Traffic & Transport
Anna van Buerenplein 1
2595 DA Den Haag
P.O. Box 96800
2509 JE The Hague
The Netherlands

www.tno.nl

T +31 88 866 00 00

TNO report

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Real-world fuel consumption and electricity consumption of passenger cars and light commercial vehicles - 2021

Date	4 March 2022
Author(s)	René van Gijlswijk, Norbert Ligterink, Akshay Bhorasar, Richard Smokers
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Samenvatting

Inleiding
Dit rapport is de 2021-editie uit een serie rapporten over praktijkverbruik van lichte voertuigen die de afgelopen jaren door TNO zijn geschreven voor het Ministerie van Infrastructuur en Waterstaat. De voor dit rapport uitgevoerde analyse van verbruikswaarden is gebaseerd op de data van tankpassen en laadpassen die verkregen is van Travelcard Nederland BV. De conclusies van de analyse hebben betrekking op bestuurders die een tankpas/laadpas van hun werkgever ter beschikking hebben gekregen, en die hun brandstofkosten hiermee vergoed krijgen. Een kwart van de totale Nederlandse personenautokilometers wordt met zakelijke auto's verreden.

De voor dit rapport uitgevoerde analyse van de tankpas/laadpasdata geeft inzicht in het praktijkverbruik en werkelijke CO_2-emissies uit de uitlaat, en in het elektriciteitsgebruik in de praktijk van personenauto's en bestelauto's.
De beschikbare data over het elektriciteitsgebruik is flink toegenomen ten opzichte van het vorige rapport. Het praktijkverbruik is in het algemeen hoger dan de officiële typekeurwaarden van de fabrikanten; deze kloof verandert wel door de tijd heen, en is in dit rapport gemonitord. De effectiviteit van het Nederlandse en Europese klimaatbeleid, dat in belangrijke mate gebaseerd is op typekeurwaarden, is afhankelijk van een goede correlatie tussen typekeur en praktijk.

Ook zijn aanvullende analyses opgenomen voor benzine- en dieselauto's om het effect van de toegenomen gemiddelde voertuigmassa te beoordelen. In een toegevoegd hoofdstuk zijn de resultaten opgenomen van een eerste analyse van het effect van weersomstandigheden op brandstofverbruik. Een beter begrip hiervan helpt de voorspelling van (de variatie in) praktijkverbruik te verbeteren.

Dataset en representativiteit
De dataset bevat tankpasdata en laadpasdata, zoals verkregen van Travelcard Nederland BV. Na filtering op validiteit van de data, bevat de dataset gegevens voor 275.000 benzineauto's, waarvan 36.700 (plug-in) hybrides, 273.000 dieselauto's, waarvan 3.800 (plug-in) hybrides, en 54.000 bestelauto's. Het elektriciteitsgebruik kon worden vastgesteld voor 6.200 elektrische auto's.

De brandstofverbruiksdata dekt de periode januari 2004 – juni 2021.
Het jaarkilometrage van de voertuigen varieert enorm, wat betekent dat de database niet alleen voertuigen bevat van typische zakelijke veelrijders, maar ook voertuigen van rijders die slechts een klein aantal kilometers per jaar afleggen. Ongeveer 45% van de nieuw verkochte auto's in Nederland zijn leaseauto's. Omdat deze leaseauto's gemiddeld een hoger jaarkilometrage hebben dan auto's in particulier bezit, bepalen deze leaseauto's in grote mate het gemiddeld brandstofverbruik van de Nederlandse personenautovloot. De resultaten van de monitoring worden daarom van belang geacht voor de Nederlandse vloot.

Omdat beleid gericht op het zuiniger maken van de voertuigvloot uiteindelijk tot doel heeft om de CO_2-emissies van mobiliteit te reduceren, worden alle resultaten in dit rapport uitgedrukt in CO_2-emissies uit de uitlaat.

Vanwege het toenemende aandeel (bio-)ethanol in benzine verandert zowel de samenstelling als de dichtheid van de brandstof, en als gevolg daarvan het brandstofverbruik in liter per 100 km enigszins. Deze effecten, die elkaar grotendeels opheffen bij de berekening van CO_2-emissies uit de uitlaat, zijn hier niet meegenomen: de CO_2-emissie per liter wordt constant verondersteld over de tijd.

Resultaten
De WLTP-typekeurwaarden voor nieuwe personenauto's zijn in 2020 lager dan in 2019, terwijl de CO_2-praktijkemissies gelijk gebleven zijn. Er zijn significant minder nieuwe diesels ingestroomd; de nog wel verkochte diesel-personenauto's waren relatief zwaar, en stootten gemiddeld meer uit dan de nieuwe diesels van 2019. Dit ondanks een daling van de typekeurwaarden. De kloof tussen praktijk en WLTP-typekeurwaarden was gemiddeld ongeveer 20 g CO_2/km voor zowel benzine als diesel, waarbij de praktijkwaarde dus hoger was. In relatieve termen uitgedrukt, was de praktijk-CO_2-uitstoot 1,13x zo hoog als de WLTP-waarde, voor zowel benzine- als dieselpersonenauto's. Als plug-in hybrides in de gemiddelden worden meegenomen, nemen deze waarden toe tot 25 g CO_2/km (1,17x).

De gemiddelde werkelijke CO_2-emissie van nieuwe personenauto's in Nederland lag in 2020 op 156 g/km voor benzine en 164 g/km voor diesel (beide cijfers inclusief (plug-in) hybrides). Als we apart naar de plug-ins kijken, is de gemiddelde praktijkuitstoot 147 g/km: een kloof van 240% met de gemiddelde WLTP-typekeurwaarde van 43 g/km.

Om de ontwikkeling van brandstofverbruik te bekijken zonder de invloed van een veranderende voertuigmassa, werd het brandstofverbruik uitgedrukt per ton leeggewicht. Uit de analyse volgt dat de brandstofefficiëntie (in liter per 100 km per ton) bij lichte benzineauto's substantieel verbeterd is in de afgelopen 10 jaar. De efficiëntiewinst was slechts beperkt voor zwaardere benzineauto's, inclusief plug-in hybrides, alsmede voor alle dieselauto's.

Uit laadpasdata en kilometerregistraties is voor elektrische auto's (EVs) een gemiddeld energiegebruik berekend. In de getallen zit het laadverlies inbegrepen. De meest efficiënte modellen gebruiken 16 kWh per 100 km, de minst efficiënte modellen tot 30 kWh/100 km. Het gemiddelde voor de Travelcardvloot is niet veranderd ten opzichte van het vorige rapport: 20,2 kWh/100 km. Als de verbruiksgemiddelden van de individuele automodellen gewogen worden naar de Nederlandse EV-vlootsamenstelling, dan is het resulterende gemiddelde elektriciteitsgebruik bijna gelijk: 20,1 kWh/100 km.

Het praktijk-elektriciteitsgebruik is gemiddeld 19% hoger dan de WLTP-typekeurwaarde, maar de verschillen onder de voertuigmodellen zijn groot: sommige modellen hebben een afwijking van +40% of meer.
Er is een voorspellend model gemaakt waarmee het praktijk-elektriciteitsgebruik van EVs voorspeld kan worden. Het is gebaseerd op massa, luchtweerstand en accucapaciteit, en is gefit naar de werkelijke gemiddelden per voertuigmodel. De gemiddelde afwijking van het model is 8%, daarmee is het model een betere voorspeller dan de WLTP-waarde. Uit analyse van omzettings- en accuverliezen, die optreden bij (AC-)laden en ontladen van de accu, blijkt dat deze significant zijn, in totaal in de orde van 10-20%.

De relatie tussen jaarkilometrage en elektriciteitsgebruik (kWh/100 km) is onderzocht. Hoewel de energieconsumptie bij snelwegkilometers hoog is bij elektrische auto's, en veel kilometers doorgaans een groot aandeel snelweg betekent, is de trend tegenovergesteld. Hoe hoger het jaarkilometrage, hoe lager het gemiddelde elektriciteitsgebruik. Bij 40.000 km/jaar valt het verbruik bij de vijf meest verkochte EVs ca. 12% lager uit dan bij dezelfde auto's die 10.000 km/jaar afleggen.

Voor het eerst kon ook een gemiddeld waterstofverbruik berekend worden voor brandstofcelpersonenauto's. De waarde is gebaseerd op tankpasdata en is een gemiddelde van 23 voertuigen. Het gemiddelde waterstofverbruik lag op 1,24 kg/100 km. Uitgedrukt in energie-inhoud is dit ruwweg twee keer zoveel als de elektrische energie die per 100 km geladen werd door EVs.

Voor plug-in hybride personenauto's is per model het aandeel elektrische kilometers geschat; waarden variëren van 12% tot 34%, hetgeen niet significant afwijkt van het vorige rapport.

Voor bestelauto's is een sterke opwaartse trend te zien in het leeggewicht: 6-7% in twee jaar tijd. De brandstofefficiencyverbetering zette tegelijkertijd door: het brandstofverbruik per ton leeggewicht daalde geleidelijk sinds 2010, met gemiddeld 1,25% per jaar.
De kloof tussen WLTP typekeurwaarden en praktijkverbruik is nog niet stabiel voor bestelauto's, vanwege een nog beperkt aantal WLTP-voertuigen in de dataset. De CO_2-emissie in de praktijk lijkt onveranderd, ca. 220 g/km.

De CO_2-emissies van de Travelcardvloot varieert door het jaar heen, van -4% tot +4% ten opzichte van het jaargemiddelde. Een poging is gedaan om deze seizoensvariatie te koppelen aan individuele omgevingsfactoren. Uit deze analyse volgt dat in totaal een variatie van -1,5% tot +1,5% kan worden voorspeld uit variaties in temperatuur, wind en zoninstraling (in volgorde van belangrijkheid). Een deel van het effect is indirect, door veranderingen in gebruikspatroon en veranderingen in bestuurdersgedrag als gevolg van variatie in temperatuur, wind en zon. De resterende variatie van -2,5% tot +2,5% kan diverse oorzaken hebben, waaronder non-lineaire effecten van weer en seizoensvariatie in brandstofsamenstelling en banden.

Er is ook een inschatting gemaakt van het effect van een toenemende bijmengverhouding van ethanol in benzine. Benzinevoertuigen vertoonden gemiddeld 2% toename in brandstofverbruik vanaf de zomer van 2020, na correctie voor normale seizoensvariatie. De toename kan hoogstwaarschijnlijk worden toegeschreven aan de intreding van E10. Om het effect van E10 in de toekomst correct mee te nemen moet meer onderzoek gedaan worden naar brandstofeigenschappen, waaronder dichtheid en koolstofverhouding en de variatie daarin.

Summary

Introduction
This is the 2021 issue of a series of reports on real-world fuel consumption of light vehicles, written by TNO for the Dutch Ministry of Infrastructure and Water management. The primary data basis of this report is tank pass and charge pass data, obtained from Travelcard Nederland BV. The conclusions from this analysis relate to drivers who have a tank pass/charge pass available from their employer and who are reimbursed for their fuel costs in this way. A quarter of the total mileage of passenger cars in the Netherlands is driven with business cars.
The analysis of this data provides insight in real-world fuel consumption and tailpipe CO_2 emissions, as well as electricity consumption of passenger cars and vans.
The real-world consumption and emissions are generally higher than the associated type approval values provided by the manufacturers; this gap changes over time, and was monitored in this report. The effectiveness of greenhouse gas policies, which are to a large extent based on type approval values, is dependent on a good correlation between real-world and type approval.

In this report, more space was dedicated to electric vehicles. Based on the data available, which has increased significantly since last year's report, a model has been formulated which allows the prediction of the average electricity consumption of new vehicle models. Also, information about charging losses was included.
For vehicles fuelled with petrol and diesel, additional analyses were done to understand the effect of increased mass on fuel consumption. In a new chapter, the results are presented of a first analysis of the effect of weather conditions.
A better understanding allows a better prediction of the (variation in) real-world fuel consumption.

Dataset and representativeness
The dataset includes tank pass data and charge pass data, as obtained from Travelcard Nederland BV. After filtering for valid data, the dataset encompasses 275,000 petrol passenger cars, of which 36,700 (plug-in) hybrids, 273,000 diesel passenger cars, of which 3,800 (plug-in) hybrids, and 54,000 vans. The electricity consumption could be determined for 6,200 electric passenger cars.

Fuel consumption data covers the period of January 2004 up to June 2021.
The annual mileage of the vehicles in the fleet varies greatly, which means that the database does not only contain vehicles of business drivers with high annual mileage, but also vehicles of drivers that cover a relatively small mileage each year. Around 45% of all new cars sold in the Netherlands are leased vehicles. As these leased vehicles on average also have higher annual mileages than privately owned vehicles, their effect on the average real-world fuel consumption across the Dutch fleet is large. The results of the monitoring are therefore considered meaningful for the Dutch passenger car fleet.

As the objective of policies for improving the fuel efficiency of the fleet is to reduce the CO_2 emissions from mobility, all results in this report are expressed in terms of CO_2 emissions from the exhaust. Due to the increasing level of ethanol in petrol, the fuel consumption in litres per 100 km as well as the C/H/O-ratio and density of the fuel change slightly.

These effects, that largely cancel each other out in the calculation of tailpipe CO_2 emissions, are not taken into account here: the CO_2 emission factor per litre kept constant.

Results
For new petrol cars, the WLTP type approval values decreased in 2020 compared to 2019, while the real-world CO_2 emissions were the same as those sold in 2019. The inflow of new diesel cars decreased considerably; the remaining new diesels were relatively heavy, and their real-world CO_2 emissions were higher than in 2019, while the type approval values decreased slightly at the same time. For new vehicles, the WLTP type approval values are on average almost 20 g CO_2/km lower than the real-world emissions, for both petrol and diesel. Expressed in relative terms, the real-world CO_2 value is 1.13 times the WLTP type approval value for both new petrol and new diesel cars. If plug-in hybrids are included, this gap increases to 25 g/km for petrol cars (real world CO_2 = 1.17 times WLTP value).

The average real-world CO_2 emissions of new passenger cars in 2020 were 156 g/km for petrol including (plug-in) hybrids, and 164 g/km for diesel including (plug-in) hybrids. New petrol plug-in hybrids in 2020 have average real-world CO_2 emissions of 147 g/km. That is a 240% gap to the average WLTP value of 43 g/km.

An analysis was made of the fuel consumption per tonne of empty vehicle weight, to cancel out the changes in average mass over time. This was done for new registrations. For petrol cars, this fuel efficiency (litre per 100 km per tonne) has improved considerably for the lightest cars, over the last 10 years. For heavier petrol cars, including plug-in hybrids, as well as for diesel passenger cars, the improvement is limited.

For electric passenger car models the average electricity consumption was calculated from charge pass records and odometer registrations. The numbers include charging losses. The most efficient models consume 16 kWh per 100 km, the least efficient up to 30 kWh/100 km. The Travelcard fleet average has not changed over time: 20.2 kWh/100 km. If the consumption numbers of the individual car models are weighted to match the Dutch EV fleet composition, the resulting average consumption is almost the same: 20.1 kWh/100 km.

The real-world electricity consumption is on average 19% higher than the WLTP type approval value, but the differences among vehicle models is large: some have an upward deviation of 40% or more.

A prediction model was made to estimate the real-world electricity consumption of battery electric cars. It is based on mass, air drag and battery capacity, and is fitted to the actually observed electricity consumption averages in the dataset.
The average deviation of the model is 8%, so the model is a better predictor than the WLTP value. Analysis of conversion losses and battery losses that occur during (AC) charging and discharging of the battery, pointed out that these are significant, in the order of 10-20%.

The relation between annual driven distance and electricity consumption (kWh/100 km) was investigated. Although driving on the highway is relatively energy consuming for electric cars, and high mileage usually means a high share of highway driving, the trend is the other way.

The higher the annual distance, the lower the average energy consumption. At 40,000 km/year the five most common car models in the dataset have an electricity consumption that is around 12% lower than for vehicles of the same models which are driven 10,000 km/year.

For fuel cell electric vehicles for the first time an average real-world hydrogen consumption value was calculated based on tank pass data for 23 vehicles. The hydrogen consumption was found to be 1.24 kg/100 km. In terms of energy content in hydrogen this is roughly twice as much as the energy in charged kilowatt-hours for battery electric vehicles.

For plug-in hybrid passenger cars, the share of electric driving was estimated for individual models; values range between 12% and 34%, which is not significantly different from the values in the previous report.

