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Fuel consumption and CO_2 emissions from passenger cars in Europe – Laboratory versus real-world emissions☆

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A B S T R A C T

Official laboratory-measured monitoring data indicate a progressive decline in the average fuel consumption and CO_2 emissions of the European passenger car fleet. There is increasing evidence to suggest that officially reported CO_2 values do not reflect the actual performance of the vehicles on the road. A reported difference of 30–40% between official values and real-world estimates was found which has been continuously increasing. This paper reviews the influence of different factors that affect fuel consumption and CO_2 emissions on the road and in the laboratory. Factors such as driving behaviour, vehicle configuration and traffic conditions are reconfirmed as highly influential. Neglected factors (e.g. side winds, rain, road grade), which may have significant contributions in fuel consumption in real world driving are identified. The margins of the present certification procedure contribute between 10 and 20% in the gap between the reported values and reality. The latter was estimated to be of the order of 40%, or 47.5 gCO_2/km for 2015 average fleet emissions, but could range up to 60% or down to 19% depending on prevailing traffic conditions. The introduction of a new test protocol is expected to bridge about half of the present divergence between laboratory and real world. Finally, substantial literature was found on the topic; however, the lack of common test procedures, analysis tools, and coordinated activity across different countries point out the need for additional research in order to support targeted actions for real world CO_2 reduction. Quality checks of the CO_2 certification procedure, and the reported values, combined with in-use consumption monitoring could be used to assess the gap on a continuous basis.

Contents

Abbreviations: 10-15 mode, Japanese Test Cycle, Phased Out From 2005 To 2011; A/C, Air Conditioning; ACEA, Association des Constructeurs Européens d'Automobiles - European Automobile Manufacturers' Association; ADAS, Advanced Driver Assistance Systems; ARS, Average Rectified Slope; ARTEMIS, Assessment and Reliability of Transport Emission Models and Inventory Systems; CO, Carbon Monoxide; CO_2, Carbon Dioxide; CoC, Certificate Of Conformity; COPERT, Emissions Calculation Tool; C_w, Air drag coefficient; DISI, Direct Injection Spark Ignition; E2HPAS, Energy Efficient Hydraulic Power Assisted Steering System; E10, Fuel containing 10% ethanol; E85, Fuel containing 85% ethanol; EC, European Commission; EEA, European Environment Agency; EHPAS, Electro – Hydraulic Power Assisted Steering; EPA, Environmental Protection Agency; EPAS, Electric Power Assisted Steering; EU, European Union; EUDC, Extra-Urban Driving Cycle; EV, Electric Vehicle; FTP, Federal Test Procedure; GDP, Gross Domestic Product; GHG, Green House Gases; GPS, Global Positioning System; HBEFA, Handbook emission factors for road transport; HC, Hydrocarbons; HDV, Heavy Duty Vehicle; HPAS, Hydraulic Power Assisted Steering; HWFET, Highway Fuel Economy Test; ICT, Information And Communications Technology; IEA, International Energy Agency; IRI, International Roughness Index; JC08, Japanese Test Cycle, Phased In From 2005 To 2011; JRC, Joint Research Centre Of The European Commission; LDV, Light Duty Vehicles; LED, Light Emitting Diode; MPG, Miles Per Gallon (US Or UK Gallon); MPI-SI, Multipoint Injection -Spark Ignition; NEDC, New European Driving Cycle; NO_x, Nitrogen Oxides; OEAMTC, Österreichische Automobil-, Motorrad- Und Touringclub; OEM, Original Equipment Manufacturer; PC, Passenger Cars; PEMS, Portable Emissions Measurement System; PM, Particulate Matter; RMS, Root Mean Square; RPM, Revolutions Per Minute; RR, Rolling Resistance; RRC, Rolling Resistance Coefficient; SC03, US driving cycle designed to measure exhaust emissions with the use of air-conditioning; SFTP, Supplemental Federal Test Procedure; SUV, Sports Utility Vehicle; UDC, Urban Driving Cycle; UDDS, Urban Dynamometer Driving Schedule; UK, United Kingdom; UN, United Nations; UNECE, United Nations Economic Commission For Europe ; US06, US driving cycle designed to measure exhaust emissions at high speeds and aggressive driving; VW, Volkswagen; WD, Wheel Drive (number of powered wheels); WLTC, Worldwide harmonized Test Cycle; WLTP, Worldwide harmonized Light Vehicle Test Procedure; WMTC, Worldwide harmonized Motorcycle Emissions Certification/Test Procedure.

☆ The views expressed in the paper are purely those of the authors and may not be considered under any circumstance as an official position of the European Commission.

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1. Introduction

Road transport contributes about one-fifth of the European Union's (EU) total emissions of carbon dioxide (CO_2), the main Greenhouse Gas (GHG), 75% of which originates from passenger cars [1–3]. Despite the fact that these emissions fell by 3.3% in 2012, they are still 20.5% higher than in 1990. Transport is the only major sector in the EU where GHG emissions are still rising [4]. The automotive sector accounts for 4% of the European GDP and 12 million jobs, or 5.6% of the employed population in Europe [5,6]. In terms of policy, the European Commission's (EC) 2011 White Paper for Transport [7] highlighted the importance of reducting GHG emissions in order to make the transition to a low carbon economy. In its 2016 communication to the European Parliament the EC stressed the potential of the transport sector to further contribute to reducing the EU's emissions and contribute to the EU's commitment under the Paris Climate Change Agreement [8]. Since 2009 the EU has set mandatory targets for the average CO_2 emissions of each vehicle manufacturer (OEM) at 130 CO_2/km (2015) and 95 CO_2/km (2021) [9]. In recent years, the issue of fuel consumption and CO_2 emissions has received significant attention by the public, environmental and consumer organizations [10]; certain consumer organizations have taken legal action against vehicle companies claiming they have exaggerated the fuel-saving credentials of their vehicles.

CO_2 emissions of passenger cars are measured as part of the vehicle certification [11] test which is based on the New European Driving Cycle (NEDC), and is also referred to as the NEDC test. The fuel consumption of the vehicles is indirectly derived from the measurement of carbon dioxide (CO_2), hydrocarbons (HC) and carbon monoxide (CO) emissions measured during the certification tests, considering the carbon mass balance in the exhaust gas. Modern vehicles meet Euro standards (Euro 5 and 6) have low tailpipe CO and HC emission levels (contributing to approximately 1% of the fuel consumption). In this sense, CO_2 emissions can be considered to be proportional to the fuel consumed during vehicle's operations. Here we use both terms interchangeably so any results and conclusions can be considered to be applicable to any of the two, unless stated otherwise.

Data from the European Environmental Agency (EEA) for year 2015 [12] have confirmed that OEMs have achieved their 130 gCO_2/km in 2014, and that the average EU emissions of all manufacturers was 123.4 gCO_2/km. In addition, provisional EEA data [13,14] suggests a further decrease as of 120.7 gCO_2/km in 2015. The OEMs have already achieved significant improvements in fuel efficiency. However, there is extensive criticism on the representativeness of these figures in terms of real-world CO_2 emissions and fuel consumption performance [15]. The difference between the two used to be estimated of the order of 12–20% [16,17] while more recent studies present even wider differences ranging up to 30% or 40% [18,19]. There is indeed increasing evidence [20–28] suggesting that fuel consumption improvements originate from test-oriented optimizations and test-related practices rather than from the implementation of fuel-saving technologies. An official investigation funded by the French ministry of transport [29] has shown that most of the reported CO_2 values cannot be reproduced under laboratory test conditions and that a reproduction of the certification test results in consistently higher CO_2 emissions by 15%, on average, with a standard deviation of 8%. Similar differences (3–17%), between declared CO_2 and ex-post NEDC measurements, are reported by other researchers [30]. Studies show (see Table 1.1) that the offset between officially reported values and real-world vehicle CO_2 emissions is increasing over time.

The gap between the certification value and real-world emissions raises scepticism at multiple levels: policy, industry, market. In terms of policy, the progress of the EU's commitments and the effectiveness of the measures adopted so far are put into question. For example, assessing current and planning future policy is hard because of the divergences in fuel consumption erode a significant portion of the expected CO_2 benefits [32]. However, industry has recognized that CO_2 emissions from road transport have not decreased as expected [5]. In terms of market impact, targets that were originally set to be met with the introduction of new technologies (e.g. introduction of lightweight materials and vehicle electrification) now misleadingly appear to be achievable only with conventional approaches, and thus, slowing down innovation [33]. In addition, new fuel-saving technologies might be less appealing to consumers when compared to existing widespread and cheaper options because their fuel consumption reduction potential appears to be smaller. Furthermore, the consumer labelling legislation requires new cars to display a label showing their fuel consumption and CO_2 emissions in order to promote efficient vehicles and provide a stimulus for fuel saving options. According to an EC study [34], it is difficult to fully quantify the impact of labelling due to the divergence between actual and communicated fuel consumption value. Inaccurate consumer information or diverging reference fuel consumption values creates an uneven playing field and masks benefits of certain vehicles and technologies or overestimates others [35].

Table 1.1
Literature values of real world – certification test CO_2 divergence by year and region.

Year	Real world – Certification value CO_2 shortfall	Reference
2005	12%	[16]
2009	19%	[17]
2011	21%	[20]
2011	25%	[21]
2012	22.5%	[23]
2013	30%	[24]
2014	38%	[25]
2014	44%	[31]
2015	41%	[27]

The increasing divergence between real-world and type-approval fuel consumption, as well as the difficulty to evaluate the actual effect of the CO_2 reduction technologies, led the EU to review the type approval procedure for passenger cars and light commercial vehicles and resulted in the introduction of the new Worldwide harmonized Light-duty Test Procedure (WLTP). The new test procedure will be used for the assessment of emissions, including CO_2, in the framework of the type approval of light duty vehicles as of September, 1st, 2017. However, CO_2 targets will be still assessed with respect to NEDC CO_2 values [36]. Consequently, the present vehicle certification test and its shortcomings will remain relevant at least for another five years.

A series of factors have been identified that cause the increasing divergence between the current official fuel consumption and the one experienced in real-world driving conditions [37]. Due to the diversity of operating conditions, drivers' behaviour, car usage and other external factors, it is unlikely that any test protocol, no matter how carefully designed, will be able to accurately capture the real-world performance of vehicles. As a result, there will be always a need to identify which factors influence emissions under real-world driving conditions and which are captured by the vehicle certification tests in order to assess their impact on real-world fuel consumption. Once this impact has been better quantified the real-certification CO_2 gap could be further analysed and broken down to contributing factors and, if possible, be corrected a *posteriori*.

This paper attempts to address two key questions of concern to scientists, analysts, policy makers and the public through an extensive literature review of existing publications on the factors affecting passenger car fuel consumption in real-world driving and laboratory conditions. The questions are:

1. Which factors affect the fuel consumption of vehicles and to what extent?
2. What would be a realistic estimate of the in-use CO_2 emissions of European passenger cars?

In the following sections the factors that affect fuel consumption and CO_2 emissions under real-world driving conditions and laboratory tests are categorized as follows:

a) *factors related to vehicle characteristics and systems*. This category focuses on the main contributors in energy consumption, which define fuel consumption and CO_2 emissions, such as vehicle mass, vehicle aerodynamics, tyres and auxiliary systems;
b) *factors related to the environmental and traffic conditions*, including factors such as weather conditions, road morphology and traffic conditions;
c) *factors related to the vehicle driver*, such as driving style and vehicle maintenance.

Finally the influence of vehicle certification test conditions, boundaries and elasticities are discussed separately.

The paper concludes with a consolidation of the information collected on the effect of the various factors, an estimate of the real-world CO_2 emissions of an average European passenger car (as defined in Table 2.1) and a short discussion on the findings of this study. It should be noted that specific engine and drivetrain technologies have not been included and are only discussed in passing, where they are linked to other vehicle-related factors affecting the real world-certification gap. This is done for two main reasons. First, it is hard to identify without detailed modelling tools the differences in the performance of individual powertrain components, inside or outside the current vehicle certification test. Second, their effect on vehicle fuel consumption is high, and hence, it would require a separate study in order to describe and present the influence of individual technologies and components on fuel consumption. In view of the introduction of the WLTP, we attempt a targeted analysis on the

Table 2.1
Average European vehicle characteristics by fuel 2015 (no alternative fuels included) [14].

Fuel	CO_2 (g/km)	Mass (kg)	Capacity (cc)	Power (kW)
All	120.7	1380	1600	66
Diesel	119.2	1526	1811	71
Petrol	122.7	1214	1358	59
Hybrids	88.1	1485	1821	81

performance of specific powertrain related technologies, over real-world and vehicle certification test protocols.

2. Background

2.1. Regulatory framework

The NEDC and the respective test protocol were first introduced in the seventies for measuring pollutant emissions and not CO_2 or fuel consumption. In the early 1980s, CO_2 emissions measurement was added to the European mandatory vehicle certification process, also known as Type Approval process (TA). However, no specific limits or targets were set at the time [38]. Curbing CO_2 emissions from road transport, especially passenger cars,[1] is a cornerstone of European climate change mitigation policies [40]. In 1995 the EC made a proposal to set a fleet average CO_2 emissions target of 120 g/km for 2005. The subsequent discussions, between the EC and the vehicle manufacturers, led to a voluntary auto industry commitment (1999) to achieve fleet average emissions of 140 gCO_2/km by 2008 [41]; reductions were monitored via an annual CO_2 emissions monitoring scheme [42]. The failure of the automotive industry to live up to their commitment led to the addoption of the 2009 European regulation for mandatory CO_2 emission limits (EU Regulation 443/2009). A fleet average mass-dependent CO_2 limit of 130 g/km by 2015 was adopted. Another 10 g of CO_2 were expected to be gained from supplementary measures not covered by the type approval test (i.e. biofuels, gearshift indicators, improved air-conditioning systems, driver education etc), in order to reach overall emission levels of 120 gCO_2/km [9]. Since then the EU implemented a strategy for reducing further CO_2 emissions and fuel consumption from passenger cars [43,44] foreseeing compulsory, fleet average and mass dependent targets of 95 g/km by 2021. Failure of a manufacturer to comply with mandatory limits results in fines ranging from €5 to €95 per gram of excess CO_2 per vehicle sold.

This policy has caused significant changes in the average official CO_2 emisisons and a shift in the major characteristics of European passenger vehicles over the past decade (see Fig. 2.1), resulting in 2015, in the sales-weighted average characteristics[2] that are presented in Table 2.1 [14]. This has been accompanied by a reduction in average engine capacity despite the apparent increase in engine power and is a direct result of engine downsizing for both diesel and gasoline engines. In constast, mass has remained relatively constant between 1300 and 1400 kg despite its significance in vehicle energy consumption. However, there is criticism of the accuracy of these CO_2 figures and how representative they can be considered in terms of real-world CO_2 and fuel consumption [15,45]. The generic term Alternative Fuel Vehicles (AFV) refers to vehicles that utilize compressed natural gas, liquified petroleum gas, ethanol, biodiesel and-other non diesel and petrol fuels. These vehicles are grouped together due to their low sales volume (~2.7% altogether). Consequently the steep annual reduction of CO_2 emissions in this case, might be a result of changes in the share of each fuel type within AFV each year. For example, ethanol vehicles have higher emissions than liquified petroleum gas vehicles which, in turn, have a higher market share in the earlier years [45].

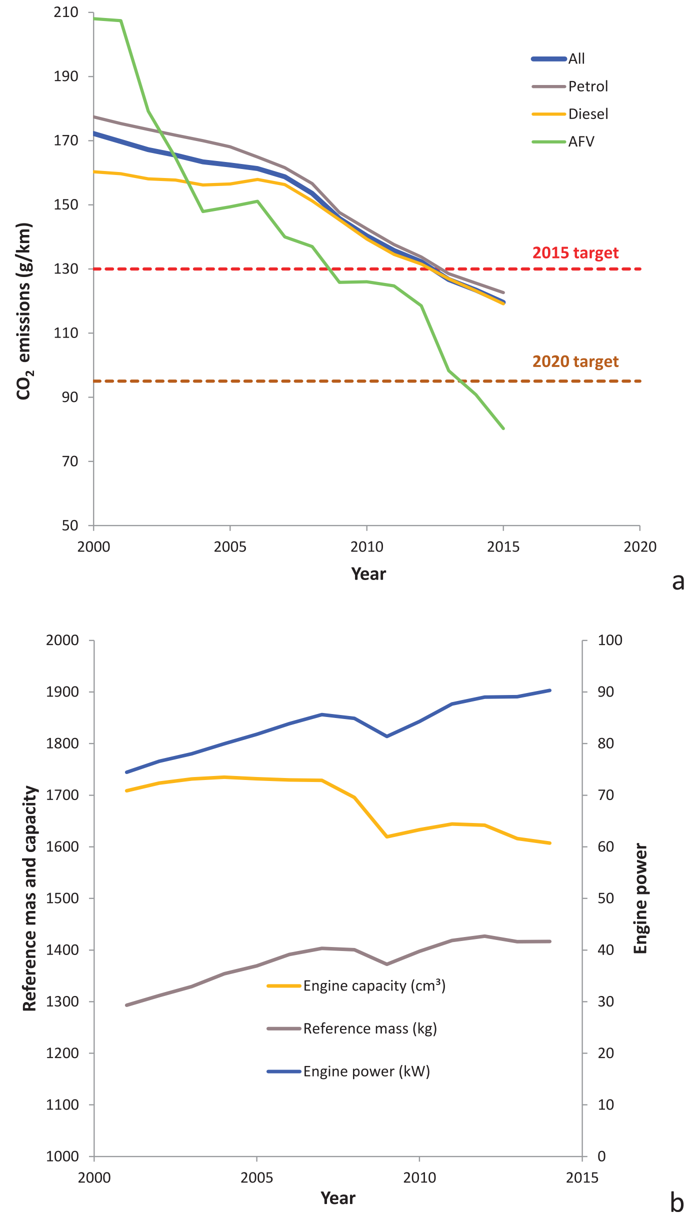


Fig. 2.1. Evolution of CO_2 emissions from new passenger cars by fuel type (a) and of average vehicle characteristics (b). Chart adapted from [45], data for 2015 estimated based on the EEA provisional data [14].

In parallel, most major vehicle markets worldwide have adopted similar CO_2 related targets or limits, (see Table 2.2). For comparison purposes the emission targets in Table 2.2 have been normalized to NEDC equivalent values[3] [46,47].

2.2. Emissions measurements and road load determination

The reference methodology for measuring CO_2 emissions, the test cycle (NEDC) [48], test boundary conditions, vehicle set up and results collection and analysis follow the procedure for pollutant emissions measurements that was originally established in the early

[1] Similar initiatives have been established for light commercial vehicles, where the limit values are higher (2017: 175 g/km, 2020: 147 g/km), thus covering the entire light duty vehicle (LDV) market in the EU. This study focuses on passenger cars only as their sales (89%) greatly outweigh those of light commercial vehicles (11%) [39].

[2] If not mentioned differently, the average CO_2 and vehicle characteristics' values used in the text hereafter refer to those of Table 2.1.

Table 2.2
Light Duty Vehicle CO_2 emissions future targets for major vehicle markets [47].

Country - Region	CO_2 Target [g/km] (expressed as NEDC equivalent values)	Year of enactment
European Union (Passenger Cars)	95	2021
European Union (Light Commercial Vehicles)	147	2020
United States & Canada	97	2025
Japan	122	2020
China	117	2020
India	113	2021
South Korea	97	2020
Brazil	138	2017
Mexico	145	2016

1970s. The test procedure has undergone slight modifications since. Currently it abides to the standard set in the global technical regulation R83 [49] of the World Forum for Harmonization of Vehicle Regulations of the United Nations' Economic Commission for Europe (UNECE) and is used in the type-approval system of several vehicle markets in the world (with the exception of US, Japan and Canada). The NEDC-based procedure for CO_2 and fuel consumption measurement is described in UNECE R101 [50].

The NEDC consists of mild accelerations and decelerations and several steady state points which fail to reflect modern driving patterns [51,18]. In addition, the test procedure disregards various real-world conditions such as additional weight, number of passengers, use of air conditioning, realistic gear shifting, cold starts, operation at higher velocities and congestion [52,53] and examines only a small area of the operating range of the engine [51]. The testing procedure exhibits unrealistic or loosely defined boundary conditions such as temperature ranges of 20–25 °C, restricted use of auxiliary systems which are widely used in real driving, lower vehicle mass, lack of air-conditioning use, unclear or even erroneous definition of resistances. The combined effects of these factors result in a systematic bias in the recording of CO_2 emissions.

