effect is greater in colder weather conditions (DOE — EPA 2014d, Toyota 2014b) and during congestion according to Andrews et al. (2007). According to VW (2010a), performing many short trips under urban conditions instead of a single long one may lead to very high fuel consumption ranging up to even 30 l/100 km, a value which is considered extreme but not unrealistic.

Letting the car idle in order to warm up and reduce this effect does not help according to the DOE — EPA (2014d) an opinion supported by Toyota (2014b).

The adoption of start–stop technologies assists in reducing fuel consumption in urban use. Whittal (2012) examined the effectiveness of start–stop systems for a Smart For Two micro hybrid and a BMW 118d. Although the research focused on test cycles used in Canada, USA and Japan it also involved on-road measurements. The results showed a decrease in fuel consumption of 9.6 % for the Smart and 8 % for the BMW, when the start–stop system was engaged. The author states that these savings could be affected by factors like ambient temperature, percentage of urban driving and frequency of stops.

9.6. Simulation scenario and results

A vehicle is rarely driven on a road as specified by the type approval tests and usually there are several variations during a trip. There can be altitude changes, different road grades on hilly and mountainous terrains, variable road surfaces and traffic conditions. These aspects are explored through simulation as described below:

9.6.1 Altitude

Altitude is not examined thoroughly in the literature and is a factor that has recently started to concern researchers (Zervas 2011, Dings 2013, Van Mensch et al. 2014). The authors suggest that because of the lower air density, the air resistance that faces the vehicle is lower resulting in lower fuel consumption. Although there have been some cases where increased fuel consumption was observed (Zervas 2011), this has not been thoroughly investigated. As suggested by (DriverSide n.d.), it could be because of the lower amount of oxygen which results in wider throttle opening. Due to the fact that the majority of the observations indicate a decrease in fuel consumption and CO_2 emissions attributed to the lower air density, it was decided to create simulation cases based on this hypothesis. The density of the air is calculated based on Equation 9-1.

Equation 9-1: Calculation of air density according to altitude.

$$\rho_{air} = \rho_b \cdot \left[1 - \frac{L_b \cdot (h - h_b)}{T_b}\right]^{\left(1 + \frac{g_0 \cdot M}{R \cdot L}\right)}$$

ρ_{air} = Density of air (kg/m^3)

ρ_b = Mass density of air for altitude of up to 11 000 m, 1 225 kg/m^3

T = Temperature (°K)

L = Standard temperature lapse rate, for altitude up to 11 000 km: –0.0065 °K/m

R = Universal gas constant for air, 8.31432 N·m/(mol °K)

g_0 = Gravitational acceleration (9.81 m/s^2)

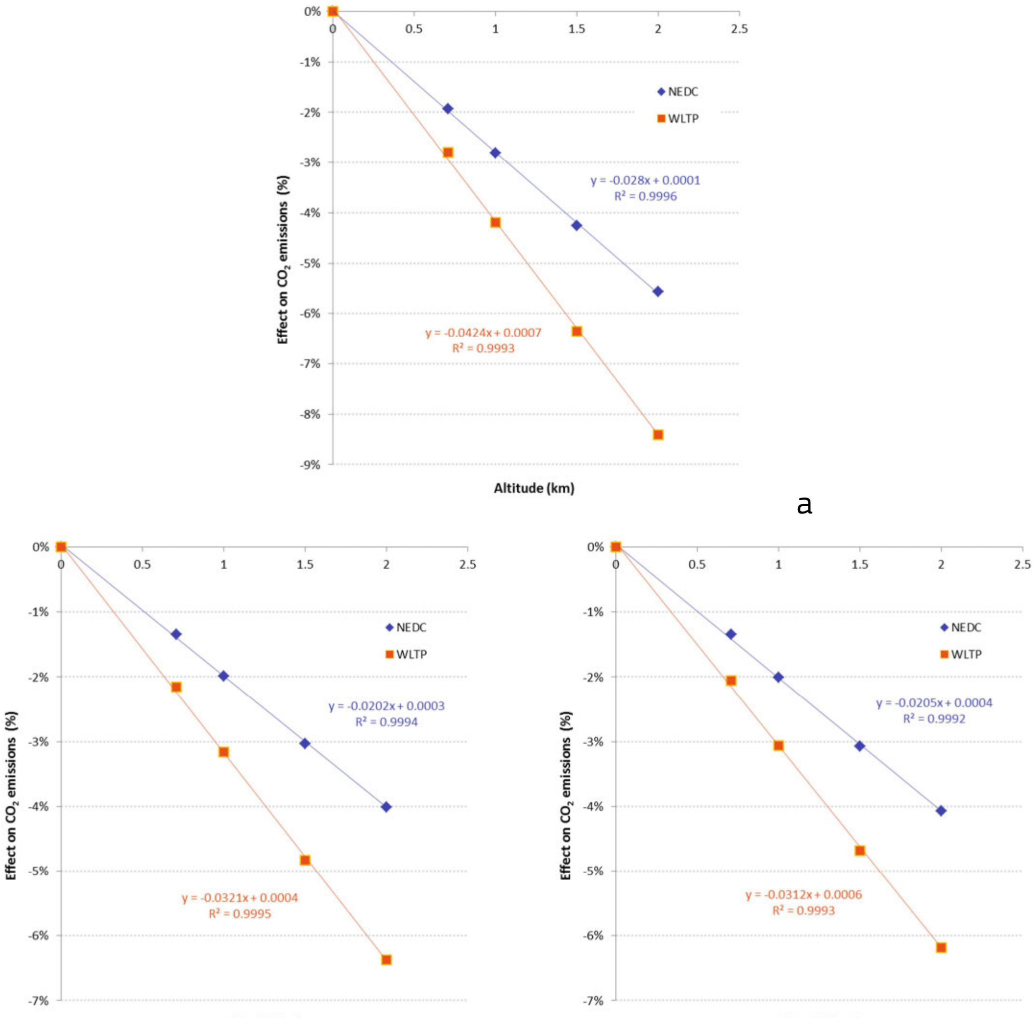
M = Molar mass of Earth's air (0.0289644 kg/mol)

The altitudes assumed were 700, 1 000, 1 500, and 2 000 m. The resulting air density is shown in Table 9-3.

Table 9-3: Air density according to altitude for temperature of 14 °C and 0 % relative humidity.

Altitude (m)	Air density (kg/m^3)
700	1.126
1 000	1.088
1 500	1.023
2 000	0.962

The effect of altitude on CO_2 emissions is shown in Figure 9-9, for a temperature of 14 °C. No grade changes for altitude are applied and the driving surface is considered to be flat.



a

b

c

Figure 9-9: Effect of altitude on CO_2 emissions for a petrol NA (a), petrol turbo (b) and a diesel vehicle (c)

9.6.2 Road grade

The grade of the road creates an extra load as the vehicle moves uphill and a reduced load as it moves downhill. The tested cases include cycles under a constant grade in the range of – 5 to 5 %, with steps of 1 %. The value of 5 % was chosen because it is the highest permissible grade according to Italian legislation in the extra urban part of a highway (Ispettorato Generale Per La Circolazione E La Sicurezza Stradale 2001).

The effect of the road grade is shown in Figure 9-10.

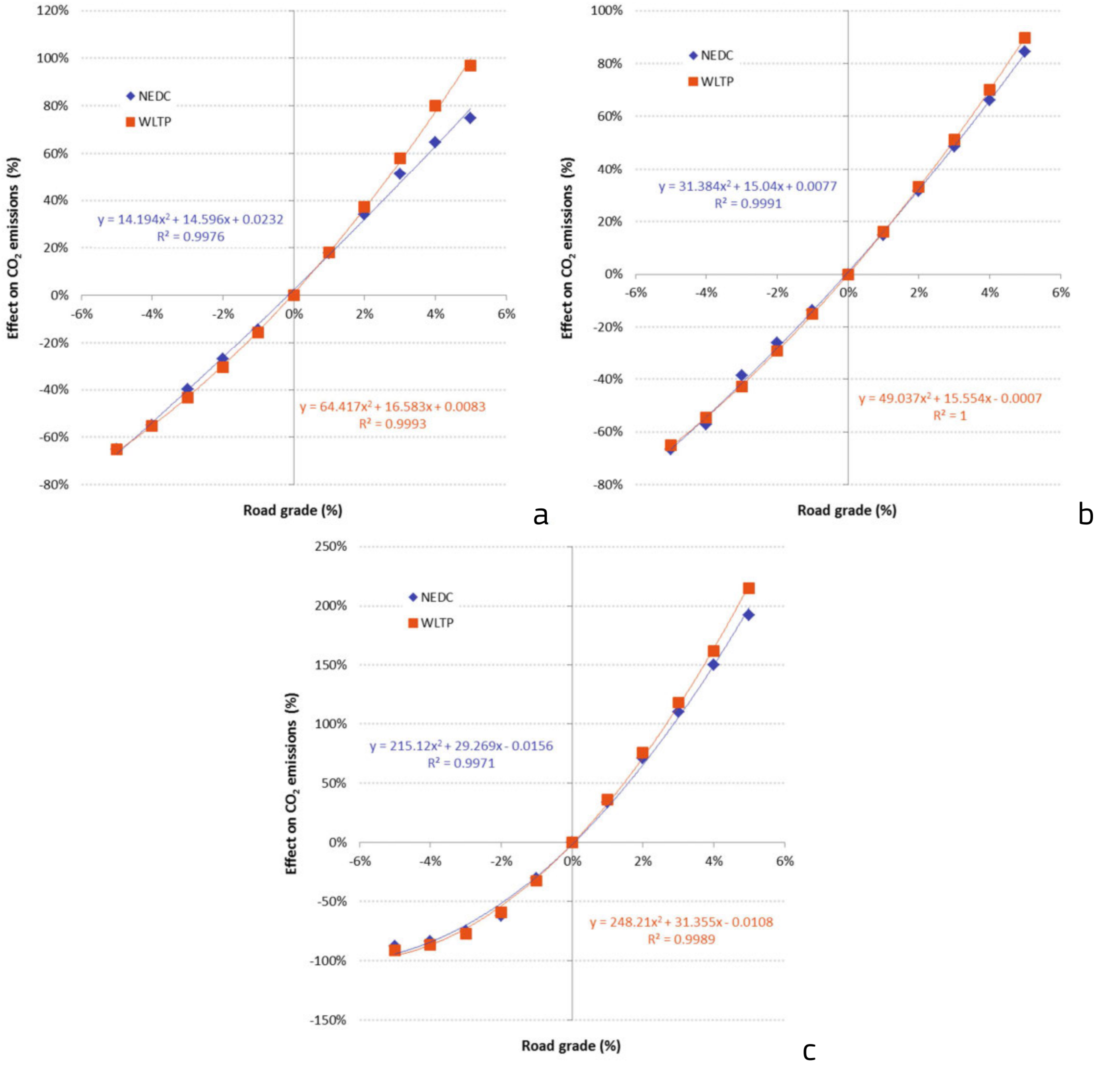


Figure 9-10: Effect of road grade on CO_2 emissions for a petrol NA (a), a petrol turbo (b) and a diesel (c) vehicle

These results show that the CO_2 emissions benefit from driving downhill does not fully offset the increase from uphill driving.

Based on these results it was estimated that imposing the same positive and negative grade value, in the range of ± 3 % where the relationship between grade and CO_2 effect remains relatively linear, on the driving profile of WLTP resulted in an excess of CO_2 emissions of about 3.5 % on average for the three vehicles. This corresponds to a constant grade of approximately 0.15 %. This fixed road grade value is used in the ‘realistic’ scenario presented in Table 11-3.

9.6.3 Trip type

In this simulation scenario the driving habits of six countries (39) of the European Union are presented, as studied by Pasaoglu et al. (2012). The authors investigated the trip types during the week, i.e. personal or business, the distance covered and the time spent travelling. Outlying values were removed, the average travel time and speed were produced and are shown in Table 9-4. The average speed and distance of the realistic scenario as presented in the chapter 'Certification test' are also added.

Table 9-4: Average speed and distance according to trip type (Pasaoglu et al. 2012)

	Trip type	Average speed (km/h)	Distance (km)
Weekdays	Business	44.1	21.2
	Personal	44.7	17.0
Saturday	Business	43.0	19.0
	Personal	48.6	21.8
Sunday	Business	51.0	24.8
	Personal	56.6	29.7
Realistic scenario	*WLTP*	*46.5*	*23.3*

Table 9-4 shows that the speed profile and the distance of the WLTP is fairly representative of real-world conditions and for this reason it was used in the cases where commuting is investigated. Four types of trip were created that correspond to an urban commuter, medium-distance commuter, long-distance commuter and interurban traveller. The parameter adjusted for each type of commuter is the weight, assuming that there are extra passengers and equipment which add extra mass. The extra mass was separated into normal and high load. The weight of each passenger is estimated at 75 kg and it is assumed that each passenger carries an additional 7.5 kg luggage for the normal load and 15 kg for the high load case.

Apart from the weight, additional parameters were adjusted to match the realistic scenario parameters shown in Table 11-3. The CO_2 emissions for each type of travel are estimated using the WLTP sub-cycles multiplied by a weighting factor that accounts for the percentage of the trip covered under the same conditions.

Table 9-5 presents the travel types with the weighting factor used for each WLTP sub-cycle to estimate CO_2 emissions along with the average speed during the trip. The average speed for each WLTP sub-cycle is presented in Table 14-33 in the Annex.

Table 9-5: Weighting factor for each WLTP sub-cycle according to travel type

Commuter type	Average speed (km/h)	Weighting factor each WLTP sub-cycle (-)			
		Low	Medium	High	Extra high
Urban commuter	32.6	0.5	0.3	0.2	0

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(39) Germany, Spain, France, Italy, Poland, United Kingdom.

Medium-distance commuter	48.6	0.15	0.35	0.4	0.1
Long-distance commuter	61.9	0.1	0.2	0.35	0.35
Interurban traveller	87.3	0.025	0.025	0.05	0.9

The extra mass assumed for each type of trip is shown in Table 9-6.

Table 9-6: Additional mass for each trip type

Trip type	Load type	Passengers (driver not included)	Equipment (kg)	Total extra mass (kg)
Urban commuter	Normal load	0	7.5	7.5
	High load	0.5	22.5	60
Medium-distance commuter	Normal load	1	15	90
	High load	2	45	195
Long-distance commuter	Normal load	1	15	90
	High load	2.5	52.5	240
Interurban traveller	Normal load	2	22.5	172.5
	High load	3	60	285

The results for each type of trip are presented in Figure 9-11, Figure 9-12 and Figure 9-13, along with the realistic WLTP scenario presented in the simulation results of the 'Certification test'.