For light commercial vehicles, a strong upward trend was seen in the empty mass: 6-7% in two years. The fuel efficiency has continued to improve at the same time: the fuel consumption per tonne of empty weight dropped 1.25% per year on average, ever since 2010.

The WLTP type approval-to-real world gap is not stable yet in the data for vans, due to a limited number of such vehicles in the dataset. The real-world average CO_2 emissions seem unchanged at around 220 g/km.

The CO_2 emissions of the Travelcard fleet vary by -4% to +4% throughout the year. This seasonal variation was attempted to be linked to individual weather aspects. In total -1.5% to +1.5% can be predicted using variations in temperature, wind, and solar irradiation (in order of magnitude of their effect). A part of the effect is indirect, by changes in the way people use their vehicles and changes in driver behaviour as a result of the variation in temperature, wind and sun. The remaining variation of -2.5% to +2.5% can have many causes, including nonlinear effects of weather and seasonal variation in fuel composition and tyres.

The effect of an increasing admixture of ethanol in petrol was estimated. Petrol vehicles on average showed an increase in fuel consumption of 2% ever since summer 2020, after compensation for normal seasonal variation. The increase can most likely be attributed to the introduction of E10. To incorporate the effect of E10 correctly in future analyses, further study of fuel properties, including density and carbon content and variations therein, is required.

Contents

1 Introduction

On an annual basis, TNO studies the fuel and electricity consumption of vehicles, based on data made available by Travelcard Nederland BV. The work is commissioned by the Ministry of Infrastructure and Water management.

This year's issue focuses more than previously on the impact of recent regulatory changes intended to make official fuel consumption and electricity consumption numbers better resemble the real-world averages.

1.1 Context

Over recent years there have been many regulatory developments affecting the type approval as well as real-world CO_2 emissions and fuel / energy consumption of conventional vehicles, electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV, or OCV-HEV: off-vehicle charging hybrid electric vehicles). A new CO_2 test procedure was enforced: the Worldwide Harmonised Light Vehicles Test Procedure (WLTP). Also a transition is taking place from the EU 2021 CO_2 target for manufacturers, to the new targets for 2025 and 2030. The regulatory changes move manufacturers to modify their vehicles to meet the targets on a fleet level. This has a direct effect on the fuel consumption and CO_2 emission values as reported by the manufacturers. The intention of the regulations is to cause a decrease of the real-world fuel consumption and CO_2 emissions. However, whether the introduction of the WLTP ensures that these values decrease at an equal rate as the type approval values, remains to be seen.

Already for many years the CO_2 targets and the reduction of officially reported numbers have shown a limited impact on real-world CO_2 emissions and fuel consumption of conventional vehicles. Additionally, there is a transition ongoing to PHEV and electric vehicles, which not only provides additional opportunities for the manufacturers to meet the CO_2 targets, but also affects trends with respect to the average gap between real-world and type approval. For PHEV the real-world fuel consumption reduction compared to similar non-plug-ins has been small in the Netherlands, because of the way the vehicles are used, with a large fraction of motorway driving for new vehicles, and a slack charging behaviour of many of the drivers.

This report is one in a long series of reports on the fuel consumption of light duty vehicles[1]. For this year's issue, sufficient data was collected since 2017 to be able to use WLTP-based type approval values as reference. NEDC-based analyses are continued as well, however. Secondly, as the electric vehicle fleet keeps expanding, the analysis of real-world energy consumption of electric vehicles gains importance. Thirdly, a first analysis of the influence of weather conditions on fuel consumption was included. Also, the effect of the transition from E5 petrol to E10 was analysed for a longer period of time. And finally, Covid-19 has had a significant influence on the way vehicles were used in the last one and a half year.

[1] Previous reports in this series can be found here: https://www.tno.nl/en/focus-areas/traffic-transport/roadmaps/sustainable-traffic-and-transport/sustainable-mobility-and-logistics/improving-air-quality-by-monitoring-real-world-emissions/overview-of-reports-of-actual-fuel-consumption-by-passenger-cars/

At the same time (March 2020), a 100 km/h speed limit was enforced. Fuel consumption data was analysed chronologically to visualise the effect of both factors.

1.2 Vehicle database

For the purpose of this report, fuel and electricity transaction data was made available by Travelcard Nederland BV. For each fuelling event, the amount of tanked fuel, the odometer reading and the time and date were recorded. For each charging event the kilowatt-hours and the time and date were recorded. After filtering for plausibility and completeness, the dataset encompasses 52 million fuel transactions and 1.8 million charging events. Rigorous filtering was necessary, because the odometer settings are entered manually by the drivers after fuelling and contain many errors and missing records. For more information on the methodology for data processing and analysis see for example reports TNO 2016 R11258 and TNO 2013 R11165.

For electric cars, odometer readings are generally not registered at charging events. Therefore odometer data, needed for the calculation of fuel consumption per kilometre, had to be sourced elsewhere. On request of the Ministry, information was sourced from the Netherlands Vehicle Authority (RDW) specifically for this purpose. Around 71,500 odometer readings were collected for the 23,922 electric vehicles in the dataset.

Table 1-1 shows the number of vehicles for which fuel consumption or electricity consumption results could be determined.

Table 1-1: Number of vehicles with valid energy consumption data

	Drivetrain type	Number of vehicles
Passenger cars	Petrol	238,403
	Petrol hybrid	24,480
	Petrol plug-in hybrid	12,197
	Diesel	269,113
	Diesel hybrid	1,826
	Diesel plug-in hybrid	1,987
	Electricity	6,210
	Hydrogen	23
	Other (natural gas, LPG; not further considered in this report)	5,540
Vans	Diesel	54,044
	Diesel hybrid	17
	Electricity	77
	Other (petrol, natural gas, LPG; not further considered in this report)	596

Data is available since 2004. The dataset is complete until end of June 2021 for tank events, and until end of May 2021 for charging events.

Vehicles stay in the database for as long as they are present in the fleets that use Travelcard passes. The total mileage during which a vehicle was followed therefore also varies from zero to over 200,000 km. For petrol and diesel vehicles, the distribution of the monitored mileage per vehicle is displayed in Figure 1-1.

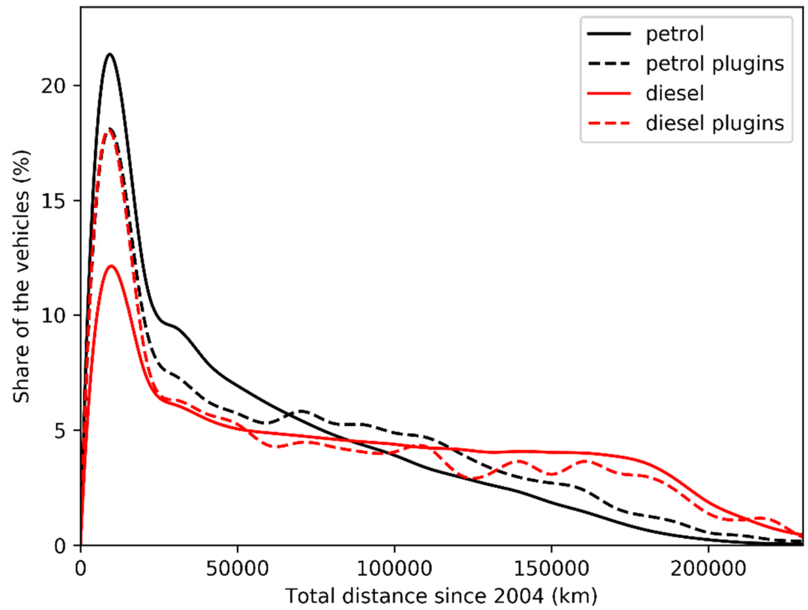

Figure 1-1: Histogram of the number of vehicles as a function of the total mileage over which the vehicle is monitored.

The differences with the analysis of 2020 are small. Regarding plug-in hybrids, a large fleet change can be expected next year. Then the last shift of vehicles for which the drivers still benefit from a 60-month low additional tax liability ('bijtelling'), namely plug-ins registered in 2016, will have disappeared from the fleet. In the meantime new plug-in sales have picked up due to manufacturer responses to tightened CO_2 targets.

1.3 Methodology

The methodology followed in this report is largely the same as in the 2020 report[2].

Petrol/diesel
For petrol and diesel cars, consecutive fuelling events are combined with the distance driven in between these fuelling events. Fuel consumption is calculated by dividing the amount of total tanked litres by the total driven distance.

The average fuel consumption for a group of vehicles is determined by dividing the sum of all tanked litres by the sum of all kilometres driven for the selection of tank events of all vehicles for which the average is determined. This produces the average over a selection of vehicles whereby the results for individual fuel events or vehicles are weighted over the kilometres driven.

[2] Real-world fuel consumption of passenger cars and light commercial vehicles, TNO report 2020 R11664, 30 October 2020.

The ‘direct’ CO_2 emissions, in other words the emissions of CO_2 from the tailpipe, can be directly related to the fuel consumption. The amount of CO_2 emitted per litre of fuel is related to the carbon content of the fuel and more or less fixed. Per litre of petrol about 2370 grams of CO_2 are emitted, while for diesel this value is 2650 gram CO_2 per litre.

These so-called emission factors are based on the relation between fuel consumption and CO_2 from the type-approval information, are representative for 100% fossil petrol and diesel, and have been assumed constant for the period over which data is available. This ensures consistency with previous reports, and forms a constant reference for the difference between real-world and type approval CO_2 emissions. The emission factors have been assumed constant for the period over which data is available. This may cause a slight difference with the actual tailpipe emissions, because the increasing biofuel admixture has an effect on both the fuel consumption in litres per 100 km and the tailpipe CO_2 emissions per litre. The increase in fuel consumption is now quantified in chapter 8 of this report, and the decrease in CO_2 emissions per litre can be calculated from changes in the C/H/O-ratio in the fuel, and the change in density, due to the added biofuel. Although these effects largely cancel each other out, a net effect remains. Based on the new information in chapter 8, this effect will be accounted for in the next report.

In older reports on this topic, up to 2016, real-world fuel consumption and CO_2 emissions were compared to type approval values as tested over the New European Driving Cycle (NEDC) to analyse trends in the real-world vs. type approval ‘gap’. Since September 2017 (new vehicle models) and September 2018 (all new cars) the Worldwide Harmonised Light Vehicle Test Procedure (WLTP) is in force, replacing the NEDC. For large vans the introduction dates are later. In the 2020 report a new series was started, analysing the gap between real-world and WLTP-based fuel consumption and CO_2 emissions. Approximately 186,000 vehicles in the dataset have WLTP-based type approval values. In this report WLTP is the basis for chapter 2. However, the NEDC-based series of the previous reports is also continued. This is possible, because the 2021 EU target of 95g CO_2 per kilometre is tied to the NEDC evaluation method. Therefore, for new vehicles the WLTP CO_2 values are translated mathematically into a derived NEDC value, or are determined with double testing the vehicles on WLTP and NEDC, usually referred to as NEDC 2.0.

The real-world fuel consumption of petrol/diesel plug-in hybrid passenger cars was also calculated in the abovementioned way. Furthermore, fuelling data of PHEVs was arranged per vehicle model for further analysis. The “low end” of the distribution of fuel economy in km/l, achieved by sorting fuelling events for a particular model by fuel economy, reveals a fuel consumption value for hybrid mode (‘empty battery’ situation). The difference between the most common value (mode) and the mean can be used to deduce an average share of electric driving for that particular model.

A more detailed explanation can be found in chapter 5. The method is an extension of approaches reported in reports TNO 2013 R10703 and TNO 2016 2016 R10938.

Electric vehicles

Because the odometer reading is not available on a charge-to-charge basis, the approach taken to calculate electricity consumption does not resemble the way fuel consumption is calculated for fuelled cars.. The goal of the method is to calculate the electricity consumption per kilometre for each vehicle individually. This is done by matching charging data with odometer data; charging data and odometer readings are obtained from two different sources and are generally not available on matching dates. Also, in some instances charging data is available intermittently, due to holidays, service, or possibly the temporary use of a different card or of unmetered charging points. All in all, extensive filtering and validity checking is necessary to select reliable series of data for the electricity consumption calculation.

The first step is to filter the electric vehicles in the database for the presence of at least two odometer readings.

Subsequently, implausible charging data are removed. To this end, for each vehicle brand, model and version ('uitvoering' in RDW vehicle registration data) a net usable battery capacity was determined. Data on battery capacity were retrieved from several sources (ev-database.nl, autoweek.nl, manufacturer specifications, RDW data, and Wikipedia). Considering charging losses, and taking an additional margin, charging events larger than 1.25 times the battery capacity of the car are removed. The correctness of the battery capacities was verified by checking the frequency of the occurrence of charging events exceeding the factor 1.25 rule for individual models/versions.

Starting point for determining the electricity consumption of individual EVs is clustering of the recorded charging events which are most likely subsequent, i.e. not interrupted by unregistered charging events. This is done by setting a maximum allowed gap between two charging events, which is dependent on the average charging frequency of the user and the length of the charging event sequence so far. Sequences are considered valid if they comply to two criteria: a) it spans a period of at least 14 days, b) it consists of at least 10 charging events.

The kilometres to be associated with the total electricity consumed in a sequence of charging events are then determined by matching odometer readings with the sequence. For this purpose a graph was plotted for each vehicle with at least two odometer readings (available for almost 6,300 vehicles). Two approaches are followed.

Approach 1 is illustrated in Figure 1-2, using a real-world case. Two sets of odometer readings and -dates are used (orange in the graph), one close to the start date of a charging sequence, and one close to the end date of this charging sequence. In the illustration these are plotted as orange dots on the left bottom and right top of the graph. The charging sequence is plotted as a row of blue dots. To align the kWh-data and odometer data in time, the cumulative kilo-Watthour-level is predicted on the dates of the odometer readings. To this end, the two closest charging samples are extrapolated (or interpolated) towards the date of the odometer reading.

In the illustrated case, extrapolation was needed, because the odometer reading dates were outside the date range of the charging sequence.
The extrapolation is indicated by small green lines. Now the data are time aligned, the calculation is simple: the electricity consumption equals ΔkWh / Δkm.

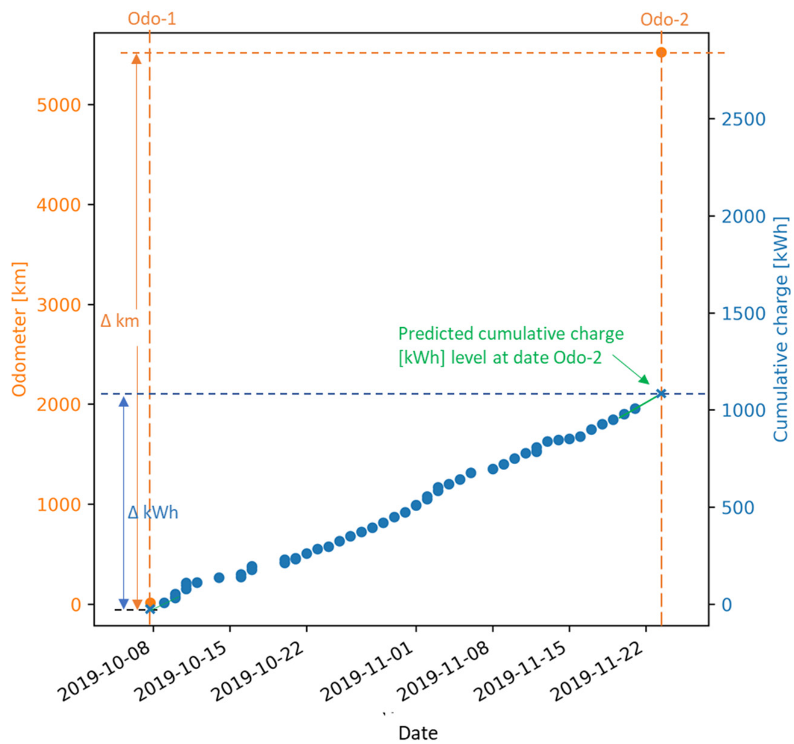

Figure 1-2: Example of approach 1 to determine electricity consumption per km.