The EU vehicle certification test foresees driving of the vehicle over the NEDC on a chassis dynamometer, an instrument that simulates the resistive forces imposed on the vehicle technically referred to as the road loads [54]. The chassis dynamometer consists of a roller, where the vehicle is placed and stabilized. The roller simulates road loads according to the test cycle's speed profile. During the test exhaust emissions are collected into sample bags and are analysed after the test is completed [54]. The procedure takes place in a test cell under controllable ambient conditions, in order to deliver accurate and reproducible results. Several other test cycles and accompanying protocols have been proposed as being more representative of real driving conditions. Most notable are the Artemis cycles [55], which have served as a basis for emissions performance assessment and emissions factors development for several years [56,57]. To address the shortcomings of the existing test procedure and limit the extent of the gap the new WLTP test procedure, designed at a global level [58], will be implemented in the European type-approval system in 2017. The development of the procedure was supported by the automotive industry, governmental and non-governmental organizations [5]. However, the WLTP is not expected to change the established CO_2 targets or the way policy is being assessed [59], and a translation of the WLTP into the NEDC-based system will take place until year 2020. To what extent, and how, the new procedure will be used in Europe for policy making and vehicle labelling with regards to vehicle fuel consumption and CO_2 emissions, remains (as of 2017) unclear.

The resistances applied during the NEDC test are determined through a coast down test which takes place at an outside test-track prior to the measurement. In this procedure, the vehicle is accelerated to 120 km/h and then it is allowed to coast down in neutral gear until it slows down to 20 km/h or until it stops. The time and vehicle speed is recorded for regular speed intervals allowing the calculation of the mean deceleration of the vehicle and the forces (resistances) acting on it. A second order polynomial model is applied in order to describe resistances [60] as follows.

$$m\,\frac{dv}{dt} = \sum\nolimits^{R} = f_0 + f_1\,v + f_2\,v^2 \quad (1)$$

where:

m is vehicle reference mass
v is vehicle velocity
R is a resistance acting on the vehicle

f_x are the road load factors (road loads) fitted on the coast down data

The model's coefficients f0, f1, f2, referred to as road loads, result from applying the above equation to the coast down test data; f_0 represents the rolling resistance that acts on the vehicle due to the deformation of the tyres, f_1 the resistance that is proportional to velocity, which mainly originates from internal losses due to rotating parts of the drivetrain such as the output shaft of the gearbox, and f_2 the aerodynamic resistance that is proportional to a vehicle's frontal area (FA) and aerodynamic resistance factor (C_d) [61].

Road loads together with vehicle mass are used for setting up the test facility (chassis dynamometer) in order to apply the appropriate resistances during a driving-cycle. Practically, the chassis dynamometer is being calibrated to reproduce the resistances calculated during the coast-down test, with few differentiations in the boundary conditions that are imposed by the respective test procedure (e.g. the simulated mass is not exactly equal to the reference mass as the legislation foresees a mass-based binning of vehicles). According to the NEDC test protocol, in laboratory conditions the total resistance applied at the wheel of the vehicle should match the sum of resistances described by Eq. (1). However, in real-world driving additional resistances and energy losses occur such as, the resistances to climb up a slope, losses due to auxiliary consumers (e.g. air-conditioning), and weather conditions. Furthermore, the vehicle mass is rarely equal to the official reference test-mass, due to the presence of additional passengers in the vehicle or other factors that increase the total mass. Such factors are presented in detail in the following paragraphs.

2.3. Divergence of official and real-world emissions

Various studies highlight the inadequacy of the certification test to simulate real-world vehicle performance [62–64,18,65,66], while the European Automobile Constructors Association (ACEA) points to the influence of the drivers on the final vehicle CO_2 emissions. For example, two drivers driving the same vehicle under the same conditions are likely to have different CO_2 emissions [66]. Meanwhile, the pressure exerted by European laws for reaching the mandatory targets has resulted in vehicle OEMs exploiting the margins of the prescribed test conditions. Such practices have widened the difference between the official values and those reported in real-world CO_2 measurements (see Table 1.1). As a result the gap between officially reported and real-world CO_2 emissions appears to increase with time. Fig. 2.2 shows the evolution of the divergence between official and measured real-world fuel consumption according to

[3] The methodology to estimate the conversion equation was based on the simulation of representative vehicle models over the investigated cycles. Subsequently, the simulation results were imported in a regression model to estimate the conversion coefficients.

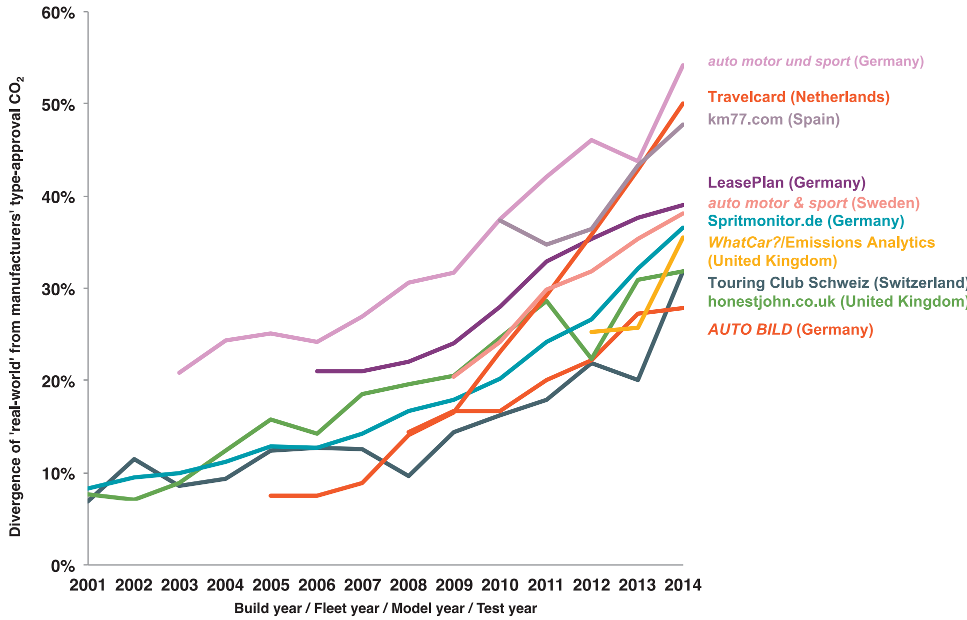


Fig. 2.2. Evolution of the divergence between official and drive "real-world" fuel consumption according to different data sources. Adaptation from [19].

different data sources [19]. It is expected that these divergences in CO_2 emissions may appear also in countries where the European test procedure (e.g. Australia and India) is used, while similar trends are reported for markets with different certification systems (e.g. US and China) [67,68].

Several of these (Fig. 2.2) fuel consumption measurements originate from car magazines or car related portals and websites and can be questioned as to their scientific merit. However, editors state that they follow a representative real-world driving pattern, while in most of the cases the fuel consumption is estimated based on tank fill-ups at the end of the test and subsequently CO_2 emissions are calculated assuming fixed carbon contents per fuel type [19]. It can be argued that these datasets are biased. However, all sources present the same increasing trend over time and similar relative annual changes. Based on values reported in previous studies [16,62,69], the gap in the period 2000–2005 was estimated to be 10%, a figure very similar to the values presented in Fig. 2.2 for the same period across all datasets. This demonstrates that any bias of these datasets is probably limited.

At this point one should distinguish between reported CO_2 emissions used for the assessment of specific policy targets and the fuel consumption values communicated to the driver of a vehicle. Indeed, the CO_2 emissions are reported for the combined NEDC value and monitoring is based on this single value that characterizes the vehicle. However, with regard to fuel consumption vehicle labelling requires that three values for fuel consumption are communicated to the public corresponding to urban driving cycle (UDC) and the extra-urban driving cycle (EUDC) together with their combined (NEDC) value. These three fuel consumption values may vary from 10 to 30% depending on vehicle characteristics for the attributed fuel consumptions tend to underestimate the equivalent conditions (e.g. when comparing UDC fuel consumption directly to that experienced over real urban driving).

In United States (US), the Environmental Protection Agency (EPA) revised its type approval procedure in 2008. It now provides two fuel economy values, expressed in miles per gallon units (MPG) [70,71]. The first is the fuel economy measured following the official vehicle test procedure in the laboratory, and it used for monitoring policy related targets. The second is an adjusted value that is the weighted fuel economy measured over a combination of supplementary tests, in addition to the official test [72]. These supplementary cycles include driving at higher speeds, use of air conditioning and low ambient temperatures. The adjusted fuel economy values are considered more realistic and are therefore communicated to car buyers. No extensive studies exist on the divergence between US real-world and laboratory emissions; the US EPA, however, monitors emissions of in-use vehicles to ensure that they remain within a margin of 30% of the standard limits [18, 38].

2.4. *Eco-innovations*

The European eco-innovation scheme is set out in legislation [9] and aims to promote the implementation of innovative technologies that reduce CO_2 emissions in real life and not (or only partially) in the certification test. Eco-innovation means an innovative technology which is accompanied by an EC approved evaluation (experimental or calculated) [74]. Vehicle manufacturers or component manufacturers can apply for a technology or a combination of technologies to be granted an eco-innovation status if they prove that the "innovation" provides benefits of more than 1 gCO_2/km compared to the standard technology and fulfils certain applicability criteria such as market penetration, technology relevance and accountability [74]. Eco-innovations enable a CO_2 emissions discount of up to 7 g/km (at fleet level) depending on their effectiveness. The latter is considered when assessing the performance of an OEM with regards to the established CO_2 targets (95 g/km sales weighted average emissions by 2021). It is expected that by 2020 most of vehicles in the market will be fitted with such technologies, helping vehicle OEMs to reach their CO_2 targets [9,75]. Eco-innovations have a positive impact over real-world conditions and are likely to reduce the type approval real-world CO_2 gap. However, due to their "innovative" status limited scientific studies exist on these low carbon technologies. In subsequent chapters specific implementations, which have been characterized as eco-innovations, are presented and discussed.

3. Vehicle characteristics and sub-systems

3.1. Mass and road loads

3.1.1. Vehicle mass

Vehicle mass is one of the main factors influencing a vehicle's fuel consumption under low velocity driving conditions [76–78,80]. The operating mass of a vehicle consists of: (i) the empty vehicle; (ii) the fuel in the tank; and (iii) the passengers and cargo. During the current European vehicle certification test a single vehicle mass value is considered (reference mass which is a vehicle empty mass augmented by 100 kg) which is then used to identify a specific inertia class for running the laboratory CO_2 measurement. An increase in the operating mass increases fuel consumption, as more power is needed to accelerate the vehicle during acceleration phases and rolling resistance is also increased proportionally [47–49]. Despite its influence on energy consumption, the average official mass of vehicles in Europe has remained constant over the past decade (see Fig. 2.1) stabilizing between 1340 and 1400 kg. This suggests an inversion of the trend of the previous years that led to continuous mass increases as vehicles became bigger, safer and incorporated more driver and passenger aids.

There are no common metrics or approaches for the measurement and quantification of the impact of additional mass on fuel consumption and CO_2 emissions of passenger cars. A wide range of values have been reported with most studies converging on figures of the order of 5–9% (6.5–12 g/km over NEDC) for mass additions of 50–200 kg over various cycles and operating conditions [50–54].

Several studies demonstrate the effect of vehicle weight reduction on fuel consumption, particularly over vehicle certification conditions. In general, weight reduction is reported to reduce fuel consumption between 5 and 10% [87,88]. The NEDC [89] reports a linear relationship between mass reduction and fuel consumption reduction with a 5%–10% decrease in vehicle weight leading to decreases between 1.3–1.8% and 2.7–3.6%, respectively. Approximately a 0.6% reduction is achieved for each 1% saving in total vehicle mass [90]. A 100 kg reduction represents fuel savings of 0.3–0.5 l/100 km (6%–10% for a fuel consumption of 5 l/100 km) [91] while a 100 kg increase in mass is reported by Mickūnaitis et al. [92] to increase fuel consumption by 6.5% (petrol cars) and 7.1% (diesel cars) [92]. Similar ranges are reported also in US vehicles with a 10% reduction in weight estimated to deliver a 5% improved fuel economy [93].

Considering the effect of mass over real-world driving, an additional 100 kg can increase fuel consumption by an average 5–7% for a medium-sized car of 1500 kg [83]. In absolute numbers, an additional 100 kg load is reported to cause an increase from 0.3 to 0.5 l/100 km (7.5–12.5 gCO_2/km) [94–98].

Weight reduction is also linked to powertrain characteristics such as engine power. With lighter vehicles and improvements in component efficiency, the peak power requirement of powertrains could further be reduced over time [99] leading to improvements in fuel consumption. A 10% weight reduction can improve fuel economy by 4–8%, depending on whether or not the engine is downsized to maintain the same acceleration performance [100].

From a load carrying capacity perspective, which is more relevant for light goods vehicles, an increase of a vehicle's mass equal to 50% of its load carrying capacity results in an average increase of fuel consumption of about 5.6%, with a scatter not greater than ±1.2% [63]. Fig. 3.1 summarizes the effect of vehicle weight on fuel consumption as found in the literature.

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 of fuel consumption. In most cases discrete mass increases are reported together with their effect on CO_2 emissions. These discrete increases make sense for passenger

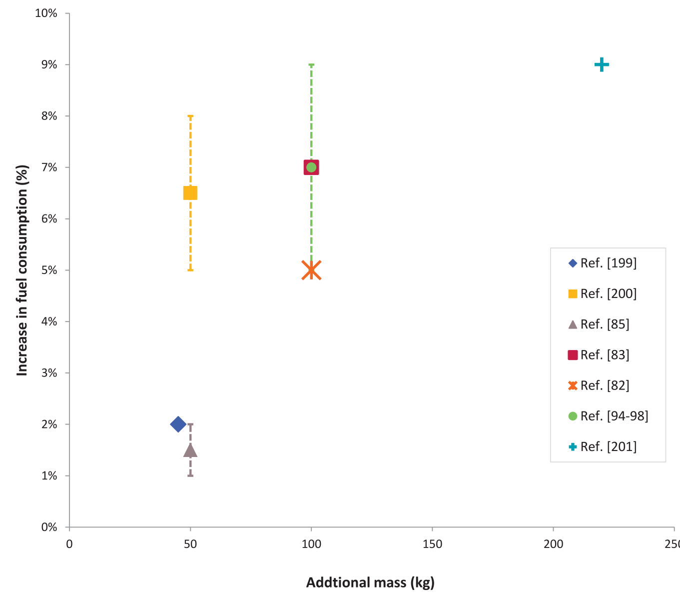


Fig. 3.1. Expected Increase in fuel consumption due to increases in vehicle mass. Error bars refer to maximum–minimum values. The references cited in this figure are [82,83,85,94-98,199–201].

cars, where the vehicle is used for transporting passengers rather than goods. In real life, the factor causing the greatest variation in passenger vehicle weight is the number of passengers, also referred to as the occupancy rate. A high occupancy rate reduces the CO_2 emissions per passenger-kilometre, which is desirable from an environmental perspective, and is examined separately.

3.1.2. Aerodynamic resistance

Vehicle aerodynamic resistance is one of the primary factors influencing fuel consumption over high speed driving conditions [101,79] and is expressed as a function of the square of vehicle's velocity and proportional to the product of aerodynamic drag coefficient (C_d), frontal area (A) and air density (ρ).

The aerodynamic drag coefficient is affected by the design of the car. Increases in the C_d x A product, hence forward referred to as aerodynamic drag, induced either by changes in the size of the vehicle or in its shape and aerodynamic design, translate directly into increased aerodynamic resistance, and thus, to decreased fuel economy and higher CO_2 emissions. Aerodynamic resistance improvement by 20% can result in fuel consumption reduction over NEDC of about 3–7% [102]; reductions of 5% and 10% in aerodynamic resistance could lead to a decrease of CO_2 emissions for NEDC of about 0.6–1.2% and 1.2–2.4% respectively [89].

Improvements of aerodynamic characteristics reduce the aerodynamic drag and increase vehicle stability by alleviating lift and side forces [79]. Focusing on the improvement of vehicle aerodynamic losses during the design and manufacturing process in the past decades has resulted in the reduction of the vehicle drag coefficient [100]. However, a continuous increase in vehicle dimensions has offset much of these resistance benefits as the frontal area of the vehicles has also increased [103].

Aerodynamic resistance under real-world driving conditions is also affected by various vehicle elements and different shape configurations [104], which are not necessarily captured by the current vehicle certification procedure. Even small modifications can increase vehicle aerodynamic resistance leading to measureable changes in fuel consumption. It is estimated that an increase of the order of 10 to 20% can result in 2–4% additional fuel consumption in highway operation [16]. Achieving drag coefficients of 0.24 in the

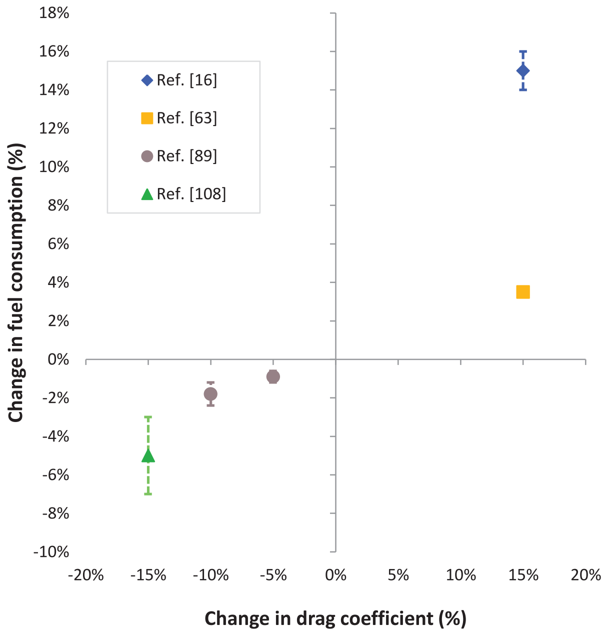


Fig. 3.2. Effect of air drag changes on fuel consumption. Error bars for minimum–maximum values. The references cited in this figure are [16,63,89,108].

near future is plausible and could lead to savings of approximately 1.6 l/100 km over motorway driving (130 km/h) [105].

Fig. 3.2 presents a summary of the findings of the effect of air drag changes on fuel consumption.

Air density, which varies depending on altitude and ambient conditions, influences fuel consumption but is not directly related to the aerodynamic design of the vehicle as will be presented onwards.

Finally, one issue that is referenced in non-scientific literature is the addition of designed devices such as spoilers [106,107], vortex generators [108] or combinations of the two for improving the aerodynamics of passenger cars. The latter devices can reduce aerodynamic resistance between 1 and 7% [106–108]. However, given the importance CO_2 emissions have gained in recent years it is likely that vehicle manufacturers have already exploited most of the benefits obtainable by an improved aerodynamic design or the addition of simple aerodynamic add-ons. Hence such improvements are possibly non representative for modern vehicles. It is possible that the practice of certain drivers of adding retrofit aerodynamic devices on their vehicles for enhancing down-force and stability at high speed driving actually increases fuel consumption. No studies on the topic were found.

3.1.3. Rolling resistance and tyres

Rolling resistance refers to the energy loss occurring in the tyre due to the deformation of the contact area and the damping properties of the rubber [79]. The resistance in vehicle motion induced by the tyre's deformation is proportional to the vertical force applied on the tyre due to vehicle weight and to the rolling resistance coefficient. The rolling resistance coefficient is a dimensionless quantity that is considered as constant or as proportional to vehicle velocity. Rolling resistance is frequently expressed in mass per mass units (kg/t). Many factors [61] influence rolling resistance tyre properties such vehicle velocity, temperature, tyre type and size. Rolling resistance of tyres under NEDC conditions is reported to account for 20–25% of total vehicle energy loss [109]. Reported reductions in rolling resistance are of the order of 5–30% (see Fig. 3.3) which leads to fuel consumption improvements of 1–3.5%. Not all reference sources use the same drive cycles or make reference to the same vehicle operating conditions and in most cases the absolute or relative values of the rolling resistance examined is not mentioned. Hence a more refined comparison is difficult to make.