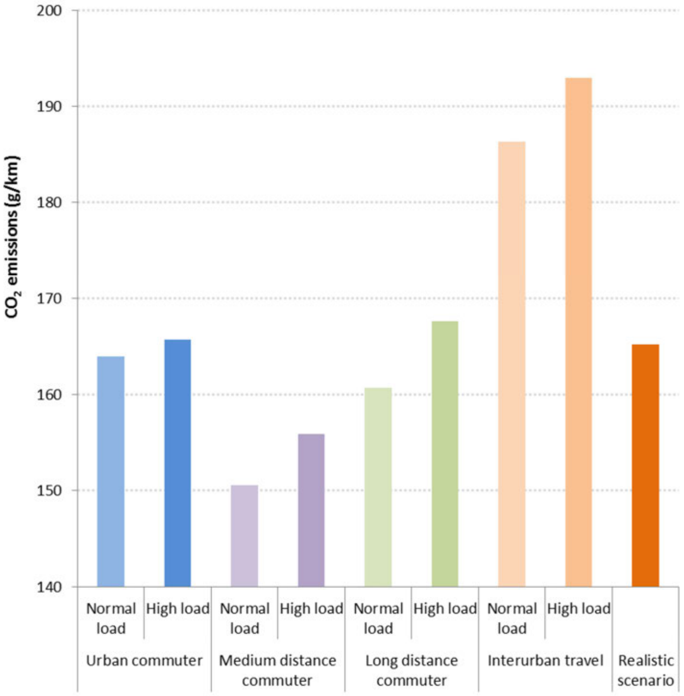


Figure 9-11: CO_2 emissions according to trip type and realistic scenario run over WLTP for a petrol NA vehicle

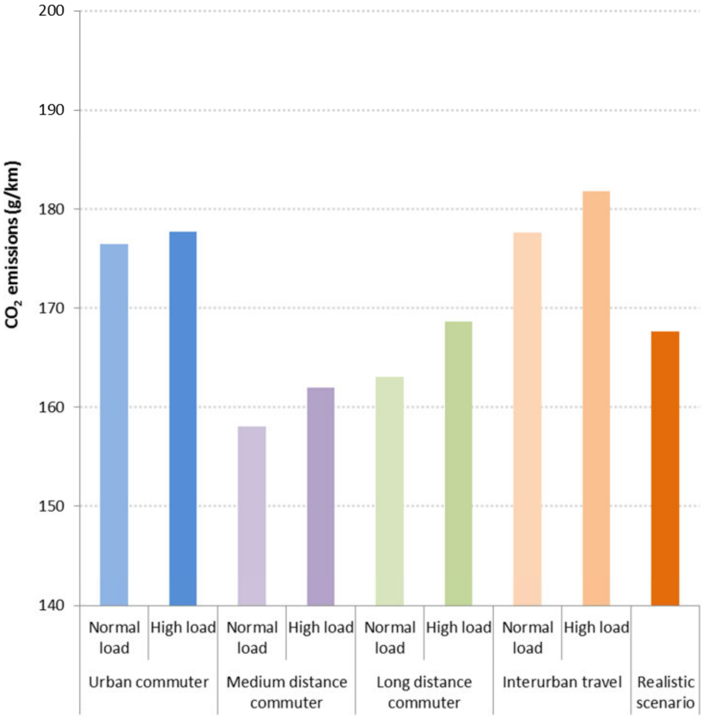


Figure 9-12: CO_2 emissions according to trip type and realistic scenario run over WLTP for a petrol turbo vehicle

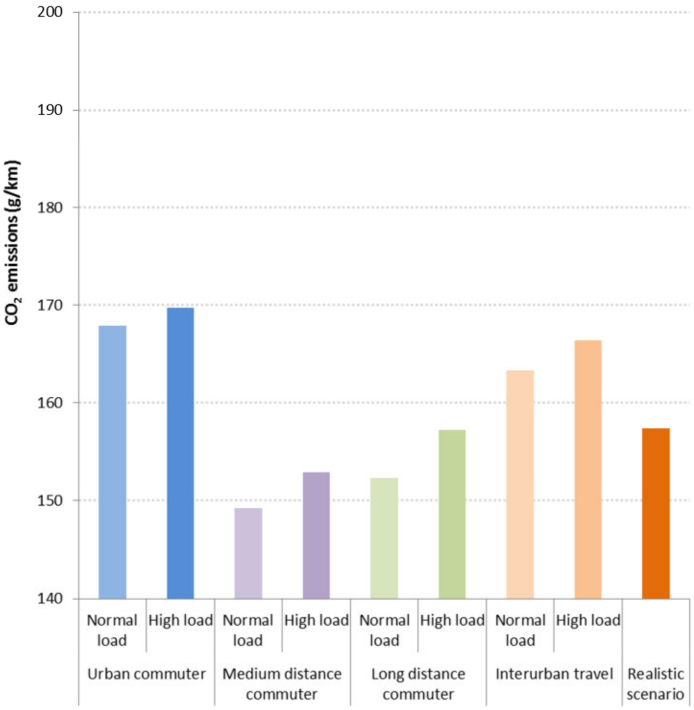
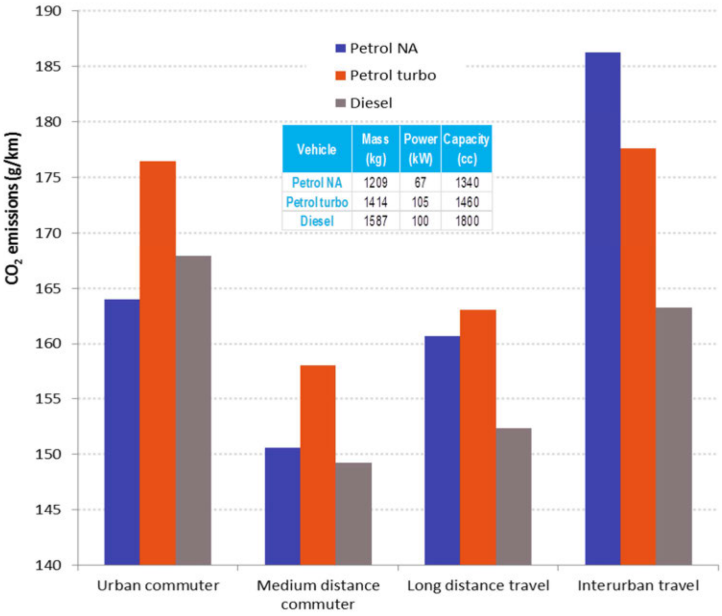


Figure 9-13: CO_2 emissions according to trip type and realistic scenario run over WLTP for a diesel vehicle

The average simulated CO_2 emissions for all trip types and vehicles is 158.6 gCO_2/km, while for the realistic scenario it is 163.9 gCO_2/km.

A comparison between the three simulated vehicle types was included for each type of trip and is shown in Figure 9-14 for a normal load. A table is included in the chart summarising the characteristics of each vehicle.



Vehicle	Mass (kg)	Power (kW)	Capacity (cc)
Petrol NA	1209	67	1340
Petrol turbo	1414	105	1460
Diesel	1587	100	1800

Figure 9-14: Comparison of CO_2 emissions between the simulation vehicles according to trip

The standard deviation between the trip types for each vehicle type is shown in Table 9-7 where the highest standard deviation is for the petrol NA and the lowest for the diesel.

Table 9-7: Standard deviation of CO_2 emissions of all trip typese according to vehicle type

Vehicle	Standard deviation (g/km)
Petrol NA	13.02
Petrol turbo	8.43
Diesel	7.65

9.7. Discussion — Overview

Road morphology was found to affect fuel consumption and CO_2 emissions.

Altitude as a factor affecting fuel consumption appears in relatively recent studies. A few studies were found and their results can only be considered indicative. The authors of these studies suggest themselves that further research is needed. An online search showed that the public is aware that elevation affects fuel consumption, but the discussions are rather confusing and provide contradictory results, opinions and explanations. The simulation results for altitude show a decrease for all vehicles by up to 4.4 % for NEDC and by 6.7 % for WLTP, both for an altitude of 2 000 m.

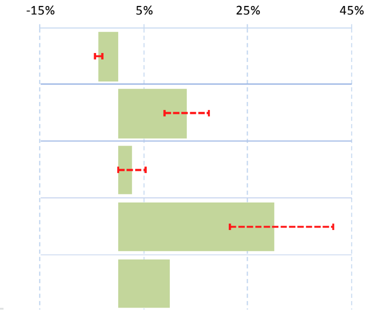
The effect of road surface on fuel consumption seems to be a new concern to researchers, as the average year of articles in the literature review is 2010. Only a few sources were found on the subject. Further investigation is needed to better quantify this effect. Additionally, the public seems unaware of any effect of road surface on fuel consumption.

The effect of road grade significantly affects fuel consumption by up to 20 % for a hilly route compared to a flat one, while energy losses from driving uphill are not completely counterbalanced by downhill driving. The simulation provided interesting results for the range of inclination of – 5 % to 5 %. At the maximum allowed road grade for an Italian highway, CO_2 emissions increase over NEDC by 85.4 % and over WLTP by 95.1 %, while for driving downhill at – 5 % the benefits are 67.7 % and 67.4 % respectively. It was surprising that only a limited number of European studies regarding road grade were available for LDVs; in contrast there are several studies looking into this topic for HDVs.

Several scientific sources were found that deal with the effect of traffic on fuel consumption. More targeted research is however needed in this field, because congestion affects both the vehicle and the driver and its effects are not limited to the duration of the trip but cause various side-effects affecting safety, health, environment and costs. The results from an online search regarding public concern did not reveal many discussions on the subject. Those there were focused more on idling and the benefit of start–stop technologies.

Figure 9-15 presents a summary of the average values (JRC estimations) based on the collected literature data.

Category	Factor		Literature median value	Sources No.
Road conditions	Road morphology	Altitude increase decreases consumption, as air density, aerodynamic resistance and oxygen concetration decrease	**-3.8%**	3
		Road grade increases fuel consumption as the car is driven uphill. Results based on American studies for a car driven on a hilly route	**13.3%**	3
	Road surface	Affected by roughness, surface texture and uneveness	**2.7%**	4
	Traffic condition	Reduced speed, increased idle time and start and stops at congestion	**30.0%**	3
	Trip type	Short trips. More cold starts and cold start emissions. Engine normal operation temperature not reached	**10.0%**	3



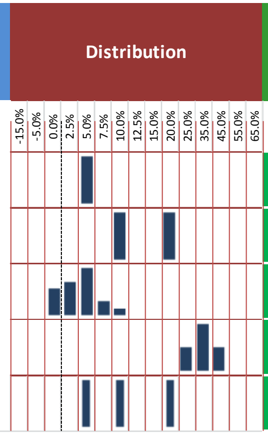


Figure 9-15: Summary table of the effect of road morphology on fuel consumption. Error bars represent minimum–maximum values reported.

10. Fuel characteristics

10.1. About fuel characteristics

Automotive fuels are blends of various types of hydrocarbons and other organic compounds (e.g. ethanol or methylesters in the case of biofuels). Their characteristics are regulated by the relevant standards (EN-590:2004, CEN/TS 15293:2011, EN-12214:2012, EN-228:2013). Additionally, (Directive 2003/30/ EC) promotes the use of biofuels and (Directive 2009/28/EC) encourages the use of low GHG fuels.

Within these limits, fuel composition and characteristics are defined by specific particularities related to climate, different regional standards, market availability of blendstocks and regional policies. The latter becomes more evident considering variations of bio-components in commercial fuel. Their presence is promoted and limited by European regulation but subjected to national regulations, targets and market particularities. For example the ethanol content in petrol is not the same for all EU Member States (EurObserv'ER 2014).

CO_2 emissions and fuel consumption are measured at the certification test with the vehicle fuelled by a specific standardised fuel with its physical properties varying over a limited range. The presence of varying blend stocks in commercial fuels can however affect engine operation in different ways, potentially impacting on consumption. Biodiesel for example offers some potential benefit such as a reduced lifecycle GHG intensity, but drivers may experience increases in volumetric fuel consumption, as engine efficiency was found to be lower (Lapuerta et al. 2008), its energy density is lower and acceleration times increase (Fontaras et al. 2009). Similarly, the annual variation between summer and winter grade fuel (40) as well as different fuel qualities (e.g. high octane petrol compared to regular petrol) can influence fuel consumption.

10.2. Seasonal variations of conventional fuel

Winter temperatures cause variations in fuel properties, like lower volatility, increased viscosity and in the case of diesel the creation of wax crystals. The creation of such crystals can lead to irregular flow, clog the filters and cause loss of power, engine stall after start, or even cause the engine not to start at all (Arnault and Monsallier 2014).

In order to prevent these effects, permitted diesel characteristics are adjusted in the relevant standard (EN-590:2004), depending on country and climate. The summary tables in the Annex (Table 14-28, Table 14-29) show the diesel fuel blend distinguished according to climate between temperate climatic zones and arctic climatic zones. For petrol vapour pressure changes between winter and summer.

A comparison between the winter and summer types of fuel would be incorrect as the use of each one is affected by additional factors, like temperature. The summer diesel fuel blend would be almost impossible to use below the freezing point. In the case of petrol, the

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(40) At low temperatures diesel can form wax crystals and according to the regulation EN-590 the fuel characteristics (e.g. density) are adjusted to prevent this. A side-effect of this adjustment could be a lower energy content of the fuel.

winter fuel blend would be more volatile at high summer temperatures resulting in higher evaporative emissions.

10.3. Biofuel effect on consumption

Biofuels were introduced 10 years ago in the European fuels market. The presence of biofuel blendstocks in fuel is reported to affect vehicle performance and consumption. Lapuerta et al. (2008) found that 96 % of the studies they reviewed claimed that vehicle power decreases when using biodiesel due to the lower energy density of the biodiesel. Oxygenated fuels, like ethanol or biodiesel, are known to increase the volumetric fuel consumption because of their low enthalpy of combustion, but they could compensate part of the loss by improving efficiency. For example ethanol presents a high anti-knock index (Cataluña et al. 2008), potentially improving combustion efficiency and decreasing the need for the addition of extra (anti-knock) compounds. The latter is mainly relevant for engines of higher compression ratios but it has benefits also in the case of conventional engines allowing a more detailed management of the spark advance that can result in efficiency improvements with reduced risk for knock.

In the following paragraphs the fuel blend is encoded as B for biodiesel and E for ethanol followed by a number which indicates the percentage of biofuel in the total fuel volume. B0 and E0 thus correspond to 100 % diesel and petrol accordingly.

10.3.1 Biodiesel

Biodiesel is a renewable source that can be produced by vegetable oils, animal fats and recycled restaurant greases and as such is non-toxic and biodegradable (DOE — EPA 2014a). Fontaras et al. (2009) measured tailpipe emissions and fuel consumption for biodiesel blends of 50 % (B50) and 100 % (B100) for the NEDC and Artemis cycle. They found for the B50 blend an increase of 9 % and 4.5 % volumetric fuel consumption over the NEDC and the Artemis cycle accordingly. The B100 blend led to an increase of 17 % for the NEDC and 10 % for the Artemis in volumetric fuel consumption. Regarding CO_2 emissions the authors state that the increase of 2-4 % that was found over the Artemis cycle for the B100 blend would have minimal impact on real-world emissions, as this percentage falls within the scatter of the baseline results. They consider that the B50 blend has no impact on emissions in this cycle. This apparent discrepancy between volumetric fuel consumption increases and CO_2 emissions increases is easily explained by looking at the carbon density of each fuel. In general for the same fuel volume biodiesel has a lower energy content and a lower carbon content. Hence for the same power output a higher fuel volume is required but emissions do not increase proportionally as would be the case for standard diesel. Their results are presented in Figure 10-1.

Studies on low biodiesel blends report only marginal impacts on CO_2 emissions and fuel consumption. Serrano et al. (2012) performed an experiment under real-world conditions with two identical vehicles. One was using diesel and the other an 80 to 20 blend of diesel and biodiesel (B20). They did not find a difference in consumption in the urban route, while they found a decrease of 0.1 l/100 km in the extra-urban route for the B20. B20 was found to be more fuel consuming by 0.05 l/100 km on the motorway. The authors hypothesise that this discrepancy is from the fact that there are lower energetic properties of biodiesel under stable operation on the motorway which however does not explain the reduction observed in the extra-urban phase. They also state that at low and medium loads with regular start and stops, the physical properties of the B20, like density and viscosity, combined with the increased amount of contained oxygen can surpass the lower energy density.