If this approach does not succeed for a particular vehicle, for instance because the odometer readings are too few, approach 2 is attempted. Approach 2 determines the slope (in cumulative kWh) of the longest sequence of a vehicle and the slope of the odometer readings. For both the regression coefficient must be over 0.9 to be considered valid. In other words, if there are more than two odometer readings, the annual mileage of the vehicle has to have been more or less constant to be valid for this approach. Also, a minimum of 3000 km must be covered, and a minimum of 25 charging events. The electricity consumption determined with this method equals kWh/year / km/year.

Approach 2 is illustrated in Figure 1-3.

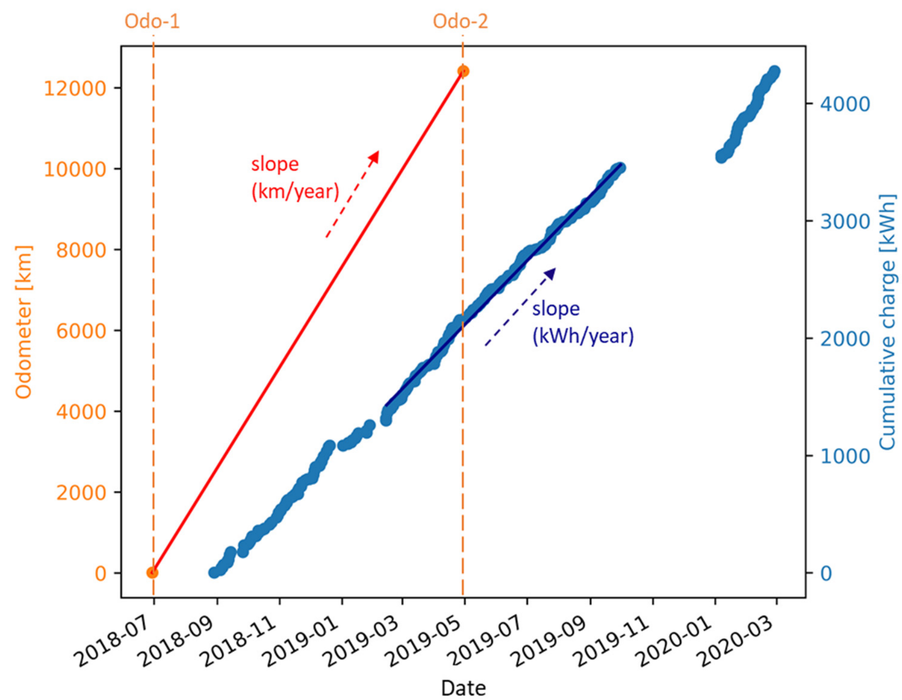

Figure 1-3: Example of approach 2 to determine electricity consumption per km.

The procedures described above yielded 7,010 sets of charging data-distance combinations for 6,287 vehicles.

Further filtering is done in two steps. First, for each vehicle a lower limit of energy consumption was calculated, being 70% of a calculated kWh/100 km-value derived from the WLTP value of the vehicle. All results below this threshold are removed. Secondly, for each vehicle an initial average and standard deviation is calculated for its energy consumption. All results outside two times the standard deviation are removed. Also, results over 40 kWh/100 km are removed. The remaining results are averaged per vehicle brand and model (every vehicle has an equal weight), and for some vehicles the version as well. Only vehicle models with ten valid observations (sequences) or more are included in the results. Models with too few valid results, in other words with too few cars with valid results in the database, are left out. This includes some models that are new on the market.

1.4 Representativeness of the results

Because the data was derived from tank passes and charge passes, which are commonly used by drivers of leased cars, it is useful to see how the use patterns relate to the Dutch average car use. The vehicles in the Travelcard fleet have a high average annual mileage compared to the Dutch fleet, which may mean a higher share of highway kilometers and thereby possibly a bias towards higher fuel consumption. However, the distribution of annual mileages in Figure 1-4 shows that the spread is large: a considerable share of vehicles are driven less than 20,000 km per year.

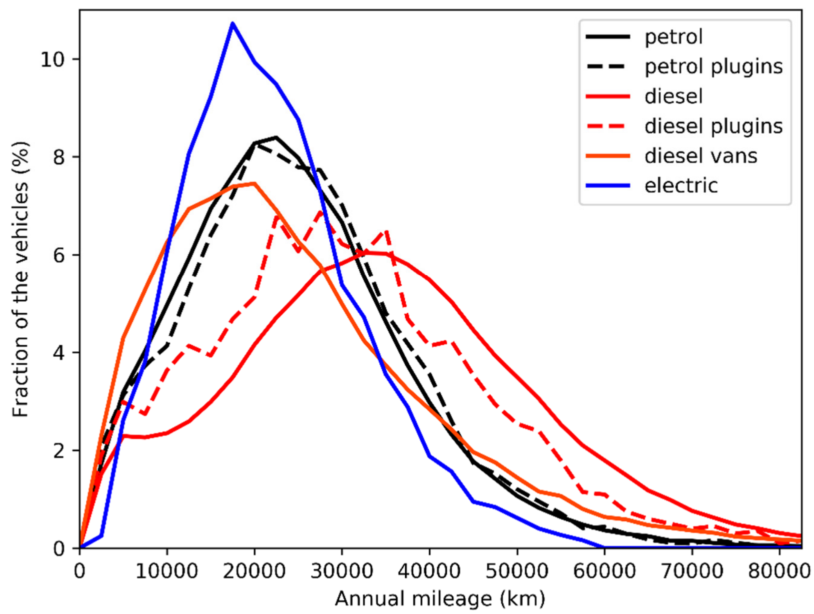

Figure 1-4: Distribution of annual mileages in the Travelcard database, per fuel/drivetrain-combination.

Table 1-2 shows the average annual mileage for the Travelcard data in this report, and the average annual mileage of the Dutch fleet, for each fuel/drivetrain separately. The average annual mileage of young vehicles in the Dutch fleet is shown separately, because the Travelcard database contains a moving fleet of mostly relatively new vehicles. Because the Travelcard dataset contains not only data for the last year, but also for all the years before (since 2004), the reference for the Dutch fleet was selected to be 2019, a relatively normal year before the influence of Covid-19.

Also shown is the most common mileage in the Travelcard data; for every fuel in the table this value is lower than the average mileage, which means that a group of high-mileage drivers inflates the average. This is indeed visible as a 'tail' in Figure 1-4.

For all fuels/drivetrains in the table the decline in average annual mileages has continued in 2020/2021, probably also reinforced by the lockdown for Covid-19.

The battery-electric vehicles in the dataset drive on average about 15% less than the petrol cars in the dataset. However, this is influenced by the fact that most of the charging data for electric vehicles is recent, which means that the lockdown has a larger relative (downward) effect on the numbers for this category.

The table has an extra entry for battery-electric vehicles, shown as '*Battery electric NL*'. This one shows the average and most common mileage for all 78,000 electric vehicles in the Netherlands that have at least two odometer readings that are at least half a year apart. This row was added to show that the average annual mileage seems to have increased considerably since 2019.

The small differences between the entries “Battery electric” and “Battery electric NL” show that the dataset for electric cars is representative for the Dutch fleet in terms of mileage.

Table 1-2: Annual mileages per fuel/drivetrain-combination

		Average annual mileage (km)				
	Most common, modal annual mileage (km)	**This report (2021)**	**2020 report**	**2018 report**	**Nether-lands 2019 [CBS]**	**Nether-lands 2019, 0-4 years [CBS][3]**
Petrol	22,500	23,600	24,700	26,700	10,900	17,000
Petrol plug-in	20,000	24,200	24,700	33,900	22,600	22,800
Diesel	32,500	33,900	34,600	37,600	22,500	35,500
Diesel plug-in	27,500	29,400	30,100	40,200	N/A	N/A
Battery electric	17,500	21,300			13,500	19,500
Battery electric NL	15,000*	20,500*			13,500	19,500
Diesel van	20,000	24,400	25,100		N/A	N/A

*) Based on the part of the Dutch EV fleet for which enough odometer data was available to calculate an annual mileage (77,945 vehicles).

[3] Vehicles with age 0, 1, 2 or 3 years. To calculate an average, the CBS data for vehicles age 0 is scaled up to a full year by dividing by 0.55. This does not correct for irregularities in sales over the year due to e.g. changes in tax regime.

2 Real-world fuel consumption of passenger cars

2.1 Introduction

This chapter shows trends in the real-world fuel consumption/CO_2 emissions of passenger cars, based on the Travelcard tank pass database. In the first part of the analysis the data is grouped by fuelling date, meaning that the results are averages over the entire fleet of vehicles present in the database for that year/month.
The second part of this chapter shows trends that can be observed when vehicles are grouped by registration year of the vehicle.

The fuel consumption and the tailpipe CO_2 emissions are directly related. Hereafter, only graphs for CO_2 emissions are displayed. The numbers can however be converted into fuel (l/100 km) using the factors mentioned in paragraph 1.3.

2.2 Real-world consumption by fuelling date

The trend of the average real-world and type approval CO_2 emissions per kilometre for all petrol and diesel passenger cars in the database is shown in Figure 2-1 and Figure 2-2. Figure 2-1 shows the recent trend for vehicles that were type approved under the WLTP regulation. Figure 2-2 shows the trend for vehicles for which an NEDC type approval value is available[4].

Comparing the graphs it is clear that the WLTP type approval values are on average quite a bit higher than the NEDC type approval values, and therefore closer to the average real-world emissions. At the same time, the average real-world emissions of WLTP approved cars have decreased more than the type approval values (Figure 2-1), reducing the gap a bit more. Figure 2-3 shows that the gap is reduced to around 15% for petrol and around 10% for diesel.

The reduction in real-world emissions in recent years is likely to be at least partially related to reduced congestion due to Covid-19, and/or an effect of the daytime highway speed limit of 100 km/h that was enforced from March 16, 2020.

A noteworthy point to make about Figure 2-2 is that the average WLTP CO_2 emissions of the considered vehicle group are almost equal for petrol and diesel vehicles. For NEDC, this has never been the case throughout the period 2004-2021, although the difference between the two has decreased in recent years.

[4] NEDC or NEDC2.0 (calculated from WLTP). Note that although the WLTP average is also plotted in the graph for reference, it cannot be directly compared to the NEDC average, because WLTP covers only a subset of the vehicles.

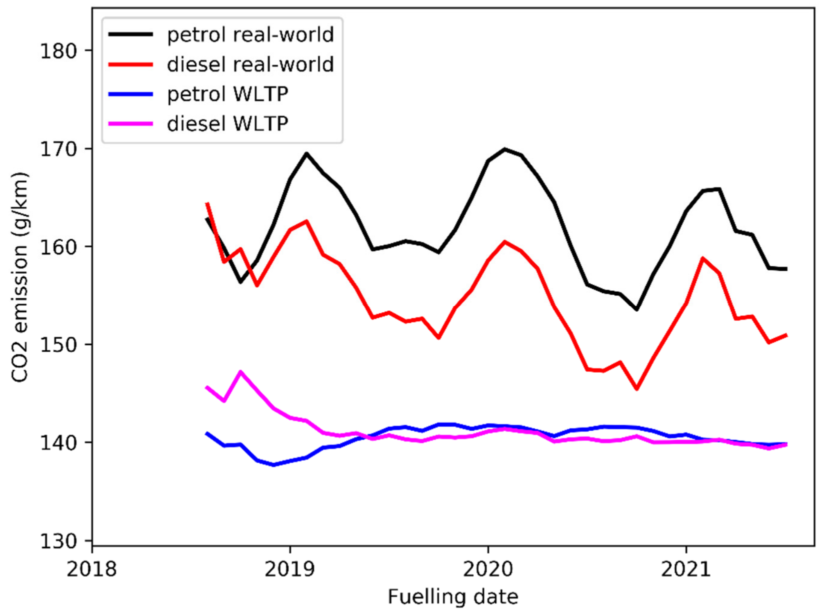

Figure 2-1: Average real-world and WLTP type approval tailpipe CO_2 emissions of WLTP approved conventional and non-plug-in hybrid petrol and diesel vehicles in the database.

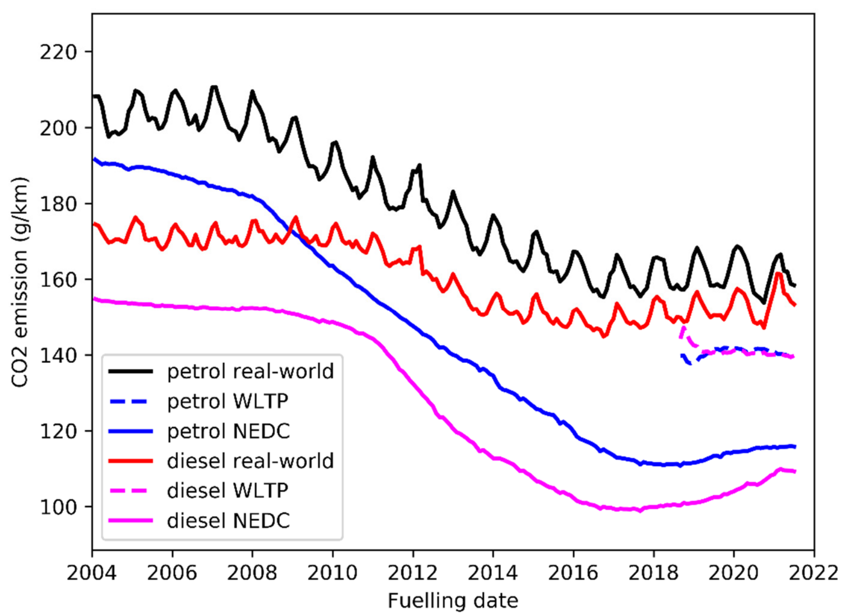

Figure 2-2: Average real-world and NEDC & WLTP type approval tailpipe CO_2 emissions of all conventional and non-plug-in hybrid petrol and diesel vehicles in the database. Note that the WLTP lines are plotted just for reference; these represent a subset of (newer) vehicles only.

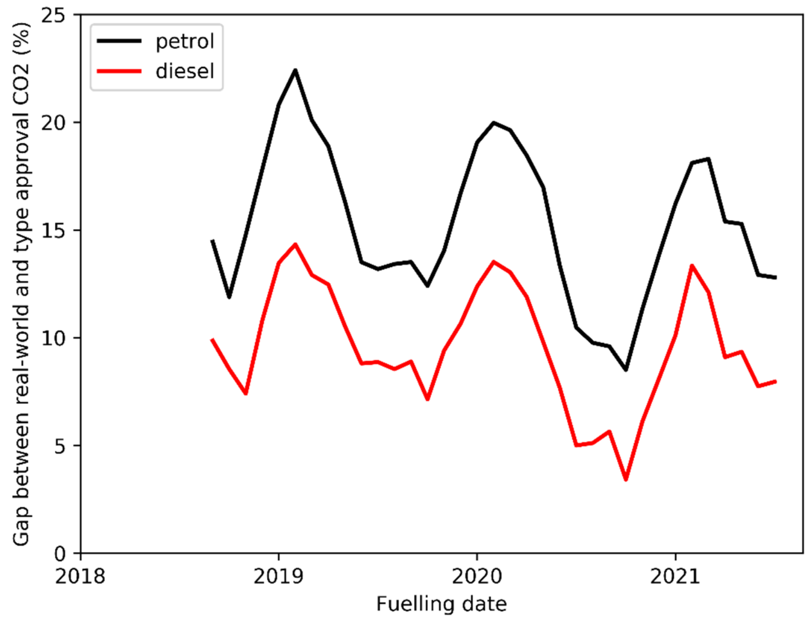

Figure 2-3: Type approval to real-world CO_2 gap for WLTP approved conventional and non-plug-in hybrid petrol and diesel vehicles

For plug-in hybrids the trends in real-world and type approval CO_2 emissions are shown in Figure 2-4 for WLTP type approved vehicles, and in Figure 2-5 for all (passenger) vehicles in the database.

In contrast with non-plug-ins, the average type approval values of plug-ins have not changed much during the change from the NEDC to the WLTP regime. This is despite the changes in the test procedure and calculations. Furthermore, vehicles may have been updated with a larger battery before the WLTP type approval occurred.

The average real-world emissions of both petrol and diesel plug-ins hover around 150 g/km: not much lower than the average for non-plug-ins in Figure 2-1.
The gap with the average type approval rating is therefore large, as can be seen in Figure 2-6.