Due to their influence on the fuel consumption of vehicles, tyres are officially categorized in energy efficiency classes (see Table 3.1) based on their measured rolling resistance. The European Regulation [110] lays down a scale of classes based on the rolling resistance coefficient (RRC). The classes range from A being the most efficient to G the least efficient. 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. The variation in RRC can reach 90%, where such a difference in RRC could result in a consumption increase of 7.5% [111]. Choosing tyres of the next higher energy class can signify a reduction in rolling resistance of the order of 10–15%, which translates to a reduction of fuel consumption of approximately 1–1.5% [89,112]. 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 [113]. It is estimated, based on tyre sales, that the average RRC of the tyres

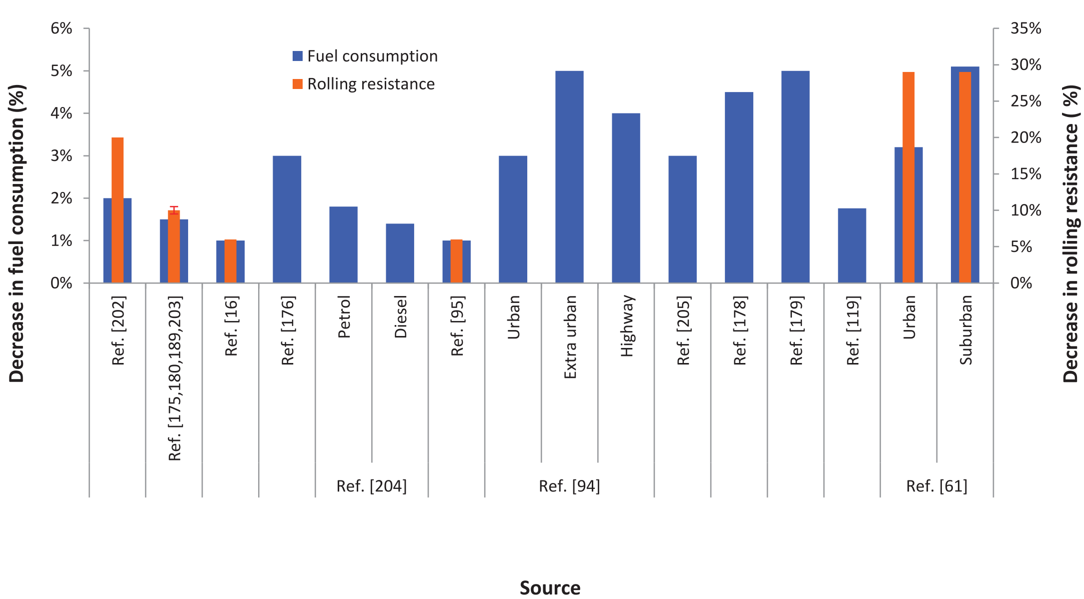


Fig. 3.3. Decrease in fuel consumption, with the use of lower resistance tyres. The references cited in this figure are [16,61,94,95,119,175,176,178–180,189,202–205].

Table 3.1
Tyre categories according to [110] and mean rolling resistance coefficient.

RRC in kg/t	Energy efficiency class	Mean RRC of the class [kg/t]
RRC ≤ 6.5	A	–
6.6 ≤ RRC ≤ 7.7	B	7.15
7.8 ≤ RRC ≤ 9.0	C	8.4
9.1 ≤ RRC ≤ 10.5	E	9.8
10.6 ≤ RRC ≤ 12.0	F	11.3
12.1 ≤ RRC	G	N/A

sold in the EU 1was 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 [114].

The tyres sold with the vehicle are not necessarily of the same energy efficiency class as the tyres that were fitted during certification. The vehicle during coast down should be equipped with the widest tyre and if more than three tyre sizes are available, the second widest should be chosen [48]. In general, the wider the tyre the higher is its rolling resistance. Nevertheless, this does not 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. It is expected that most vehicles when undergoing the type approval procedure are equipped with a high energy class tyre (A or B) while the majority of vehicles are sold with tyres of lower energy class. This situation creates a discrepancy between the certified and the in-use fuel consumption because the assumed rolling resistance during the certification test is different from the one actually occurring on the road. An increase of 20% in rolling resistance, which corresponds to a change from tyre of energy class A to a tyre of energy class C, can increase fuel consumption by 2% [115]. This situation 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. When the same vehicle is sold with tyres belonging to an intermediate RRC class the fuel consumption should be corrected accordingly via linear interpolation of the two limit values.

An important issue relates to the use of replacement tyres. The majority of aftersales tyres (replacement tyres) in the EU falls within classes C and E [116] with the penetration of higher energy class tyres in the market remaining as low as 1% [114]. The average annual mileage of a passenger car is estimated to be 14,000 km [117], thus over a 10 year period and until a vehicle is retired, three to five sets of tyres are replaced. This tendency of European drivers to choose low energy class tyres contributes in the widening of the gap. On the other hand, important benefits in real world CO_2 emissions can be gained, relatively easily, by promoting replacement tyres of higher energy class in existing, older model-year vehicles.

Winter tyres, which are mandatory during winter season in some European countries (e.g. Germany) [118], also exhibit higher rolling resistance compared to regular tyres and lead to an increase in fuel consumption [119]. Winter tyres of the same characteristics and size can be to be one or two energy efficiency classes lower. A 1 kg/t difference between all weather and winter tyres foreseen by the legislation for maximal allowed values [114]. This can lead to increases of the order of 2–3%. It is expected that winter tyre RRC will improve with time as does RRC of regular tyres.

3.1.4. Factors affecting both mass and road loads

The factors discussed below present two distinct characteristics. Their effect on fuel consumption can be attributed to more than one factor, namely changes in mass and road loads. In addition, their contribution to the real world fuel consumption cannot be easily captured with simple fuel consumption reporting or tests such as those used for producing the data of Fig. 2.2. Hence, a wide variation in test conditions and eventually the reported impacts on fuel consumption should be expected.

3.1.4.1. Trailer towing. Trailer towing affects both the total mass and the road loads of the vehicle leading to increased fuel consumption. The total mass is increased due to the additional weight of the trailer and its load, while the extra wheels introduce additional rolling resistance. Vehicle aerodynamic resistance is also influenced by the trailer, which can increase both the frontal area and the drag coefficient [120]. The driving style is also adjusted to the towing conditions. In general, towing causes a reduction in vehicle speed and leads to a milder driving. The reduced speed counterbalances the effect of deteriorated aerodynamics. Finally, additional energy is needed for lights and other trailer accessories.

The increase in fuel consumption due to towing was examined in a study [121] in which a passenger car was tested towing an unloaded trailer and the same trailer loaded at 60% of full load capacity. The total weight of the empty trailer was 310 kg and 564 kg including the 60% capacity load. Tests were carried out at speeds ranging from 70 to 90 km/h. The vehicle mass was 1408 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 within the frontal area of the vehicle, so any effect on aerodynamic resistance is expected to be limited. Fuel consumption was correlated to vehicle speed and resulted in an increase from 33% to 43% for the unloaded trailer and from 37% to 45% for the loaded trailer for the tested speed range. Experiments performed [122] on a Sports Utility Vehicle (4.0 L V6 engine, 2268 kg, 2.53 m^2 frontal area) towing a trailer of 1588 kg total weight, width of 1.83 m and height of 1.83 m revealed similar trends but higher increases compared to the reference test performed without the trailer. The frontal area was increased by 37% (to 3.47 m^2) when towing. Fig. 3.4 presents the fuel consumption in comparison to the standard configuration in the two cases.

3.1.4.2. Roof rack and roof box. Roof racks act as the basis for attaching a roof box (i.e. luggage box, ski boxes or for other equipment). Although roof racks usually serve as a basis for installing a roof box, they can be also found as a stand-alone component. Their installation worsens the aerodynamic resistance of the vehicle and leads to increases in fuel consumption estimated of the order of 1–3% for a speed range of 70–90 km/h [121].

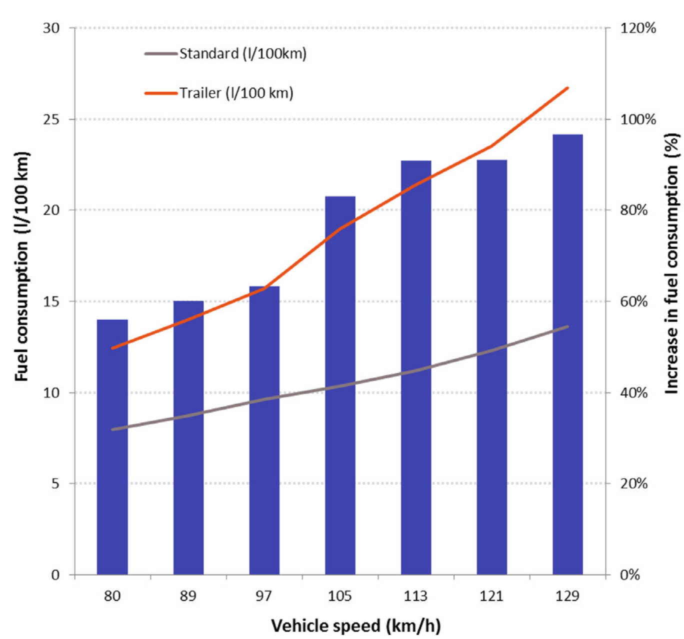


Fig. 3.4. Increase in fuel consumption for towing a trailer for various speeds, based on [122]. Adapted chart, bars correspond to percentage increase.

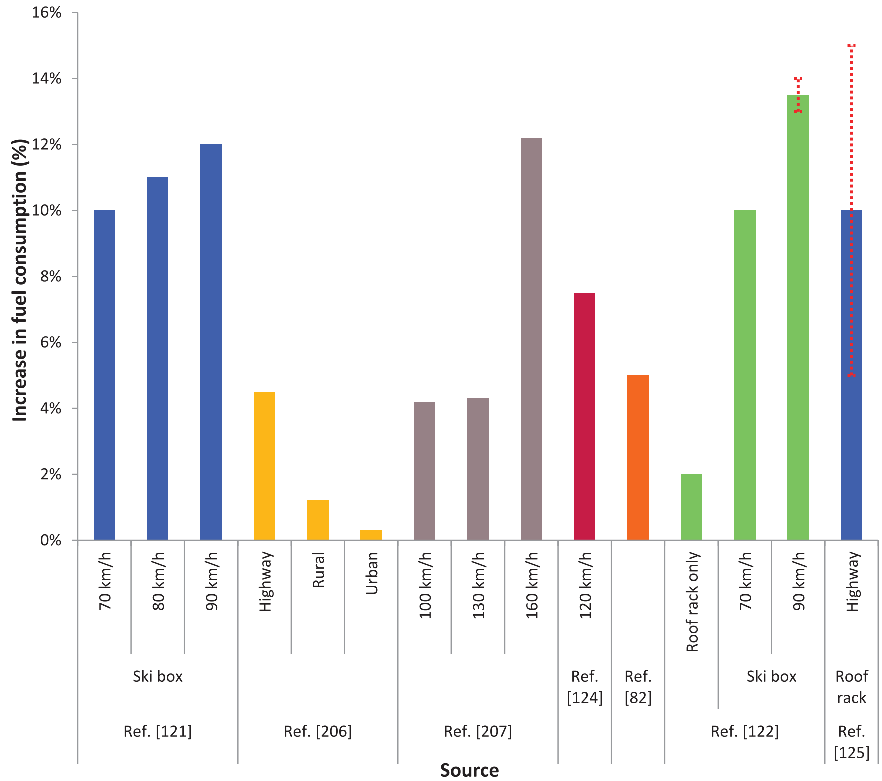


Fig. 3.5. Percentage increase in fuel consumption for a non-laden roof box. The references cited in this figure are [82,121,122,124,125,206,207].

A roof box increases the aerodynamic resistance and mass of the vehicle leading to an increase in fuel consumption. The addition of a roof box on a roof rack increases vehicle frontal area between 0.22 and 0.45 m^2 and increases vehicle aerodynamic drag [123]. The average increase in frontal area is estimated to be 0.37 m^2or 15% for an average European passenger car. Apart from the effect on aerodynamics, the additional average weight of the empty roof box is estimated at 15 kg, and hence, has a marginal effect on fuel consumption. During motorway conditions at 120 km/h a non–laden roof rack can on average increase fuel consumption by 7.5% [124]. Depending on conditions and box type, the effect of non-laden roof boxes is reported to be of the order of 5–14% compared to the fuel consumption measured without the box (see Fig. 3.5).

Taking into consideration an average maximum load of 60 kg [123], a laden roof box increases the mass of the vehicle on average by 75 kg resulting in a 5.5% mass increase for a vehicle with 1360 kg mass, equal to the weight of an average passenger. According to the values presented in Fig. 3.1, this can increase consumption between by 2 to 5%., without taking into consideration the impact on air drag. A study [125] observed an increase between 20 and 30% for a loaded roof box in highway operation, without specifying the average speed of the vehicle. Regarding the combined effect of weight and aerodynamic resistance increase due to a laden roof box, an effect ranging from 5 to 25% depending on the vehicle speed was found averaging at about 15% for speeds between 100 and 120 km/h (see Fig. 3.6).

3.1.4.3. Roof add-ons. Various items such as taxi signs and advertising signs attached on a car can also increase the frontal area, drag coefficient and fuel consumption (see Table 3.2). Based on the findings of Chowdhury et al. [104] the combined effect on fuel consumption was calculated for an average (see Table 2.1) European gasoline vehicle under realistic driving conditions.

The literature reviewed did not provide information to cover in full detail the effects of these add-ons individually. Nonetheless, vehicles with add-ons are expected to circulate in an urban environment with low relative speeds, where the effect of aerodynamics on fuel consumption and CO_2 emissions is minimal.

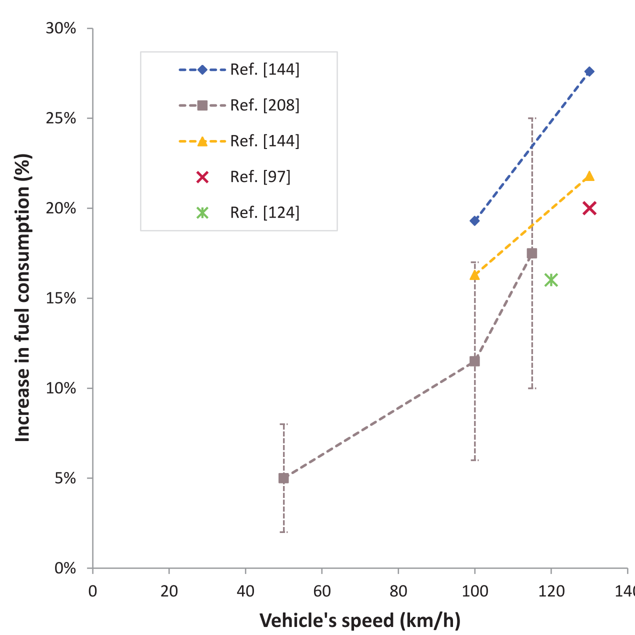


Fig. 3.6. Increase in fuel consumption because of laden roof box (influence on both mass and aerodynamics considered). Different vehicle configurations considered in each study.

Table 3.2
Examples of various add–ons and their effect on drag coefficient and frontal area [104]. Estimates on potential fuel consumption increase made according to [23] assuming an average gasoline vehicle.

Add – ons	Increase in drag coefficient (C_d) (%)	Increase in projected frontal area over the baseline (%)	Increase in fuel consumption (without mass) (%)	Mass increase (%)	Increase in fuel consumption (including mass increase) (%)
Advertising sign	7.2	0.8	4	~0	4
Taxi sign	5.1	2.0	3	~0	3
Roof rack	20.4	1.2	9	0.1	9.6
Roof rack with ladder	24.0	2.5	11	0.4	11.6
Barrel	33.1	4.9	15	0.1	15.4

3.2. Auxiliary systems

The auxiliary systems of a car comprise of all the elements that improve driving safety and comfort. This however at the cost of an increased electrical, or mechanical power supply that in turn increase fuel consumption [126,86]. The main vehicle systems reported in literature are:

- Air conditioning systems;
- Heating systems;
- Steering assist systems; and
- Other electrical consumers and auxiliaries (e.g. headlights, windscreen wipers, heated seats).

Vehicle's auxiliaries were found to represent 3.2% of the fuel consumption over the NEDC [127], a rather high value considering official European certification conditions. During the official certification test eventually the vehicle battery is fully charged, so no engine power is directed to electric components, and auxiliary components operate at the lowest power consumption level possible (see paragraph 6.1). The additional fuel consumption induced by auxiliary systems in real world conditions is estimated to be of the order of 3% [128], with the air-conditioning effect not taken into consideration. Other studies do not quantify the impact of auxiliary systems on fuel consumption but attempt to quantify fuel savings gained by the application of certain technologies like the full electrification of auxiliary systems. The latter is reported to reduce fuel consumption by 3% (gasoline and diesel) [129], a figure that is probably overestimated given the findings of the studies presented previously.

In terms of absolute energy consumption induced by auxiliary systems, a wide range of values is reported by Carlson et al. [130] over chassis dyno tests, ranging from 135 W to 1200 W, depending on the test cycle investigated. In the same study, the required on-road auxiliary load over 12 months, for a variety of ambient and driving conditions, was calculated to be between 310 and 640 W. The electric power demands of auxiliary systems and other components are expected to increase in the future bringing current 12 V electrical systems to their limits of operation [131]. The total electric loads of present vehicles can reach up to 2.2 kW but could increase to 4.2 kW in the future pushing the need to adopt 48 V systems to handle higher loads with lower electric currents, and hence, with less power lost due to Joule heating. According to Kühnlenz [131] 48 V systems can replace 12 V systems by 2030, facilitating also a transition to mild hybrid vehicles.

3.2.1. Air conditioning (cooling)

One of the most influential factors affecting real-world fuel consumption is the operation of Air Conditioning (A/C) systems [132,16,133–136,130]. 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 [137]. Although it was estimated in 2002 that by 2014 the majority of the vehicles sold in the European, American and Asian markets would be equipped with A/C systems [138], the use of A/C is not included in the present (NEDC) or future (WLTP as of 2017) European type approval tests, but is considered for future inclusion.

The effect A/C use on fuel consumption depends mainly on the desired interior temperature [130] and ambient conditions (temperature, air humidity and solar radiation) and to a lesser extent on other aspects such as speed and driving patterns [139]. Because of this weak connection to traffic conditions, the additional litres of fuel per hour of driving (l/h) is proposed [135,139] as the most appropriate metric for quantifying the impact of A/C on fuel consumption, instead of a percentile increase. Some researchers, however, claim a stronger connection between traffic conditions and the additional fuel consumption induced by the A/C operation, with the relative influence being reduced as vehicle speed increases (4%, 2.5%, and 1% for urban, rural and motorway driving respectively [140]). This observation does not necessarily contradict the fixed fuel consumption-per-driving-hour approach; increased fuel consumption at high speed conditions reduces the relative fuel losses resulting from the A/C system.

There is a lack of consensus on the measurement conditions and the reporting of the impact of A/C on fuel consumption. Measured [133] CO_2 emissions of an air conditioned vehicle without any heat soaking and of a vehicle exposed to solar radiation of 850 W/m^2 resulted in increases in CO_2 emissions over NEDC of 2056 gCO_2/h (an additional consumption of 0.85 l/h). Similarly an increase in fuel consumption of 1 l/h is reported in [141] but without making explicit reference to the conditions of A/C operation. Certain studies report the effect of A/C on a l/100 km basis. According to [139], fuel consumption increases and exceeds 1 l/100 km at high load points, which are rare in real-world driving conditions, and the same study recommends common guidelines for determining A/C effect. An average increase of 1.25 l/100 km was found over the NEDC in an EU funded project [142] aiming to develop a common type approval procedure for A/C systems. Finally, relative increases of 14%, 10% and 11% for the urban, highway and combined cycle respectively have been reported [143] (see Table 3.3).

The type of A/C, manual or automatic, has an impact on fuel consumption. Manual A/C are considered systems that operate continuously while automatic A/C try to maintain a predefined cabin temperature. Tests of the effect of manual and automatic A/C at 50 km/h and 100 km/h showed that the impact on CO_2 emissions is higher in manual A/C than in automatic ones and that, similarly to

Table 3.3
Effect of A/C on fuel consumption (l/100 km) over urban, highway and combined cycles [143].

	City	Highway	Combined
A/C off	9.0	6.4	7.6
A/C on	10.4	7.0	8.6

what has already been discussed, the overall impact is lower at a speed of 100 km/h than at 50 km/h [144,145].

For hybrid vehicles the relative effect of A/C operation is reported to be higher compared to conventional vehicles, an expected outcome as hybrid vehicles present much lower fuel consumption. Comparing a conventional (1406 kg, 3000 cc) against a hybrid vehicle (907 kg, 1300 cc), [146] performed tests over the US SFTP 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. Fuel consumption increased from 10.7 l/100 km to 14.7 l/100 km and from 2.77 l/100 km to 6.57 l/100 km for the conventional and the hybrid vehicle respectively.

Regarding the contribution of specific A/C components in the additional energy demand, Nielsen et al. [147] reports that 175 W of the A/C imposed electrical load can be attributed to the cooling fan and the clutch operation of the compressor, while another 475 W of the mechanical load can be attributed to the energy needs of the compressor. Experimenting with various improvements they have achieved a 46% reduction in the electrical load and a 27% in the mechanical load.

Fig. 3.7 provides a summary of the results retrieved from the various sources. In order to normalize the findings, an average speed of 100 km/h was assumed for calculating the respective values. Different studies consider different assumptions regarding the ambient-cabin temperature; it has not been possible to take those into consideration.

3.2.2. *Heating (electric heating or A/C)*

Recent improvements in engine fuel efficiency have reduced the performance of the vehicle heating system, due to lower engine heat rejection to the coolant, for systems that rely on engine heat to maintain cabin temperature or remove the vapour from vehicle windscreens. Missing heat is compensated by electric heating which in turn leads to an increase in electric power demand [148]. Such systems may require an additional 400–2000 W [149] of electric power to operate. The additional power requirement has an impact on fuel consumption, with an increase of 600 W resulting in fuel consumption increases of 5–10% (about 6–12 gCO_2/km for a 2015 average car) over the NEDC [150].