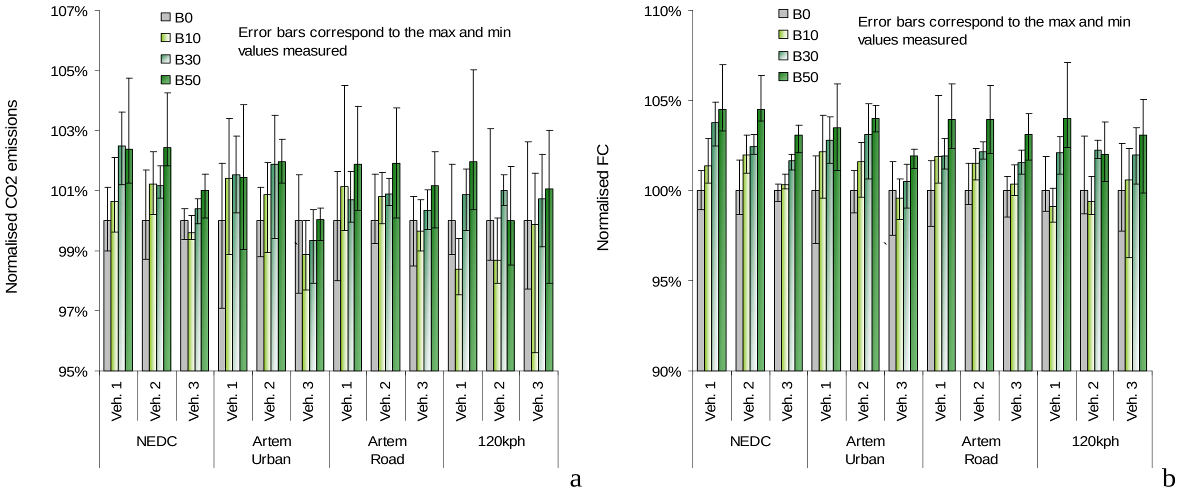

Figure 10-1: Fuel consumption and CO_2 emissions for B0, B10, B30 and B50 fuel blends (Fontaras et al. 2014b). Straight diesel consumption and emissions equal 100.

Figure 10-2 shows a summary of the effect on energy consumption for various biofuel blends according to the values found in the literature.

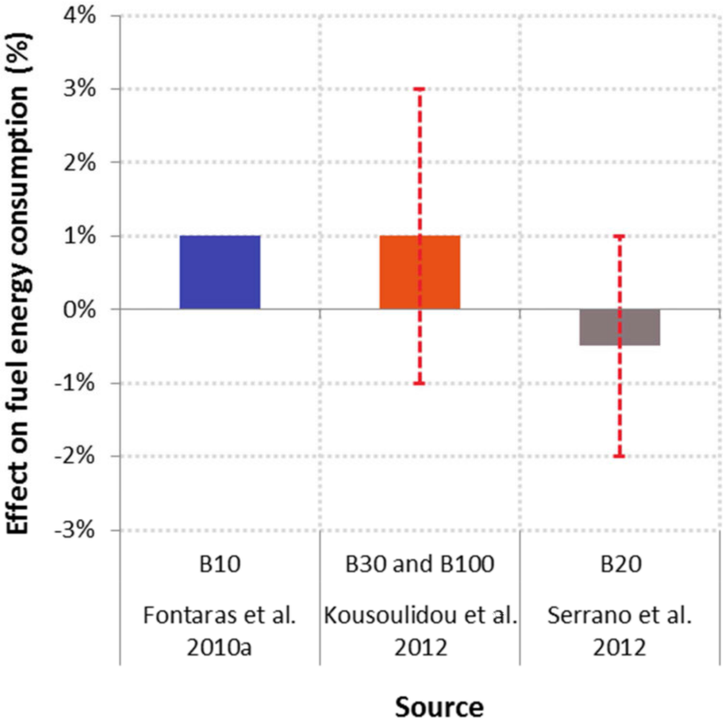

Figure 10-2: Effect on fuel energy consumption for various biodiesel blends

Studies point out that fuels are delivered to drivers and priced on a volumetric basis despite the fact that the same volume of biocomponents have a lower energy content. The energy content per volume is lower if the fuel is mixed with biofuels, as for example pure biodiesel has about 9 % lower heating value (Lapuerta et al. 2008).

10.3.2 Ethanol

The addition of ethanol in the fuel blend improves the octane number and the combustion speed, but may cause additional wear and corrosion to electric fuel pumps. It can also cause ignition difficulties at low temperatures (Park et al. 2010). Because of its high octane number, ethanol has an anti-knock effect which is a valuable property.

Delgado and Susanna (2012) have tested on the NEDC a petrol vehicle without special modifications and a flex fuel vehicle (FFV). The fuel blends used were E5 and E10 for the petrol vehicle and E85 for the FFV. The results were compared to E0 fuel. They found that total CO_2 emissions reduced by 1.2 % for E5 and 4.6 % for E85, while they increased by 1.4 % for E10. Fuel consumption was found to decrease by 2.5 % for E5, while it increased by 4.2 % for E10 and by 12.1 % for E85 (See Table 14-27 for more details).

Bielaczyc et al. (2013a) measured emissions of E5, E10, E25 and E50 blends for NEDC. They found a small decrease in CO_2. In the United States petrol contains ethanol up to 10 % (E10) and since 2011 the use of E15 has been introduced for 2001 and newer vehicles and FFVs (DOE — EPA 2014b). The Department of Energy (2014b) indicates that consumers experience higher fuel consumption (41) due to the lower energy density of ethanol.

The British car magazine What Car? (2014) compared E0 and E10 CO_2 emissions for a Dacia Sandero and a Mini Paceman and found that with E10 they increased by 11 g/km in the case of the Sandero and 2 g/km in the case of the Mini. The authors also claim the ECU might have misdiagnosed the sensors' data due to the different fuel composition and injected more fuel.

The fuel endurance for petrol–E10, diesel–B10 and E85 is illustrated in Figure 10-3.

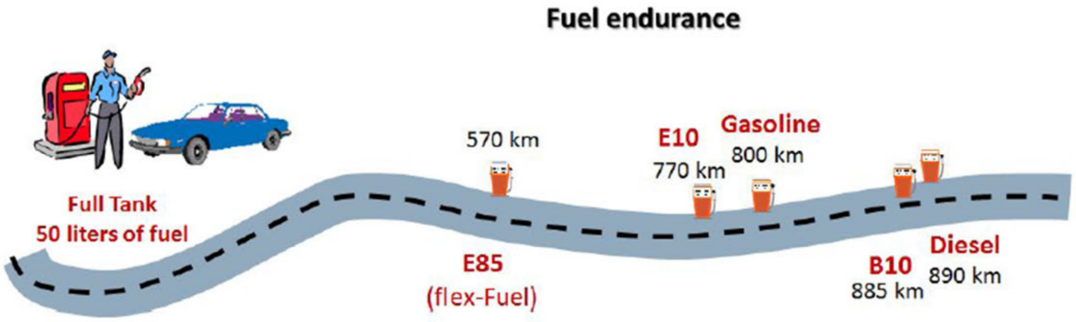

Figure 10-3: Fuel endurance for petrol, diesel and ethanol and biodiesel blends (Pidol 2014)

From the above it can be seen to be difficult to find homogenous information comparing fuel consumption for differing biofuel blends. Despite the plethora of the studies few

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(41) According to the Department of Energy, the decrease in terms of fuel economy is 3-4 % MPG on E10 and 4-5 % on E15.

sources were identified comparing neat petrol and E10 in terms of fuel consumption. These studies are presented in Figure 10-4.

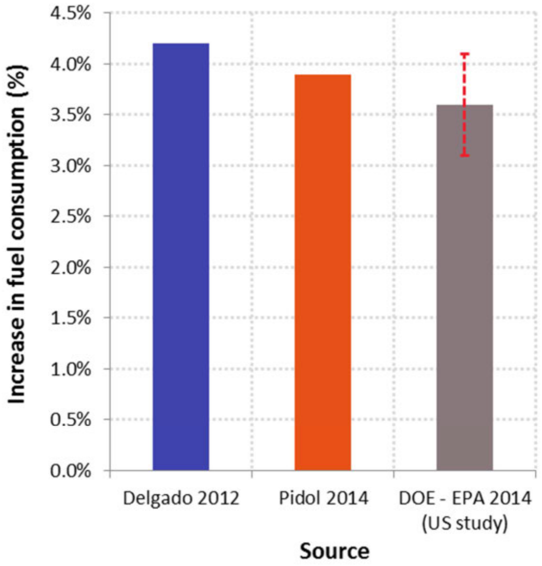

Figure 10-4: Increase in fuel consumption for an E10 fuel blend compared to E0

10.4. Simulation plan and results

The baseline fuel that was used in all the simulations of this study is E5 for petrol and B5 for diesel vehicles. The alternative fuels that were tested were E10 for petrol and B100 (FAME (42)) for diesel vehicles. The characteristics of the alternative fuels were provided by the European Biofuels (2011) and Martini et al. (2013), while some values were estimated based on these characteristics. The values used in this simulation scenario are shown in Table 10-1.

Table 10-1: Ethanol and FAME fuel blend characteristics (European Biofuels 2011, Martini et al. 2013).

	E5 (Baseline)	E10 splash	B5 (Baseline)	B100
Fuel carbon content (g CO_2/g fuel)	3.106	3.062	3.112	2.722
Fuel density (kg/l)	0.738	0.740	0.837	0.88
LHV (kJ/kg)	42 720	41 930	42 690	37 100

The simulation shows the impact on fuel consumption along with the impact on CO_2 emissions for each fuel type.

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(42) Fatty Acid Methyl Ester.

Table 10-2 Simulated impact of E10 and B100 introduction on fuel consumption and CO_2 emissions of passenger cars

	E10 effect on CO_2	E10 on fuel consumption	B100 effect on CO_2	B100 effect on fuel consumption
Petrol	0.43 %	1.85 %	-	-
Diesel	-	-	0.6 %	15 %

10.5. Discussion — Overview

The literature on biofuels' effect on emissions is extensive and difficult to summarise. A significant amount of articles quantify the measured impact of different biofuel blends on fuel consumption. The total impact on CO_2 emissions is reported to be marginal for low biofuel concentration blends.

Users seem concerned to a lesser degree about the fuel blend. They are concerned when they notice seasonal differences in performance and also about the operational capabilities and effect on the condition of their vehicles with the use of biofuels.

The simulation results show a marginal increase of 0.4 % in CO_2 emissions for E10 for both cycles. Regarding fuel consumption there is an increase of 1.9 %.

The diesel vehicle shows a small increase of 0.6 % in CO_2 emissions on both cycles for B100, but a significant increase in fuel consumption of 15.1 %.

Figure 10-5 presents a summary of the average values (JRC estimations) based on the collected literature data (See also Table 14-30 and Table 14-31). The fuel blend characteristics that were found did not offer a common basis for comparison and for this reason the results are indicative.

Category	Factor		Literature median value	Distribution	Sources No.
Fuel characteristics	Difference in fuel properties	B10 fuel blend compared to B0	**1.0%**	2.5%	2
		E10 fuel blend compared to E0	**3.8%**	5.0%	3

Figure 10-5: Summary table of the effect of fuel characteristics on fuel consumption. Error bars represent minimum–maximum values reported.

11. Certification test

11.1. Literature review

The term test margins (also denoted as test elasticities or test flexibilities) refers to the aspects of the type approval test which can be legally exploited in order to deliver lower fuel consumption and CO_2 results than would occur in real-world driving conditions. More precisely with the terms 'margin', 'flexibility' or 'elasticity' we refer to a specific provision or interpretation of the certification procedure, or an absence of such a provision or clear interpretation, that results in the measurement of lower CO_2 emission values compared to the values that would occur if provisions, interpretations or practices more accurately reflecting the operation of the vehicles under average real world conditions were followed, within the boundaries and technical limitations of the same measurement procedure (43). A series of margins have been identified to date like the speed profile of the test cycle, the test temperature, calculation of vehicle resistances, vehicle preparation, etc.

The existing type approval test in the European Union was established in the 70s to measure at the time regulated pollutant emissions but not CO_2 or fuel consumption. The testing of the latter was introduced early in the 80s. It is based on the New European Driving Cycle (NEDC), which has received a lot of criticism and is currently considered outdated (Mock et al. 2013). This consists of smooth accelerations and decelerations which fail to reflect modern driving patterns (Kågeson 1998, Dings 2013). In addition, the test protocol disregards various real-world conditions like additional weight, number of passengers, use of A/C, realistic gear shifting, cold starts, operation at higher velocities and congestion (Ligterink 2012), while it examines only a small area of the operating range of the engine (Kågeson 1998).

Table 11-1 presents a summary of the factors related to the test margins and their effect, either quantitatively or qualitatively, according to the corresponding authors. Additionally, the quantification of the test elasticities found in literature is presented in Figure 11-1 (average values per elasticity group).

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(43) Although such flexibilities might result in not being 'illegal' their intentional exploitation to achieve benefits should be considered against the spirit of the law and the principle of good faith governing EU certification schemes.

Table 11-1: Test elasticities of the European type approval test and their effect in reported CO_2 emissions as quantified by different literature sources

Factor	Effect	Source
High idle time	Start–stop technology overrated. Leads to decreased fuel consumption in the NEDC	Dings (2013), Mock et al. (2013)
Use of inertia classes (44)	CO_2 values off by 4-6 g/km compared to real values	Mock et al. (2012)
	Increased CO_2 emissions from 2 % to 11 %	Dings (2013)
Non-realistic acceleration and driving patterns	Discrepancy between NEDC and real-world consumption	Demuynck et al. (2012), Mock et al. (2013), Weiss (2013)
	Variations of up to 30 % in the NEDC	Hill (2011)
	Fuel consumption underestimated from 10-20 %	Pelkmans and Debal (2006)
Short test cycle	Long cold start, increased fuel consumption between 3 % and 14 %	Ligterink (2013)
	Underestimate hot emissions compared to real-world driving cycles	Joumard et al. (2000)
Different wheel and tyre specifications in the NEDC than in real-world	Decreased fuel consumption by 2 %	Mock et al. (2013)
Flat surface, no simulation of altitude changes	Discrepancy between NEDC and real-world consumption	Mock (2012), Weiss (2013)
Fully charged battery, not charging during the test	Lower fuel consumption than in real-world conditions	Kadijk et al. (2012), Mock et al. (2013)
Test temperature between 20-30 °C	Soak temperature of 30 °C compared to 20 °C reduces CO_2 emissions 1.7 %	Kadijk et al. (2012)
	Average temperature in Europe is about 14 °C, which could result to higher emissions by up to 6 g/km	Mock et al. (2013)
	Discrepancy in consumption could be up to 2 % between 20 °C and 29 °C.	Dings (2013)
Auxiliary systems are not taken into consideration	Increased emissions, especially for A/C	Schipper (2011)
	Use of A/C increased fuel consumption by 5 %	Mock et al. (2013)
	Increased consumption between 2.8 and 10 %	Johnson (2002)
	Increased consumption: 4 % in urban, 2.5 % in rural and 1 % in motorway	Weilenmann et al. (2010)
Special gear oil may be used in transmission	Decreased consumption by 1 %	UBA (2010)
Declared results is allowed to be lower than measured	Decreased results by up to 4 %	Kadijk et al. (2012), Dings (2013)
Wheel and tyre optimisation	Increased rolling radius by 5 % decreases CO_2 emissions by 2.5 %	Kadijk et al. (2012)
Road load	Real-world road load is 30 % higher at high speeds compared to type approval; Mainly affects constant part	Van Mensch et al. (2014)