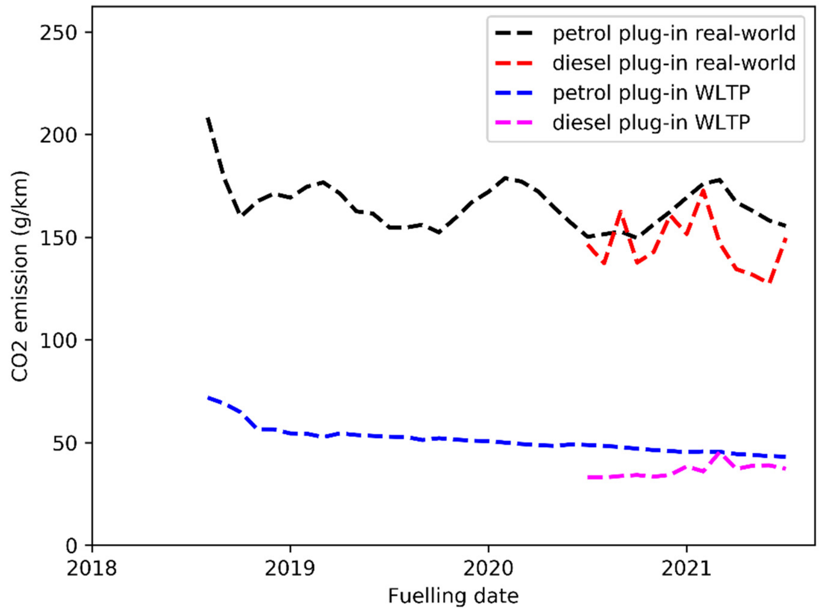

Figure 2-4: Average real-world and WLTP type approval tailpipe CO_2 emissions of WLTP approved plug-in hybrid petrol and diesel vehicles in the database.

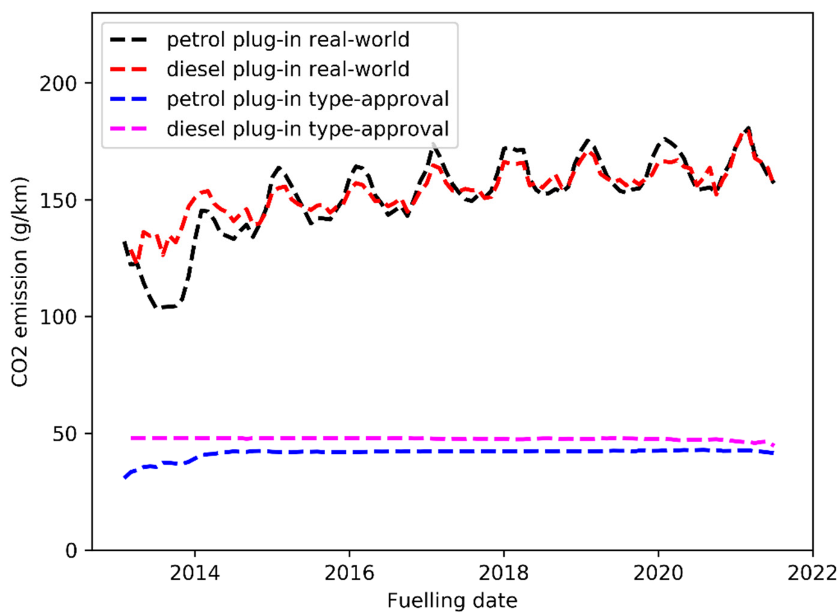

Figure 2-5: Average real-world and NEDC type approval tailpipe CO_2 emissions of all plug-in hybrid petrol and diesel vehicles in the database.

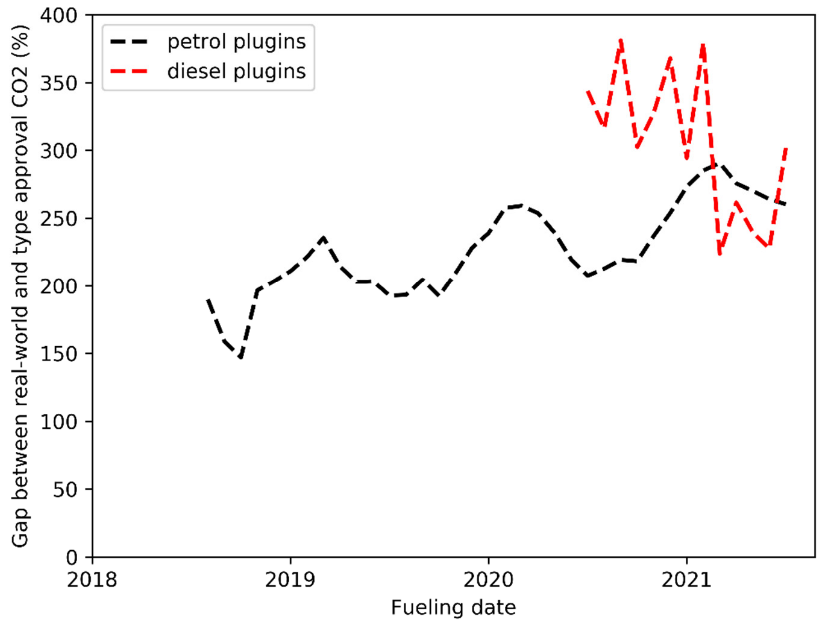

Figure 2-6: Type approval to real-world CO_2 gap for WLTP approved plug-in hybrid petrol and diesel vehicles

2.3 Real-world consumption by vehicle registration year

The developments on the level of the complete fleet as described above are largely determined by the developments in new vehicles. To analyse these developments, the fuel consumption data was regrouped by the registration year of the vehicles. For each vehicle the fuel consumption was averaged over the entire duration it was part of the Travelcard fleet, and the value was attributed to its year of first registration.

The analysis focuses on the most recent trends, i.e. the developments since the changes in type approval procedure were effectuated in 2017. This means that hereafter the analysis is done only on WLTP approved vehicles. The analysis of NEDC-based vehicles can be found in the previous report[5].

New passenger cars in the year 2020 had average real-world CO_2 emissions of 156 g/km (petrol, including (plug-in) hybrids) and 164 g/km (diesel, including (plug-in) hybrids. These numbers were approximately the other way around in last year's report, reporting on 2019: 163 and 158 g/km for petrol and diesel respectively. At least two factors play a role here: the calculated result for the fuel consumption of new cars is not stable yet in the data, and the consumption of diesel vehicles in the Travelcard fleet has increased fast over the last few years (from 153 g/km in 2018, through 158 g/km in 2019, to 164 g/km for cars registered in 2020). In the next chapter it is demonstrated that mass is a large factor in that increase.

[5] Real-world fuel consumption of passenger cars and light commercial vehicles, TNO report 2020 R11664, 30 October 2020.

In Figure 2-7 the evolution of the gap between real-world and type approval CO_2 emissions is shown across the registration years. This is done for WLTP approved vehicles, which started to come onto the market in significant numbers in 2018. As concluded in the previous paragraph, the gap is smaller than was the case with the old, NEDC-based type approval numbers. The trend, however, seems to be upwards: the real-world emissions show a slight upward trend, while the type approval values actually decreased slightly, leading to a gap of almost 25 g/km for petrol and just under 20 g/km for diesel in 2020. Figure 2-8 shows the numbers excluding plug-in hybrid vehicles. From a comparison of the graphs it can be derived that the low type approval value for petrol vehicles in 2020 compared to the previous years, and thereby the increased gap, is mostly caused by inflow of plug-ins. The fact that the real-world emissions did not decrease at the same time can be explained from the high real-world emission of these plug-ins (see Figure 2-6). For diesels, the small number of plug-ins have no real influence on the numbers.

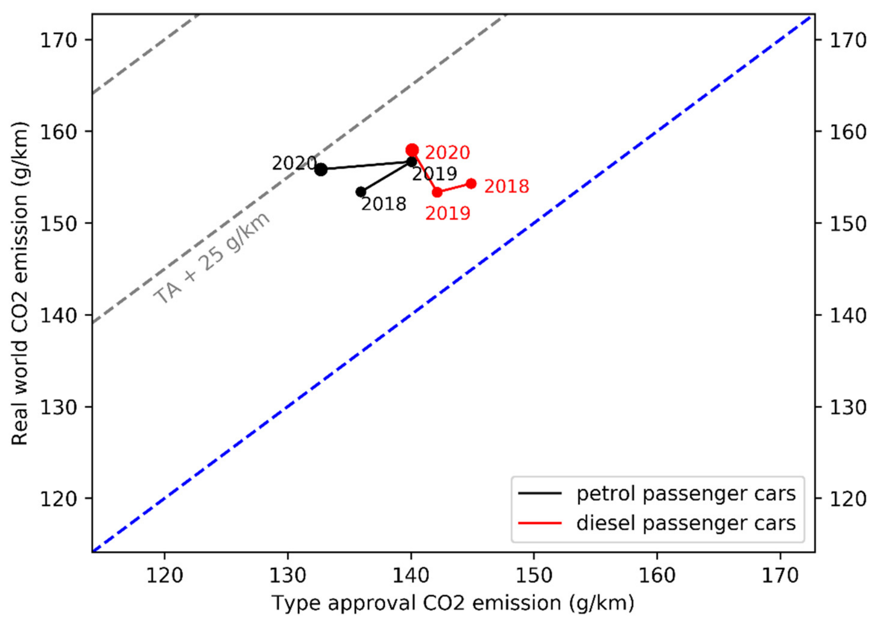

Figure 2-7: Average real-world CO_2 emissions versus the average WLTP type approval values of new petrol and diesel cars, including plug-in hybrids, differentiated by the year of registration.

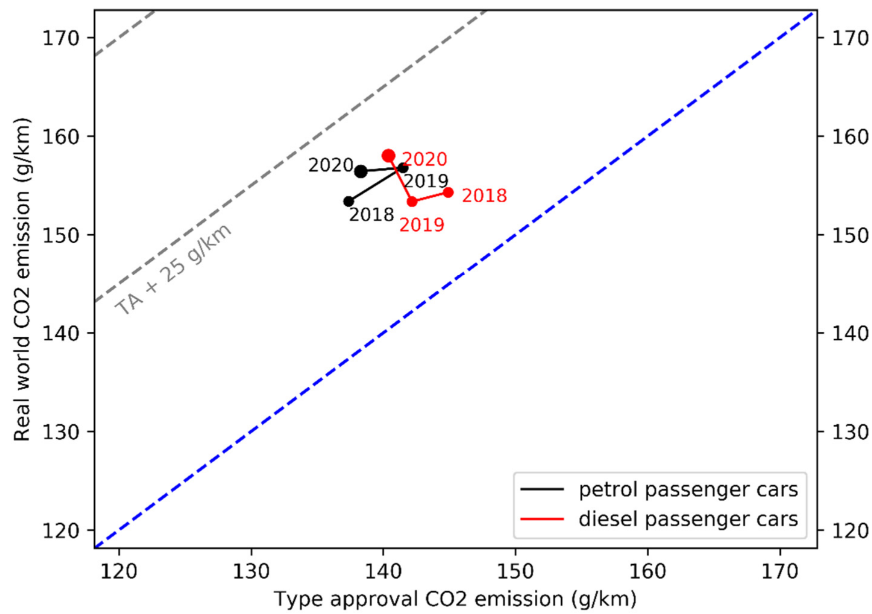

Figure 2-8 Average real-world CO_2 emissions versus the average WLTP type approval values of new petrol and diesel cars, excluding plug-in hybrids, differentiated by the year of registration.

New petrol plug-in hybrids in 2020 have an average real-world tailpipe CO_2 emission of 147 g/km; that is 104 g/km higher than the average WLTP type approval value of 43 g CO_2/km. Thereby the relative gap is around 240%.

3 Trends

3.1 Introduction

Using the same dataset, an analysis was made of some trends that are relevant for understanding the observed development in real-world emissions. One of the main factors influencing the differences in average fuel consumption among different registration years, is vehicle mass. A higher mass leads to larger rolling resistance and, although to a lesser extent for hybrids, higher braking energy losses. From modelling work[6] it was observed that mass generally also correlates well with the frontal area of a vehicle, which influences the fuel consumption on the highway to a large extent.

Other factors such as improvements in drivetrains, aerodynamics and tyres also influence the trends in chapters 2, 5, and 6 as well, but this chapter focuses on mass aspects only.

3.2 Mass trends

The development of vehicle mass is visualised in Figure 3-1 and Figure 3-2 for petrol and diesel vehicles in the database, including (non-plug-in) hybrids. The real-world fuel consumption trend is shown as well for reference. The two y-axes of the graphs do not start at zero, but have equal ratios between top and bottom. A difference in angle of the two lines indicates a change in fuel consumption per kg of vehicle mass. The next graphs will further detail the fuel efficiency trends.

After a decrease in mass since 2010 the mass trend of petrol cars is upwards again after 2016. The relative increase in fuel consumption is much smaller.

[6] Work carried out in the LIFE+ MILE21 project (LIFE17 GIC/GR/000128); the full report D C 3.1 is available at https://www.mile21.eu/project/activities.

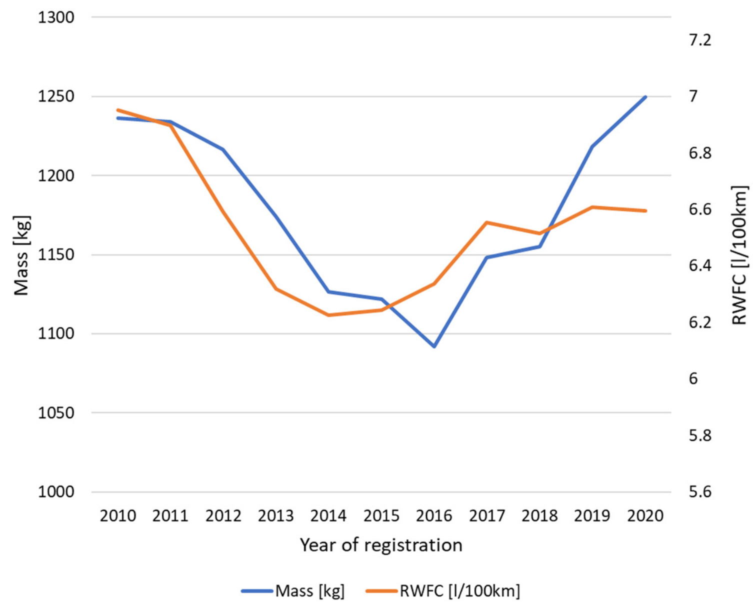

Figure 3-1: Trend of average vehicle mass and real-world fuel consumption per registration year for petrol passenger cars (incl. hybrids, excl. plug-in hybrids).

For diesel passenger cars (Figure 3-2) mass and fuel consumption increases have gone hand in hand since 2015. The average mass of diesel cars in the database has increased by 15% since 2015.

Figure 3-2: Trend of average vehicle mass and real-world fuel consumption per registration year for diesel passenger cars (incl. hybrids, excl. plug-in hybrids).

Diesel vans have become more efficient, especially in the last few years, see Figure 3-3. The variations, however, are relatively smaller than for passenger cars (note that the scale on the y-axis is much smaller than that of the graph for diesel passenger cars).

Figure 3-3: Trend of average vehicle mass and real-world fuel consumption per registration year for diesel vans (excl. plug-in hybrids).

3.3 Fuel consumption per ton

If the mass evolution and the trend in real-world fuel consumption are combined, it is possible to visualise the improvements in vehicle efficiency across the registration years. The trends in the other chapters of this report are influenced by both the mass trend (previous paragraph) and the efficiency trend.

The mass-independent efficiency gain is shown by dividing the fuel consumption by the mass of the vehicle; this results in a fuel consumption in litres per 100 km per ton of empty vehicle mass. Figure 3-4, Figure 3-5, and Figure 3-6 show the average real-world fuel consumption per ton of vehicle mass (empty), for petrol passenger cars, diesel passenger cars, and diesel vans, of different empty mass categories. In the graphs, every group of vehicles of a certain mass range is plotted separately, to show the differences over time. Hybrids and plug-in hybrids are included in the graphs.

The declining lines in the graphs show that generally newer vehicles consume less fuel than older vehicles with the same empty mass. This is least profound for diesel passenger cars, probably because the most important efficiency gains were made in the period before 2010. For petrol the improvement is largest for the lightest cars. For vans, the newest vehicles are indeed the most efficient in all mass categories. Note that the <=1100 kg-line first inclines steeply, and then disappears; this is due to the fact that vans of this mass category disappeared from the market.