A study [148] examined the operation of heating systems for various outside temperatures and found that their use in Frankfurt (Germany) resulted in an increase in fuel consumption of 0.15 l/100 km and 0.25 l/100 km (3.7–6.2 gCO_2/km), which corresponds to 2.6% and 4.4% respectively for an average European car. It is expected that hybrid electric vehicles, which exhibit prolonged periods of engine shut-off, are affected more by the operation of heaters in terms of available range in electric mode and fuel consumption.

3.2.3. *Steering assist systems*

Steering assist systems contribute to driving safety and comfort, but they also require an additional energy supply that results in increased fuel consumption. Steering action is considered rare compared to the total vehicle operating time. In typical highway travel the power steering assisted system can remain idle for about 76% of the time [151].

There are three types of steering assist systems [152]: Hydraulic Power assisted Steering (HPS); Electro–Hydraulic Power assisted Steering (EHPS); and Electric Power assisted Steering (EPS). HPS has been the main power assisting system for many years and is powered by the combustion engine belt drive, even when in standby hence it is a significant energy consumer. In recent years, there has been an effort to implement power-on-demand type of systems that led to the evolution of EHPS, a partially on-demand system, and EPS.

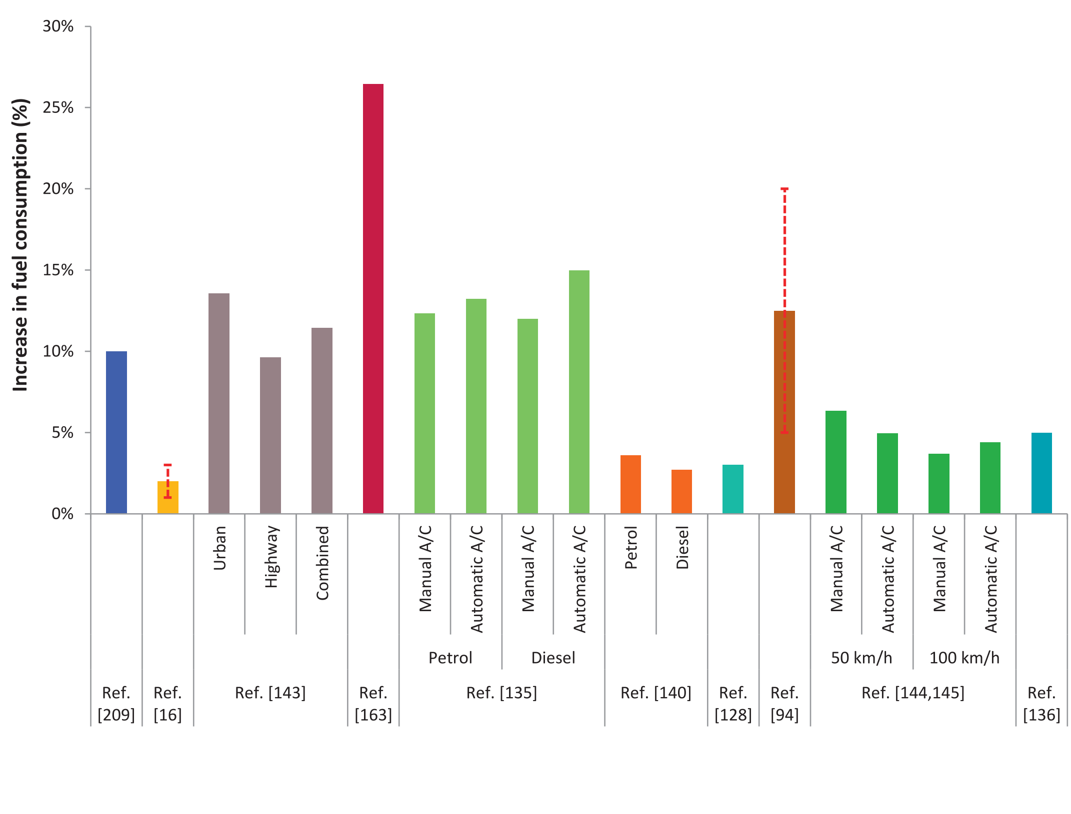


Fig. 3.7. Estimated fuel consumption increase based on the findings retrieved from different sources. Use of A/C and an average speed of 100 km/h are assumed to normalize values that are not expressed in l/100 km. The references cited in this figure are [16,94,128,135,136,140,143–145,163,209].

In EHPS the hydraulic pump is driven by operating an electric motor that has a lower power demand. In contrast, the EPS steering assistance comes directly from an electric motor, which is only activated when power assistance is required, resulting in lower energy consumption [153]. In terms of required power, HPS can demand ~270 W, EHPS ~38 W and EPS ~18 W [154]. The HPS system may cause an 8% increase in fuel consumption with the EHPS and EPS a 2% and less than 1% increase, respectively [152]. According to [16], electrical power steering increases fuel consumption by 2–3%, a value that lies probably in the high range considering modern vehicles.

Since the HPS is the most fuel inefficient system it has been suggested [151] that the use of EHPS is needed, where HPS pump is disconnected by an electromagnetic clutch when steering is not required. On-road measurements on vehicles featuring these systems showed a decrease of 5% and 4.1% for highway and urban driving accordingly compared to normal use of the HPS system. The overall decrease in the NEDC was 3.9%, where the decrease was higher in the UDC than the EUDC, 4.8% and 2.7% respectively. This suggests that the steering system can have a measureable impact on vehicle certification CO_2 emissions.

Based on the data collected, the operation of the steering assist system can increase fuel consumption by 1–2%. Part of this extra fuel consumption is possibly also captured during the vehicle certification test despite the lack of actual steering. Steering is fundamental under real-world operation therefore the impact of driving assistance systems on CO_2 emissions cannot be avoided. No specific study was found that quantifies the contribution of the steering assist system over the European vehicle certification fuel consumption test. Further investigation is therefore necessary to provide accurate estimates.

3.2.4. Other electrical consumers and auxiliaries

Components and devices such as lights, pumps or the ventilator, monitors and sound systems, can be classified in this category. These require additional electric energy to operate and hence result in increased fuel consumption and CO_2 emissions. Systems such as engine and vehicle control units, fuel pumps and injection systems, various sensors (i.e. gas, speed, temperature, force and torque, etc.) are excluded as they affect fuel consumption under any driving conditions and it is difficult to distinguish potential CO_2 increases they impose over real driving compared to the vehicle certification test [155,156].

During the past 40 years there has been a trend towards a higher in-use electrical power demand, which in the case of the US market, appears to be increasing since 2005 [156]. Such trends are expected also for the European passenger cars as new and more sophisticated auxiliary systems such as GPS, air cleaning, air conditioning, adaptive cruise control, collision warning and avoidance systems are introduced in the fleet [155]. Such devices impose higher electrical loads resulting in increased alternator operation, which in turn increases the engine power demand and subsequent fuel consumption. Officially, the total electrical power requirements of a European passenger car over real-world driving are estimated to be 750 W [157]. This figure is lower compared to the 2500 W reported for US vehicles [156] but still higher than the 350 W estimate for the European vehicle certification test [157]. Only limited use of electrical consumers takes place during the European vehicle certification test and some OEM experts suggest that 350 W might be an overestimated value and that 150 W is a more representative one [158]. This discrepancy, however, suggests a measureable shortfall between type approval and real-world consumption. In addition to the above a standard practice, in the present certification scheme, is to run the test with battery fully charged, hence the operation of the alternator is restricted further increasing the deviation between real fuel consumption.

Estimates on the effect of electrical systems on fuel consumption and CO_2 emissions diverge. Johnson [159] claimed that the use of accessories can increase fuel consumption by 2.8% (3.6 gCO_2/km for a 2014 vehicle), while a research found that a vehicle with all electrical systems switched on can present an increase of up to 16% or about 20 g/km of CO_2 in terms of certification values [18]. A study [160] regarding lighting equipment found that complete lighting functions (i.e. Xenon headlamps, front position bulbs, rear LED lamps, licence plate bulbs and interior lights) requiring 144 W of electric power increase fuel consumption by 0.14 l/100 km (3.5 gCO_2/km). Older lighting equipment technology used during the 1980s led to an increase between 0.18 and 0.28 l/100 km (4.5–7 gCO_2/km). The use of LED headlamps in the future can decrease power demand as they are more efficient. The use of daytime running light can also increase fuel consumption by 0.28 l/100 km (7 gCO_2/km). This was one of the main arguments against the mandatory adoption of this technology, a measure proposed by the EC in 2008 [161,162]. Fig. 3.8 presents the power needs and the potential increase in fuel consumption of various auxiliaries. Based on these results in a rainy, winter, night scenario (i.e. where use of headlights, windscreen wiper, rear window heating and wiper and electrical booster heater is assumed) a car would consume 1.5 l/100 km more fuel, an increase of 26% compared to the official value for an average European car.

3.2.5. Eco-innovations related to electrical systems

The EC has approved the implementations of innovative low-energy consuming vehicle technologies. These can be categorized into three groups: LED lighting; solar photovoltaic roofs; and efficient alternators.

Regarding LED lights, various applicants have demonstrated that LED lights were more efficient compared to standard lights, such as halogen headlights [164–167]. The average benefits in CO_2 emissions from this technology are expected to be about 1 gCO_2/km. As of 2016, many new European cars are fitted with this technology.

Solar roof systems have been awarded an eco-innovative status [168,169] and such systems utilize a photovoltaic panel that is attached to the roof and charges an on-board battery. The stored electricity is then used for powering various electric systems of the vehicle and can result in direct savings due to reduce electric power demand. The expected benefits in terms of real world CO_2 reductions are estimated at 2 gCO_2/km.

Various high efficient alternator implementations (See Table 3.4) have also been granted eco-innovation status. In this case, a comparison was conducted with a baseline alternator exhibiting 67%

Table 3.4
High efficient alternator technologies by applicant.

Alternator technology	Commission implementing decision
Alternator utilizes synchronous rectification using metal-oxide-semiconductor field-effect transistors achieving efficiency of at least 77%	[170]
Reduced rectification, stator iron and stator copper losses. At least 77% efficiency	[171]
Alternator output from 100 A to 250 A	[172]
Alternator utilizes high efficiency diodes and synchronous active rectification achieving efficiency of at least 78%	[173]
Reduced rectification losses by utilizing low-energy loss diode	[174]
Reduced stator iron losses by utilizing thin, high-grade electromagnetic steel stator core	
Reduced stator copper losses by utilizing ultra-high fill factor stator and applying axial cooling structure	

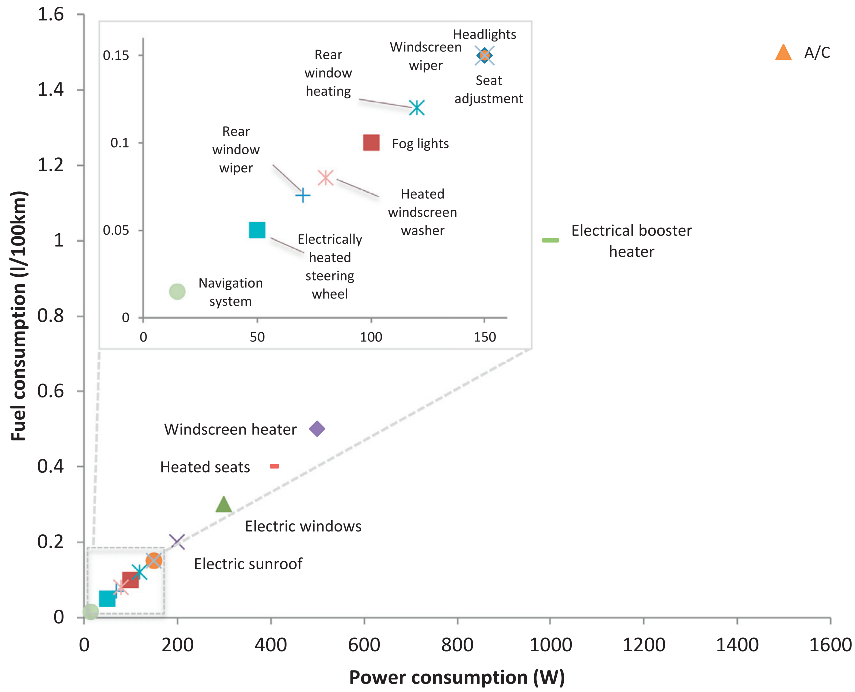


Fig. 3.8. Power consumption and fuel consumption increase of various auxiliaries [163].

efficiency over the NEDC, a value that is assumed representative for new passenger cars. The average benefits in CO_2 emissions from this technology are expected to be about 1–2 gCO_2/km.

3.3. Friction and lubricants

It is estimated that up to 25% of fuel energy spent during the vehicle certification test is consumed to overcome the friction of the car's components, which refers to the engine, transmission and brakes. According to [175], a passenger car consumes on average 340 l of fuel annually to overcome friction for an average mileage of 13,000 km. The most common technology option for reducing friction in the vehicle's mechanical parts is the use of lubricants with low viscosity. A lubricant's viscosity should be:

- Low enough for the lubricant to flow to the parts that need it; and
- 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 will not provide sufficient protection for the moving parts. This can result in increased friction, wear, heating and oxidation. When viscosity is higher than necessary problems may also occur. Inadequate flow could lead to increased drag and friction leading to higher operating temperatures and energy consumption. Low viscosity lubricants maintain their ability to protect the mechanical parts of the vehicle. Therefore the characterization 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 literature, the use of low friction lubricants decreases fuel consumption [94,175–179]. This effect seems to be greater in the urban than in the suburban cycle [177]. An average improvement in fuel consumption is estimated at about 4% and alternating motor oil of high and low viscosity between summer and winter seasons could also contribute to decreased fuel consumption [180].

Motor oil viscosity is inversely dependent on temperature: the higher the temperature, the lower the viscosity but the measure of viscosity decrease is important. At low ambient temperatures lower viscosity allows easier engine cranking and starting, rapid oil distribution in various components and lower friction losses. At normal engine operating temperatures (T>90 °C) viscosity should be in the proper range to maintain good lubrication characteristics, minimize oil consumption and friction losses [181]. For a cold start cycle such as the NEDC, normal operating temperature is reached close to the end of the test (1180 s), while it could take longer in congested traffic [182]. During the warm up phase the fuel consumption is affected by the rate of viscosity decrease with temperature. A 5W-30 oil at 30 °C fuel consumption can be up to 20% higher than at 80 °C [183]. Another study [184] focuses on the effect of oil temperature on fuel consumption over the NEDC for initial ambient temperatures of 25 and −7 °C. The higher viscosity of the oil at −7 °C resulted in significant increases of about 15% compared to 25 °C ambient temperature. Fig. 3.9 summarizes the findings regarding the impact of lubricant on fuel consumption.

It is expected that for the vehicle certification test, OEMs use the most appropriate and fuel efficient lubricants exploiting any potential CO_2 benefit. 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 replacement/use of fuel efficient engine lubricants

3.4. Maintenance and ageing

3.4.1. Tyre maintenance and pressure

In addition to tyre category and characteristics, tyre condition and maintenance can also influence the RRC. While tyre wear may reduce the RRC it is also associated with loss in grip and other undesirable characteristics that can make tyres unsafe and dangerous to use [185]. It is difficult to assess these influences on fuel consumption. Tyre wear control is part of the mandatory technical inspection

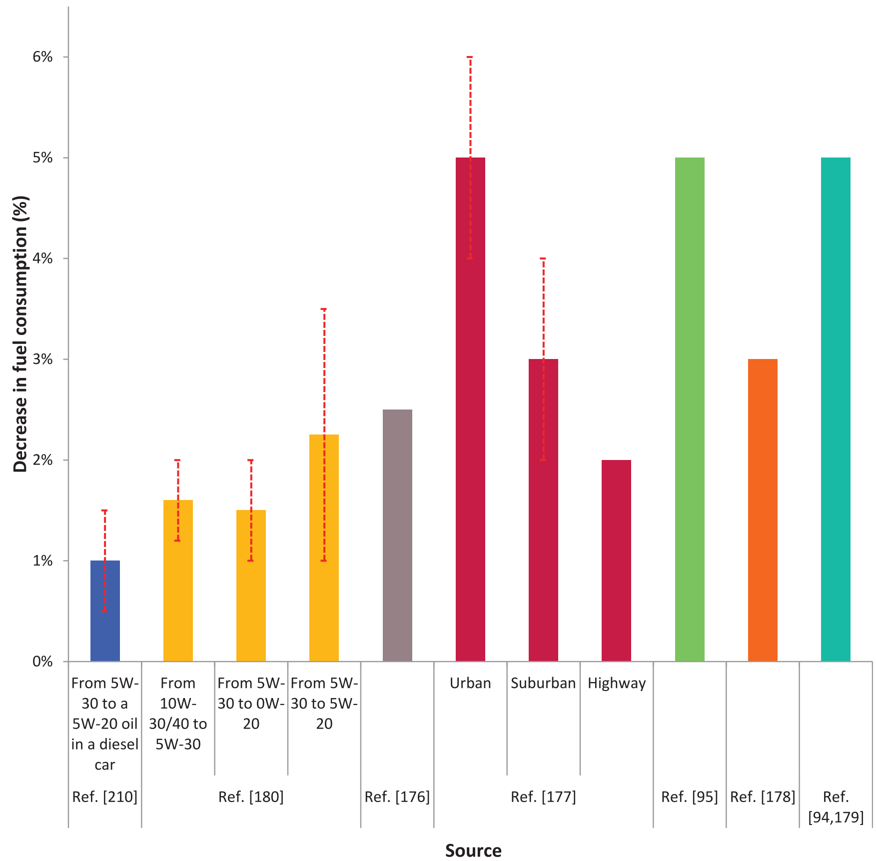


Fig. 3.9. Decrease in fuel consumption by switching to lower viscosity motor oil. The references cited in this figure are [94,95,176–180,210].

of European cars that is performed on a biannual basis [186]. The most important aspect of proper tyre maintenance is tyre pressure control.

Ageing, accumulated mileage and temperature variations can lead to pressure losses. Low tyre pressure results in higher rolling resistance [16,187], directly increasing fuel consumption [188,189]. All tyres have a designated operating pressure and deviating from it affects their rolling resistance. Fig. 3.10 demonstrates how rolling resistance and fuel consumption can be linked to tyre pressure, making use of data reported in [61]. The effect of pressure on rolling resistance is not linear with deflations of 0.3 bar causing increases of 6%, while deflations of 1 bar causing increases of 30%. The same study found that 21% of the French vehicles had under-inflated tyres

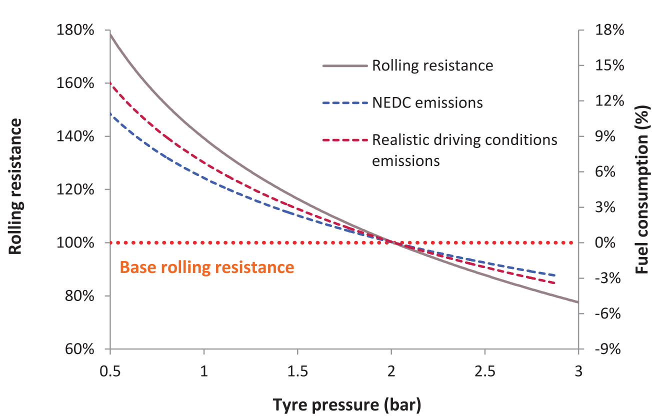


Fig. 3.10. Evolution of tyre rolling resistance as a function of tyre pressure. Base rolling resistance equals 100%, measured at 2.1 bar according to ISO 8767 (Adapted from Michelin [61]).

by 0.3 and 0.5 bar while a 35% had underinflated tyres by more than 0.5 bar below the recommended pressure. Only 32% of the vehicles had pressure levels within the recommended range and 12% had over inflated tires by 1 bar reducing rolling resistance by 20% in the expense of tire life.

A study [122] examined the effect of low tyre pressure on fuel consumption over constant speed conditions in a range between 64 and 129 km/h with an 8 km/h interval and found a 6–10% (0.40–0.46 l/100 km) increase in fuel consumption. An average under-inflation of 0.18 bar results in a 0.7% increase in fuel consumption in a city and 1% on a highway [190]. Fig. 3.11 presents a summary of the findings of tyre pressure effect on fuel consumption.

Due to the influence of tyre pressure on fuel consumption and safety all new passenger car models released in the United States (from 2008), and the European Union (from 2012) must be equipped with a tyre pressure monitoring system (TPMS). The extent of the availability of technology in the EU is presently unknown. In addition, no studies were found regarding how much drivers respond to the indications of the TPMS or whether tyre deflation has been improved.