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(44) The road loads for each vehicle are simulated on the chassis dynamometer by using distinct inertia classes instead of the real vehicle's weight. Their use was mandatory for the calibration of a mechanical dynamometer but it is rendered obsolete with the modern digital equipment. However the inertia classes are still used as a part of the type approval test, Mock, P. (2011). 'Inertia classes, vehicle emissions tests, and the dead hand of the past.' **From the blogs** http://www.theicct.org/blogs/inertia-classes-vehicle-emissions-tests-and-dead-hand-past. Mock, P. (2011), 'Inertia classes, vehicle emissions tests, and the dead hand of the past.' **From the blogs** http://www.theicct.org/blogs/inertia-classes-vehicle-emissions-tests-and-dead-hand-past. Mock, P. (2011), 'Inertia classes, vehicle emissions tests, and the dead hand of the past.' **From the blogs** http://www.theicct.org/blogs/inertia-classes-vehicle-emissions-tests-and-dead-hand-past. Mock, P. (2011), 'Inertia classes, vehicle emissions tests, and the dead hand of the past.' **From the blogs** http://www.theicct.org/blogs/inertia-classes-vehicle-emissions-tests-and-dead-hand-past. Mock, P. (2011), 'Inertia classes, vehicle emissions tests, and the dead hand of the past.' **From the blogs** http://www.theicct.org/blogs/inertia-classes-vehicle-emissions-tests-and-dead-hand-past. Mock, P. (2011). 'Inertia classes, vehicle emissions tests, and the dead hand of the past.' **From the blogs** http://www.theicct.org/blogs/inertia-classes-vehicle-emissions-tests-and-dead-hand-past. (Mock, P. 2011)

	of road loads (F0) as other components (F1 and F2) appear to be less sensitive	

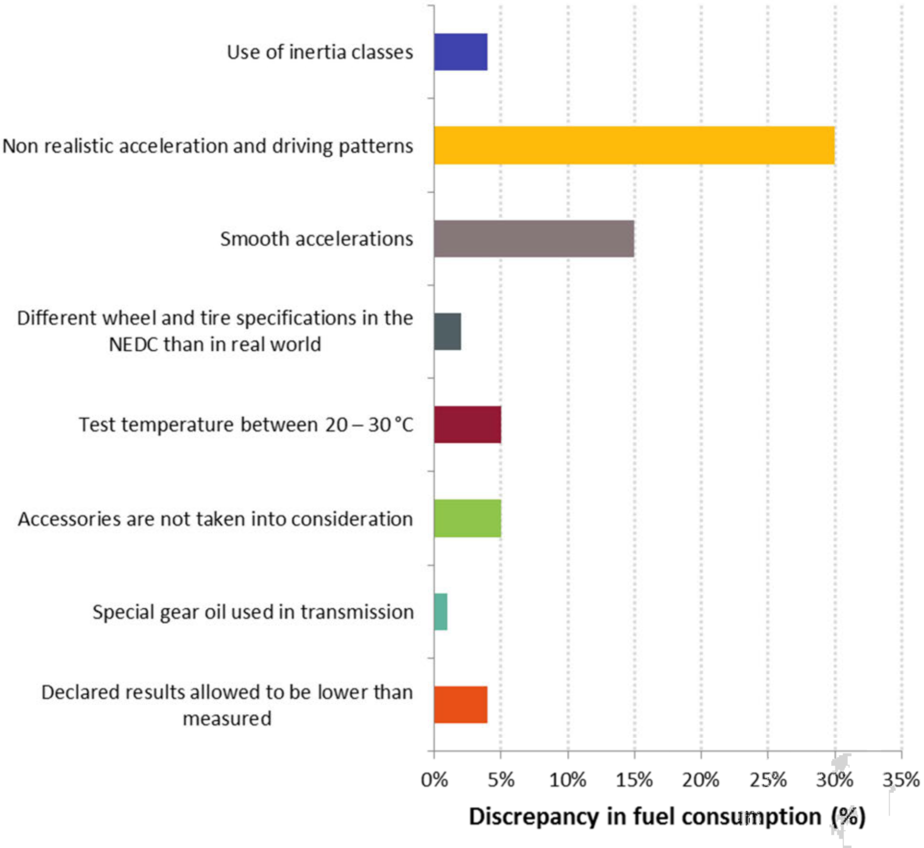

Figure 11-1: Discrepancy in fuel consumption between type approval and real world due to the test margins (average values of sources included in Table 11-1)

As mentioned, real-world emissions depend on various factors like the driver's behaviour, vehicle characteristics as well as road and ambient conditions (Ericsson 2000, Brundell-Freij and Ericsson 2005). Kadijk and Ligterink (2012) have determined the discrepancy between real-world and type approval road load values for six vehicles. The vehicles are classified as Euro 4-6 and the road load divergence as shown in Figure 11-2 is inversely proportional to vehicle speed.

Regarding cycle dynamics and velocity pattern, (André et al. 2006) argue that a set of driving cycles should be used to test all vehicles as they differ in performance levels and usage characteristics. Currently no test cycle takes into account the lateral acceleration of the vehicle which could require up to 48 % more power consumption than under NEDC (45) (Lin et al. 2011).

Test preconditioning may have a significant effect also over the NEDC test. A series of Petrol and diesel vehicles were tested on a laboratory NEDC test and a discrepancy of 15 ± 10 % was found between laboratory and type approval test (Weiss 2011). The authors attribute this difference to the preparation of the vehicle in terms of e.g. tyre

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(45) The authors developed a new driving cycle to include lateral accelerations and. Real-world measurements are also available.

pressure and battery state of charge and to the specific settings of the chassis dynamometer. Within the same project, the vehicles were driven on PEMS test routes and a deviation of 18 ± 10 % for Petrol vehicles and 24 ± 7 % for diesel was reported. The results are presented in the Figure 11-3.

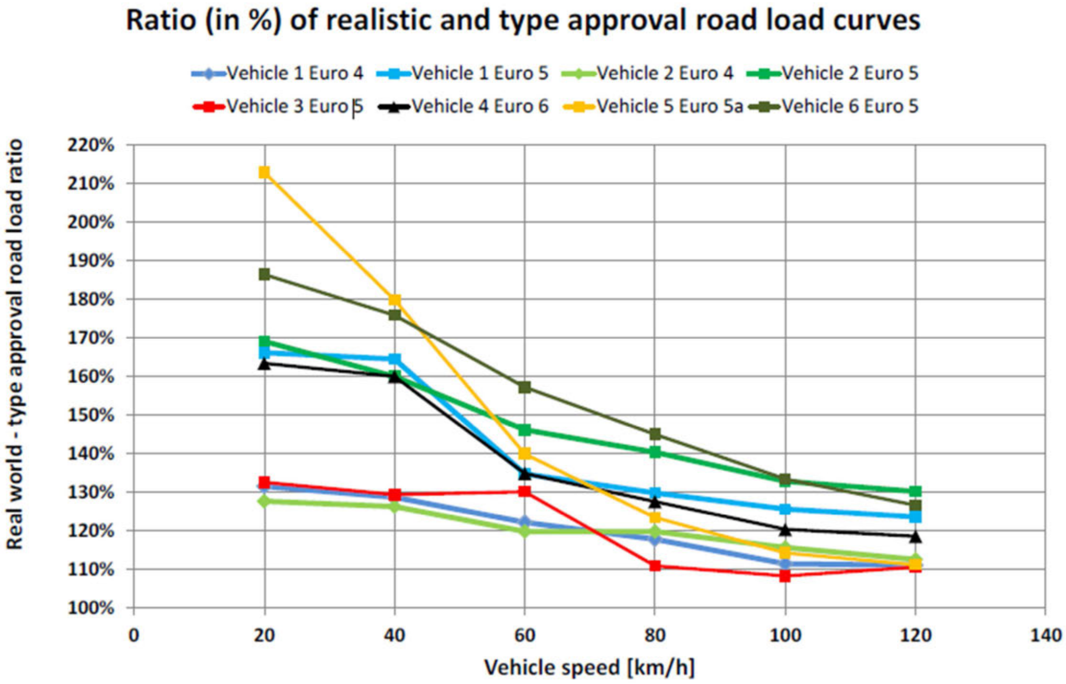

Figure 11-2: Ratio of realistic and type approval road load curves (TA = 100 %) from Kadijk and Ligterink (2012)

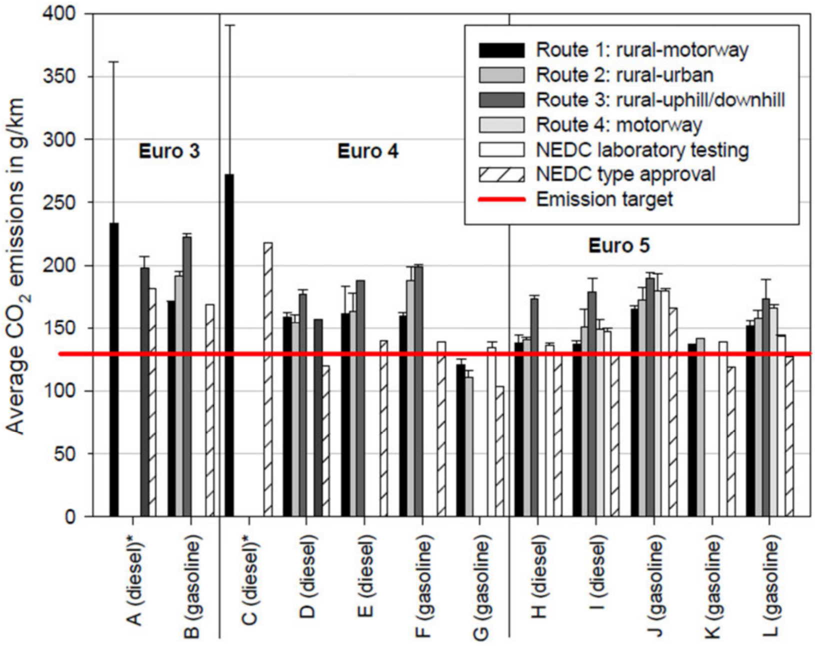

Figure 11-3: Average CO₂ emissions found in PEMS road test and in-house NEDC laboratory test for Petrol and diesel vehicles. Emissions target refers to 130 gCO2/km in 2015 (Weiss 2011).

11.2. Simulations

The baseline models were used to run five different scenarios. These scenarios comprised two cases based on the NEDC test protocol, two cases based on the WLTP protocol and a fifth case aiming to simulate real-world driving conditions. A summary of all five scenarios is presented in. An additional sixth case (certification value) demonstrated the potential effect of the 4 % vehicle clustering margin as describe previously.

The NEDC base and NEDC type-approval (NEDC T/A) scenarios closely followed the boundary conditions of the baseline models presented in paragraph 2.2.2. The inertia class of each vehicle was defined according to the vehicle masses reported in Table 2-4, road loads were calculated for the base NEDC assuming the following fixed values:

- Rolling resistance (9 kg/t) in order to calculate the constant road load factor of each vehicle (F0);
- 0.3 N/km for the factor proportional to vehicle speed (F1);
- 0.038 $N{\cdot}h^2/km^2$ for the factor expressing aerodynamic losses (F2).

The temperature of the base test was assumed to be 23 °C, a value lying inside the 20 °C-25 °C range foreseen by the legislation (46). A fixed alternator power consumption of 0.15 kW was considered for the WLTP to account for the various systems of the vehicle. The WLTP cycle was considered to be neutral in terms of battery charge/discharge, as were the NEDC base and the Realistic scenario. A NEDC-based certification-like scenario (NEDC — margins) was assumed taking into consideration various possible flexibilities that are present in the current test procedure. In this case a 20 % reduction of factor F0 was applied to account for the possibility to use tyres of lower rolling resistance during the test and the effect of test track grade on the road load calculation which is not considered in the current road load measurement process. Temperature was set to its maximum limit of 25 ˚C and electric consumption was set to 0kW in order to reflect the possibility to start the certification test with the vehicle battery fully charged.

WLTP-H and WLTP-L scenarios were developed for the TMH and TML vehicle configurations respectively. Masses were adjusted taking into account the maximum and minimum laden masses of the tested vehicles as foreseen by the WLTP test procedure, taking into account the reductions in vehicle mass imposed previously in order to match the EEA database average mass values; compulsory use of two axis-chassis dyno was considered (+ 3 % in simulated vehicle inertia compared to + 1.5 % for the NEDC cases). Having the WLTP H & L test masses the road loads were adjusted accordingly assuming an estimated range of variation for tyre rolling resistance of 0.13 kg/t and a 0.042 m^2 range of variation in aerodynamic resistances. For more details on the calculations of WLTP H & L road loads refer to (UNECE 2015).

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(46) It should be noted that the WLTP procedure foresees an after test (*ex post*) correction for compensating the difference of test temperature (23 ˚C) compared to the European average (15 ˚C) which was not considered in this analysis due to lack of necessary data; as a result WLTP values could be about 1 % higher when corrected.

Table 11-2 Summary of simulation scenarios

Scenario	Realistic scenario	WLTP-H	WLTP — L	NEDC Base	NEDC with margins	Certification value
Mass	Avg. WLTP H & L + 75 kg	WLTP-L + 150 kg	NEDC Inertia class + 40 kg	NEDC inertia class		Same boundary conditions as for NEDC with margins. Final CO_2 value reduced by 4 % according to the family criterion in current T/A.
Road loads	Avg WLTP-H & L	WLTP-L + 30 % F0, + 7 % F1 & F2	Base + 20 % in F0, + 3 % in F1 and F2	Base RLs (RR: 0.009 kg/ton, F1: 0.3 N·h /km, F2: 0.038 N·h^2/km^2)	Base – 20 % F0 Reduced rotating inertia 1.5 %	
Driving profile	WLTC			NEDC	NEDC	
Gearshifting	Case specific WLTP gear-shifting depending on road loads			NEDC time-based		
Temperature	14 °C	23 °C			25 °C	
Alternator power consumption	0.5 kW Bat. Charge Neut.	0.15 kW — Battery charge Neutral			0 kW	
Road grade	0.25 %	0 %				

Finally for the realistic scenario the test parameters were adjusted according to Table 11-3, while the effect of these parameters is discussed in detail in their respective chapters. In a summary the following assumptions were made. Vehicle mass was assumed to be equal to the average of WLTP H and L scenarios, augmented by 75 kg to account for an occupancy rate of 1.7 passengers (~ 52 kg) and 23 kg of extra equipment loaded on the vehicle. Road load values were assumed to be the average of WLTP H & L, lying between the best and worst case in terms of vehicle resistances. The WLTC speed profile and driving mix was assumed to be a balanced estimate for average European conditions. Temperature was set to 14 °C in order to account for average European temperature conditions. Electric loads were increased from 0.15 kW to 0.5 kW in order to account for the use of various electric equipment and potential use of an air conditioning/heating device. A positive road grade of 0.15 % was assumed[47]. Gearshifting was applied according to WLTP rules, taking into consideration the ‘realistic’ road loads and the applied road grade.

The results of the abovementioned scenarios are summarised in Figure 11-4 subfigures a, b, c for the three individual vehicles.

It is observed in all cases that the potential shortfall between the certification value and that of the realistic scenario differ by approximately 35 %, a value that is consistent with literature findings. It is interesting to mention that the certification value is already 12-

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(47) The value was chosen after simulating the fuel consumption over WLTC with constant grades ranging from – 5 % to + 5 % over a 1 % step. Results indicated an average fuel consumption increase compared to the zero road grade case, as the fuel reduction achieved over negative grade cycles did not completely cancel out the increases in fuel consumption over the positive grade cycles. The average fuel consumption increase calculated over all tests was estimated to correspond to a constant + 0.15 % constant road grade over WLTP.