In all three graphs, the lightest vehicles have the highest specific fuel consumption, which means that the fuel consumption is less-than-proportional to mass. However, this levels out; the lines for the heavier categories are closer together. For petrol up to 2017 the vehicles with the lowest mass specific fuel consumption are not even the ones in the heaviest category, but the ones of 1300-1500 kg. This is because of the high share of hybrids.

Some trends in the graphs can be explained from the influence of changes in tax regulations in the Netherlands on the sold fleet composition. For instance, further analysis pointed out that in the years 2012-2015 also non-hybrids were relatively efficient, which holds for both petrol and diesel. To illustrate the impact of different driveline shares, Figure 3-7 is introduced.

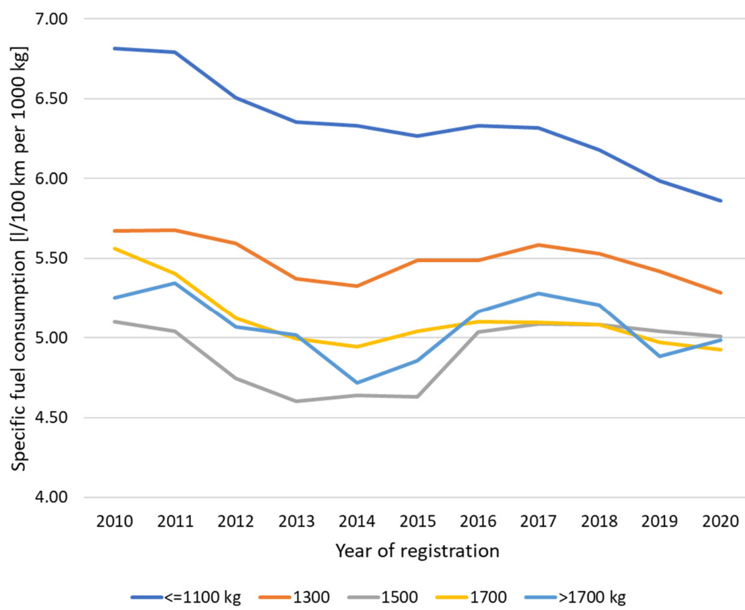

Figure 3-4: Mass specific fuel consumption of petrol passenger cars, including plug-ins, per mass category

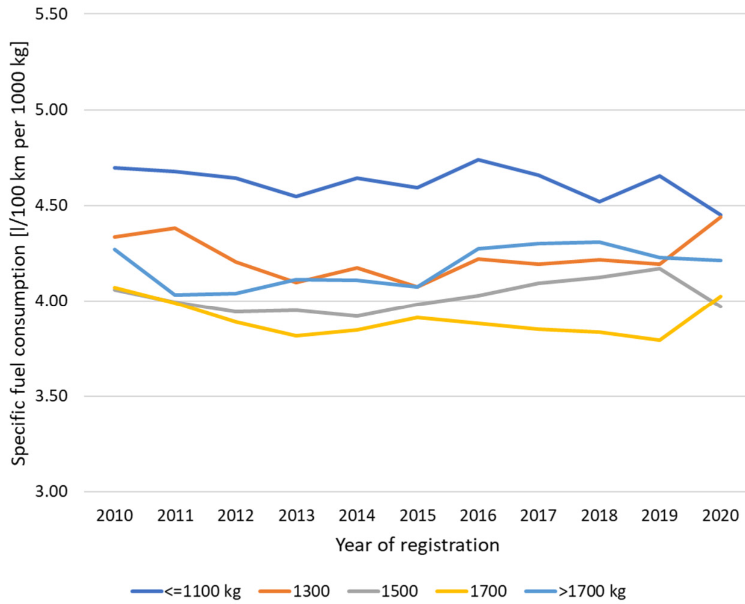

Figure 3-5: Mass specific fuel consumption of diesel passenger cars, including plug-ins, per mass category

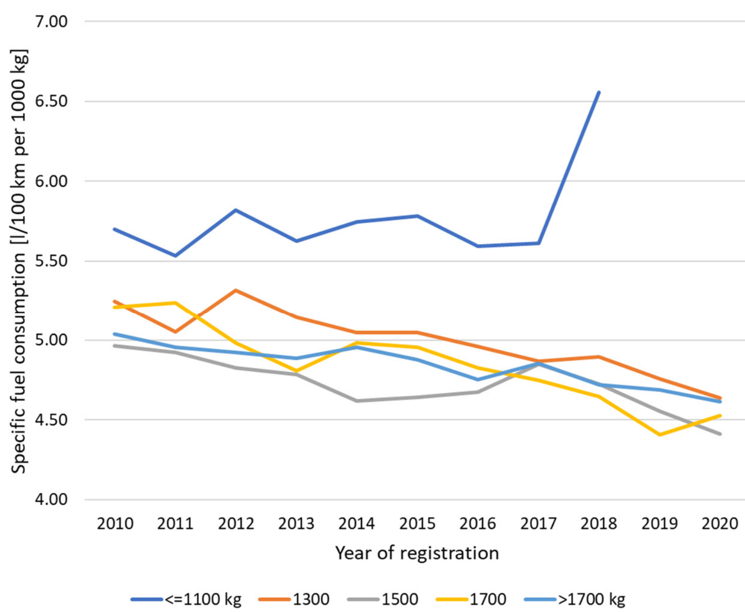

Figure 3-6: Mass specific fuel consumption of diesel vans, per mass category

Figure 3-7 shows the number of passenger cars present in the Travelcard database, split per registration year, per fuel and per drivetrain type. For the diesel-line it is important to recognize that the inflow diminished in 2020, and that the drop in 2016 coincides with dropping the 14%-ruling for cars with low NEDC CO_2 value (end of 2015).

Judging from the previous graphs, the diesels sold in the years before that were not only lower on NEDC CO_2, but more economical in the real world as well. For petrol it is slightly more complex. Plug-in sales peaked in 2015, just before the 0% tax liability was stopped, but non-plug-in petrol sales (to Travelcard customers) already dropped considerably in 2013. Apparently the remaining non-plug-ins sold were relatively efficient as well.

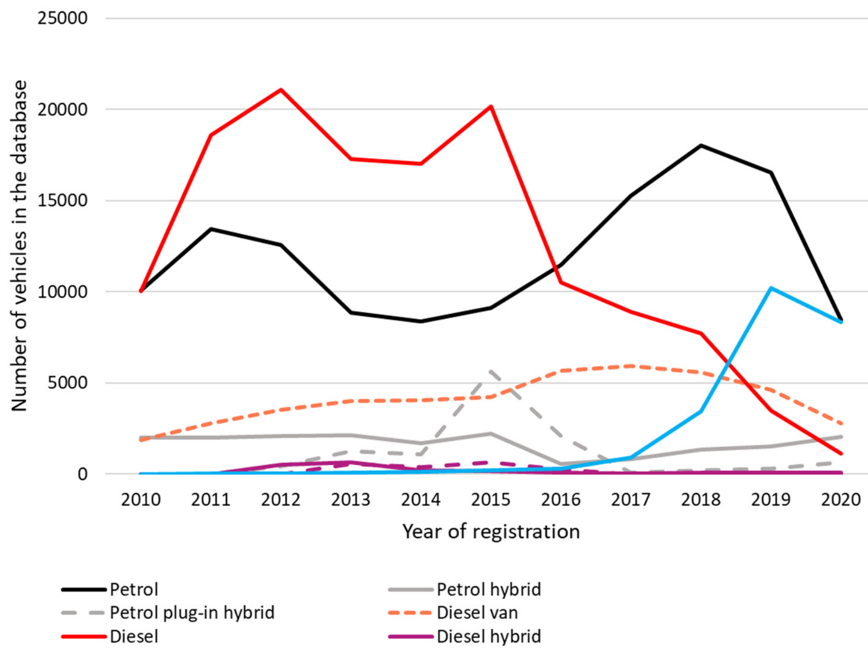

Figure 3-7: Number of passenger cars of every registration year in the Travelcard database

3.4 Power-to-mass ratio

Based on the Travelcard database, a fuel consumption prediction model was made, which uses just fuel type, empty mass, year of first registration and engine power as inputs[7]. During the development of the model it became apparent that some vehicles have a much higher fuel consumption and CO_2 emission than expected. Besides mass and mass per ton of empty mass, the relative engine power is also of importance to understand real world emissions.

For most vehicle models, the average fuel consumption can be predicted quite well using just fuel type, empty mass and registration year (as a proxy for build year) of the vehicle. For some individual vehicle models, the average real-world fuel consumption was found to be quite different than the average of vehicles with similar parameter values. One of the factors observed to have a large influence for some models is the power-to-mass ratio. In theory, an oversized engine has a relatively low efficiency in normal operation, because losses are partially independent of the delivered power. If the engine operates at a low load, the share of these losses is large. For underpowered vehicles, the opposite should be the case, which could make them run more efficiently than average.

[7] Work carried out in the LIFE+ MILE21 project (LIFE17 GIC/GR/000128); the full report D C 3.1 is available at https://www.mile21.eu/project/activities.

In the real world there are more factors in play however, not in the last place related to differences in driver input for different cases, so the actual effect is difficult to predict.

In Figure 3-8, the deviation of real-world CO_2 emissions from model prediction is plotted as a function of the power-to-mass ratio. The graph includes all passenger cars and vans in the Travelcard database. Each dot represents a group of vehicles with similar mass and engine power. The semi-transparent lines indicate the number of vehicles (frequency distribution) across the power-to-mass range. These show that most vehicles are in the range of 50-90 kW/tonne.

The light orange line also reveals that there is still a significant group of diesel vehicles with a power-to-mass ratio below 50 kW/tonne. These are small diesel passenger cars, and a category of vans with relatively low power engines. This category of vans is slowly disappearing, but was the standard around 20 years ago, in terms of power/mass ratio. The orange dashed line is the suggested model adaptation to correct for low-powered diesels; it reaches up to 50 g CO_2/km for diesels with 30 kW/tonne.

The scattered cloud of blue dots on the right-hand side of the graph represents mostly sportscars, and some high-power SUVs. The number of vehicles of this category in the dataset is rather small though. The dashed blue line indicates the model adaptation for high-power petrol cars.

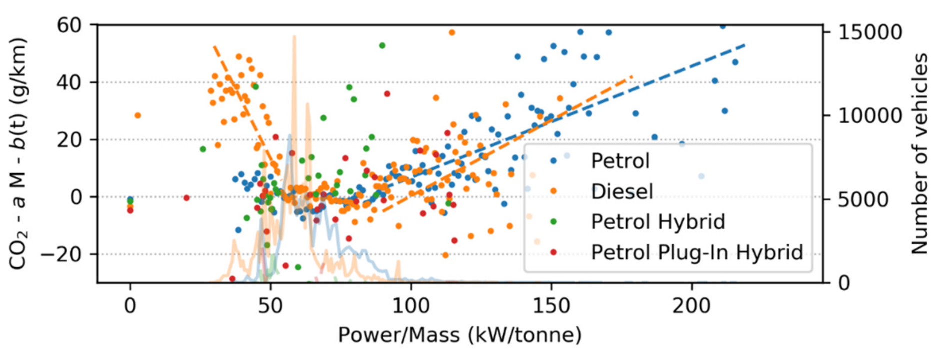

Figure 3-8: Deviation of real-world CO_2 emissions from the prediction model calculation, as a function of the power-to-mass ratio. Every dot is a bin of vehicles with similar mass and power.

In the same project a second model was designed, that can fine-tune (or personalise) the fuel consumption prediction of a vehicle based on information about the use pattern and -conditions. It is described in deliverable D C3.2 and can be downloaded here as well: https://www.mile21.eu/project/activities.

4 Real-world electricity consumption and hydrogen consumption of battery-electric and fuel cell passenger cars

4.1 Introduction

As described in paragraph 1.3, real-world electricity consumption of electric vehicles has been monitored by combining charging sessions data with odometer readings for each full electric car in the Travelcard fleet. Note that charging sessions include home charging as well as public fast and regular charging. Vehicles with intermittent charging patterns were rejected from the dataset. Most vehicles monitored last year are still in the fleet, and many new electric vehicles entered the fleet since the analysis for the last report. Therefore the amount of available, usable data has doubled. In total 9,659 series of charging events of 8,461 unique vehicles were available for deriving the electricity consumption per vehicle model. Charging data were available up to 31 May 2021 and are expressed in paid kilowatt hours (kWh). The 9,569 series were further filtered for outliers (see paragraph 1.3), after which 7,010 series of charging events were considered valid and used for further analysis (6,287 unique vehicles).

Because the data in this chapter were derived from paid kilowatt hours, the following energy consumption items are included as well:

- Charging losses. These may vary from model to model and from charger to charger.
- Conditioning of the vehicle interior while connected to the charger. Most electric vehicles have a built-in timer that allows pre-heating and -cooling of the interior before the time the user sets to depart.
- Conditioning of the battery while connected to the charger. Almost all electric vehicles cool the battery when necessary during charging. The higher the charging speed, the larger the (relative) heat production. Some vehicles also prevent the battery from freezing in the winter.

These numbers are not included in the dashboard readings (they don’t affect the range), and the last two are not considered in the official WLTC energy consumption values either.

The last paragraph of this chapter shows the first results of the average hydrogen consumption of fuel cell electric passenger cars.

4.2 Average electricity consumption per model

Table 4-1 shows the average electricity consumption, as well as the number of observations (series of charging events) and the standard deviation. Vehicle models having less than 10 observations were not further analysed. In some occasions vehicle model variants could be distinguished, e.g. for the different versions of the Nissan Leaf. When the next report in this series is due, the amount of data as well as the completeness of RDW registration data is expected to be sufficient to distinguish variants for most vehicle models.

Table 4-1: Average electricity consumption per brand and model.

Brand	**Model**	**Series of charging events**	**Unique vehicles**	**Average [kWh/100 km]**	**Standard deviation**
Audi	E-Tron	427	380	27.3	6.1
Azure Dynamics	Transit Connect Electric	=<10	=<10		
BMW	I3	241	204	17.8	4.4
BMW	I3S	59	49	18.4	4.3
Citroen	C-Zero	=<10	=<10		
DS	DS3 Crossback	=<10	=<10		
Fiat	500E	=<10	=<10		
Ford	Focus Electric	=<10	=<10		
Hyundai	Ioniq	406	364	16.1	3.7
Hyundai	Kona	736	658	17.3	4.0
Jaguar	I-Pace	190	167	26.3	7.2
Kia	Niro	641	614	18.0	3.9
Kia	Soul	22	17	21.1	6.7
Lexus	UX300E	=<10	=<10		
Maxus	EV80	=<10	=<10		
Mazda	MX-30	=<10	=<10		
Mercedes-Benz	B 250 E	22	17	20.7	6.1
Mercedes-Benz	EQC400 4Matic	23	22	25.8	6.6
Mercedes-Benz	eVito	=<10	=<10		
MG	ZS EV	42	42	18.1	6.8
Mini	Cooper SE	13	12	17.2	4.0
Mitsubishi	i-MiEV	=<10	=<10		
Nissan	E-NV200	60	55	25.4	5.1
Nissan	Leaf	90	87	20.6	5.5
Nissan	Leaf 40Kwh	307	274	18.8	4.6
Nissan	Leaf 62Kwh	140	124	21.3	4.9
Opel	Ampera-e	182	165	19.9	4.9
Opel	Corsa-e	24	24	23.7	5.7
Opel	Vivaro-e	=<10	=<10		
Peugeot	e-208	32	32	22.4	5.8
Peugeot	e-2008	45	44	22.8	3.5
Peugeot	Ion	=<10	=<10		
Peugeot	Partner	=<10	=<10		
Polestar	2	82	82	28.4	5.8
Porsche	Taycan	=<10	=<10		
Renault	Fluence Z.E.	=<10	=<10		
Renault	Kangoo Express Z.E	22	21	21.2	5.2
Renault	Twingo	=<10	=<10		
Renault	Zoe	436	396	20.2	4.8

Brand	**Model**	**Series of charging events**	**Unique vehicles**	**Average [kWh/100 km]**	**Standard deviation**
Seat	MII	=<10	=<10		
Skoda	Citigo	=<10	=<10		
Smart	Fortwo ED	=<10	=<10		
Smart	EQ Forfour	28	26	19.5	5.4
Smart	EQ Fortwo	=<10	=<10		
Smart	Forfour ED	=<10	=<10		
Tesla	Model 3	1100	1014	19.2	4.8
Tesla	Model S	381	337	20.6	5.1
Tesla	Model X	70	70	24.8	5.7
Volkswagen	Crafter	=<10	=<10		
Volkswagen	Golf	769	608	17.4	4.0
Volkswagen	ID.3	299	288	23.5	6.2
Volkswagen	ID.4	33	34	24.6	5.0
Volkswagen	Up	42	28	17.9	4.5
Volvo	XC40	46	42	29.9	6.3

The standard deviations are included to illustrate that the variation among drivers of the same vehicle model is large. For electric vehicles the energy consumption per kilometre is relatively independent of speed for lower speeds, but increases with the square of the speed above 100 km/h, due to higher air drag at higher velocities. Therefore, the share of highway driving and the actual speed driven has a large influence on the average energy consumption.