3.4.2. Other factors

Other factors related to vehicle maintenance and condition may also affect fuel consumption in real-world driving conditions. In particular, wheel misalignment, suspension system maintenance and air filter clogging.

Wheel alignment is the adjustment of the tyre's camber, toe and caster angles to ensure that the vehicle is not deviating from its direction [191]. Misaligned wheels can increase fuel consumption by increasing hysteresis losses [16,137,192,193] by up 3% for a 2 mm of toe misalignment [194]. In some extreme cases, it is suggested that wheel misalignment can reduce tyre life from 80,000 km down to

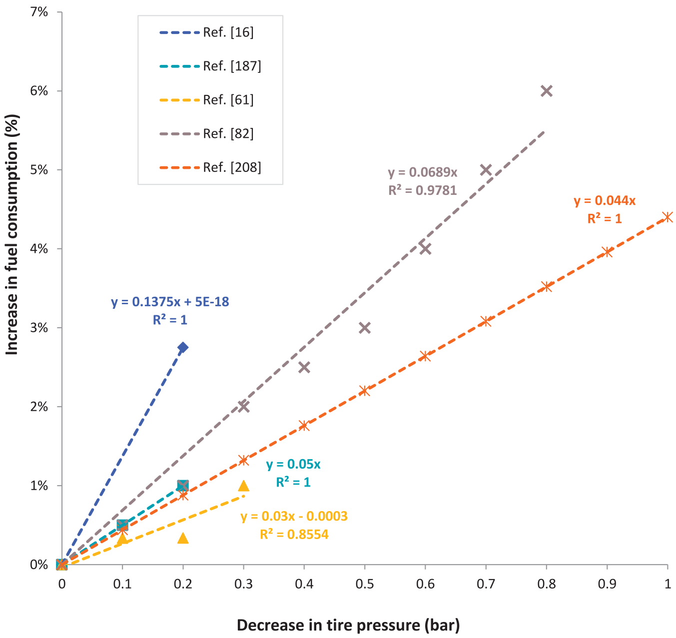


Fig. 3.11. Effect of lowered tyre pressure on fuel consumption. The references cited in this figure are [16,61,82,187,208].

8000 km and increase vehicle fuel consumption by 30% compared to its operation with wheels fully aligned [195]. Only a few studies quantify this effect. However, there are several studies for heavy-duty vehicles, where the impact seems to be greater [193,196].

Clogged air filters were found to increase fuel consumption in old carburetted cars by 2 to 6% [126], but there was no information on similar effects occurring on modern fuel injection spark ignition cars. It is assumed that the effect is much lower as fuel injection in modern cars is adapted to ensure a correct mixture. One report [16] states that fuel consumption can increase by 6% due to filter clogging. This case, for old carburetted cars, is also verified by the U.S. Department of Energy - U.S. Environmental Protection Agency [120] and presented on their fuel economy website. Tests [197] on two turbocharged vehicles with clean and clogged air filters resulted in no significant change in fuel economy or CO_2 emissions. According to [198] for compression ignition engine vehicles the greatest effect of a clogged air filter is a decrease in maximum power and acceleration.

4. Environmental and traffic conditions

4.1. Weather conditions

Weather conditions refer to all factors associated to meteorological phenomena that can have a direct or indirect influence on vehicle fuel consumption. The current vehicle certification test is performed at fixed temperature, pressure and humidity; such conditions do not reflect weather variations that a driver experiences throughout the year. Three categories appear to have the largest impact on the fuel consumption and CO_2 emissions of passenger cars: wind, temperature and altitude (ambient pressure) [211]. Weather conditions such as rain, snow or fog can also impact fuel consumption by affecting the way the vehicle is driven and by influencing resistance, the operation of auxiliary units or the engine. Ambient conditions are not stable and may vary depending on geographical location, weather pattern, and yearly seasons.

4.1.1. Rain and snow

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 and increases road loads and hence fuel consumption. A limited number of studies have quantified the effect of rain and wet roads on fuel consumption. A study [211] examined the effect of water presence on the fuel consumption of real vehicles travelling under transient conditions. Tests in two flat routes with water depths of 1, 2 and 4 mm were compared against tests on a dry road surface and concluded that the fuel consumption in each case increased by 30%, 90% and 80% respectively. Fuel consumption was found to be higher for 2 mm than 4 mm depths because of the reduced vehicle speed at 4 mm caused by the increased amount of rain and reduced visibility. A US study regarding heavy-duty vehicles (HDV) also indicates that fuel consumption increases [212] with rain. Snow and ice can also increase fuel consumption. The wheels can slip on the road wasting energy as they have reduced grip, while driving speeds are lower than normal. In addition, some cars use four–wheel drive for better grip, fact which results in higher fuel consumption [213].

4.1.2. Ambient temperature

Ambient temperature can influence all kinds of external resistances on the vehicle. Low ambient temperature results in increased air density and higher aerodynamic resistance [103], while increased air temperature decreases aerodynamic resistance [214]. 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, resulting in lower rolling resistance [189,215]. Temperature can also have a more significant impact on the fuel consumption of hybrid electric vehicles under real-world driving conditions because battery capacity is reduced with lower temperatures [216].

4.1.3. Cold-start

Ambient temperature determines the temperature of the vehicle and its components when starting after prolonged parking periods, resulting in increased fuel consumption during the their warm up phase (cold start effect). Cold start occurs when the vehicle starts operating and lasts until all vehicle components reach their nominal operating temperature for the first time (warm up phase). Cold start is known to influence fuel consumption particularly in the case of short distance trips [213,217]. Lubrication systems and their components [218], tyres [188,189], vehicle transmission, engine and exhaust after-treatment system [201,219] operate differently at starting conditions and during the warm up phase of the trip, leading to increased fuel consumption. The effect of cold start depends on the initial temperature of the various components and the duration of their warm up phase. The latter is not the same for all components with exhaust after-treatments system usually reaching operating temperature within 200 s regardless of the operating conditions, while components such as the gearbox stabilize thermally after more than 15–20 km, depending on the operating conditions [220–223]. The cold start effect of each individual component on fuel consumption disappears after its warm up phase. Predicting the full impact of ambient temperature at cold start conditions on a vehicle's fuel consumption is not straightforward.

The type approval test foresees a starting temperature of 20–30 °C, with most tests performed at 25 °C, although according to [224] starting a vehicle at 25 °C is not representative of average real-world operation. A temperature in the range of 14 ± 4 °C is considered more representative of the European average ambient temperature in autumn and spring [224]. Starting temperatures lower than 20 °C instead of 25 °C can result in a 6% increase in fuel consumption due to excess cold start consumption [201]. Even within the foreseen temperature range, measured fuel consumption can vary by more than 2% [18,225], while [214] reports an increase of 2–3% in fuel consumption per 10 °C decrease in air temperature. Finally, despite that type approval foresees emissions tests also at very low temperatures (−7 °C), which are not uncommon in northern

European countries, CO_2 and fuel consumption are not reported in this case. According to [226] the fuel consumption of Euro 4 petrol and diesel cars was measured to be 78% lower at 23 °C (0.04 l) compared to −20 °C (0.18 l) and 69% lower compared to −7 °C (0.13 l).

The cold start effect may have a different impact on vehicle fuel consumption depending on powertrain technology. Vehicles tested [227] over NEDC under temperatures of 25 °C and −7 °C showed increases in fuel consumption of 21% for a multiport injection (MPI) spark ignition vehicle and 16% for a direct injection spark ignition vehicle (DISI). An American study [221] on the effect of the cold start in the urban cycle found an increase of 15% and 20% for conventional vehicles and a 20% to 37% for hybrids at temperatures of −6.7 °C compared to warm operation. In the same study, the difference between cold start at 22 °C and warm operation was between 6% and 12%. Measurements in Europe over the NEDC [217] on 8 petrol and 5 diesel cars at temperatures of 22 °C and −7 °C showed an increase a 15% increase in fuel consumption for the gasoline vehicles and 20% for the diesel. Finally, the effect of cold start on the starting temperature is more pronounced in hybrid electric vehicles. A Canadian study [228] tested a conventional petrol vehicle and three hybrids at temperatures of −8 °C and 20 °C. The increase in fuel consumption for the hybrids varied from 56% to 107% for the city cycle and from 31% to 77% in the unified cycle, while the discrepancy for the conventional car was lower at 23% and 19% respectively.

Fig. 4.1 presents a summary of the values found in literature linking cold start temperature to excess fuel consumption over certification cycles. Literature data are combined with the results of an analysis undertaken by the EC's Joint Research Centre (JRC) [229] that was based on internal vehicle measurements following the NEDC at various temperatures [217,230].

In real-world driving conditions the effect of cold start on fuel consumption depends on the distance travelled, the duration of the trip and the number of sub-trips. Short distance trips exhibit higher fuel consumption compared to medium or longer distance due to high energy losses of non-thermally stabilised components [120,231]. For a trip with characteristics similar to those of NEDC (11 km, 20 min, 20–25 °C, 33 km/h) fuel consumption increases by 10% due to cold start (Fig. 4.1). This increase is higher for shorter distance trips and lower average speed values. An increased frequency of short urban trips where vehicle components are partly or fully cooled down can result in additional fuel consumption compared to the officially reported value. According to [205], performing many short trips under urban conditions instead of a single long trip amplifies the effect of cold start and may lead to high fuel consumption up as much as 30 l/100 km. However, allowing the car to idle in order to warm up and reduce the cold start effect does not save fuel [120,231].

Advanced thermal management systems can accelerate the warm up phase for the engine and gearbox and limit the effect of cold start on fuel consumption These systems incorporate separate cooling circuits for engine block and cylinder head, cooling systems with switchable components (e.g. the coolant pump, cooled exhaust manifolds), exhaust gas heat recovery (e.g. Rankine cycle and thermoelectric generator) and other technologies that control the vehicle's cooling system. Fig. 4.2 presents the effect of such systems. Advanced thermal management can have a benefit over the vehicle certification test cycle and real-world conditions but it is not possible to quantify the contribution of such systems to the gap between official and real fuel consumption. In the case of hybrid vehicles, heat storage systems ensure that the cooling down of the powertrain system during low load or fully electric operation mode does not exceed certain boundaries [232].

4.1.3.1. Eco-innovations related to cold start. Two groups of technologies that relate to cold start have received the Eco-innovation status: engine encapsulation and enthalpy storage tanks. Engine encapsulation is a technology that reduces the cold start effect by reducing the cooling of the powertrain system during the stop time [233]. The system reduces the heat loss by slowing the cool-down of the engine when it is turned off. This technology can have important savings in urban driving where a large number of non-consecutive trips take place.

With regard to the enthalpy storage tank, heat from the coolant is stored into a thermally insulated tank when the vehicle is turned off [234]. Upon restarting the engine, the hot coolant is circulating in order to heat the engine compartments, therefore reducing the cold start effect. The average CO_2 emissions benefits of these two technologies considering various parking times at a 14 °C ambient temperature (the average European temperature) are expected to be about 1–4 gCO_2/km depending on the vehicle type, size and technology.

4.1.4. Wind conditions

Ambient winds are almost always present and affect the aerodynamic performance of vehicles when driving at higher speeds. Wind

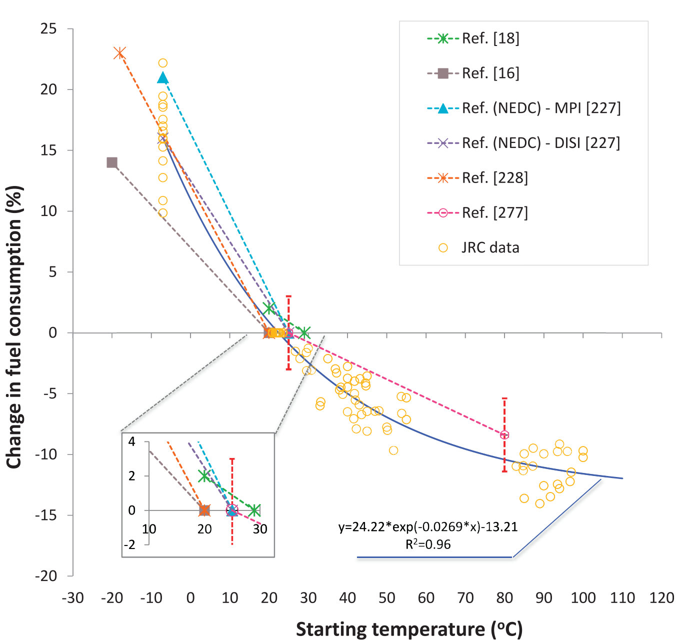


Fig. 4.1. Percentage increase in fuel consumption related to starting temperature. The references cited in this figure are [16,18,227,228].

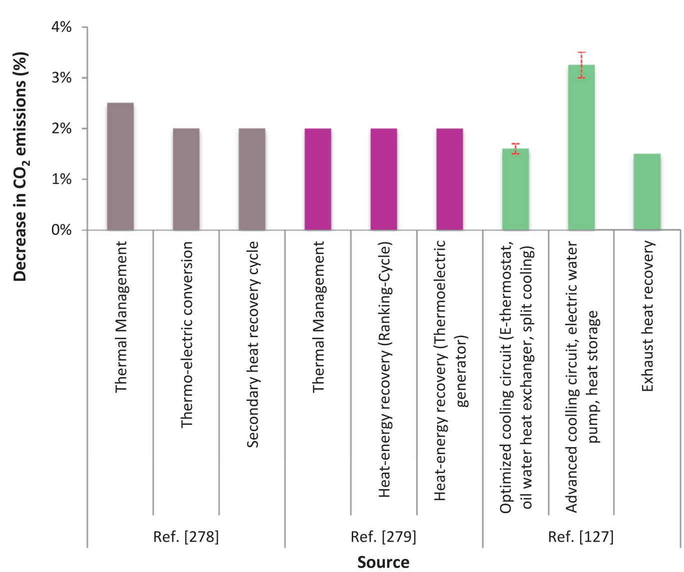


Fig. 4.2. Decrease in CO_2 emissions by technology type. The references cited in this figure are [127,278,279].

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 and result in an asymmetric flow around the vehicle affecting drag, lift and pitching moment that can cause instability [235]. When the vehicle turns, or when the velocity is reduced, the angle between the direction of the apparent wind and that of the vehicle speed (yaw angle) changes and the car exposes a larger area to the wind than its actual frontal area. Depending on the conditions this may lead to increases in aerodynamic resistance. In real-world conditions wind is affected by roadside objects and other vehicles that cause a non–uniform airflow and turbulence, conditions that deviate from the ideal ones found in the laboratory or during the coast down test [236]. Despite the effect of crosswinds, yaw angle and speed, the majority of published studies examine aerodynamics at zero yaw angle wind conditions [237].

Wind tunnel tests for yaw angles from 0° to 40° found that the aerodynamic coefficient obtains the maximum value at a 35° yaw angle [238] having a significant impact on large square shaped vehicles such as sports utility vehicles (SUVs) or trucks. A study [235] focusing on the impact of crosswind angle and velocity on the air drag coefficient showed a decrease in drag coefficient from 0.55 to 0.45 when yaw angle changed from 0° to 15° respectively. However, drag coefficient increased at higher yaw angles reaching 0.60–0.65 at 90° for crosswind speeds of 80–120 km/h respectively (9–18% increase compared to 0°).

The effect of crosswind under different yaw conditions on car aerodynamics was investigated by Landström et al. [237] taking into consideration the effects of the rotating wheels and air inlets. Fig. 4.3 presents the difference in the drag coefficient for various yaw angle values for four car configurations. There is a significant increase in drag in yaw angles between 8° and 18°.

Additionally, wind velocity is important as for example a velocity of 3 m/s can influence air drag, either positively or negatively, by up to 10% [116] that in turn translates in a 2% average CO_2 emissions increase [89,101]. Wind conditions can therefore have a measurable impact on in-use fuel consumption and CO_2 emissions, increasing the gap between reported values and the consumption experienced by the drivers.

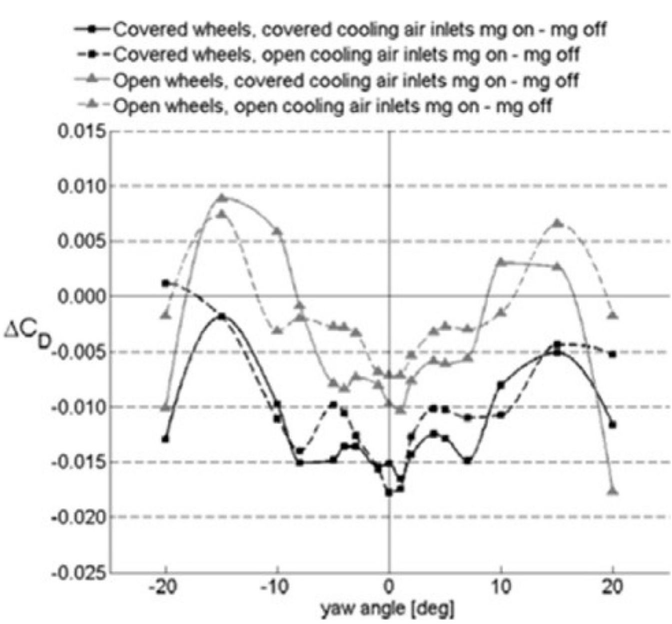


Fig. 4.3. Difference in aerodynamic coefficient for various yaw angle values (adapted from [237]).

4.2. Altitude

An increase in altitude is reported to decrease fuel consumption [18] as lower atmospheric pressure leads to reduced air density and lower air drag [81,239]. At 1000 m above sea level the density of air is approximately 10% lower compared to that foreseen for the official testing of vehicle road loads (air drag) and fuel consumption. The resulting decrease in air drag can lead to a 2–3% reduction in fuel consumption reduction.

Lower air density can also influence fuel consumption by affecting engine operation when the air/fuel mixture in the engine is controlled by means of throttling. Due to the lower oxygen content of air, a wider throttle opening is necessary for charging the engine in order to achieve the same power output, fact which in turn may result in lower pumping losses and lower fuel consumption. Operating at high altitude has been found to result in a 3.5% decrease in fuel consumption compared to the NEDC measurement and 2.6% decreased compared to the FTP cycle [240]. Decreases in the same order of magnitude (4–5%) have been also reported for test tracks located at high altitude and in warm climates [18]. Paradoxically, an increase in fuel consumption of 6.2% was found [240] in highway driving conditions. A possible explanation of this observation at high speed/load conditions could be that the vehicle operated close to full load conditions. In such cases the reduction in engine power output due to the engine's lower volumetric efficiency may result in fuel enrichment introduced to compensate the power deficit and [241] notes that such enrichments would increase fuel consumption in the case of naturally aspirated engines. A study [239] on naturally aspirated engines investigated the effect of altitude on fuel consumption and exhaust emissions over a cruising driving cycle and the NEDC. The authors found an increase in fuel consumption that accounts for 0.2 l/100 km per 1000 m of altitude increase for both cycles.

4.3. Road

With the term “road” we refer to the road characteristics such as morphology, road surface and road shape. All of them can impact real-world CO_2 emissions but none of them is currently reflected in vehicle certification tests. Road morphology refers to the geomorphological characteristics of the road. The characteristics that have an effect on fuel consumption are altitude, road shape, road surface and grade. The structural condition of the road surface is described by the roughness and the texture while construction materials used for the road surface include asphalt and cement.

4.3.1. Road grade

A car that is driven uphill requires more power to overcome gravity 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. Researchers [242] performed measurements and simulations on a passenger car, investigating the effect of grade on CO_2 and testing the CO_2 emissions sensitivity over a fixed route. They identified increases in CO_2 emissions of up to 2% for grades of 0.25% and 5% for grades of the order of 1%. In the case of negative slope the reductions in fuel consumption reported were approximately −1% and −3.5% for grades of −0.25% and −1% respectively. The study notes that in order to 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 and concludes that transport management and urban planning projects should be incorporating road grade into their analysis where prediction of real-world vehicle CO_2 emissions and fuel consumption is required. As reported by Park and Rakha [243] a 1.5% increase in roadway grade increases fuel consumption by 9%. Measurements [244] of passenger car fuel consumption over two different routes leading to the same destination, with one route being flat while the other one containing uphill and downhill sections, showed increases of 15–20% for the hilly route. The fact that the additional fuel consumed when travelling uphill is not fully compensated by the fuel savings when travelling downhill contributes to the fuel consumption gap. This hysteresis in fuel consumption due to road grade should be taken into consideration when comparing real-world fuel consumption with official data.

4.3.2. Road roughness and texture

The roughness of the road is the vertical deviation of the intended longitudinal profile of the surface [245] and is measured by means of the International Roughness Index (IRI). The IRI is based on the average rectified slope (ARS), 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.) [246]. Roughness depends on the construction and the condition of the road and is used as an indicator for maintenance. A typical range of IRI values is 2–16 mm/m, with 2 being high quality surface similar to that of airport runways and superhighways while values of 12 mm/m and above correspond to eroded surfaces with deep depressions. An IRI value between 3 and 7 mm/m can be considered as typical for most European roads. Rough roads limit maximum speed, while causing discomfort to the passengers [247,248]. Fuel consumption increases by up to 3% for an average light commercial vehicle and by 4% for a medium sized passenger car for an IRI value of 5 mm/m compared to a reference IRI = 2 mm/m surface [248]. The roughness of roads deteriorates with time leading to increases in fuel consumption of vehicles.