15 % lower compared to what could be an expected NEDC-based measurement result if limited application of margins took place.

These figures reflect the expected behaviour of vehicles with characteristics close to those of the average new registrations in Europe. The analysis should be expanded in order to cover vehicles of different characteristics, in particular with respect to mass and engine size.

Table 11-3: Parameters adjusted for the realistic scenario

Parameter	Value	Source	Notes
Occupancy rates of 1.7	+ 52 kg	(EEA 2010a, EEA 2010b)	
Test temperature	14 °C		Indicative European average
Constant road grade	0.25 %	In-house calculations	Based on simulation results, chapter 'Road (morphology, surface, traffic)'
Electrical auxiliary load	0.5 kW	(European Commission 2013)	Usage factor applied, see Table 14-32 in Annex

Figures also reveal a relatively limited difference in CO_2 emissions between the NEDC base scenario and the WLTP-L scenario in particular for Petrol vehicles. For the three cases investigated the average difference was in the order of 1 g CO_2/km. Given the fact that the two scenarios mainly differ in the cycle profile and the constant part of the road loads assumed, it is concluded that the introduction of the new driving profile combined with the corresponding gear shifting strategy does not significantly change the CO_2 emissions and fuel consumption of the vehicles, when expressed on a per kilometre basis (g/km). In fact it is estimated that applying the same road load and mass settings between WLTC and NEDC driving profiles would result in marginally lower CO_2 emissions for WLTC. This is partly expected for three basic reasons, the amount of idling which in WLTC is considerably lower than in NEDC (13 % to 23 % respectively) and the contribution of cold start extra fuel consumption which over WLTC is divided by a longer distance (23 km) compared to NEDC (11 km) as reported also by (Marotta et al. 2015).

Although the difference due to only the cycle and the gear shifting is not expected to be high, their increased realism with respect to the NEDC will produce, as a result, that the technologies introduced to reduce fuel consumption and CO_2 emissions over the new cycle to meet the targets that will be defined by the legislation, are expected to be as effective also in real life conditions. This is one of the elements that will prevent, in the future, that the gap between in-use and type-approval figures might increase considerably.

Comparing the simulation results between NEDC with test margins and the realistic scenario reveals important differences in CO_2 emissions ranging from 35 to 42 g CO_2/km.

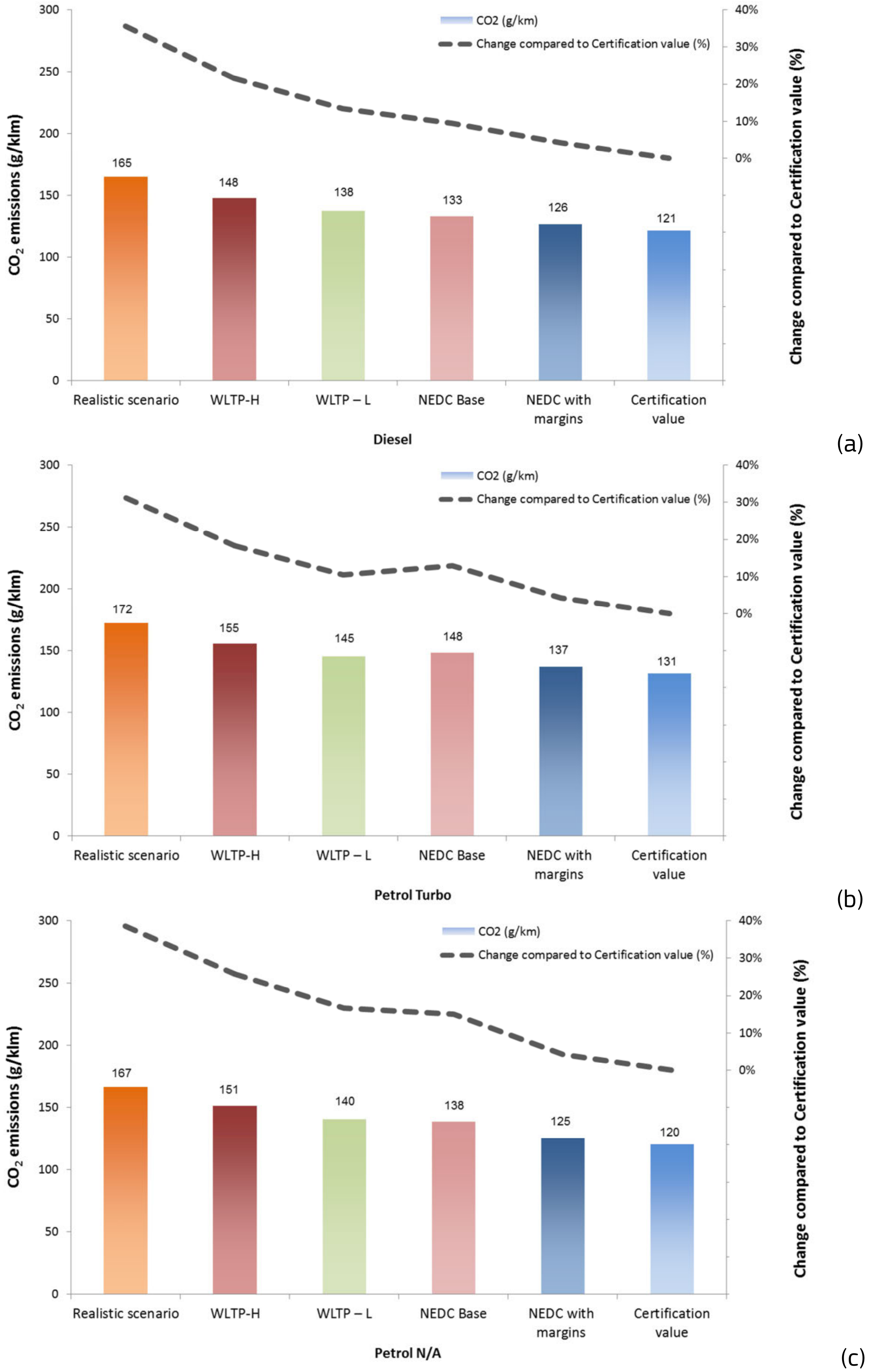


Figure 11-4: Results of the six scenarios investigated for the diesel (a), Petrol turbo (b), Petrol naturally aspirated (c) vehicle

This corresponds to a shortfall of about 26 %. The gap is significantly lower when looking at the WLTP-Real world difference ranging from 18-28 g CO_2/km.

Given that the final WLTP result is likely to be slightly higher due to the additional corrections foreseen (correction for the imbalance in the battery state of charge, for the average European temperature of 14 °C, etc.), its introduction is likely to significantly improve the apparent shortfall between certified and real-world emissions. A certain discrepancy, which based on the present data and assumptions is estimated in the order of 10-20 % is likely to remain (and can be considered natural due to the controlled conditions of a test in the lab). However the more strict definitions of test procedures and the limited margins coupled with a more realistic driving cycle and gear shift strategy of WLTP compared to NEDC will likely prevent the widening of the gap after the WLTP implementation, which as a matter of fact is even more important than the gap itself.

11.3. Overview

Several elasticities of the existing certification test are reported in literature as this subject has been under discussion for a long time. Systematic exploitation by OEMs has led, among other things, to an increase between the reported fuel consumption and the consumption experienced by drivers in real-world conditions. Due to the variety of factors affecting the results, the authors are aware that there could be margins that have not been identified yet by researchers and could also be potentially exploited. Figure 11-5 presents a summary based on values found from the literature review.

The adoption of the new World Harmonised Light Duty vehicle test procedure (WLTP) including the corresponding test cycle (WLTC) is expected to address several of abovementioned elasticities and provide a more realistic and robust test basis. The shortfall between the current certification values and what was estimated to be a representative real world performance of an average European vehicle was estimated in the order of 30 % while the same is figure drops to about 13 % considering the likely boundaries and characteristics of the forthcoming test protocol. The analysis showed that under the new test procedure test CO_2 values may increase by a factor of 8-16 %, estimates that involve a wide margin of uncertainty, given the unknown configuration and characteristics of the vehicles, particularly during the WLTP testing.

A short online search in forums and public, non-scientific websites, revealed that the users seem rather concerned about the type approval test itself. This internet search yielded a wide number of online magazine articles that provide information about the shortfall between type approval test and real-world values. Although drivers are not concerned directly about the weakness and the margins of the test, they do question its reliability. For this reason, many discussions and requests for more reliable results were found in magazines and online forums.

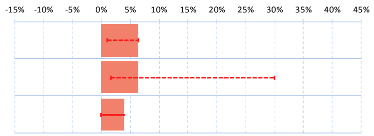
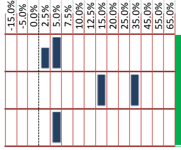
Category	Factor		Literature median value		Distribution	Sources No.
Certificationt test margins	Test Inputs / Various factors	Mean value of various factors involved in certification test (road loads, masses, practices etc)	**6.4%**			13
	NEDC protocol and cycle design	Boundary conditions of certification test, smooth accelerations, decelerations and driving pattern	**6.5%**			
	Lower value declaration	Declared values is allowed to be lower than measured values	**4.0%**			

Figure 11-5: Summary table of the effect of test conditions on fuel consumption. Error bars represent minimum–maximum values.

12. General discussion — Conclusions

12.1. Literature review and simulation scenarios

The literature review identified factors affecting fuel consumption and CO_2 emissions. Many factors had already been well assessed, like ambient temperature or mass increase, but some were identified as having a more subtle effect on fuel consumption, like altitude. In addition, further factors were identified which had not been studied in literature before, like for example the vehicle suspension system. Suspension type and condition could affect fuel consumption, however very little data was found for passenger cars while sufficient data was found for heavy-duty vehicles.

The simulation scenarios have taken into consideration the effect of several dominant factors on three versions of a passenger car. The effect of each factor was simulated by adjusting the model parameters accordingly. On one hand, the elements described thoroughly in the literature have a clear effect on vehicle operation, allowing for a straightforward simulation plan. On the other hand, the least studied elements in the literature like for example altitude, with only some indications about its effect on fuel consumption triggered an in-house investigation to simulate and quantify them properly. The scope and length of the report does not allow for thorough investigation of each individual factor. Such knowledge gaps in literature should be addressed in the future via more detailed analyses and if possible experimental testing.

The opinion of the public on the factors affecting fuel consumption was also investigated by means of a simple online search, as more detailed research would be beyond the purpose of this study. In some cases the public was found to be well informed with regard to optimising its fuel consumption, e.g. through eco-driving (48).

The independent simulation of each factor has provided results which are in most cases similar to the literature review, but in some cases there were also deviations. These deviations are attributed to the fact that in laboratory tests, when examining a single factor there could be additional factors affecting fuel consumption that are difficult to identify and are not included in the simulation scenario.

In real-world, the discrepancy between type approval and actual fuel consumption is due to a combination of factors. It is apparent that even small changes in these factors can cause significant deviations on fuel consumption and CO_2 emissions while most of them cannot be controlled by the users (e.g. the ambient conditions). In several cases, the simulations were performed combining two factors. However, in one case a combination of several factors is used that was estimated to be closer to real-world conditions.

Table 12-1 contains a summary of the findings of the review and Table 12-2 summarises the simulation results. Table 12-3 points out whether a factor was addressed in the simulation or not and if so, to what extent.

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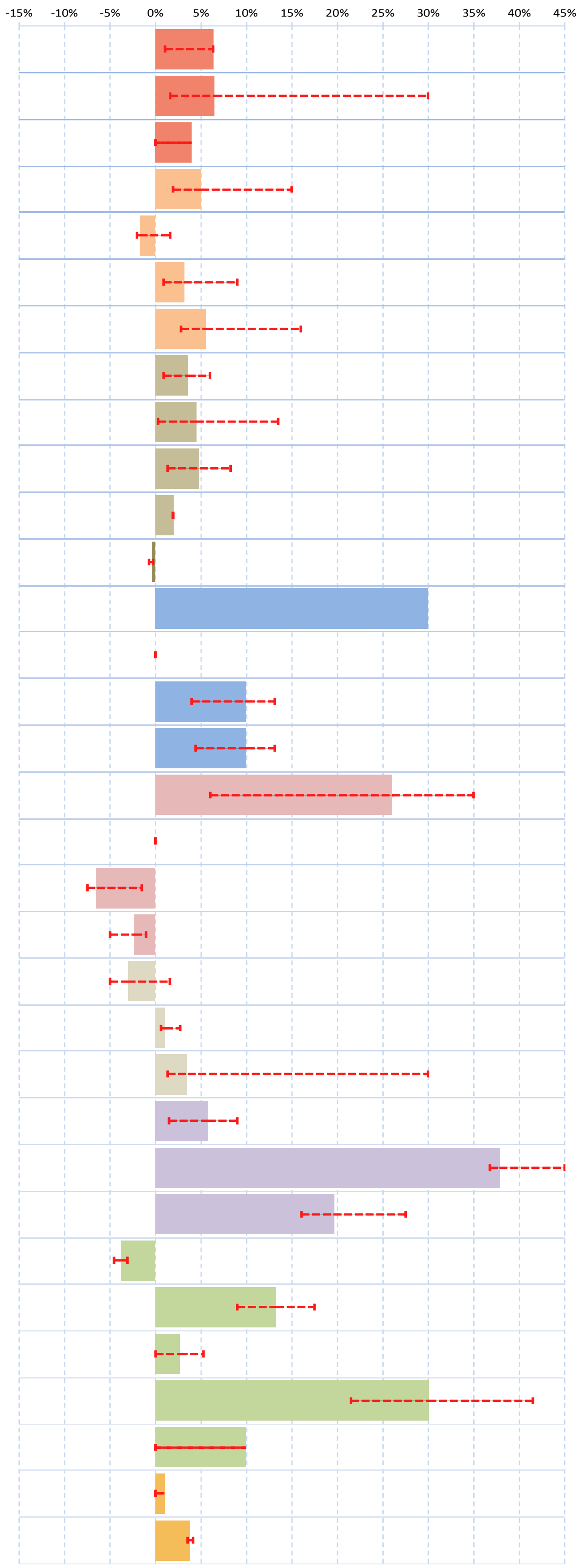
(48) Several concerns of relevance to this study are being expressed by drivers, as whether A/C or open windows are more energy efficient.

Table 12-1: Summary table of the various factors affecting fuel consumption. Error bars indicate minimum–maximum values found in the literature.