In urban areas, brake energy recovery helps reducing the energy consumption. However, losses do occur, and frequent and heavy braking on any road can still increase the energy consumption. The use of airconditioning and heater influences the energy consumption as well, especially over short trips and at low speeds (more time per kilometre). Another factor that plays a role is the charging efficiency: for slow charging it varies from vehicle model to vehicle model. For fast charging, faster means higher losses.

For some models the electricity consumption has decreased significantly compared to the previous analysis. The amount of data has doubled, which means that the pool of drivers (use cases) for each model has changed quite a lot. Furthermore, it can be expected that insofar electric vehicles were driven at high speeds on the highway, the 100 km/h speed limit introduced in March 2020 should have had a large influence.

Figure 4-1 shows the vehicle models sorted by average real-world consumption. The top of the chart consists of SUVs and vans: tall vehicles with relatively unfavourable shapes in terms of aerodynamics. For large van models not enough data is available yet, but dependent on the speed driven, even higher values can be expected for these.

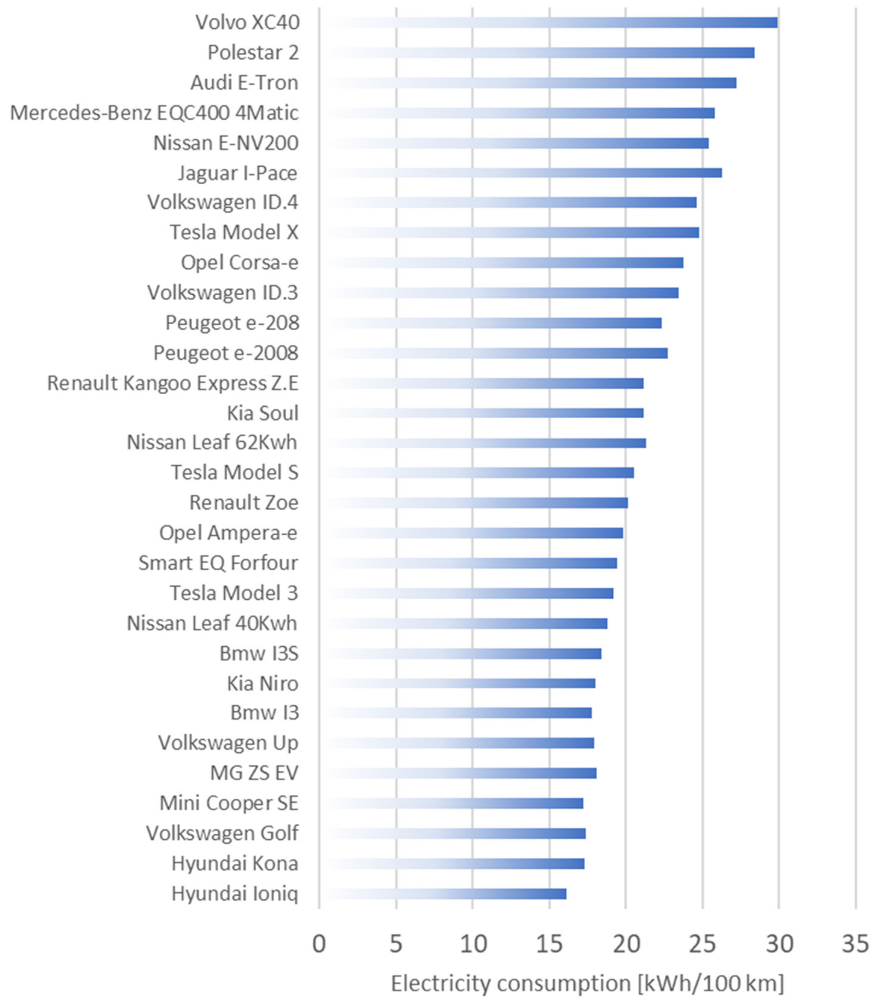

Figure 4-1: Average real-world electricity consumption per vehicle model, measured at the charger (includes charging losses).

The average electricity consumption of the 28 passenger car models in the graph is 20.2 kWh/100 km (weighted across the models). If accounted for the number of vehicles of each model on the road, the average for the present Dutch fleet (per August 2021) is 20.1 kWh/100 km. 85% of the electric vehicles in the Dutch fleet is one of the 28 models in the graph.

4.3 Comparison with WLTP declared values

The presented real-world electricity consumption values are generally higher than the values declared by the manufacturer under the WLTP regime. A per-model comparison is made in Figure 4-2.

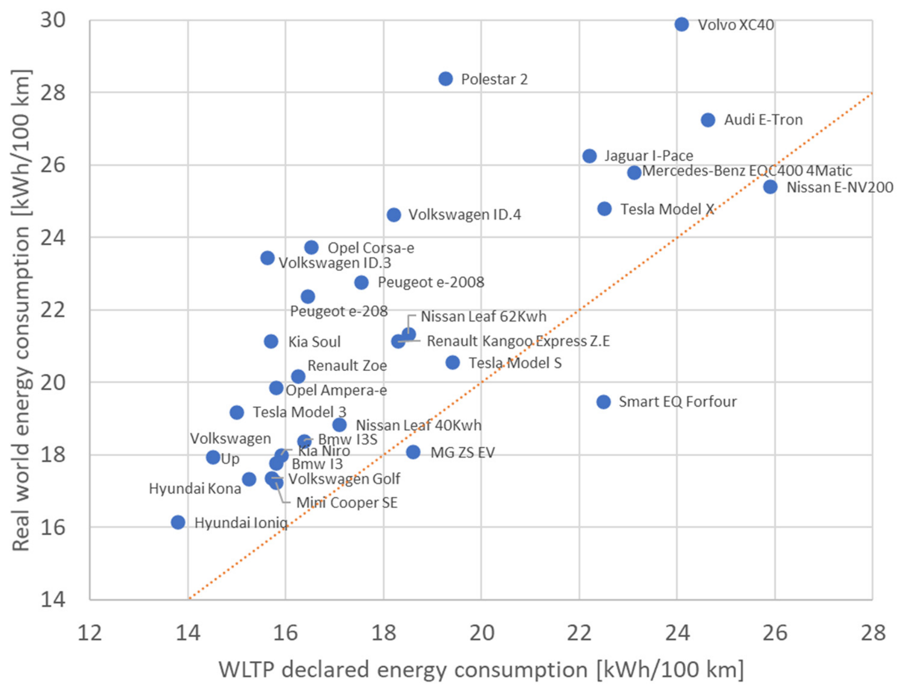

Figure 4-2: Comparison of real-world electricity consumption and WLTP declared values for full electric vehicles.

On average, the real-world value equals 1.19 times the WLTP declared value. This result is in line with the deviation between the WLTP and real-world energy use of conventional cars, but probably caused by different underlying issues. WLTP does include charging losses (AC charging).

In the graph, the vertical distance from a point to the red line indicates the difference between real-world and type approval. The difference between real-world and type approval energy consumption varies to a large extent from model to model. The MG ZS EV and the Nissan E-NV200 stay closest to the declared value, while the real-world energy consumption of the Smart EQ Forfour is lower than its WLTP value. The Polestar 2 has the largest deviation in an upward direction.

4.4 Prediction model

On the basis of the data in Table 4-1 and some additional properties of each vehicle model, a regression model was made that can be used to predict the average electricity consumption that can be expected from vehicle models that are not in the table. The best prediction could be made on the basis of mass, aerodynamic drag area and battery size (as an indicator for technological progress).

The following formula was drawn up:

$$RWEC_{vehicle\ model} = 0.00679 \cdot m + 11.09 \cdot CdA + 0.0063 \cdot c_{battery} + 1.29$$

With
RWEC = electricity consumption in kWh/100 km

m = mass in running order in kg
CdA = aerodynamic drag area in m^2 (Cd*A)
$c_{battery}$ = gross battery capacity in kWh (values as published by manufacturers)

The CdA-values used to develop the model were taken from manufacturer brochures and websites, or calculated from a Cd value provided by the manufacturer and a calculated frontal area. The information is not always official, and of an unknown accuracy.

For the Tesla Model 3, m is 1830 kg, CdA is 0.52 m^2 and c is 75 kWh. Filling these numbers in the formula results in a predicted average electricity consumption of 20.0 kWh/100 km. Note that also these calculated values are including charging losses and energy consumption for conditioning the vehicle and battery. The calculated value can differ from the one in Table 4-1, as a result of relatively efficient or inefficient technology used in a certain model, but also as a result of different behaviour of drivers of a certain model compared to the average. For instance, a larger range gives more freedom to drive faster on the highway. The average deviation of the model is 8%.

It is interesting to see how well the model predicts the energy consumption of the three outliers in Figure 4-2. For the Volvo, the model prediction is 11% lower than the real-world value, and for the Polestar even 16%. For the Smart the model prediction is close to the real-world value in Figure 4-2; possibly the declared WLTP value of this vehicle is too high.

The largest deviation of the model from the real-world average was for the Opel Corsa: the model prediction is 20% lower than the actual real-world value; for the technically equal (but slightly smaller) Peugeot e-208 it is still 16%.

The relative effect of the battery capacity as an indication of technological advancement is small. A larger battery increases the real-world electricity consumption (by a small amount). It is not clear what causes this (the higher mass of a larger battery is already accounted for in the mass factor), although a larger battery obviously gives more freedom to drive faster on highway trips.

4.5 Consistency of results

This is the third analysis of electricity consumption of electric vehicles done on the basis of charge pass data. The amount of available data has increased significantly. To see if that caused a trend in the results, the average consumption of several vehicle models was compared for the three reporting years, see Figure 4-3.

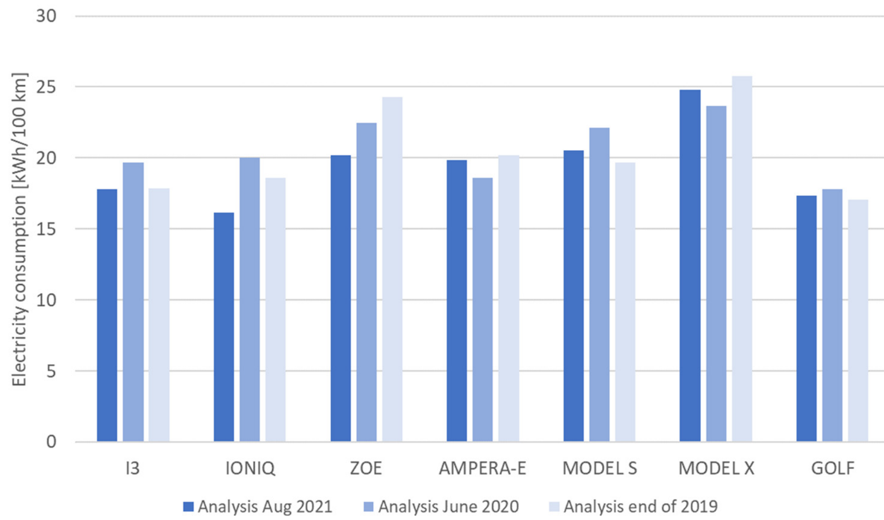

Figure 4-3: Evolution of results for models on the market for a longer period of time. The overall amount of data in 2021 is 2.8 times higher than in 2020, and 15 times higher than in 2019.

There is no clear upward or downward trend that applies to all models. However, the most significant changes were downward, for the Hyundai Ioniq and the Renault Zoe.

4.6 Charging losses

Within the Green Vehicle Index programme[8], detailed measurements were done on a number of electric vehicles. Amongst other things, the total losses were determined between the (AC) grid and the power output from the battery.
This includes the losses of the inverter and the losses in the battery during charging and discharging. The results are shown in Table 4-2. Note that the charging speed was not the same for the three vehicles, so the results are not entirely comparable; e.g. inverters work most efficient at (close to) their maximum power. Regardless, in all cases the losses were over 10%.

Table 4-2: Losses of charging plus battery charge/discharge cycle for seven electric vehicle models.

Vehicle model	Charging + battery cycle losses	Average charging power (kW)
Fiat 500	20.8%	N/A
Ford Mustang Mach-E	18.3%	N/A
Lexus UX 300e	10.3%	N/A
Nissan Leaf e+	16.4%	N/A
Volkswagen ID.3	10.8%	10.5
Hyundai Kona Electric	13.1%	3.6
Renault ZOE	19.4%	3.7

With an annual mileage of 15,000 km, a 10% loss equals approximately 9.5 GJ per year.

[8] https://www.gvi-project.eu

4.7 Annual mileage and energy consumption

Vehicles that cover large distances per year are likely to have a higher share of highway driving, and therefore a higher electricity consumption per km. On the other hand, when driving short trips or at low speeds, heating and airconditioning use can increase the energy consumption per kilometre a lot as well. An analysis was made for the most common vehicles in the database to see if there is a correlation between annual distance and energy consumption. Figure 4-4 shows the relation between the average electricity consumption and the annual mileage, for the five vehicles for which the most data is available in the charge pass database. Vehicles were grouped per 5000 km, e.g. all Hyundai Kona's with 15,000-20,000 km per year form one group. A marker is only placed in the graph if such a group has at least 5 observations (vehicles).

The graph reveals that, on average, the electricity consumption decreases with increasing annual mileages. This means that despite higher average speeds consumption is slightly lower. The downward trend is more or less constant.

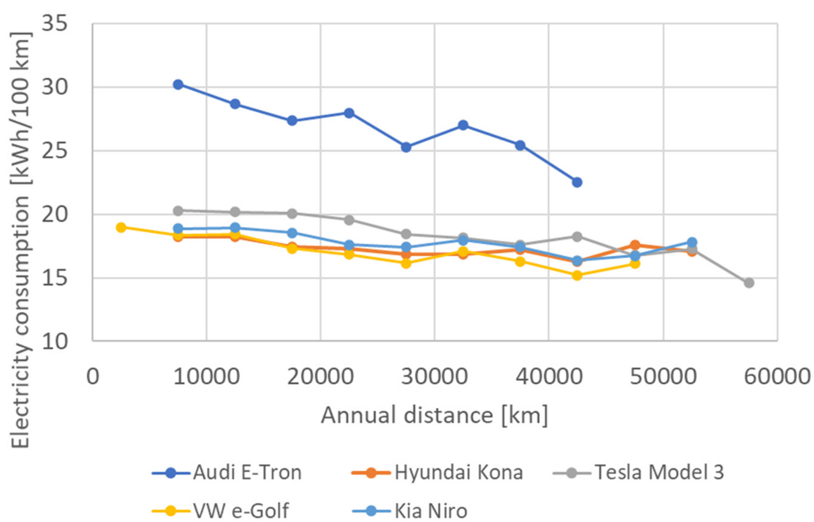

Figure 4-4: Average electricity consumption as a function of annual mileage

The upward effects of high velocity, braking losses in dynamic driving despite brake energy recovery, and interior heating and cooling (relative) for short trips are balanced in a certain way to lead to this trend. However, other factors can play a role as well. Fast DC charging may have smaller total losses in charger and battery than AC charging. Drivers that cover high annual mileages may optimize their driving style for range, amongst other things because longer trips occur more frequently.

4.8 Hydrogen consumption of fuel cell electric vehicles

The tank pass data contains 552 hydrogen fuelling records of 23 fuel cell electric vehicles (FCEVs). After filtering out unreasonable consumption numbers (smaller than 0.5 kg/100 km and larger than 5 kg/100 km), the average consumption for all the vehicles in the database is 1.24 kg/100 km.

Because the amount of data is limited, no vehicle model specific value can be provided. In the dataset, the following vehicle models were present: Hyundai Nexo, Hyundai IX35, Toyota Mirai.