Texture is the deviation from a planar surface and plays a part in road surface friction resistance and assists in the braking of vehicles [249]. While vehicle suspension deflection and dynamic tire loads are affected by longer wavelength (roughness), road texture affects the interaction between the road surface and the tyre footprint. Road texture is defined based on its wavelength and its effect varies accordingly with its size. As a means of quantification in a single value the root mean square (RMS) of texture depth is used [250]. The smaller the wavelength the more beneficial its effects such as better friction, lower rolling resistance and noise reduction. The texture RMS is linearly linked to the rolling resistance coefficient with pavements of higher RMS exhibiting higher rolling resistance coefficients and fuel consumption [251]. High RMS values can increase rolling resistance by 5 to 10% [252], while changes in texture could result in a 5–10% increase in fuel consumption [188].

Road construction materials define road texture and roughness. Cement pavements tend to exhibit high roughness and texture compared to asphalt pavements [188]. In Sweden fuel consumption increases by 0.8% on cement roads compared to asphalt roads at a speed of 50 km/h. This difference increases to 3.3% at a speed of 70 km/h. In the Netherlands a speed of 90 km/h increases fuel consumption by 2.7% on concrete roads. In the US urban driving speeds of less than 50 km/h fuel consumption is 4% higher by on asphalt than on concrete roads [253].

4.4. Traffic conditions and congestion

Traffic refers to the number of vehicles that are moving on a road at a given time. Increased traffic will affect the speed profile of the vehicles during a trip but may also influence the behaviour of the drivers. Increased traffic in most occasions leads to increases in the vehicles' fuel consumption [254] that may be severe under low speed urban driving conditions and in heavy traffic [255]. The urban part of NEDC represents relatively intense traffic conditions [136,256,257] exhibiting an average speed of 18 km/h.

Increased traffic affects fuel consumption in several ways. It reduces the average and maximum speed of the trip, it increases transient operation (accelerations-decelerations) and can result in congested conditions that are characterized by low vehicle speeds, vehicle standstills and increased engine idling [254,258,259,261]. The impact of traffic on vehicle fuel consumption is not uniform and depends on the characteristics of the vehicle fleet and the geographical area where the vehicle is driven [200–202].

In the case of Europe, a typical example of the effect of average speed/traffic conditions on CO_2 emissions and fuel consumption [262] can be found in Fig. 4.4. The continuous lines demonstrate the predictions of two widely used European emission inventory tools (COPERT and HBEFA) [263,264] while the dots and the corresponding error bars demonstrate the average experimental results and their standard deviation respectively. The experimental results which were obtained from tests on various Euro 5 vehicles over different driving cycles (NEDC, Artemis, and WMTC) confirm the capacity of such tools to capture the effect of different traffic conditions on CO_2 emissions. Trips with low average speed (<30 km/h) exhibit the highest CO_2 emissions and the highest divergence from the NEDC result which, at 18 km/h, reaches on average 40% for the diesel and 60% for the petrol cars. The optimal trip speed in terms of CO_2 are in the range of 60 to 80 km/h where emissions tend to be 15% and 23% lower compared to the NEDC ones for diesel and petrol vehicles respectively. The trend is reversed above 80–90 km/h and the gap is widened as speed increases. The situation is different for hybrid vehicles where the contribution of the electrical system, during urban driving conditions, offers significant fuel consumption reductions [265].

It is reported that in high speed driving increased traffic may lead to reduced fuel consumption as drivers are forced to maintain

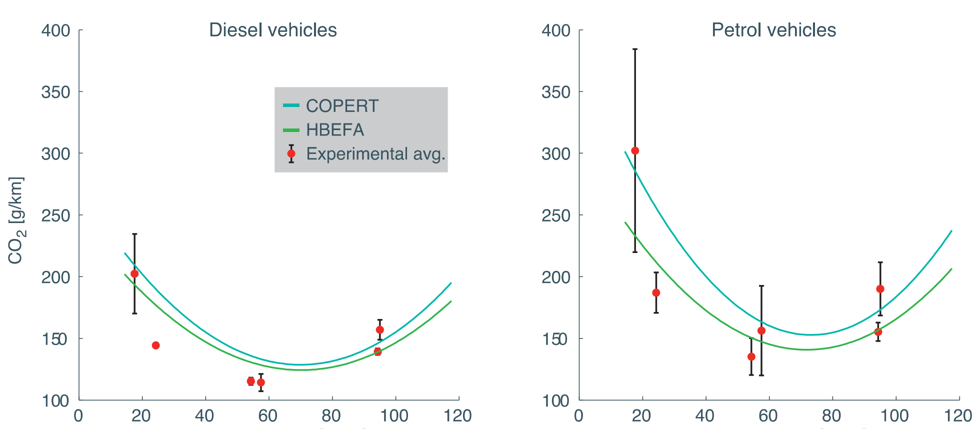


Fig. 4.4. Impact of average driving speed on CO2 emissions of Euro 5 vehicles [262].

lower speeds and to adapt their driving to the trajectory of the leader vehicle [266].

Heavy traffic can result in congestion and alter operating conditions on a given road. Congestion is the deterioration of smooth, free-flowing traffic conditions due to increased travel demand and/or reduced traffic movement capacity [267]. Congestion is in general considered to be the traffic condition leading to the highest fuel consumption and can result in a 40% higher fuel consumption compared to driving the same trip in uncongested conditions [268]. A US study [269] estimated that the fraction of fuel wasted due to traffic congestion will reach 2.6% of the overall fuel consumption by 2020. Another study [266] compared CO_2 emissions from cars operating at steady state conditions to the emissions during real-world driving conditions and found an increase of 40% at 45 km/h due to congestion. The average increase in fuel consumption for congested roads calculated from all the examined cases is about 26%. Fig. 4.5 shows the effect of congestion on fuel consumption for various route types.

Vehicle standstill in congested roads leads to prolonged idling times, which in turn has a fuel consumption penalty. Vehicle idling applies if the vehicle does not feature any engine start and stop system [270,18] as start stop systems are designed to switch off the engine at vehicle standstill. In the EU an estimated 43% of new gasoline vehicles and 55% of new diesel vehicles (2013) [271] are equipped with start stop systems. The suppression of idling during the vehicle certification test and in real-world driving can reduce fuel consumption [272] by up to 8% for a small size and 9.5% for an average sized vehicle [273]. The latter values are considered relatively high for modern European passenger cars, not equipped with start stop systems, tested over NEDC where the contribution of idling in the total CO_2 emissions is about 2–3% for manual transmission vehicles and 4–5% for automatic transmission vehicles.

Finally, congestion can lead to fuel consumption increases by affecting how the drivers actually drive as it can cause delays and increases drivers' stress [274]. In an effort to compensate for such delays, drivers may adopt a more aggressive driving style compared to how they would normally drive for the rest of their trip. However, optimizing driving behaviour is considered important to improve the overall energy consumption [275] with the eco-driving concept being discussed as early as 1986 [276].

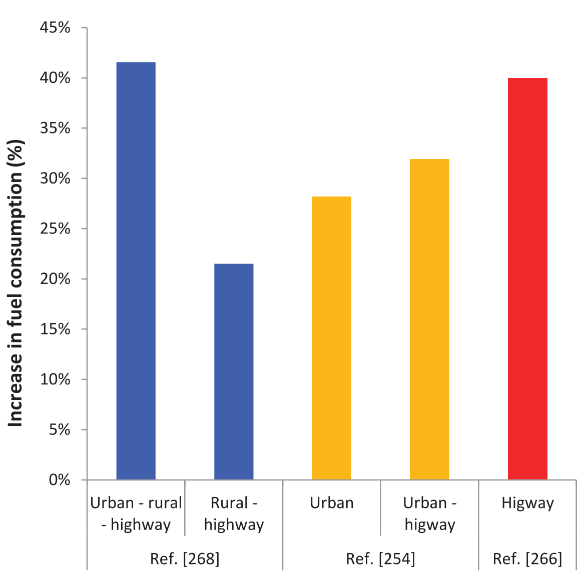


Fig. 4.5. Effect of congestion on fuel consumption compared to free flow traffic by route type. The references cited in this figure are [254,266,268].

5. Driver and user related factors

5.1. Driving

The way the vehicle is driven has a substantial impact in fuel consumption. The term more frequently used to characterize the way a vehicle is being driven is driving behaviour. Driving behaviour refers to the personal driving style of a driver and is characterized by instantaneous and average speed, acceleration and choice of gears [280]. Driving behaviour may depend on the personal character, age and gender of the driver [126,280], as well as on external factors such as roads, journey type, weather and traffic conditions [281]. Aggressive driving is known to increase fuel consumption and CO_2 emissions [126,137,281], while driver training leads to decreased fuel consumption [16,282,283].

5.1.1. Aggressive driving

Aggressive driving, in some cases referred to also as "dynamic driving", is characterized by high accelerations and decelerations, high maximum vehicle speeds and high engine operating RPMs that lead to increased fuel consumption [281,126,86]. It is difficult to define an average driving behaviour to be used as a European reference. The maximum speed is the factor with the highest influence on fuel consumption [284]. In a dataset of over 500,000 vehicles, where users register online their fuel consumption between fuelling events and provide also information about their driving style, users who declared a "speedy" style have on average 7% higher fuel consumption compared to those declaring a balanced driving [19]. However, it should be noted that when testing vehicles in real-world driving conditions, it is difficult to distinguish the effect of traffic conditions from that of aggressive driving [285]. Fig. 5.1 summarizes the values collected regarding the effect of aggressive driving on fuel consumption.

Considering the average value of the results presented in Fig. 5.1, it has been estimated that fuel consumption for aggressive driving can increase by 25%. Increases are substantially more pronounced in urban driving conditions. This observation is attributed to the

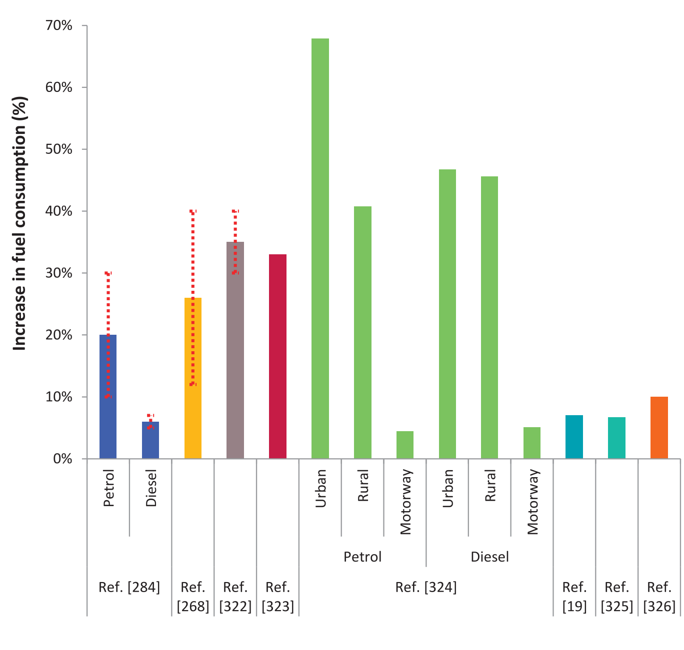


Fig. 5.1. Increase in fuel consumption for aggressive driving compared to normal driving. Error bars correspond to minimum–maximum observed values. The references cited in this figure are [19,268,284,322–326].

influence of idle consumption, the frequent start and stops and the frequent accelerations in urban conditions. The tests on the highway resulted in lower increases because of the minimal idling and accelerations and high average speed. The identified difference between EU and US could be traced back to the fact that cars in the US exhibit higher fuel consumption compared to their European counterparts. This means that the baseline fuel consumption is already higher in the US (see also Table 2.2) so the relative fuel penalty introduced by aggressive driving is lower [218].

5.1.2. 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.

An internet search of manufacturers' websites for information about these technologies revealed three general types of modes: (a) Eco, for reducing fuel consumption; (b) Normal, which is the baseline operation of the car; and (c) Sport, for better performance in terms of vehicle responsiveness and power output, which is expected to be the most fuel consuming mode.

Certain modes [286] claim to offer a 20% improvement in fuel consumption by using pedal and gear recognition, brake energy recuperation, optimizing shifting and A/C temperature control, while providing additional information for more efficient driving to the driver. 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, but no figure for the fuel consumption penalty associated with this mode was found [287]. Similarly, Toyota [288] claims that the “Sport” mode option leads to faster acceleration by increasing throttle response, higher gear shifting, more performance – oriented RPM and adjusted electric power steering assist for a sportier feeling. However, the CO_2 or fuel consumption penalty was not reported. According to VW [289], the “Eco” mode leads to more environmental friendly driving with less emissions and lower fuel consumption by optimizing engine, gearbox and A/C performance. The decrease is not specified by the manufacturer and the expected CO_2 penalties for the sport mode, which results in faster accelerations and better steering response, are not provided. Certain non-OEM affiliated sources [290] claim to have observed a 11% increase in fuel consumption for the “sport” mode without providing detailed information on how such numbers are produced. Finally, some hybrid electric 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 such as garages and to decrease noise late at night [291,292]. It was not possible to find an extensive scientific study regarding driving modes, as there is no common definition for the terms and every manufacturer uses its own settings.

5.1.3. Eco–driving

Drivers can be trained in practices that reduce fuel consumption, pollutant emissions [293] and result in safer driving. Fuel efficient driving consists of earlier gear shifting for achieving lower engine RPMs, maintaining steady vehicle speeds, anticipation of traffic movement, smooth deceleration and stopping [16,219]. The website of the Natural Resources of the Government of Canada [294] shows five fuel efficient driving techniques compared to an average driving style, without quantifying their benefit. These techniques include gentle accelerations, coast down decelerations, maintaining a steady speed and avoidance of high speeds, which in essence summarize the main principles of Eco-driving.

A study investigated the effect of four speed patterns on fuel consumption in three vehicles for a fixed distance on a chassis dynamometer [295]. Eco-driving conditions comprised smooth changes in velocity and maintaining constant speed. The study found an 11.7% decrease in fuel consumption compared to average driving. It was also found that the installation of certain accessories on the vehicle, such as the gear shift indicator or fuel consumption indicators, which directly or indirectly instruct the driver how to drive in a more efficient manner, have a quantifiable effect in decreasing fuel consumption [265,18]. Of course this does not guarantee that all drivers follow the suggested gear shifting in real-world driving conditions. The use of gear shifting indicators was tested during the NEDC and it was found that the most prominent improvement was in the urban phase, while the gains in the extra-urban phase were negligible [296]. However, higher CO_2 savings were achieved in the cold start accounting for a 4.3% reduction compared to the baseline, while in the warm start the reductions were estimated to be 3.6%.

Fig. 5.2 summaries the effectiveness of eco-driving strategies. The simplest strategy presented here is optimal gear shifting, while further training consists of more elements such as smooth accelerations and decelerations, braking and traffic anticipation. A study [297] suggests that improved navigation systems and intelligent use of navigation data is expected to improve the efficiency of eco-driving strategies. The authors of [19] have conducted a statistical analysis on data provided by individual drivers who declared their fuel consumption and driving style voluntarily. Although eco-driving technique was not specified in the data collection form, drivers who characterized their style as economical resulted in 9% lower fuel consumption compared to the ones who declared normal driving style.

5.1.4. Four-wheel drive

Many cars are sold with a switchable two-wheel (2WD) and four-wheel (4WD) drive mode. It is not obligatory to test such vehicles during certification in 4WD mode and the common practice is to perform the vehicle certification test in two-wheel mode [158]. Laboratory measurements [298] on a chassis dyno over a low speed driving cycle in 2WD and 4WD modes revealed 1.5% savings in fuel economy for the 2WD mode. Engaging four-wheel traction in real-world driving conditions increases the power losses in a vehicle's driveline leading to an increase in fuel consumption. A four wheel drive vehicle in real-world operation can have an increased fuel consumption of 0.5 l/100 km [141]. No scientific references were found with regard to the extent to which drivers use the 4WD mode in real-world driving conditions.

5.1.5. ADAS

Several new vehicles are equipped with Advanced Driver Aid Systems (ADAS) that deploy a series of sophisticated sensors such as rear view cameras and radars to provide additional information to the driver and the vehicle [299]. These systems are marketed as fuel saving technologies [300], offering advice to the driver on optimal practices or in some cases by acting independently of the driver on the vehicle's operation and controls [301]. The deployment of such systems does not aim only to reduce fuel consumption, but also to increase road safety by providing warnings such as possible collisions with other vehicles and by detecting pedestrians and traffic signs [302,303]. In addition, integrated communication systems utilize data collected by ADAS that is shared with other vehicles and infrastructure and inform other drivers on the traffic conditions [303]. The EC funded ICT-emissions project investigated vehicle and infrastructure information exchange in order to optimize traffic flow [304]. The study showed that information exchange can lead to reductions in CO_2 emissions exceeding 15% in urban driving for a combination of ADAS, stop-start systems and eco-driving patterns [305]. An ACEA backed study investigated the effect of ADAS on fuel consumption by deploying dynamic navigation tools to reduce trip fuel consumption and driving recognition patterns that provide

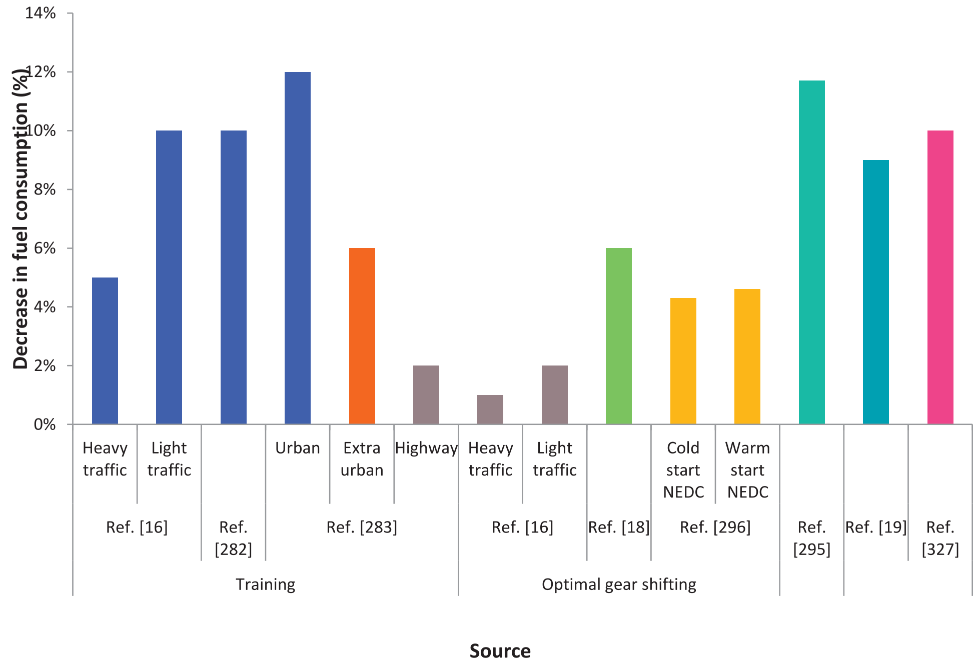


Fig. 5.2. Decrease in fuel consumption for Eco – driving compared to normal driving. The references cited in this figure are [16,18,19,282,283,295,296,327].

feedback to the driver. The study found a 5–20% improvement in fuel consumption compared to average driving [306].

5.1.5.1. Eco-innovations related to ADAS systems. Two groups of technology, which can be considered as ADAS systems, have been granted eco-innovation status: predictive energy management and coasting. Predictive energy management is a technology that focuses on hybrid vehicles [307]. The technology receives geospatial data from the navigation system of the vehicle and adapts energy usage strategy and recuperation by predicting upcoming changes to the slope of the route. The expected CO_2 reduction benefits of this technology are approximately 1–3 gCO_2/km.

Coasting technology [308] utilizes an automatic gearbox that disengages the engine from the wheels to permit the vehicle to coast when engine idling leads to fuel savings compared to engine braking mode. The engine is idling and continues to provide power to the auxiliary equipment. The expected CO_2 reduction benefits are about 1–5 gCO_2/km.

5.2. 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 were scarce and insufficient for drawing a solid conclusion. The main source found was a study [122] for US vehicles quantifying the effect of open windows on CO_2 emissions. The study presents the results of measurements on two vehicles over 64 to 129 km/h with an 8 km/h interval. A sedan and an SUV vehicle were tested with all windows closed and open. In the case of the sedan in a speed range between 65 and 130 km/h, open windows resulted in an increase in CO_2 emissions of 5.6 to 8.3%. The influence of open windows was less prominent in the case of the SUV, leading to increases between 0.3 to 2.3%. The increased in aerodynamic resistance caused by the opening of windows is low in the case of the SUV compared to the resistance of the aerodynamically optimized sedan vehicle.