Category	Factor		Literature median value	Sources No.
Certification test margins	Various factors	Various factors involved in certification test	6.4%	13
	NEDC design	Smooth accelerations, decelerations and driving pattern	6.5%	
	Lower value declaration	Declared values is allowed to be lower than measured values	4.0%	
Auxiliary systems	Air conditioning	Increased electrical supply is required	5.0%	10
		Improved MAC systems, EV HVAC - heat pump, active seat ventilation, solar reflective paint, solar control glazing, solar roofs	-1.7%	8
	Steering assist systems	Hydraulic Power Assisted Steering, Electro - Hydraylic Power Assisted Steering, Electric Power Assisted Steering. Improved steering pump	3.2%	3
	Other vehicle auxiliaries	Engine management, fuel injection, fog lamps, brake lights, wipers, dipped beams, brake assist, heated windscreen, fan, etc	5.5%	6
Aerodynamics	Roof add - ons and modifications	Various add - ons that are attached to the roof, except for a roof box	3.6%	2
	Roof racks / boxes (air drag increase)	Effect on fuel consumption with the addition of an un - laden roof box. Increased aerodynamic resistance	4.5%	5
	Open windows	At a speed of 130 km/h, based mainly on an american study	4.8%	3
	Sidewinds effect	Change in aerodynamic drag and frontal area, depends on wind velocity and angle. Results for 10% air drag increase (caused from 15° to 30° yaw angle or from 4 - 8 m/s wind velocity)	2.0%	5
	Improvements	Spoilers, vortex generators	-0.4%	3
Weather conditions	Rain	Wheels have to push through water. Increase for 1 mm of water depth on road surface	30.0%	3
	Snow/Ice	Decreased tyre grip, wasting energy. Lower than normal driving speeds. Decreased tyre pressure	Qualitative data	
	Temperature, the type approval test current range is 20 - 29 °C	0 °C compared to 20 °C	10.0%	15
		-20 °C compared to 0 °C	10.0%	
Driving behaviour/style	Aggressive driving	High acceleration and deceleration, braking and maximum speed	26.0%	10
	Driving mode	Consumption varies according to Eco or Sport mode. Non scientific research claims increase up to 11% for Sport mode	Qualitative data	6
	Eco - driving	Optimal gear shifting, smooth accelerations and decelerations, steady speed maintenance, anticipation of movement and traffic, Green - Light Optimal Speed Advisory (GLOSA)	-6.5%	6
Vehicle condition	Lubrication	Use of low viscosity motor oil results in lower internal friction	-2.4%	13
	Tyres	Low resistance tyres by 10 - 20%	-3.0%	19
		Lower tyre pressure by 0.2 bar	1.0%	
	Other	Clogged air filters, misaligned wheels, poorly tuned engine	3.5%	5
Operational mass	Vehicle mass	Increased mass by 100 kg	5.8%	17
	Trailer towing	Affects weight, rolling resistance, aerodynamics and driving behavior	37.9%	3
	Roof racks / boxes (mass increase)	Fuel consumption increases as speed increases	19.7%	5
Road conditions	Road morphology	Altitude increase decreases consumption, as air density, aerodynamic resistance and oxygen concetration decrease	-3.8%	3
		Road grade increases fuel consumption as the car is driven uphill. Results based on American studies for a car driven on a hilly route	13.3%	3
	Road surface	Affected by roughness, surface texture and uneveness	2.7%	4
	Traffic condition	Reduced speed, increased idle time and start and stops at congestion	30.0%	3
	Trip type	Short trips. More cold starts and cold start emissions. Engine normal operation temperature not reached	10.0%	3
Fuel characteristics	Difference in fuel properties	B10 fuel blend compared to B0	1.0%	2
		E10 fuel blend compared to E0	3.8%	3



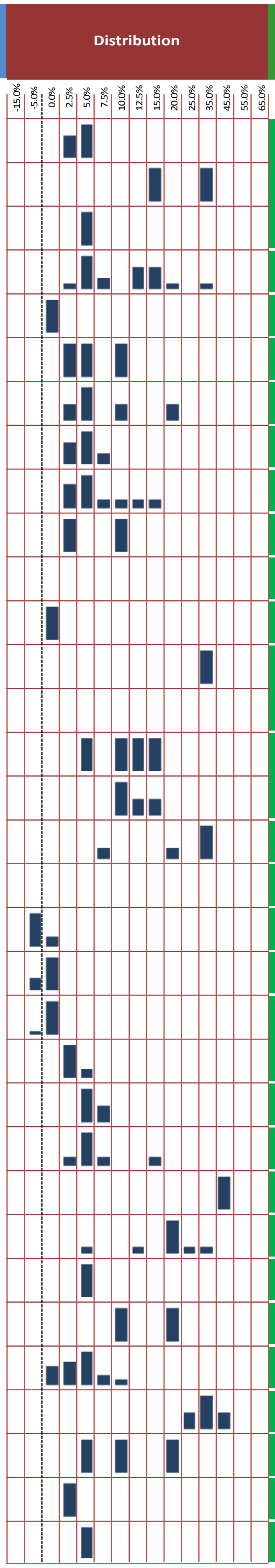
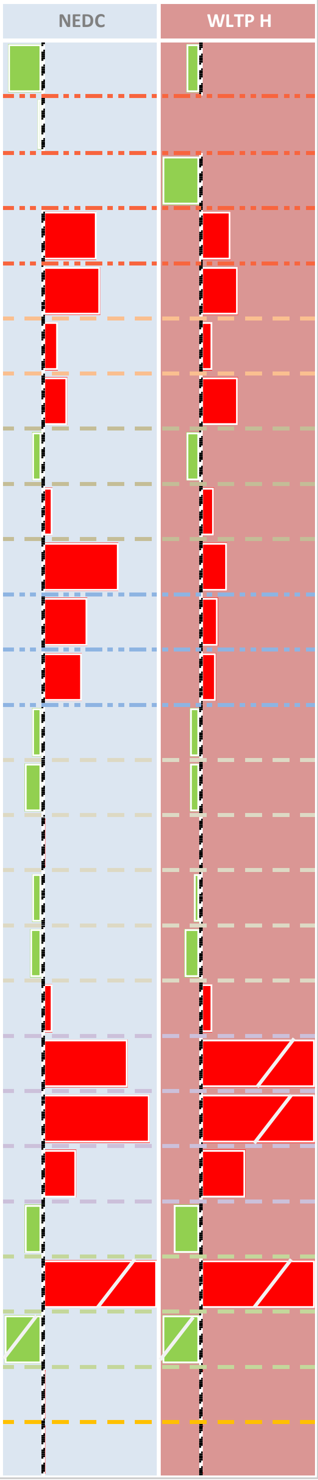


Table 12-2: Summary of the weighted average of the simulation results according to factor and test cycle (49)

Factor	Case			Effect on CO_2 emissions (%)	
				NEDC	WLTP H
Certification test	Hot start			-8.7	-3.5
	NEDC at 25 °C starting temperature, alternator disconnected			-0.9	-
	WLTP L			-	-9.9
	Realistic scenario*			14.2	7.9
Auxiliary systems	Electrical load (0.6 kW)			14.9	9.6
	Mechanical load (0.4 kW)			3.8	2.8
Aerodynamics	Unladen roof box (air drag increase)			6.5	9.7
	-10% air drag			-2.2	-3.3
	+10% air drag			2.3	3.5
Weather conditions	Starting temperature compared to hot start (88 °C)	-7 °C		19.8	6.7
		14 °C		11.5	4.5
		20 °C		10.2	3.9
Vehicle condition	Lubricants (Petrol reference SAE 5W-30, Diesel reference SAE 10W-40)	SAE 5W-20	Petrol	-2.2	-2.2
			Diesel	-4.1	-2.5
		SAE 10W-30	Petrol	0.6	0.2
			Diesel	-2.3	-1.4
	Tires	-20% rolling resistance		-2.8	-3.7
Vehicle mass	Extra mass	+100 kg		2.6	2.8
	Trailer towing	Unloaded (+310 kg, +65% air drag)		22.1	29.7
		Loaded (+560 kg, +65% air drag)		28.0	37.3
	Laden roof box (mass and air drag increase)			8.9	11.3
Road	Altitude	2000 m (Decreased air density)		-4.4	-6.7
	Constant grade throughout the cycle	+2%		33.4	35.8
		-2%		-28.4	-31.2
Fuel	E10 and B100 (Petrol reference E5, Diesel reference B5)		Petrol	0.4	0.4
			Diesel	0.6	0.6



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(49) * Realistic scenario parameters: Occupancy rates of 1.7 (+ 52 kg), test temperature of 14°C, constant road grade 0.15 % and additional 0.52 kW electrical auxiliary use.

Table 12-3: Comparative table of factors found in the literature and extent of its simulation

Factor	Case	Simulation scenario	Comments
Certification test	Various factors	Yes	NEDC and WLTP comparison. Type approval values compared to realistic scenario
	NEDC design	Yes	
Auxiliary systems	Air conditioning	Yes	Factor emulated for a range of electrical and mechanical loads. Few precise data available on the energy requirement of specific auxiliaries and components or their usage factors
	Steering assist systems	Yes	
	Other vehicle auxiliaries	Yes	
Aerodynamics	Roof add-ons and modifications	Partially	Few data was available for various roof add-ons
	Roof racks/ boxes (air drag increase)	Yes	The roof box was investigated regarding its aerodynamic effect.
	Open windows	No	The open windows and side winds effect were not investigated due to parameterisation difficulties. Air drag changes were investigated.
	Side winds effect	No	
	Improvements	Yes	This case was simulated as a change in air drag
Weather conditions	Rain	No	The mechanism affecting energy demand is explained in literature, but there was very little information about the actual energy losses.
	Snow/Ice	No	
	Starting temperature	Yes	This factor was properly accounted for.

Factor	Case	Simulation scenario	Comments
Driving behaviour — style	Aggressive driving	No	No simulation as the focus was mainly on type approval relevant cycles
	Driving mode	No	
	Eco-driving	No	
Vehicle condition	Lubrication (motor oil)	Yes	Simulation by adjusting the motor oil viscosity
	Tyres (rolling resistance)	Yes	
Operational mass	Vehicle mass	Yes	Factor simulated for a range of additional masses
	Trailer towing	Yes	Factor simulated by adjusting mass and aerodynamic coefficient and frontal area
	Roof boxes (mass increase)	Yes	Factor simulated by adjusting mass and air drag
Road conditions	Road morphology	Yes	Altitude and road grade were investigated. The altitude was simulated as lower air density while no other parameters were adjusted (e.g. combustion properties). The road grade was investigated as a constant grade factor over the entire cycle (both positive and negative grades tested)
	Road surface	No	Factor not simulated due to lack of information on the energy loses of the tyre
	Traffic condition and trip type	Indirectly	Lack of traffic pattern and difficulty of adjusting simulation parameters
		Partially	Trip type cases were tested for various types of trips using the WLTP sub-cycles
Fuel	Biofuels	Yes	Fuel blends were compared with the baseline fuel. The literature review made comparisons with a variety of blends that hindered statistical analysis and further comparison

Several cases were partially or not at all investigated because of lack of quantitative or qualitative information in literature. These cases include:

- Roof add-ons: There are a variety of different add-ons that can be attached, e.g. police sirens, taxi signs or items on the roof rack. Little relevant information was found about them in literature. The values of the frontal area and the air drag increase are sufficient for simulating them.

- Open windows: In this case the regular flow of the air around the vehicle is affected and significantly affects the air drag. There is little information about this effect in literature. It is however known that the corresponding increase in air drag is related to the aerodynamic design of the vehicle. The better the aerodynamic design, the less is the impact on the air drag. For this reason, changes in air drag were simulated to account to a certain extent for this effect.

- Side winds: It was difficult to simulate this factor as its effect on the air drag is related to the yaw angle and relative wind speed. The frontal area that the side wind faces changes depending on the yaw angle of the vehicle. In addition, there is little information in literature about the effect on air drag according to the wind speed. An attempt to address this gap in knowledge by means of simulation scenarios was the simulation of different air drag values.

- Rain and snow or ice: In this case the majority of the studies found in literature addressed the issue of tyre grip. Little information was found about the energy losses due to slipping and the extra resistance the tyre has to overcome.

- Driving behaviour and style: This factor was not simulated as the focus was on type approval test cycles.

- Road surface: The effect of the road surface was not simulated because of lack of information on the energy losses of the tyre related to the road surface. Road roughness, texture and materials bring about changes in the resistance to the movement of the tyre that were not quantified adequately in the literature.

- Traffic condition: This case is studied well in literature, but there appears to be a lack of traffic patterns. A traffic pattern for idling and commuting time would allow for producing results for a congested and non-congested road. Due to this gap in knowledge it was difficult to produce robust and comparative results.

- Trip type: In this case various types of commuters and travellers were investigated. The simulation of these trip types was realised by applying a weighted average of the WLTP sub-cycles. The weight for each sub-cycle was adjusted according to the trip type.

12.2. Combined effects

The deviation of the fuel consumption and the CO_2 emissions from the official test is usually the result of a combination of factors. A small variation in ambient temperature, road grade and operational mass are examples of how real-world emissions can be significantly affected.

An example of combination of factors is the mounting and loading of a roof box that increases the aerodynamic drag and mass. The effect of the increased air drag is more evident at higher speeds. This was confirmed by a comparison between the simulation case with laden roof box, affecting air drag and total vehicle mass and a case where only the mass was increased. The results show a significant difference of about 15 % between these cases for the Extra High sub-cycle of the WLTP.

The factors can be dependent or independent from the driver. In the former case proper driving training and information could reduce the impact on fuel consumption and reduce CO_2 emissions.

All the factors identified in this study can potentially affect in some degree fuel consumption and CO_2 emissions during vehicle operation, therefore resulting in a deviation from the type approval values. As it is not feasible to test all possible combinations of factors, the combination of changes in mass and aerodynamic resistances was simulated more thoroughly, as these two variables are linked to and affected by a series of factors, and in addition can be influenced by drivers' choices and practices. The results showed a linear correlation of the two factors resulting in an additive effect, which was graphically represented in Figure 8-19, Figure 8-20 and Figure 8-21. It would also be interesting to investigate in a future study how the combinations of other driver-independent factors affect fuel consumption and emissions (e.g. weather, road condition) over the certification test cycles.

The factors which cannot be influenced by the drivers, like ambient conditions, can be represented in the certification test by providing to the public a multitude of reference values closer to real-world conditions, derived from vehicle simulations, empirical formulas or other forms of fuel consumption calculation.

12.3. Type approval vs. realistic scenario

The so-called realistic scenario is intended to examine some of the factors which jointly contribute to the shortfall between type approval values and real-world operation. This realistic scenario was designed based on the usage factor of various auxiliaries, mean temperature in Europe and average occupancy rates, and the simulations were carried out over the WLTC speed time profile. The values of these factors were selected based on average European approximations. The deviation from type approval values is within the ranges reported in literature. It may be possible, by taking some real-world conditions into consideration, to improve the certification test and thereby decrease the divergence between the type approval test values and those observed under real driving conditions.

In the realistic scenario considered, the operating temperature was set at a lower value (14 °C) than the ones usually used in the certification test in order to reflect the mean temperature in Europe. In conjunction with other adjustments of the input parameters (like mass, road loads and electrical consumers), the simulation results show a significant increase in emissions which was calculated to be about 36 % higher than the certified emissions.

A graphical summary of the sales-weighted average value (50) of the simulations performed on the three different vehicles is presented in Figure 12-1. The figure illustrates how a real-world CO_2 performance of 167.6 g CO_2/km can correspond to a type approval value of 123 g CO_2/km. For each step, an explanation of the differentiating factors is provided.