The energy content of hydrogen is 120 MJ/kg. This means that the tanked hydrogen is equivalent to 1.24 * 120 / 3.6 = 41 kWh/100 km; roughly twice as much as for battery electric vehicles. The difference is mostly related to the losses in the fuel cell stack.

5 Real-world fuel consumption of plug-in hybrid passenger cars

5.1 Theory

As in the previous reports in this series on 'real world fuel consumption', an analysis has been made of the share of electric driving for plug-in hybrids.

Plug-in hybrids operate in different modes, which are normally chosen by the vehicle's software, although a preference can be selected by the user via a button. The different modes are explained in a slightly simplified way in Table 5-1.

Table 5-1: Modes of operation of plug-in hybrid vehicles (simplified).

Mode	**Brief explanation**	**Battery**	**Description**
EV mode	Full electric	Charge depleting	Vehicle is propelled by the electric motor only, and behaves like a full-electric vehicle. All consumed energy is derived from the battery.
Hybrid mode	Petrol/diesel, part of the time with support of electric motor	Charge depleting (blended)	The blended CD strategy gradually depletes the battery, ideally choosing the best combination of electricity and fuel to make optimal use of the engine when it is needed. The engine assists the electric motor when power demand exceeds the limits of the electric motor or when the control strategy deems the use of the engine more efficient.
		Charge sustaining	After reaching the end of its charge depleting range, a plug-in hybrid vehicle will switch to charge sustaining mode. The mode can also be selected by the user. In this mode the vehicle uses regenerative braking and power from the engine to keep the battery state of charge constant. The switch to charge sustaining operation is triggered by the battery reaching a specific state of charge (usually ~20%).This behaviour is similar to that of a hybrid vehicle without a plug.

All modes lead to reduced tailpipe CO_2 emissions compared to conventional combustion engine vehicles. The use of energy from the battery, which is charged from the grid, avoids the use of fuel, thereby avoiding tailpipe CO_2 emission. This happens in EV mode, but also in charge depleting hybrid mode.

Furthermore, in all hybrid modes, the combustion engine can operate in a more efficient way than normal because of the interaction with the electric motor/generator. Lastly, brake energy is recovered in both EV and hybrid mode. However, from the fuelling data available, it appears that these mechanisms do not lead to markedly lower fuel consumption and CO_2 emissions for most of the current plug-ins monitored.

If the vehicle is not (often) charged from the grid, the benefits are smaller, and may not outweigh the negative effects of the additional mass that comes with the plug-in hybrid system. By analysing the variation in fuel consumption (l/100 km) per tank event, an estimation can be made of the fuel consumption with an empty battery (charge sustaining mode), and that information can in turn be used to estimate the share of full-electric driving (EV mode), and the electricity consumption in that mode. Since fuel consumption is roughly proportional to mass for an average vehicle, the 200 kilogram extra for battery and electric motor, i.e., 5% to 15% extra energy consumption, should be compensated party by efficient engine operation in hybrid mode, brake energy recuperation, and electric charging. Therefore, benefits depend on the technology and usage. [9]

5.2 Results

In Figure 5-1 the frequency distribution is plotted of the fuel consumption across all fuelling events of a particular plug-in hybrid model. The shortest distances driven per litre are related to driving on the combustion engine.

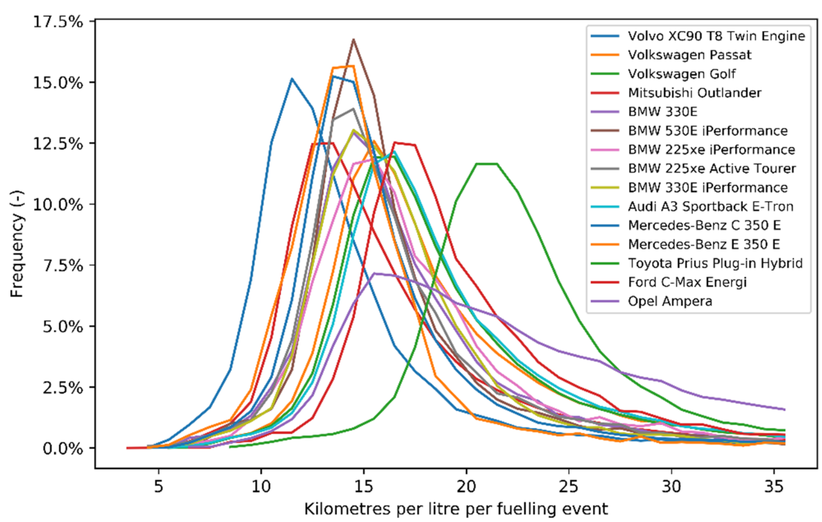

Figure 5-1: The frequency distribution of the distance driven per fuelling event (km/l) of all petrol plug-in hybrid models with data of more than 5000 fuelling events.

Many plug-in hybrid vehicle models have a typical engine-only fuel consumption of between 8 and 16 kilometres per litre (12 to 6 litres per 100 km). The exception is the Toyota Prius Plug-in Hybrid with 20 kilometres per litre.

[9] TNO report 2016 R10419, Supporting analysis on real-world light-duty vehicle CO2-emissions.

On the other hand, the tail of the distribution, i.e. the largest distances per litre, is related to periods with substantial amounts of electric driving. The longer the tail, and the more skewed the distribution, the more electric driving can be assumed.

The position of the peak is a good indication of the fuel consumption on the combustion engine while the total average fuel consumption is derived from the combined data. From these two results the share of electric driving is deduced. For the different models the electric share ranges from 12% to 34% of the driven kilometres, as shown in Table 5-2. Note that the list of models shown is slightly different from the ones displayed in Figure 5-1.

Table 5-2: The fuel consumption and share of distance driven electrically, deduced from the distribution of fuel consumption.

	Combustion engine only		**All driving**	
Make and model	**km/litre**	**l/100 km**	**km/litre**	**Share of km driven electrically**
Mitsubishi Outlander	12.3	8.1	15.9	22.3%
Mercedes-Benz C 350 E	11.7	8.5	15.3	23.0%
Volkswagen Golf	13.6	7.4	18.1	24.9%
Audi A3 Sportback E-tron	15.2	6.6	18.5	17.9%
Volvo V60	13.1	7.6	15.8	17.0%
Volvo XC40	11.7	8.5	17.5	33.1%
Opel Ampera	15.9	6.3	23.9	33.6%
Ford C-Max Energi	14.6	6.8	19.2	23.8%
Volkswagen Passat	14.1	7.1	17.8	20.4%
Chevrolet Volt	16.3	6.1	22.1	26.0%
Toyota Prius Plug-in Hybrid	20.1	5.0	22.9	11.9%
Volvo XC90 T8 Twin Engine	9.7	10.3	13.1	25.9%
Volvo V60 (diesel)	14.9	6.7	19.0	21.4%

6 Real-world fuel consumption of vans

Despite the fact that electric van sales are rising, light commercial vehicles are in majority still fitted with a diesel engine. The average diesel consumption was calculated for 54,061 light commercial vehicles. Note that for the years 2014, 2015 and 2016 fuelling data is available for only a limited fleet of vans (~7,700 vehicles). Therefore the results per fuelling date for these years are less stable than the results for the more recent years, and may not have the same market coverage.

The most common annual mileage among vans is 20,000 km/year, and the average annual mileage is 24,400 km/year, as can be read in paragraph 1.4.

The average empty mass of vans is increasing since 2018 and has continued increasing in 2020 and 2021, as visible in Figure 6-1.

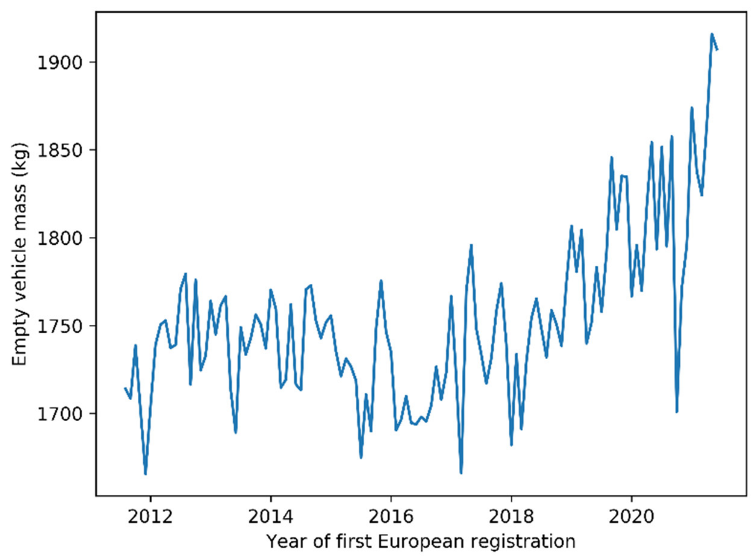

Figure 6-1: Evolution of average empty mass of vans in the Travelcard database.

A dip in average mass occurs in September 2020. Further analysis points out that this seems to be related to a problem in the supply chain of one of the major manufacturers of larger vans.

Vans have been type approved according to the WLTP since September 2018. The first WLTP-vans that came to the market were small vans with low CO_2 emissions, see Figure 6-2. The vans registered in 2020 and 2021 have, on average, similar real-world CO_2 emission levels to the fleet average of the years before. This can be seen in the graph that is based on NEDC, Figure 6-3. Note that the NEDC graph contains all vehicles: for newer, WLTP approved vehicles, an NEDC CO_2 number had to be provided by calculation as well.

The graphs show that also for vans the change to WLTP has led to higher type approval values. The average calculated NEDC value for the latest vehicles was around 170 g/km, while the corresponding WLTP values are around 200 g CO_2/km.

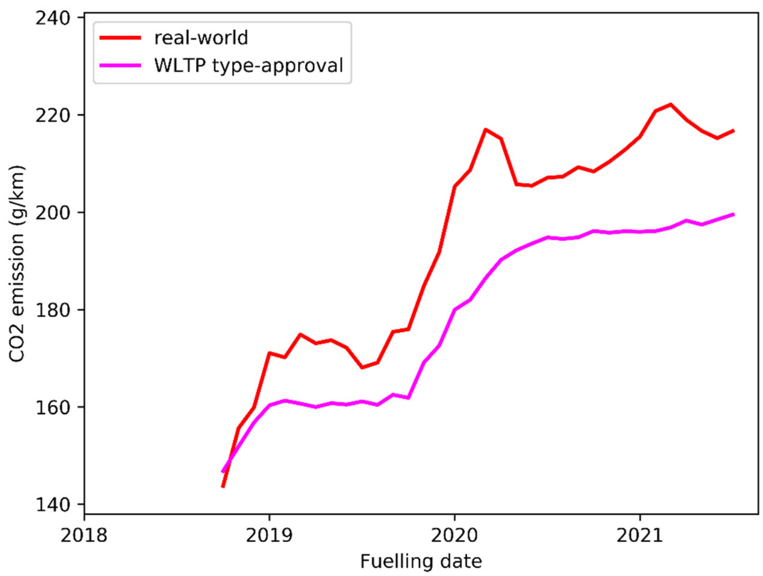

Figure 6-2: Average real-world and type approval CO_2 emissions of light commercial vehicles in the Travelcard fleet that were WLTP type approved. The number of vehicles was limited at the start of the lines.

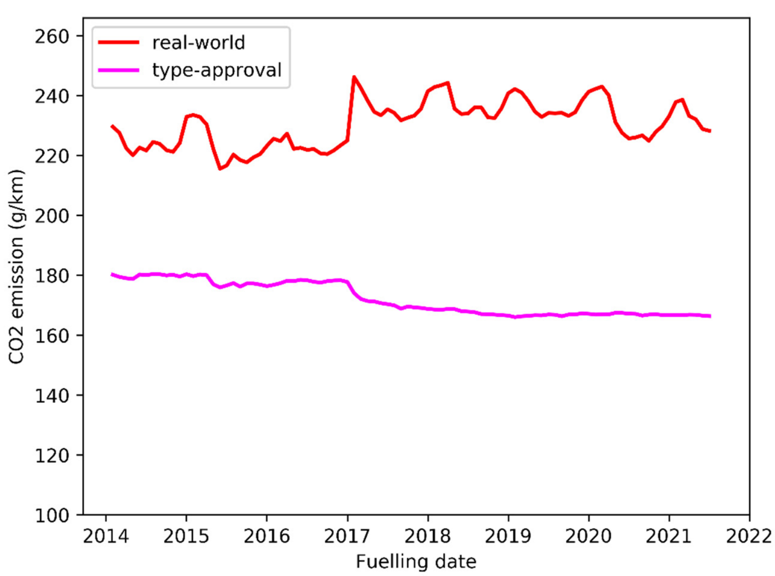

Figure 6-3 Average real-world and NEDC-based type approval CO_2 emission of all light commercial vehicles in the Travelcard fleet. The number of vehicles was limited at the start of the lines.

The kink in 2017 in Figure 6-3 coincides with the first CO_2 emission target for light commercial vehicles (EU regulation EC/510/2011), of 175 grams per kilometre in 2017, although this 175 g/km-target had already been met in 2014 on a European level. There is no visible development towards the 2020-target of 147 g/km in the graphs.

For further analysis, the fuel consumption data for vans is regrouped by the registration year of the vehicles. For each vehicle the fuel consumption was averaged over the entire duration it was part of the Travelcard fleet, and the value was attributed to its year of first registration.

As displayed in Figure 6-4, the average real-world CO_2 emissions and the average WLTP type approval CO_2 emissions have both increased from 2018 to 2020. The gap has increased slightly to 15 g/km.

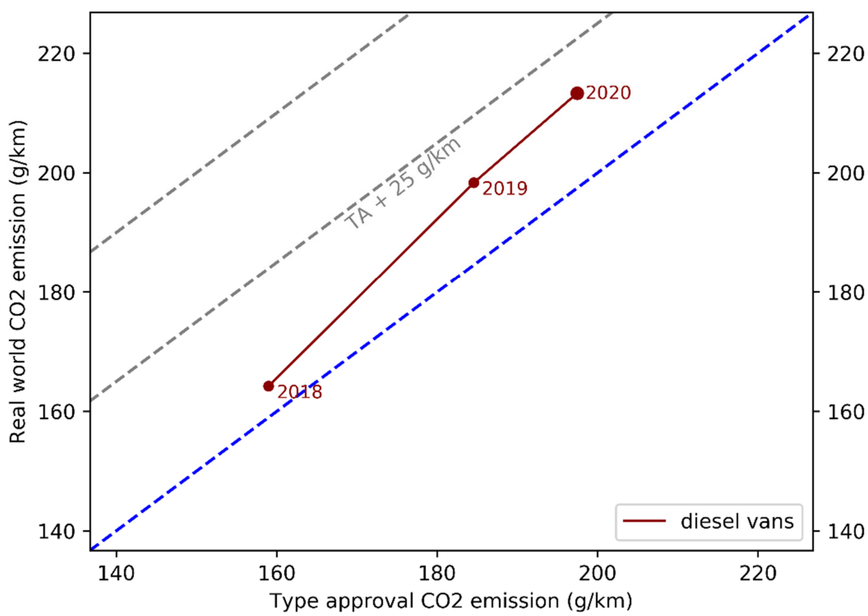

Figure 6-4: Average real-world CO_2 emissions versus the average WLTP type approval values of new diesel vans, differentiated by the year of registration.

7 Effects of weather on fuel consumption

This chapter describes a first exploration of the effects of weather on fuel consumption on a fleet level, using empirical data.
The effect of ambient temperature on the fuel consumption is well known.
From physical principles it is expected that the effect is most pronounced in the air drag of the vehicles, related to the air density decreasing with increasing temperature. This predominantly affects the fuel consumption at higher velocities, i.e. on motorways, where air drag is responsible for more than half of the fuel consumption. It can be expected that the effect on air drag is about 3.5% per 10 degrees temperature difference, and about half of that difference as resulting impact on the overall fuel consumption.[10] The effect observed in the data is larger, as shown in Figure 7-1, which is probably due to additional temperature dependencies of rolling resistance and traffic. Typically, in colder weather with precipitation the car is also used more for shorter trips, leading to more congestion, than in warmer weather where walking or cycling is more common as an option.
With the type of data that is available, it is difficult to establish a causal relationship between temperature and fuel consumption. The multi-regression analyses show the correlation, but the changes in fuel consumption may also be caused indirectly, i.e. by the different use of vehicles and changes in driving behaviour due to the season or due to ambient conditions. In order to provide some additional evidence to the observed effects, decomposed in the multi-regression analyses, also the relations between the individual parameters (themselves cross-correlated) and the fuel consumption are given hereafter.