Opening the windows could be viewed as a more fuel efficient practice for reducing the temperature in the car's cabin compared to the use of air-conditioning. Limited information is available as to which of the two is the best in terms of fuel saving and up to what speed. OEAMTC [144] 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 [309] in their Eco-driver's manual suggests that windows should be left open up to the speed of 65 km/h.

5.3. Occupancy rates

Occupancy rate is defined as the number of passengers per vehicle, including the driver, and it directly affects the weight of the cars under real-world driving conditions operation and its fuel consumption. The EEA [310] reported a decreasing trend in occupancy rates from 1.75 in 1980 to 1.6 in 2003 for Denmark, the Netherlands and the United Kingdom. The International Energy Agency (IEA) [180] reported even lower figures, 1.37 for urban vehicle occupancy and 1.15 for commute vehicle occupancy in Europe. The EEA [311] states that according to the last available data (pre 2008), the average number of passengers per car (including the driver) was approximately 1.45 passengers per vehicle for the selected countries (in the UK – 1.58; Germany – 1.42 and Netherlands – 1.38). The possible reasons for this decrease is the greater individualization of society, the decline in household sizes and the increase in car ownership, but they comment that the rate of decline has slowed in recent years. EEA considers the trend to be representative of the whole EU.

Based on the information collected, an occupancy rate of 1.5 passenger/vehicle can be considered representative of the EU average conditions. However, this value varies between countries and depends on the driving conditions with long distance trips having higher rates than short urban trips. Given the rate of decrease one would expect even lower occupancy rates today. Nevertheless, since 2008 the promotion of car-pooling, the appearance of new car-sharing services and the economic crisis may have further slowed down this trend because commuters have more opportunities for sharing a trip and have fewer resources to spend in order to drive their vehicles individually. It was not possible verify this assumption nor to retrieve more updated information regarding occupancy rates at the European level. The EEA has decided to discontinue the reporting of the occupancy rate indicator and archived the content as of 2015. This lack of data is an issue that needs be addressed in future research.

An occupancy rate of 1.5 passengers/vehicle corresponds to an additional mass of about 40 kg, not accounted for during the vehicle certification test. The average payload, excluding passengers, is estimated to be 55 kg [65], adding up to a total 95 kg of average extra load, that is not taken into consideration. This additional weight could lead to a 5–7% increase of in fuel consumption according to the values (see Fig. 3.1). The reduction in vehicle occupancy limits the gap between official and real-world fuel consumption because the vehicle mass is closer to the one used in the official test [260]. However, a high occupancy rate is desirable in all transport modes as it leads to lower emissions and consumption per passenger. Considering the inelastic nature of passenger transport demand, increased occupancy rates can lead to CO_2 savings. Assuming an occupancy rate of 1.5 passengers per vehicle, the 2015 average CO_2 emissions of 120.7 g/km would translate into approximately 80 gCO_2/(passenger*km). In comparison, the equivalent values for city buses are estimated to be in the range of 15–30 gCO_2/(passenger*km) [312,313] depending on the operating conditions and bus type.

5.4. Fuel choice

Automotive fuels are blends of various types of hydrocarbons and other organic compounds, whose characteristics are regulated by the relevant standards [49,314]. In the certification test, vehicles use standardized fuels and their physical properties vary within a limited range. On the other hand, commercial fuel composition and characteristics may vary within a wider range due to climatic conditions, regional policy and market availability of blend-stocks. The latter becomes more evident considering variations of biocomponents in commercial fuel. For example the ethanol and biodiesel contents in conventional petrol and diesel fuels respectively are not uniform across EU [315]. In several countries different biofuel blends are available in the market in addition to standard fuel e.g. 10% or 85% Ethanol – Gasoline blends (E10, E85).

Choosing a fuel with high biofuel concentration is beneficial considering the overall GHG emissions over its lifecycle but can have a noticeable effect on fuel consumption and to a lesser extent on tailpipe CO_2 emissions. Using straight biodiesel is reported to increase fuel consumption by 9% [316] due to biodiesel's lower energy density. Biodiesel's effect on tailpipe emissions is limited leading to lower increases of about $2 \pm 1\%$ [317] as a result of the lower carbon content of the biofuel. Using E10 fuel increases the fuel consumption by 3.5–4% and marginally reduces tailpipe CO_2 [230,318,319] while E85 may increase fuel consumption by 30–35% while reducing tailpipe CO_2 by 5–7% [230].

Finally, climatic conditions require variations in fuel properties, in particular for diesel fuels, related to volatility, viscosity, formation of wax crystals and freezing point. The creation of crystals can lead to irregular fuel flow, filter clogging, loss of power, engine stall after start, or engine failure [320]. In order to prevent these effects, permissible diesel characteristics are adjusted each season [321], depending on country and climate. No data were found on the effect of seasonal fuel variation on fuel consumption, which will essentially depend on the fuel's energy content variation.

6. Vehicle certification test

A divergence between certification and in-use values can be expected due to the vehicle certification test's boundary conditions and other related factors related to the inherent inability to capture all possible operating conditions in a laboratory based test, particularly if this is a single driving cycle test. It is impossible for any kind of standard and lab-based test to cover all possible conditions of real-world driving. Nonetheless, it is important to point out the significance of various elasticities associated with any official laboratory test as they make reproduction of the results difficult for individual researchers. In addition, it is important that any test procedure retains a stable offset, or gap, compared to reality, at least on a statistical basis. Divergences appear to increase over time as discussed previously and can be linked mainly to two factors:

i. Vehicle technologies or vehicle use do not display same CO_2 effect in the laboratory and in real-world driving conditions, therefore requiring test procedures to be revised and updated;
ii. Vehicle manufacturers have learnt to exploit the margins of flexibility allowed by any test procedure.

The second element is important as it can be used by vehicle manufacturers at zero cost and can disrupt market competition. Manufacturers who exploit the test margins obtain an unfair competitive advantage compared to those who achieve the same fuel consumption by implementing costly technologies. As a consequence, when the vehicle certification test is undertaken by an independent body, significant deviations (beyond the natural test-to-test variability) between the test result and the official certification value arise.

A series of laboratory tests [328] conducted on petrol and diesel vehicles under the European type approval test procedure (NEDC test) showed a discrepancy of $15 \pm 10\%$ between laboratory measurements and type approval values. This difference is attributed to the preparation of the vehicle in terms of, for example, tyre pressure and state of battery charge and to the chassis dynamometer settings. Within the same project, the vehicles were driven on PEMS test routes and a deviation of $18 \pm 10\%$ for petrol vehicles and $24 \pm 7\%$ for diesel was reported. (see Fig. 6.1). Recent tests [29] carried out on behalf of the French ministry of transport have shown in some cases even higher deviations. Vehicles tested in an ex-post reproduction of the certification test were found to emit on average 15% more CO_2 than the certification value (with some vehicles emitting up to 50% more CO_2). The deviation represents a clear indication that the current European type-approval system, at least for what concerns the certification of fuel consumption and CO_2 emissions, has significant flaws that are being exploited in a way that the improvements in fuel consumption appear only during the vehicle certification procedure and have very little or no relevance in real driving conditions. In the following section, an overview of the main test flexibilities in the NEDC test procedure is reported.

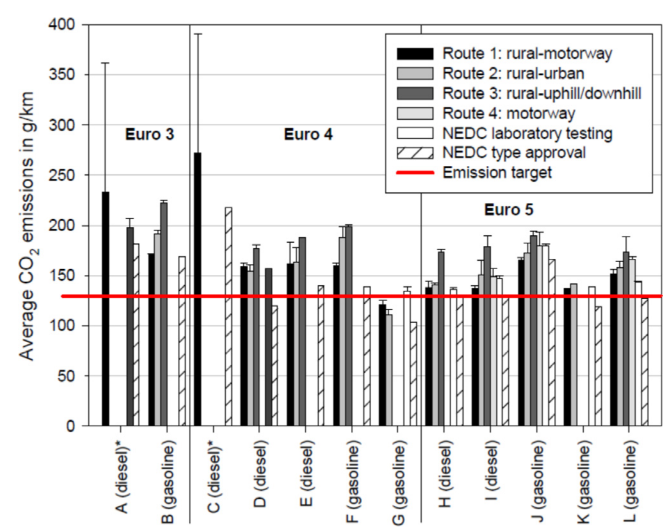


Fig. 6.1. Average CO_2 emissions found in PEMS road test and in–house NEDC laboratory test for petrol and diesel vehicles. Emissions target refers to 130 gCO_2/km in 2015 [328].

Table 6.1
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
Use of inertia classes	CO_2 values off by 4–6 g/km compared to real values	[201]
	CO_2 emissions different from 2% to 11% compared to actual vehicle reference mass	[18]
Non-realistic acceleration and driving patterns	Discrepancy between NEDC and real-world consumption	[136,256,257]
High idle time	For vehicles equipped with Engine Start–Stop technology leads to unrealistic decreases in CO_2 emissions (Overrated Start–Stop effect)	[18,136,329]
Short test cycle	High cold start share leads to increased fuel consumption between 3% and 14%	[330]
	Underestimates hot emissions compared to real-world driving cycles	[331]
Different wheel and tyre specifications in the NEDC than in real-world	Leads to lower fuel consumption by 2%	[136]
Flat surface, no simulation of altitude changes	Lower CO_2 and fuel consumption over NEDC compared to real-world operation	[84,257]
Fully charged battery, not charging during the test	Lower CO_2 and fuel consumption over NEDC compared to real-world operation	[136,332]
Test temperature between 20 and 30 °C	Driving NEDC at 29 °C compared to 20 °C could lead to lower CO_2 and fuel consumption by 2%	[18,332]
	Average temperature in Europe is about 14 °C. Driving NEDC at 14 °C would increase CO_2 by up to 6 g/km	[136]
Auxiliary systems are not taken into consideration	Lower NEDC CO_2 compared to real world	[126]
	Use of A/C increased NEDC consumption by 5%	[136]
	Increased consumption between 2.8 and 10% when considering auxiliaries	[140, 159]
Special gear lubricant may be used in transmission	Decreased NEDC consumption by 1%	[178]
Declared result is allowed to be lower than what would be measured	The same CO_2 value can be applied to vehicle variants exhibiting up to 4% higher NEDC CO_2 emissions compared to a measured parent vehicle. Certification measurement is likely to take place for the least polluting vehicle. As a result official CO_2 value can be lower up to 4%.	[18,332]
Wheel and tyre optimization	Permitted increase in rolling radius by 5% decreases NEDC CO_2 emissions by 2.5%	[332]
Road loads	Real–world road loads are 30% higher at high speeds compared to type approval; Coast down tests performed with different wheels compared to the one actually sold with the vehicle (lower rolling resistance, higher moment of inertia result in artificially lower road loads and consequently CO_2)	[81]
Non-realistic vehicle preconditioning	Setting the chassis-dynamometer to reproduce the vehicle road-loads requires the vehicle to be warmed up to reproduce the conditions of the coast-down tests. An NEDC cycle is foreseen for vehicle warm up, resulting in lower temperatures in the vehicle's driveline and hence higher internal losses compared to those occurring during the actual coast down test. As a result, lower forces are applied to the vehicle by the dyno to match the same road loads which in turn lead to lower CO_2 emissions by 1–3 gCO_2/km.	[333]

6.1. Test margins

The terms “margin”, "flexibility" or “elasticity” refer to a specific provision or interpretation of the certification procedure or an absence of such a provision or clear interpretation that, if applied, results in the measurement of lower CO_2 emission values. The comparative term “lower” assumes as a reference the values that would occur if provisions, interpretations or practices more accurately reflect real-world driving conditions within the boundaries and technical limitations of the applicable measurement procedure. Although such flexibilities might not be “illegal” their intentional and systematic exploitation in order to achieve benefits should be considered to be against the spirit of the law.

The lack of binding prescriptions for certain elements of the test procedure can be due to two main reasons: (i) to make the procedure manageable in practical terms; and (ii) due to the lack of knowledge on the effect of a particular flexibility. In both cases, the problem arises for CO_2 and fuel consumption certification if the margins can be legally exploited in order to deliver lower values. Many European studies have been conducted on this issue. Table 6.1 presents a summary of the factors related to the test margins and their effect. In addition, Fig. 6.2 presents the test elasticities (average values per elasticity group) found in literature.

Regarding the longitudinal vehicle dynamics resulting from the speed profile of a single test cycle, researchers [55] argue that a set of driving cycles should be used instead. Different vehicles, differing in performance levels and usage characteristics, should be tested under different conditions.

The reference mass, as introduced in the current type approval process, 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 does not 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. The NEDC reference mass is linked to specific tiers (inertia classes). Inertia classes define the vehicle inertia that is simulated during the vehicle certification test. Each tier represents a range in the vehicle reference mass. The

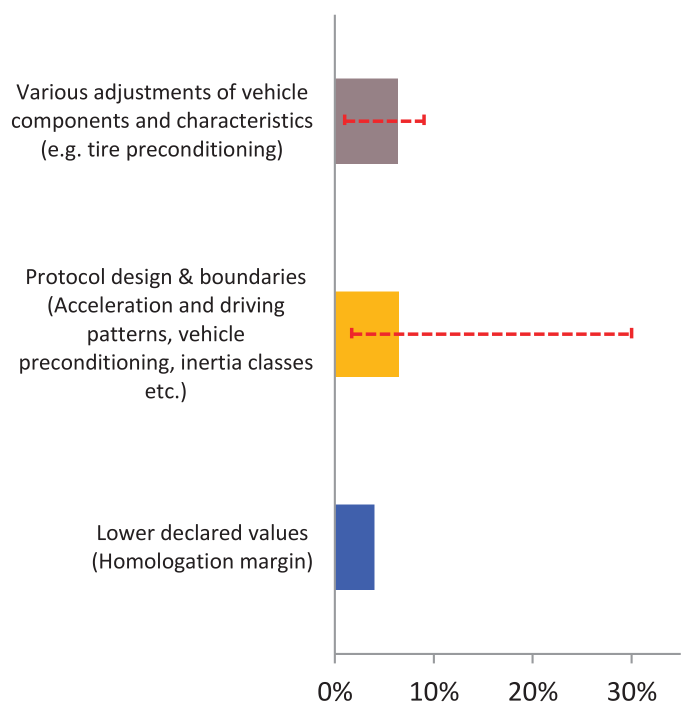


Fig. 6.2. Discrepancy in fuel consumption between type approval and real world due to the test margins (median values of sources included in Table 6.1).

inertia used in each tier is the average mass of the tier. This led to a non-continuous distribution of vehicle mass contrary to what happens in reality where mass is a continuous quantity. This has been further exploited by vehicle manufacturers who have designed their vehicles in order to have a reference mass always close to the higher limit of the tier, and thus resulting in a vehicle inertia which is systematically lower that the reference mass.

Another important element affecting directly tyre rolling resistance during the test is tyre pressure. In NEDC there is no prescription concerning the tyre pressure, the common practice is therefore to inflate the tyre up to the maximum permissible pressure (~3 bar), obtaining an advantage on the RRC. Keeping the pressure to the maximum permissible pressure results in a small but measurable benefit in CO_2 emissions due to the reduction of the tyre's rolling resistance characteristics and its contact surface with the chassis dyno. In addition to the pressure, another element affecting the vehicle rolling resistance is the tyre tread. In particular, the higher the depth of the tyre tread, the higher the RRC [175]. During type-approval tyre depth can be between 50 and 90%. Adopting the minimum depth [48], CO_2 emissions can be thus underestimated, capturing only a fraction of the tyre's tread lifetime contribution to emissions.

The present vehicle certification test is undertaken with the battery fully charged, as no indications on the state of charge of the battery are reported in the legislation, something that does not correspond to real-world driving 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. As vehicle controllers are set to maintain a constant state of charge at about 80–90% of the battery's capacity, it is likely that all electrical demands during the test are met through the discharge of the battery and no loads burden the alternator and the engine. In practical terms, electric loads are excluded from the officially reported CO_2 values [65].

The above constitute a summary of the main test flexibilities that can be used to artificially reduce CO_2 emissions during the certification tests. Going into the details of all possible flexibilities is beyond the scope of the present paper.

6.2. *Vehicle certification testing in Japan and the United States*

The majority of the vehicles sold in Europe (about 90%) are produced by European manufacturers [39], followed by manufacturers based in the USA and Japan and with a low portion of the sales from South Korea [39]. The vehicle certification test in Japan and the United States has been revised to provide realistic values. In Japan the certification test was based on the 10–15 mode that was a cycle comprised of three segments accounting for urban driving (10 mode) and one segment for highway driving (15 mode) [334]. The 10–15 mode was replaced by the JC08, which is a more stringent procedure, that was phased in from 2008 to 2011 [335,336]. The JC08 is considered to deliver realistic emission values [337] but it has a lower average speed than the NEDC (22.7 km/h compared to 44.1 km/h of the NEDC, excluding stops) in order to compensate for the lower speed limits in Japan, which are set at 100 km/h at the express way [338], comparatively lower than the 120–130 km/h [339] set in Europe.

The US EPA utilizes a set of cycles that comprised of city and highway cycles, with an average speed of 34.1 km/h and 77.7 km/h, respectively. After 2008 three supplementary tests were included to address different driving conditions. The high-speed supplementary test includes the US06 test cycle that has an average speed of 77.9 km/h, but has higher top speed than the highway speed cycle (128.7 km/h and 96.5 km/h, respectively) and stronger accelerations (13.6 km/s^2 and 5.1 km/s^2, respectively). The effect of the use of air-conditioning is measured over the SC03 test cycle at 35 °C with the A/C switched on. Finally, the effect of low temperature on emissions is measured with a city cycle at a laboratory temperature of −6.7 °C [72]. Emission standard compliance is measured under the city and highway cycles that provide the unadjusted emission values, but they do not take into consideration the driving conditions previously mentioned. For this reason the values are adjusted based on the supplementary tests and the adjusted fuel economy is provided to the customers [340]. Fig. 6.3 presents the ratio between on-road and official CO_2 emissions. A divergence of about 30% for the unadjusted values and close to zero for the adjusted can be seen. Additionally, the data shows that while there was a negative gap in the adjusted values there has been a converging trend to zero in recent years [136]. In addition to the certification procedure, the US EPA has a surveillance programme and conducts tests on in-use vehicles to ensure that they comply with emission standards and they do not deviate from the laboratory measurements by a factor of 1.3 [15,73]. Violations can lead to significant fines for the vehicle manufacturer [10].

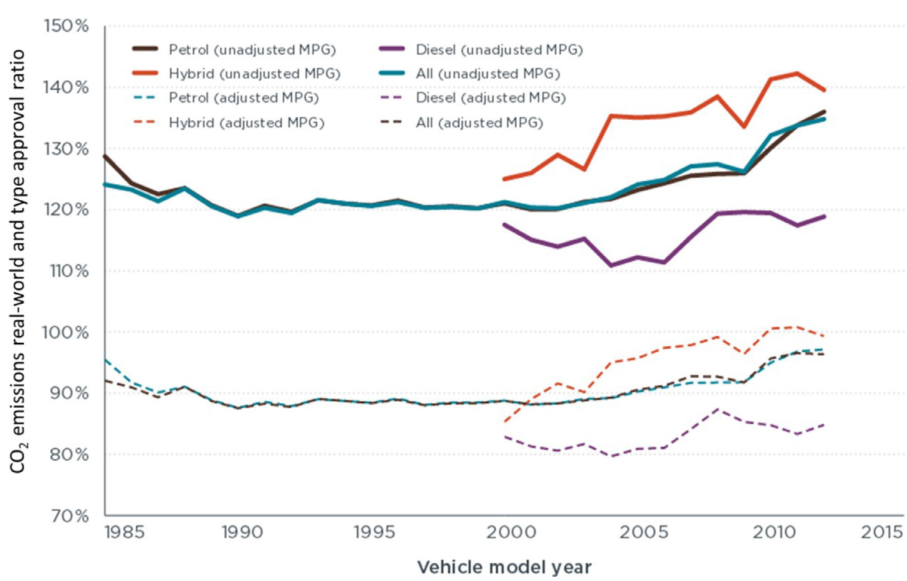


Fig. 6.3. Ratio of on-road and official CO_2 emissions values by year [136].

6.3. The WLTP introduction

The limitations in the NEDC procedure has resulted in the demand for a new, more realistic and robust test procedure. As a result, in 2009 the World Forum for Harmonization of Vehicle Regulations initiated action to develop a new harmonized procedure. In 2014 the United Nations Economic Commission for Europe (UNECE) adopted the first global technical regulation including the main aspects of the new procedure [59]. The Worldwide Harmonized Light Duty Test Procedure, WLTP, is the name of the procedure. In 2016 a new package was adopted to cover all the aspects of the vehicle tests for fuel consumption, CO_2 emissions and pollutant emissions. The introduction of the new test procedure in the different type-approval systems will depend on the specific country. The EU will be the first to introduce it (by the end 2017) followed by Japan. China, India, South Korea are expected to introduce it immediately after. US will first assess the possible benefits before deciding whether to adopt it or not.