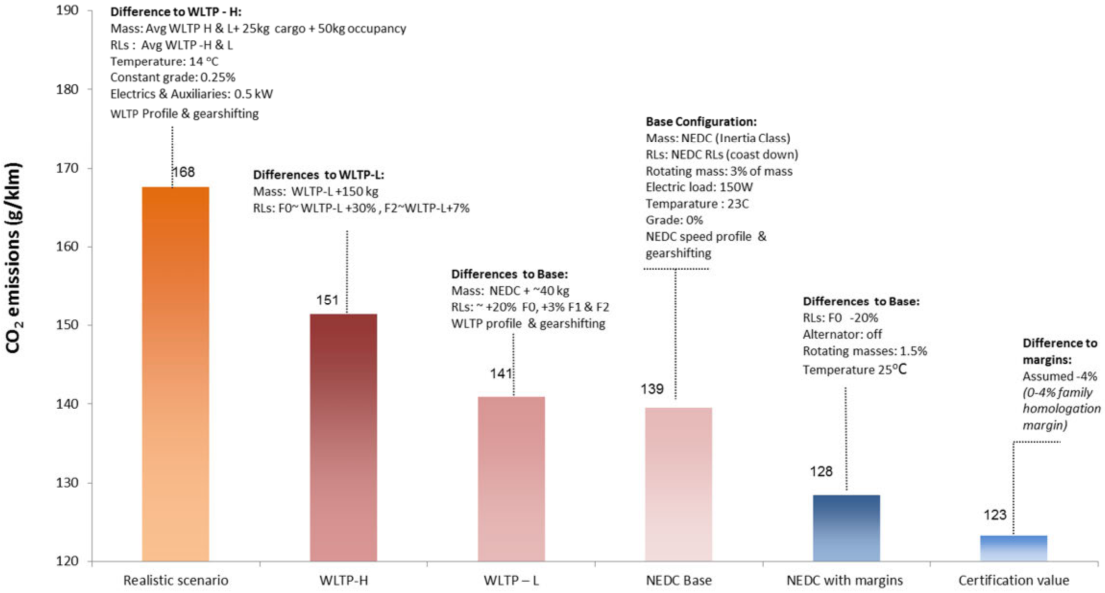

Figure 12-1: Comparison of CO_2 emissions for different scenarios and assumptions. Each value represents a weighted average of three vehicles considered in this report

The upcoming WLTP test is expected to address many of the limitations of the current type approval test, although it is impossible for any laboratory test to capture all the factors that affect in-use fuel consumption. The values provided by the WLTP are expected to be closer to real-world conditions as the test temperature is lower, the driving profile more dynamic, the inertia classes supressed, the real mass used and the cycle longer. Furthermore, the vehicle is tested for a larger cold-start temperature range considering also the effect of cold start at 14 C. There are other issues addressed by the WLTP but at the same time there remain factors affecting fuel consumption in everyday operation that are neither included in the test nor easily identified.

The deployment of new technologies in cars can affect, either positively or negatively, energy demand. They become thus a challenge to the certification test as this could underestimate or even overestimate CO_2 emissions. A thorough investigation of the daily vehicle usage and driving conditions would be an asset properly addressing and adapting to the new conditions.

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(50) Petrol NA 25 %, Petrol turbo 25 % and 50 % diesel.

12.4. Proposal for future research

The current study has investigated a variety of factors affecting energy consumption and has attempted to quantify, wherever possible, their effect. In some cases it was not possible to quantify accurately some effects based on literature review only and vehicle simulation was used instead. In the current paragraph some subjects are suggested for future research.

- Auxiliary use: The use of auxiliaries could be studied according to the habits of the drivers and a usage factor should be determined. Also the location where the vehicle is used should be taken into consideration. Knowing the habits of the drivers could assist in optimising energy demand under certain conditions and reduce CO_2 emissions. Additionally, the local prevailing ambient conditions, like temperature, significantly affects the use of auxiliaries.

- Open windows: The effect of open windows should be studied in more depth taking into consideration the aerodynamic shape of the vehicle. Also, since air drag is affected in this case, it should be correlated to vehicle speed.

- Rain and snow or ice: The effect of tyre friction losses on the overall vehicle energy losses is not studied thoroughly in the literature, although there are many studies about tyre grip under various conditions. This effect should be investigated together with the use of additional auxiliaries (e.g. wipers, headlights) as otherwise driving would be difficult or even dangerous.

- Towing: Towing could be studied for different trailer masses and aerodynamic shapes. In order to find an optimal energy consumption value it is also recommended to test combinations of different vehicle shapes and trailers.

- Altitude: The effect of altitude on fuel consumption has recently started to be of concern to researchers. From the preliminary data obtained it seems to have a measurable effect. Further study about this effect is needed as deviations in fuel consumption can occur due to altitudinal differences between the certification test site and real-world operation location.

- Road condition and surface: It is recommended that the effect of the road condition and the surface on energy consumption be investigated further. Proper road design could reduce fuel consumption and subsequently CO_2 emissions.

- Traffic: Location-specific studies about traffic, in correlation to the time of the day, vehicle speed and idling time, are significant in estimating deviations in fuel consumption. There was little data in this area and a study could provide information that could be of assistance also in other fields, like traffic lights control or public transport design and scheduling.

- Trip type: The trip type and driving habits are considered not adequately addressed currently in literature. Identifying driving habits or when and where a vehicle is usually used would also help in evaluating the reasons for the shortfall between type approval and real-world operation. Anonymised data could be taken into consideration in the type approval test design and would be also a guide to the public for better trip planning. Additionally, it could be of use for public transport planning and infrastructure design.

Finally it should be noted that despite the fact that numerous data are reported during the type approval process of vehicles, little information is actually publicly available. Knowing the aerodynamic characteristics of a vehicle, auxiliary consumers, or other kind of losses would be valuable information for guiding an educated consumer choice. In this sense future type approval and labelling mechanisms can be designed to be more market and information oriented allowing the customer to select a vehicle and customise it based on actual needs. Similar approaches have already been adopted or are in the process of adoption for other vehicle segments (e.g. Heavy Duty vehicles) in various countries. As a first step, a more detailed and possibly interactive CO_2 and/or fuel consumption database can fill in this gap which is presently addressed to some extent only by private websites, magazines and drivers' forums.

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14. Annex

14.1. Literature review

14.1.1. Auxiliary systems

Table 14-1: A/C use increase in fuel consumption with the use of A/C

Increase in fuel consumption	Source
7.2 %	Johnson (2002)
5-20 %	EcoDrive (2010a)
Petrol: 3.6 % **Diesel: 2.7 %**	Weilenmann et al. (2010)
1-3 %, depending on light or dense traffic	ECMT (2005)
10 % (EU vehicle)	Rugh et al. (2004)
5 %	Mock et al. (2013)
3 %	Leduc et al. (2010)

Table 14-2: Steering characteristics, required power and fuel consumption of auxiliary steering systems (Wellenzohn 2008)

Mission profile	HPAS	EHPAS	EPAS
Rack load N	13 000	13 000	2 600
Steering wheel speed °/s	360	360	360
Rack speed mm/s	60	60	60
Active required steering power W	780	180	156
Inactive required steering power W	390	15.6	10
Increase in fuel consumption l/100 km	0.51	0.18	0.05
Increase for average European car as of 2012 (EEA 2013a)	9 %	3.2 %	0.9 %

Table 14-3: Increase in fuel consumption according to type of A/C and type of fuel (Roujol and Joumard 2009).

Type of car	Type of A/C	Increase in consumption
Petrol	Manual	0.70 l/h
	Automatic	0.75 l/h
Diesel	Manual	0.68 l/h
	Automatic	0.85 l/h

Table 14-4: Power needs and increase in fuel consumption for various auxiliaries (Dudenhöffer and John 2009).

Auxiliaries	Power consumption (W)	Fuel consumption (l/100 km)
Headlights	150	0.15
Fog lights	100	0.1
Electric windows	300	0.3
Electric sunroof	200	0.2
Rear window heating	120	0.12
Rear window wiper	70	0.07
Seat adjustment	150	0.15
Electric mirror adjustment	20	0.02
Heated seats	400	0.4
Electrical booster heater	1 000	1
Windscreen heater	500	0.5
Electrically heated steering wheel	50	0.05
A/C	1 500	1.5
Windscreen wiper	150	0.15
Heated windscreen washer	80	0.08
Navigation system	15	0.015
Total	4 805	4.805

14.1.2 Aerodynamics

Table 14-5: Increase in fuel consumption with the attachment of a non-laden roof box.

Increase in fuel consumption	Source
For a ski box: **70 km/h: 10 %** **80 km/h: 11 %** **90 km/h: 12 %**	Lenner (1998)
Highway: 4.5 % **Rural: 1.2 %** **Urban: 0.3 %**	André (2004)
100 km/h: 4.2 % **130 km/h: 4.3 %** **160 km/h: 12.2 %**	Autobild (2009)
By 5 %	De Haan (2012)
At 120 km/h: 7.5 %	EcoDrive (2011)
Only for the roof rack: about 2 % **With a ski box:** **70 km/h: 10 %** **90 km/h: 13-14 %**	Thomas et al. (2014)

Table 14-6: Effect of roof rack and ski-box on fuel consumption for speed range 70-90 km/h (Lenner 1998).

Speed (km/h)	Reference	Roof rack		Ski-box	
	Fuel consumption (l/100 km)	Fuel consumption (l/100 km)	Increase	Fuel consumption (l/100 km)	Increase
70	6.89	7.07	3 %	7.58	10 %
80	7.45	7.6	2 %	8.26	11 %
90	7.9	7.99	1 %	8.87	12 %

Table 14-7: Fuel consumption for a Toyota Corolla with open windows compared to standard consumption for various speeds (Thomas et al. (2014)).

Vehicle speed (km/h)	Standard consumption (l/100 km)	Open windows (l/100 km)	Increase in fuel consumption (%)
64	4.1	4.3	5.6 %
72	4.4	4.7	6.6 %
80	4.8	5.1	6.6 %
89	5.1	5.5	7.1 %
97	5.5	6.0	7.7 %
105	6.0	6.5	8.4 %
113	6.5	7.0	7.7 %
121	7.0	7.7	9.2 %
129	7.6	8.3	8.3 %

Table 14-8: Fuel consumption for a Ford Explorer with open windows compared to standard consumption for various speeds (Thomas et al. (2014))

Vehicle speed km/h	Standard consumption (l/100 km)	Open windows (l/100 km)	Increase in fuel consumption %
80	8.0	8.0	0.3 %
89	8.7	8.7	0.7 %
97	9.4	9.6	1.6 %
105	10.2	10.4	1.3 %
113	11.0	11.2	1.4 %
121	12.0	12.3	2.6 %
129	13.3	13.6	2.3 %

Table 14-9: Comparison of pressure values with and without rear spoiler (Kodali 2012)

Velocity (km/h)	Without rear spoiler		With rear spoiler	
	Min. P (Pa)	Max. P (Pa)	Min. P (Pa)	Max. P (Pa)
50	– 187	125	– 277	142
100	– 756	496	– 1 070	567
180	– 2 470	1 600	– 3 640	1 840
250	– 4 770	3 090	– 7 070	3 550

14.1.3 Weather conditions

Table 14-10: Effect of ambient temperature on fuel consumption compared between a maximum and a minimum temperature

Source		Maximum temperature °C	Minimum temperature °C	Increase in fuel consumption (%)
Dings (2013)		29	20	2
ECMT (2005)		0	– 20	10
Bielaczyc et al. (2013b)	**MPI**	25	– 7	21
	DISI	25	– 7	16
Christenson et al. (2007)		20	– 18	23

14.1.4 Simulated cold start effect over NEDC and WLTP sub-cycles

The cold start effect is widely discussed in the literature and it seems to be a significant topic of discussion of how it should be implemented in the certification test procedure. Initially, vehicles were allowed a short warm up period of 30 seconds for NEDC, which was eventually discarded. During vehicle operation the temperature rises eventually to optimum operational levels, which could cause variations in CO_2 emissions compared to the cold effect phase. This effect was examined and a comparison is presented between cold and hot start and the sub-cycles for the three vehicles in Figure 14-1, Figure 14-2 and Figure 14-3. The starting test temperature for the cold case scenario is 23 °C both for the NEDC and WLTP.

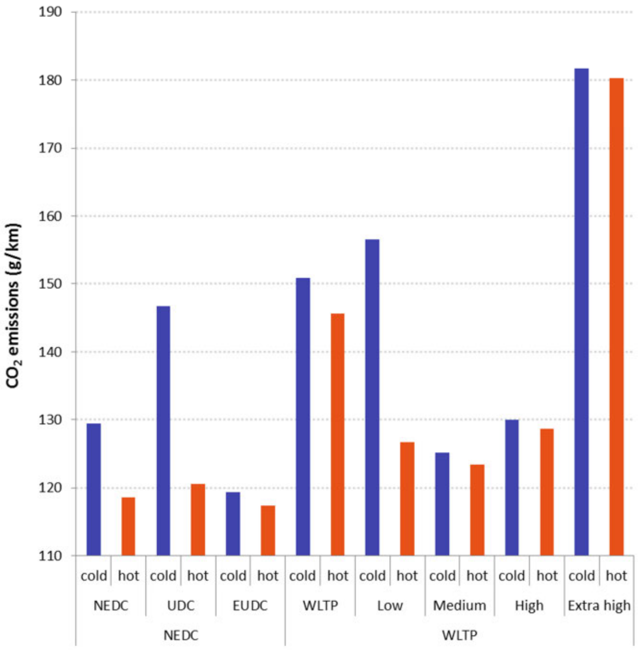

Figure 14-1: 'Cold' and 'hot' CO_2 emissions for NEDC, WLTP and their sub-cycles for a Petrol NA vehicle

The results show that the cold start effect is more significant during the first sub-cycles of both cycles (UDC, Low phase of WLTP), which was anticipated. But the most significant observation is that at the high speed part of both cycles, where most engine components have warmed up, there are still significant discrepancies. For the EUDC the average increase due to the cold start compared to a hot condition is 1.9 %, while for the Extra high part of the WLTP the increase is 0.4 %. In the extra high part of the WLTP the small discrepancy is attributed to the fact that in the hot scenario all the components of the engine are thermally stabilised at operational temperatures, while in the cold scenario the gearbox is not yet thermally stabilised.

The overall difference between a cold and a hot start condition is on average 9.5 % for the NEDC and 3.7 % for the WLTP.

The cold start scenario is the baseline scenario used for comparisons throughout this study, unless stated otherwise.

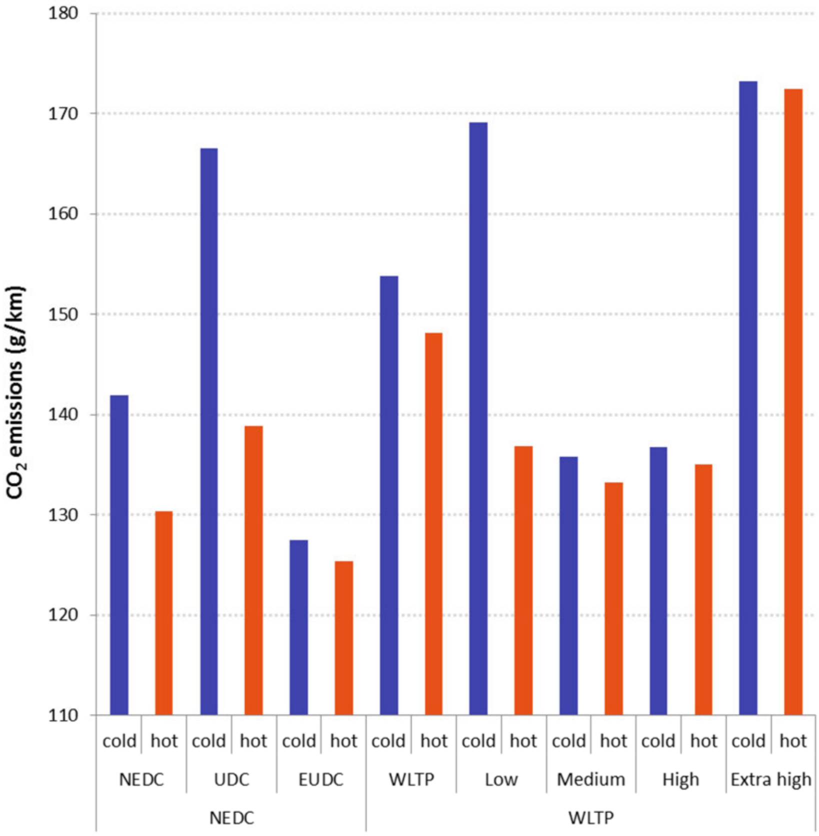

Figure 14-2: 'Cold' and 'hot' CO$_2$ emissions for NEDC, WLTP and sub-cycles for a Petrol turbo vehicle

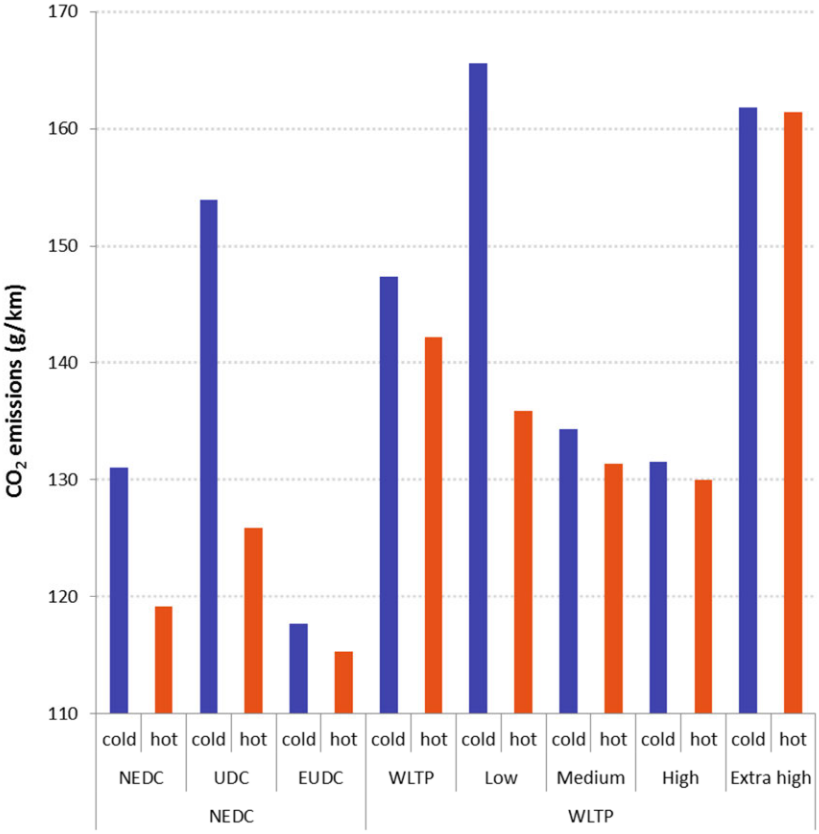

Figure 14-3: 'Cold' and 'hot' CO$_2$ emissions for NEDC, WLTP and their sub-cycles for a diesel vehicle

14.1.5 Driving

Table 14-11: Increase in fuel consumption for aggressive driving

Increase in fuel consumption/CO_2 emissions	Source
12-40 %	De Vlieger et al. (2000)
30-40 %	Ericsson (2001)
By 33 %	EEA (2001)
Petrol: 10-30 % **Diesel: 5-7 %**	André and Pronello (1997)
Up to 10 % (American study)	Berry (2010)
by 6.7 % (American study)	Nam et al. (2003)

Table 14-12: Fuel consumption for aggressive driving compared to normal driving for a Petrol car according to road type (Lenaers 2009)

Behaviour	Fuel consumption (l/100 km)		
	Urban	Rural	Motorway
Normal	10.8	6.37	7.49
Aggressive	18.13	8.97	7.82
Increase	67.9 %	40.8 %	4.4 %

Table 14-13: Fuel consumption for aggressive driving compared to normal driving for a diesel car according to road type (Lenaers 2009)

Behaviour	Fuel consumption (l/100 km)		
	Urban	Rural	Motorway
Normal	7.93	4.47	5.46
Aggressive	11.63	6.51	5.74
Increase	46.7 %	45.6 %	5.1 %

Table 14-14: Driving strategies that decrease fuel consumption

Factor	Impact on fuel consumption/CO_2 emissions	Source
Training	5 % less consumption (heavy traffic), 10 % (light traffic)	ECMT (2005)
	Decreased consumption by 5.8 %	Beusen et al. (2009)
	– 10 % consumption (urban: – 12 % Extra urban: – 6 %, Highway: – 2 %)	Barkenbus (2010)
Optimal gear shifting	Decreased emissions up to 6 % (NEDC)	Dings (2013)
	Decreased consumption: 1 % (heavy traffic), 2 % (light traffic)	ECMT (2005)
Adaptive Cruise Control Systems	Decreased emissions by up to 7.42 %	Maier et al. (2014)

Table 14-15: Improvement in fuel consumption with the use of lower viscosity motor oil.

Improvement in consumption	Source
Up to 2.5 % less consumption	European Commission (2006)
Average 4 % less consumption (urban: 4-6 %, outside the town: 2-4 %, Highway: 2 %)	Dena (2009)
Up to 5 % less consumption	EcoDrive (2010b), AGVS (2013),VW (2010b)
Up to 3 % less consumption	UBA (2010)

Table 14-16: Decrease in fuel consumption by switching to lower viscosity motor oil.

Change of motor oil	Decrease in consumption	Source
From 10 W-30/40 to 5 W-30	1.2-2 %	IEA (2005)
From 5 W-30 to 0 W-20	1-2 %	IEA (2005)
From 5 W-30 to 5 W-20	1-3.5 %	IEA (2005)
From 5 W-30 to a 5 W-20 (diesel car)	0.5-1.5 %	Bennett and Chudasama (2000)

14.1.6 Vehicle condition

Table 14-17: Fuel consumption for each tyre class (Continental 2012)

Tyre class	Fuel consumption (l/100 km)	Increase in fuel consumption (JRC estimations)
A	6.6	0.0 %
B	6.7	1.5 %
C	6.82	3.3 %
E	6.96	5.5 %
F	7.11	7.7 %
G	7.26	10.0 %

Table 14-18: Decrease in fuel consumption with the use of low rolling resistance tyres

Modification	Decrease in fuel consumption	Source(s)
'Green' tyres vs 'Black' have RR 8.5 kg/t and 12 kg/t respectively	In urban: 3.2 %, suburban: 5.1 %	Michelin (2013)
10 % lower RR	By 1-2 %	IEA (2005), TRB (2006), BFE (2012), Holmberg et al. (2012)
20 % lower RR	By 2 %	Burgess and Choi (2003)
5-7 % lower RR	By 1 %	ECMT (2005)
Low RR tyres	By 3 %	European Commission (2006)
	Average by 4 % (urban 3 %, Extra urban 5 %, highway 4 %)	EcoDrive (2010b)
	Up to 3 %	VW (2010b)
	By 4-5 %	UBA (2010)
	Up to 5 %	AGVS (2013)
NEDC: Lower RR per 1 kg/t	By 0.1 l/100km (Petrol), 0.08 l/100km (Diesel)	Barrand and Bokar (2008)
Tyre Width: 185 mm tyre compared with 225 mm tyre (6 % lower RR)	By 1 %	VW (2009)

Table 14-19: Increase in fuel consumption for under inflated tyres

Lower pressure than the recommended	Increase in fuel consumption (%)	Source
By 0.2 bar	2.5-3 %	ECMT (2005)
By 0.3 bar	1 %	Michelin (2013)
By 0.2 bar	1 %	ADAC (2012c)
By 0.2, 0.3, 0.5, 0.8	1 %, 2 %, 3 %, 6 % respectively	De Haan (2012)
Per 0.1 bar	0.44 % (American study, unit conversion)	DOE — EPA (2014d)

Table 14-20: Increase in fuel consumption for various speeds for 75 % and 50 % tyre pressure (Thomas et al. 2014)

Speed	Standard	75 % Tyre pressure		50 % Tyre pressure	
km/h	km/l	km/l	Increase in fuel consumption	km/l	Increase in fuel consumption
64	24.4	23.9	2 %	22.0	10 %
72	22.7	22.2	2 %	20.6	10 %
80	20.9	20.6	2 %	19.2	8 %
89	19.5	19.2	2 %	18.0	8 %
97	18.1	17.7	2 %	16.8	7 %
105	16.8	16.4	2 %	15.6	7 %
113	15.4	15.1	2 %	14.5	6 %
121	14.2	13.8	3 %	13.4	6 %
129	13.1	12.7	4 %	12.4	6 %

14.1.7 Operating mass

Table 14-21: Increase in fuel consumption for additional weight

Additional weight	Increase in fuel consumption	Source
20 %	5 %	Mellios (2011)
45 kg	2 % (US study)	EPA (2014a)
50 kg	5-8 %	Eglin (2012)
	1-2 %	Goodyear (2013)
100 kg	7 %	FORUM Umweltbildung (2008)
Per 100 kg	5 %	De Haan (2012)
220 kg	9 %	Mock et al. (2012)

Table 14-22: Increase in fuel consumption with the attachment of a laden roof box

Type of load	Increase in fuel consumption	Source
Broad roof box	100 km/h: 19.3 % 130 km/h: 27.6 %	OEAMTC (2012)
	Up to 50 km/h: 2-8 % 100 km/h: 6-17 % 115 km/h: 10-25 % (American study)	EPA (2014a)
Narrow roof box	100 km/h: 16.3 % 130 km/h: 21.8 %	OEAMTC (2012)
Roof box	130 km/h: 20 %	ADAC (2012a)
	120 km/h: 16 %	EcoDrive (2011)

Table 14-23: Increase in fuel consumption for various speeds for a laden roof box (Thomas et al. 2014)

Speed (km/h)	Standard consumption (l/100km)	Laden roof box (l/100 km)	Increase in fuel consumption (%)
64	4.1	4.9	19 %
72	4.4	5.3	21 %
80	4.8	5.9	24 %
89	5.1	6.5	27 %
97	5.5	7.1	29 %
105	6.0	7.9	32 %
113	6.5	8.6	33 %
121	7.0	9.4	34 %
129	7.6	10.4	36 %

14.1.8 Road (morphology, surface, traffic)

Table 14-24: Road surface type and fuel consumption (adapted from Ardekani and Sumitsawan (2010))

Type of road surface	Fuel consumption in l/100 km
Portland cement concrete	10.7
Asphalt concrete	11.6

Table 14-25: Effect of congested roads on fuel consumption and travel time (De Vlieger et al. 2000)

Route length (km)	Traffic condition	Travelling time (min)	Fuel consumption (l)	Fuel consumption (l/100 km) (JRC estimations)	Increase in fuel consumption (JRC estimations)
35	Normal	43	2.7	7.7	0 %
	Congested	103	3.8	10.9	41 %
30	Normal	49	2.8	9.3	0 %
	Congested	76	3.4	11.3	21 %

Table 14-26: Fuel consumption for normal driving conditions and peak hours (Spalding 2008)

	Fuel consumption for normal driving conditions (l/100 km)	Fuel consumption for peak hour conditions (l/100 km)	Increase in fuel consumption (%)
1st Route	12.53	16.06	28 %
2nd Route	12.35	16.29	32 %

Table 14-27: Effect of ethanol fuel blend on CO_2 emissions and fuel consumption (Delgado and Susanna 2012)

CO_2 emissions (g/km)					
	Petrol vehicle			FFV	
	E0	E5-S	E10	E0	E85
UDC	219.52	214.64	223.90	237.53	225.78
EUDC	141.05	138.75	141.92	152.31	145.33
Total	169.75	167.74	172.18	183.34	174.93
Difference (%)	-	– 1.2 %	1.4 %	-	– 4.6 %
Fuel consumption (l/100 km)					
	Petrol vehicle			FFV	
	E0	E5-S	E10	E0	E85
UDC	9.3	8.93	9.68	10.08	11.42
EUDC	5.91	5.75	6.12	6.4	7.31
Total	7.14	6.96	7.44	7.75	8.82
Difference (%)	-	– 2.5 %	4.2 %	-	12.1 %

14.1.9 Fuel characteristics

Table 14-28: Diesel characteristics for temperate climatic zones (EN-590:2004)

Characteristics	Class A	Class B	Class C	Class D	Class E	Class F	Units
CFPP	5	0	- 5	- 10	- 15	- 20	°C
Density at 15 °C	820-860	820-860	820-860	820-860	820-860	820-860	kg/m^3
Viscosity at 40 °C	2-4.5	2-4.5	2-4.5	2-4.5	2-4.5	2-4.5	mm^2/s
Cetane index	46	46	46	46	46	46	
Cetane number	49	49	49	49	49	49	

Table 14-29: Diesel characteristics for arctic climatic zones (EN-590:2004)

Characteristics	Class 0	Class 1	Class 2	Class 3	Class 4	Units
CFPP	- 20	- 26	- 32	- 38	- 44	°C
Cloud point	- 10	- 16	- 22	- 28	- 34	°C
Density at 15 °C	800-845	800-845	800-845	800-840	800-840	kg/m^3
Viscosity at 40 °C	1.5-4.0	1.5-4.0	1.5-4.0	1.4-4.0	1.2-4.0	mm^2/s
Cetane index	46	46	45	43	43	
Cetane number	47	47	46	45	45	

Table 14-30: Increase in fuel consumption for a B10 fuel compared to B0

Source	Increase in fuel consumption (%)
Pidol (2014)	0.6 %
Fontaras et al. (2014b)	1.1 %

Table 14-31: Increase in fuel consumption for an E10 fuel compared to E0

Source	Increase in fuel consumption (%)
Delgado and Susanna (2012)	4.2 %
Pidol (2014)	3.9 %
DOE — EPA (2014b) (US study)	3.6 %

14.2. Simulations

14.2.1 Certification test

Table 14-32: Electrical auxiliaries, their usage factor, nominal power and total usage (European Commission 2013)

Auxiliaries	Usage factor (UF)	Nominal power (kW)	Total usage (kW)
Type of lighting			
Low-beam headlamp	0.33	0.055	0.01815
High-beam headlamp	0.03	0.06	0.0018
Front position	0.36	0.005	0.0018
Fog — front	0.01	0.055	0.00055
Fog — rear	0.01	0.021	0.00021
Turn signal front	0.15	0.021	0.00315
Turn signal side	0.15	0.005	0.00075
Turn signal — rear	0.15	0.021	0.00315
Rear position	0.36	0.005	0.0018
Licence plate	0.36	0.005	0.0018
Wipers			
Low speed (front)	0.08	0.15	0.012
High speed (front)	0.02	0.15	0.003
Other			
A/C	0.42	1	0.42
Steering	1	0.05	0.05
Total			0.52

14.2.2 Driving

Table 14-33: Average speed of WLTP sub-cycles

WLTP sub-cycle	Average speed (km/h)
Low	18.9
Medium	39.5
High	56.7
Extra high	92.3

15. Abbreviations

A/C	Air conditioning
CFPP	Cold filter plugging point
ECU	Engine control unit
EHPAS	Electro-hydraulic power assisted steering
EPAS	Electric power assisted steering
EUDC	Extra urban driving cycle, NEDC sub-cycle
FAME	Fatty acid methyl ester
FFV	Flexi fuel vehicle
FTP	Federal test procedure
HC	Hydrocarbon
HPAS	Hydraulic power assisted steering
HDV	Heavy duty vehicle
LCV	Light commercial vehicle
LDV	Light duty vehicle
LHV	Lower heating value
NA	Naturally aspirated
MPG	Miles per gallon
NEDC	New European Driving Cycle
OEM	Original equipment manufacturer
PC	Passenger car
PEMS	Portable Emissions Measurement System
PM	Particulate matter
RPM	Rights per minute
RR	Rolling resistance
RRC	Rolling resistance coefficient
SC03	SC03 — Supplemental Federal Test Procedure with A/C
SOC	State of charge
SFTP	Supplemental Federal Test Procedure
TA	Type approval
UDC	Urban driving cycle, NEDC sub-cycle
VG	Vortex generator
WLTC	Worldwide harmonized Light vehicles Test Cycle
WLTP	Worldwide harmonized Light vehicles Test Procedures

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