In Europe the WLTP is expected to address many of the limitations of the current type approval test and act as a valuable reference basis for vehicle CO_2 certification and monitoring. Table 6.2 presents the main improvements of the WLTP with respect to the NEDC. The changes are divided in four categories, namely: (i) road-load determination; (ii) laboratory test; (iii) processing test results; and (iv) Certificate of Conformity (CoC).

With regards to (i) a series of changes take place. In WLTP for example the definition of the mass has changed (to be more realistic by e.g. including the effect of optional equipment). In addition, the mass is allowed to vary in a continuous way (inertia classes have been removed). A new more detailed protocol regarding the calculation of resistance forces is introduced; tyre characteristics are strictly defined as are the boundary conditions for tyre pressure and pressure during the test. For example, the WLTP prescribes that the type-approval test is carried out with the tyre pressure set at the minimum of its range, resulting in an approximate 0.3% increase in CO_2 emissions [341]. The WLTP standard for the minimum tyre tread depth is more stringent (80%–100%) than under NEDC (50–90%). In category (ii) the new speed profile and gears shifting calculation algorithm are the main changes whereas more strict definitions regarding the test temperature boundaries and the vehicle preconditioning are introduced. The world harmonized driving cycle (WLTC) is expected to address the issue of a non-realistic speed profile or traffic conditions. The WLTC cycle was produced from around 1 million km of real-world vehicle activities and is subdivided in four different phases reflecting traffic conditions at different average speeds [59]. With regards to the processing of the final results, new concepts are foreseen such as the correction of the fuel consumption for the difference between the test temperature (23 °C) and the average European temperature value of 14 °C and the correction addressing the effect of battery depletion during the test (battery State Of Charge correction). Finally, the current type approval extension mechanism, resulting in up to 4% lower emissions compared to the tested one, is abolished and a new definition of vehicle families and how the certification can be extended to vehicles of similar characteristics is introduced. Errors and flexibilities in the test execution and road load determination have been also corrected. This will contribute to achieving a more realistic certification value. The impact of the introduction of WLTP on the average fleet-wide CO_2 is estimated to be of the order of 15–25% [26,277,342,343], increasing the average CO_2 of new passenger cars between 18 and 30 g/km (although any calculation has a wide margin of uncertainty due to the fact that the new definitions in the protocol regarding vehicle classification, road load determination and type approval extension cannot be easily quantified). WLTP in its first stage is lacking any correction for the use of air-conditioning and there is no ex-post correction of the protocol based on the real-world performance of vehicles. So although the real world – certification gap will be reduced to a certain extent a measurable difference is likely to remain. Due to the

Table 6.2
Comparison of NEDC and WLTP [50].

Category	Item	in NEDC	in WLTP	Impact on CO_2
Road Load Determination	Vehicle test mass	Present	Modified	↑
	Tire selection	Present	Modified	↑
	Tire pressure	Present	Modified	↑
	Tire tread depth	Present	Modified	↑
	Calculation of resistance forces	Present	Corrected	↑
	Inertia of rotating parts	Absent	Introduced	↑
	Default road load coefficient	Present	Modified	?
Laboratory test	Driving cycle	Present	Modified	↑
	Test temperature	Present	Modified	↑
	Vehicle inertia	Present	Modified	↑
	Preconditioning	Present	Modified	↑
	Gear Shift Strategy	Present	Modified	↓
Processing test results	Battery state of charge correction	Absent	Introduced	↑
	Correction for the average EU temperature	Absent	Under discussion	↑
	Correction of cycle flexibilities	Absent	Under discussion	±

existence of specific CO_2 targets associated with the NEDC, the old procedure will remain as a legal reference for all CO_2 related targets until year 2021.

7. Summary discussion and conclusions

Several studies have focused on the issue of the gap between real-world and vehicle certification fuel consumption and CO_2 emissions. Passenger car emissions are reported to be higher in real-world driving conditions compared to the official laboratory test-based values. The present (2014–2015) gap is estimated to be of the order of 30–40% while there are sources claiming that it reaches as much as 50%. For an average European passenger car, which is reported to emit in 2015 slightly more than 120 gCO_2/km, this gap translates in an extra 36–48 gCO_2/km or an increase of fuel consumption of about 1.5 to 2 l/100 km (petrol equivalent). This corresponds to a significant increase in the operating costs of vehicles in real-world driving conditions. A conclusion common in almost all studies is that the gap has been increasing with time. This trend can be traced back to a series of factors related to the actual use of vehicles (e.g. frequent use of A/C systems, electric auxiliaries, traffic conditions) and test related shortcomings. Some researchers conclude that the introduction of European mandatory CO_2 targets in 2009 pushed vehicle OEMs to optimize the fuel consumption over the official cycle taking advantage in several cases of the margins allowed by an old and to some extent outdated test procedure. These margins are also the topic of various studies with an approximate influence estimated to be between 10 and 20%. This range has been also demonstrated by recent tests conducted in various countries.

A series of factors affecting fuel consumption of passenger cars over laboratory and real-world driving conditions were identified. Several factors had been thoroughly assessed in previous studies, such as the influence of ambient temperature on cold start or the influence of mass increase. For some other factors such as rain or snow, scarce data were available despite their apparent influence on vehicle fuel consumption. The majority of the studies reviewed investigate the impact of these factors on CO_2 emissions and/or fuel consumption over experimental tests undertaken on-road or in the laboratory. In fewer cases simulation and other analytic approaches are used for quantifying the effect. One of the difficulties in pooling together all this information and extracting quantifiable results is the absence of a common reference. Indeed the baseline in each study is different as are the test conditions and the vehicle under investigation. In order to consolidate the information collected, the reported effect of each factor on consumption or emissions was normalized and expressed as a percentile effect on CO_2 emissions over real-world driving conditions when compared to the respective laboratory reference test. The median of these normalized values can be considered as an indicator of each factor's potential impact on fuel consumption (Table 7.1). In addition to the median value, the standard deviation of the findings is provided as a measure of the spread of the results and the accordance between different studies. The standard deviation, together with the extreme values found, provide a first estimate of the uncertainty associated with the quantification of the effect of each factor. It is observed that for most factors the value of the standard deviation is comparable or even higher than the median value. Hence, there is a high uncertainty in these estimations and also a high dispersion of the results from different studies. The latter occurs due to a number of reasons such as the use of different types of vehicles and the absence of common protocols and testing procedures.

The information of Table 7.1 was used for formulating a scenario on the passenger car real-world CO_2 emissions and for calculating an indicative value for the CO_2 gap in 2015. The characteristics of the vehicle considered in the calculation correspond to those of the average European passenger car as presented in Table 2.1 (120 gCO_2/km, 1380 kg, 1600 cc). Wherever it was necessary to translate from fuel consumption to CO_2 emissions a fuel mix of 46% petrol and 54% diesel was considered and a weighted average value was used. The main assumptions made for this “real-world” operation scenario were the following:

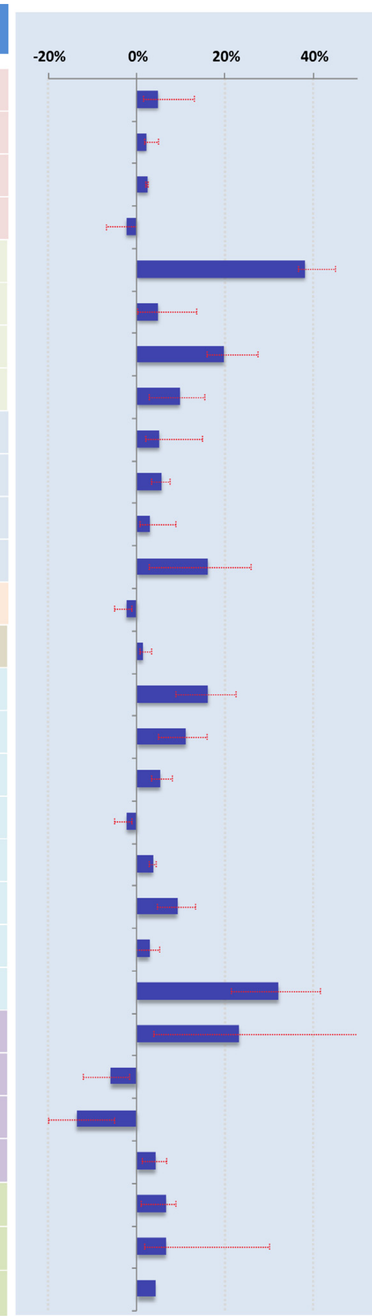
- A flat 15% increase was considered due to the test protocol flexibilities; 6% originated from optimal adjustments of the certification vehicle compared to the production vehicles, 5% originated from the protocol design and its foreseen boundaries and 4% reflected the fixed homologation tolerance allowed.
- An additional mass equal to 100 kg was assumed accounting for an occupancy rate of 1.5 person/vehicle, extra luggage and additional equipment compared to the certification vehicle
- An increase of 2% in CO_2 emissions was assumed reflecting an increased aerodynamic resistance due to factors such as side-winds, lower average air density, open windows, differences in vehicle body/shape
- A 20% increase in rolling resistance was considered (2.4% increase in emissions), 15% of which is attributed to the use of lower energy class replacement tyres and 5% to the combined effect of winter tyres, deflated tyres and driving on wet roads
- The weighted effect of annual temperature variation on vehicle cold start emissions was estimated to be 2.9%; vehicle operation was assumed to take place at four different ambient temperatures 4, 12, 20 and 28 °C for 15, 35, 35 and 15% of the year respectively resulting in a mean annual temperature of 14 °C.
- Additional auxiliary electric loads were set equal to 250 W resulting in additional 6 gCO_2/km
- A constant increase of 2.5% was considered to account for the hysteresis in fuel consumption when driving at mild road grades of 0.5–1% (zero altitude change)
- An additional fuel consumption of 0.5 l/100 km due to the use of air-conditioning for 50% of the year (temperatures > 20 °C) resulting in a weighted average increase of 5%

Finally, the effect of the traffic conditions should be taken into account. Increases and decreases in fuel consumption and CO_2 emissions can occur, depending on the mix of traffic conditions, when comparing against conditions similar to those experienced over a cycle/trip with characteristics similar to those of the NEDC. The NEDC has a relatively mild mix of 36% urban driving and 64% extra urban driving with a total average speed of 33 km/h. Based on the results presented in Section 4.4, in the majority of traffic conditions fuel consumption lies between ±15% of the fuel consumption experienced at 33 km/h. The same range was assumed as the lower and upper boundary of the real-world emissions calculated in this exercise.

Fig. 7.1 presents the results of the gap calculation broken down to the main contributing factors. Starting from a baseline of 120 gCO_2/km, an additional 18 gCO_2/km would account for the margins of the present certification test and a more realistic baseline for an average European car would be at 138 gCO_2/km. With the main test margins addressed, an emissions level of 140 gCO_2/km could be considered as the low starting point of the upcoming WTLP certification scheme (16% increase compared to baseline). Other vehicle related factors such as mass, aerodynamics and road loads contribute another 10.4 gCO_2/km to the gap, 4.4, 2.6 and 3.4 gCO_2/km respectively each. Part of their effect is also likely to be captured by the WLTP as more strict definitions for vehicle mass and road loads are foreseen, which take into account the least favourable conditions (e.g. lowest energy class tyres, vehicle with higher aerodynamic resistance). The effect of annual temperature variation on cold start was estimated to contribute another 4.1 gCO_2/km. When including the temperature effect, vehicle emissions reach at 152.6 gCO_2/km, a value that could be viewed as the highest end point of the WLTP

Table 7.1
The potential influence of different factors on CO_2 emissions over real-world conditions compared to the official test value. Reported value (%) represents the median value extracted from literature. Error bars indicate the minimum–maximum values.

CATEGORY		FACTOR	MEDIAN	STD
Vehicle characteristics and sub-systems	Effect of mass and road loads	Vehicle mass	5%	3%
		Aerodynamic resistance	2%	1%
		Different energy class of replacement tyres	2%	
		Low rolling resistance tyres	-3%	2%
	Factors affecting mass and road loads	Trailer towing	38%	4%
		Roof racks/box (non laden)	5%	4%
		Roof boxes (laden)	20%	6%
		Various roof addons	10%	5%
	Auxiliary systems	A/C (cooling)	5%	4%
		Heating (Electric heating or A/C)	6%	2%
		Steering assist systems	3%	3%
		Other electrical consumers	16%	10%
	Friction and Lubricants	Low viscosity lubricants	-3%	1%
	Maintenance	Low tire pressure (0.25 bar deflation)	1%	1%
Environmental and traffic conditions	Ambient temperature (compared to 20°C)	Temperature at -7°C	16%	6%
		Temperature at 0°C	11%	5%
		Temperature at 10°C	5%	3%
		Temperature at 30°C	-2%	2%
	Altitude	Elevation of 1000 m	4%	1%
	Road	Uphill driving (~1.5% grade)	9%	4%
		Road surface (roughness and texture)	3%	2%
	Traffic	Congestion	32%	9%
Driver and user related factors		Aggressive driving	23%	19%
		Eco-driving techniques	-6%	3%
		Advanced Driver Assistance Systems	-14%	6%
		Open windows (at 100 km/h)	4%	3%
Certification test related factors		Adjustment of vehicle characteristics	6%	3%
		Protocol design & boundaries	7%	10%
		Homologation margin	4%	



(26.5% increase compared to baseline). Further to these contributors, additional electric consumption over realistic conditions, road grade and air conditioning would add an extra 5.9, 3.5 and 5.9 g/km respectively increasing the total real-world emissions to 168 gCO_2/km. The latter translates in a CO_2 gap of 40%, a value that is in line with the observations of several studies (see Fig. 2.2 and Table 1.1). Of course this estimate does not take into account the possible traffic conditions in which a vehicle may operate, but should be considered as an indicative average situation. Traffic conditions add substantial uncertainty to the calculation. Real-world emissions of the same vehicle could reach up to 193 gCO_2/km in cases of intense traffic or when driving at very high speeds. Similarly emissions could be as low as 142.8 gCO_2/km for mild speed, free-flow driving. In such extremes the difference from official emissions would be 61% and 19% respectively.

The above calculation should be viewed from a qualitative perspective rather than from a strictly quantitative one. The uncertainty behind the qualified assumptions made for the calculation remains high and difficult to quantify. In addition there are other factors influencing the performance of vehicles in real world. In reality not all factors are equally present. Calculations of higher accuracy would require the application of in-use weighing factors on each individual factor in Table 7.1 to account for its share in real-world operation. Highly influential factors, such as trailer towing, rarely occur hence

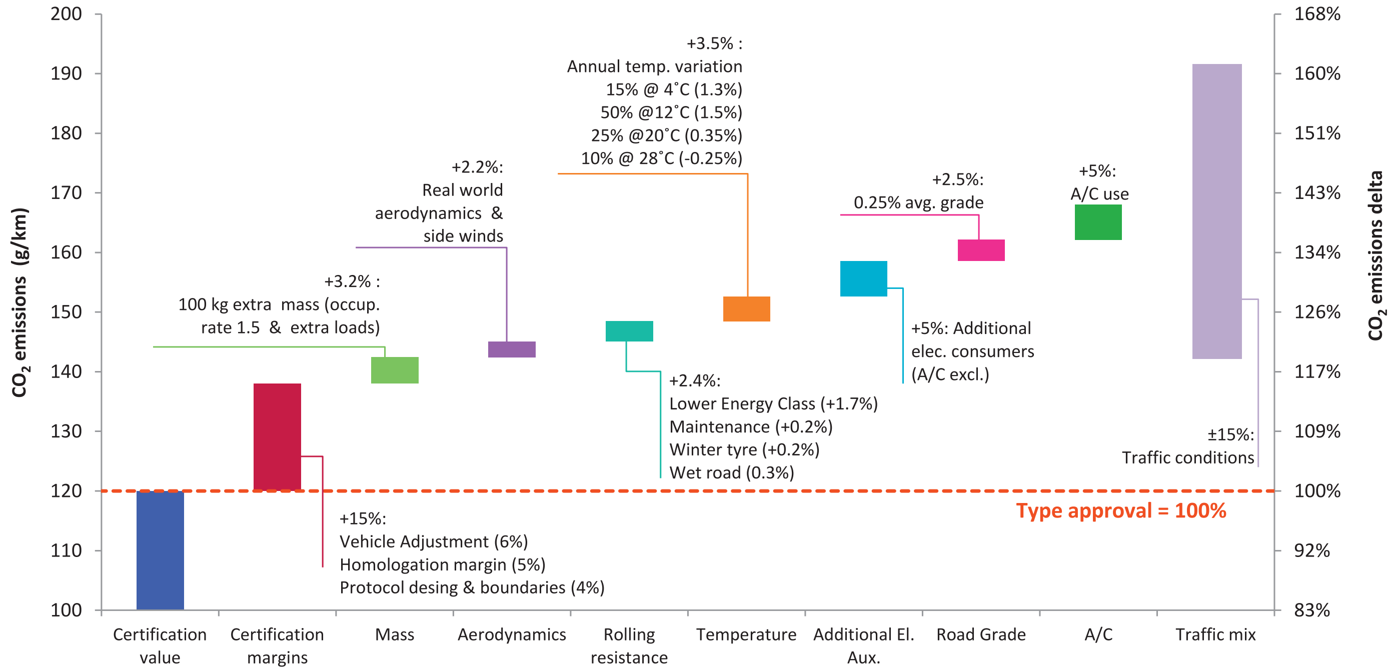


Fig. 7.1. Reality vs Certification gap estimation for an average 2015 passenger car; breakdown of factors contributing to the gap.

their contribution in the CO_2 gap is minimal. On the other hand, some factors, which on a first view appear less influential (e.g. side winds), might have a more significant contribution to the gap as vehicles are exposed to side winds when driven in highway conditions. Unfortunately, only scarce information can be found in existing literature that would allow a robust calculation of a realistic in-use share for each factor. Few studies are investigating how vehicles are actually used in real life, despite the fact that the real-world versus type approval fuel consumption gap is being frequently studied. In conclusion, the values presented here regarding the real-world CO_2 gap could be viewed as a realistic estimate of an average European situation on which additional more focused and thorough research can be based in order to support policy initiatives in the future and technology development in the future.

The upcoming WLTP is expected to address many of the limitations of the current legislation, including several of the issues highlighted in this paper. The values provided by the WLTP are expected to be closer to real-world driving conditions by about 26 ± 6 gCO_2/km. However, WLTP cannot fully bridge the gap. The lack of quantified understanding of the real-world driving conditions is a problem that has to be addressed even after the new testing protocol is established in Europe. The main reason is that no single test, no matter how sophisticated and well designed, will ever be representative of the real-world operation of all vehicles and conditions. There are factors affecting fuel consumption in everyday operation which are neither included in the test nor easily identified. In order to reduce the gap and ensure that the on-road emissions are within a reasonable margin, there should be established some form of vehicle in-use monitoring contributing to the strategic target of reducing overall CO_2 emissions from the transport in the future. Vehicle manufacturers will eventually learn how to optimize vehicle performance over the new test procedure. Hence, attention should focus on the evolution of the gap over time, which shall not increase progressively, and on the underlying factors causing it. Furthermore, technology progresses fast and any test procedure sooner or later becomes outdated. Given the pace of new technology development, a more dynamic approach should be foreseen, including verification activities, continuous research on the topic and real-world data collection. Some form of ex-post calculation of the gap or correction of the in-use emissions estimates will be necessary for environmental, policy or consumer information purposes. Even if part of the road transport sector becomes electrified, the need to reduce energy consumption of vehicles will remain as mobility needs will continue to grow.

At this point it should be stressed that defining a single pan-European CO_2 emission targets and gap correction factors may not be the most effective approach for reducing road transport CO_2 emissions in real world. Each region has its own characteristics, particularities and mobility needs. Proposing actions tailored at regional level would maximize the CO_2 benefits but is very difficult due to the lack of data and information sources. Even at regional level, environmental, traffic and vehicle operating conditions may vary significantly making any estimates difficult to validate and policy initiatives difficult to assess. As discussed previously, there is a lack of consistent information generation and data collection practices that would facilitate the definition of a more precise “reality” and enable more accurate estimates of the real-world fuel consumption. These are issues which should be raised for further discussion by researchers, policy makers and other stakeholders, i.e. how additional information on traffic, environmental conditions, and vehicle characteristics can be generated and made available for more targeted research and in-depth analysis.

Achieving sustainable mobility is a challenge that surpasses the borders of individual countries or regions. It is important for the global scientific community to revisit the issue of road transport CO_2 emissions in a more systematic manner if we are to achieve the transition to a low-carbon transport sector.

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