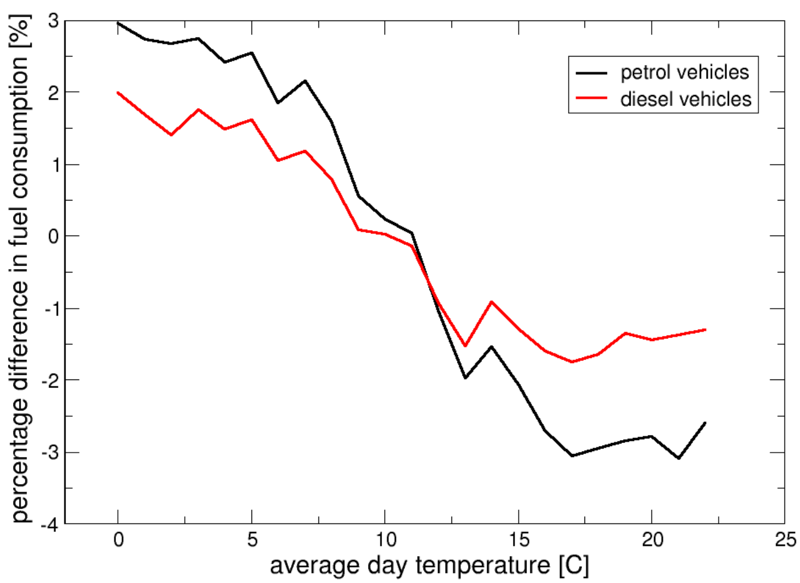

Figure 7-1: The deviation of the fuel consumption from the average for different average day temperatures, for petrol and diesel vehicles in the Travelcard database.

[10] Correction algorithms for WLTP chassis dynamometer and coast-down testing, TNO report, 2015, R10955 and Supporting analysis on real-world light-duty vehicle CO2-emissions, TNO report 2016 R10419.

Besides temperature, other aspects of the weather that may affect the fuel consumption are analysed with KNMI data for the period 2004 to 2021, using mainly day average values, and the weather of three days before the fuelling, as a midpoint of the period of use given the typically weekly fuelling of these vehicles. In the meteorological data the parameters that are correlated with the fuel consumption data are: daily mean temperature, daily mean wind speed, minimum day temperature, maximum day temperature, solar irradiation, and daily precipitation.

From multi-regression analyses of meteorological data with the variation in fuel consumption over time, the effects can be estimated from the data. The use of maximum and minimum temperatures is found to have limited additional value over the mean, and precipitation shows little correlation with fuel consumption. The dominant effect is ambient temperature, with a 0.28% decrease in fuel consumption with 1 degree higher temperature for petrol vehicles, as shown in Figure 7-1. For diesels the effect is -0.17% per degree ambient temperature increase.

In magnitude the second effect is wind. With a 1 m/s higher average wind speed the increase in fuel consumption is 0.30% for petrol vehicles and 0.25% for diesels. The average wind speeds are 3.3 metres per second, with a variation of 1.3 metres per second. If wind speeds are much higher the effect is larger. From Figure 7-2 it can be inferred that above 4 m/s average wind speed the effects are increasing significantly. The difference between petrol and diesel vehicles is smaller for wind than for temperature, indicating either a difference in vehicle use and size, or a limited (average) difference in engine efficiency between petrol and diesel engines when driving at higher velocities, where wind effects play a major role.

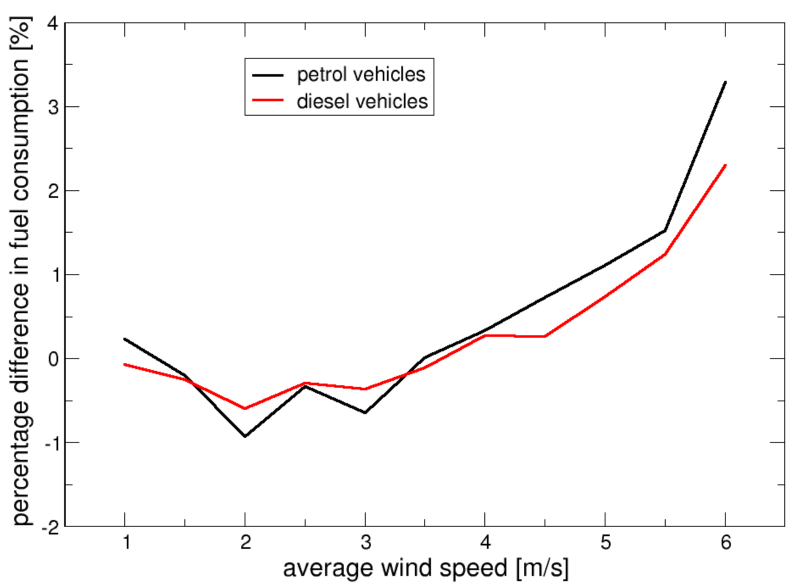

Figure 7-2: The deviation of the fuel consumption from the average for different average wind speeds. The relation clearly shows the quadratic dependency with wind speed that is expected from physical principles.

The third effect in magnitude is the solar irradiation, in J/cm^2 (1017 +/- 783).
For an increase in solar irradiation of 100 J/cm^2 the fuel consumption of petrol cars decreases by 0.085%. For diesels the effect is 0.039% per 100 J/cm2 solar irradiation increase. The effect of solar irradiation shows a similar, yet slightly different trend than the effect of ambient temperature. See Figure 7-3.

Since the fuelling cannot be related directly to the time and place of driving the vehicle and the associated local and temporal weather variations, these results are based on the daily averages at the national level, and therefore the correlations between the conditions and the fuel consumption are limited. If more specific information on weather conditions per vehicle were available, the effects would probably be somewhat larger, possibly up to two times.

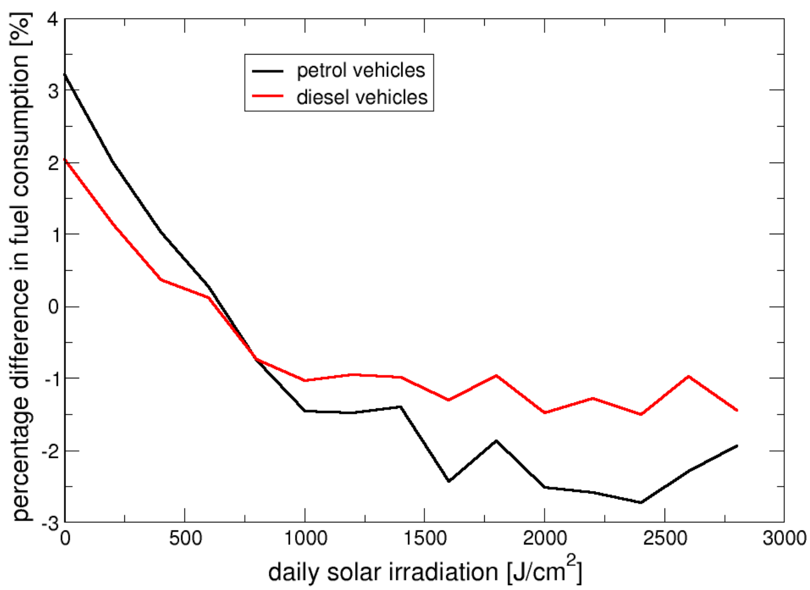

Figure 7-3: The deviation of the fuel consumption from the average for different daily levels of solar irradiation. The solar irradiation is strongly correlated with ambient temperature. However, it can be noted that at the highest solar irradiation the improvement in fuel efficiency is limited.

The analysis shows that ambient conditions cause substantial variations in fuel efficiency. This explains a large part of the seasonal variations, as e.g. shown in Figure 2-1 and Figure 2-2. In addition it is expected that changes in vehicle use and traffic over the year also affect the fuel consumption. Overall the fuel consumption is found to vary between -4% and 4% around the yearly average. Corrected for the known average weather effects, the remaining variation is between -2.5% and 2.5%.See Figure 7-4. In the latter some seasonal effects may be expected to remain in that variation, probably because the extremes are higher than the averages used in the correlation, but a large share of the remaining variation is likely to depend on factors not directly related to weather conditions, like vehicle usage, fuel composition, tyres.

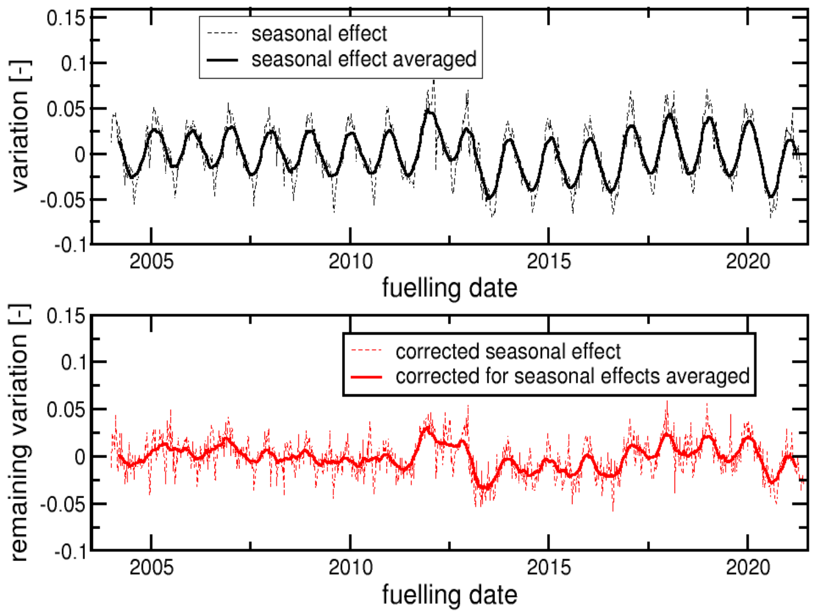

Figure 7-4: After the correction for impacts of daily mean temperature, average wind speed, and irradiation, some seasonal effects in the fuel consumption of petrol cars remain, especially for the years after 2016..

It seems that modern petrol vehicles, registered after 2016/17, have larger remaining seasonal dependencies (after correction for variations in average temperature, wind speed and solar irradiation), than earlier generations.
See Figure 7-4. It can also be that in the earlier period 2004 to 2012 other effects like heavy congestion limit these correlations.

Concluding, just under half of the seasonal variation in fuel consumption on a fleet level can be described (predicted) using information about temperature, wind and solar irradiation. A part of this effect is secondary, due to changes in vehicle use and driving style as a result of changes in weather conditions. The remaining variation can have many causes, including nonlinear effects of weather not explored yet, and seasonal variation in fuel composition and tyres. A detailed investigation for specific groups of vehicles and for specific conditions can give more understanding of the relation between fuel consumption and each of the influencing factors.
This can lead to better predictions of real-world fuel consumption in the future.

8 The transitions to E5 and E10 petrol

In the long-term-trends in fuel consumption, seasonal effects dominate, and over the years changes in these seasonal effects can be observed. The underlying causes for these changes are not easily isolated, because the seasonal variation in fuel consumption is also affected by severe winter cold, economic situation, and congestion levels that change from year to year. To isolate factors of interest such as the 100 km/h speed limit introduction and the Corona pandemic proved to be difficult. See Figure 8-1. From the figure it could be inferred that fuel consumption in 2020 and 2021 is about 1% to 2% lower than before in 2017 and 2018. However, something similar happened in the period 2013 – 2016.

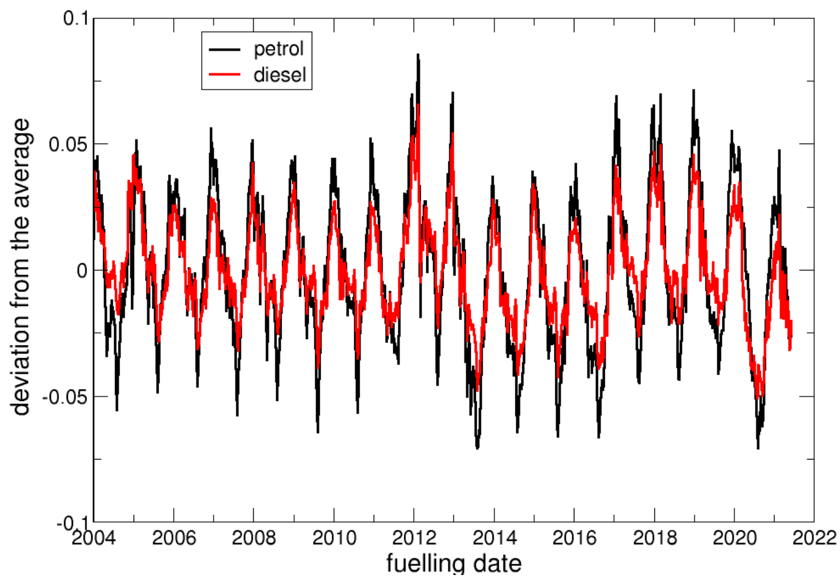

Figure 8-1: The seasonal changes in fuel consumption on a fleet level. For every individual vehicle in the Travelcard fleet the time dependent deviation from its long-term average fuel consumption was calculated, and averaged.

By contrast, the effect of E10 on fuel consumption can actually be isolated, by looking at the long-term trends in the differences in seasonal variation between petrol and diesel vehicles. Other influences than E10, such as weather, may have a different amount of effect on diesels than on petrols, but the trend is the same, because they are exposed to the same on-road conditions. Figure 8-1 shows indeed that for vehicles of the two fuel types the seasonal trends are roughly the same, albeit less pronounced in the case of diesel. A correlation analysis points out that, on average, the seasonal variation for petrol is 162% of the variation for diesel. Knowing that, the actual fuel consumption of petrol cars can be plotted relative to a predicted fuel consumption of petrol cars using the expected seasonal variation of petrol (162% of the variation of diesel). This way a structural change in fuel consumption can be discovered. This is done in Figure 8-2. It can be noted that from the summer of 2020 onwards the actual petrol consumption is constantly and systematically above the average, and hovers around +2% compared to the average for the entire period.

It is likely that this is due to the introduction of E10 fuel. In 2005 there seems to be a similar step upward, possibly related to the introduction of E5 that occurred around that time; however, since the dataset starts in 2004, the preceding period is too short to draw a definite conclusion.

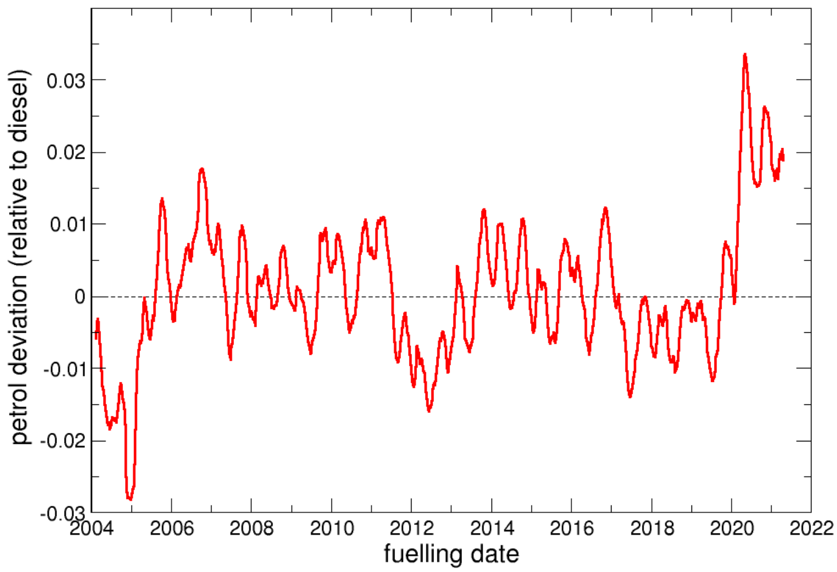

Figure 8-2: The changes in petrol fuel consumption relative to the changes in diesel fuel consumption. Both in autumn 2005 and summer 2020 there seems to be a jump upwards of about 2%.

Very likely the higher petrol consumption from the summer of 2020 can be linked to the introduction of E10 fuel in the Netherlands. The variations in fuel consumption are less than the jump in 2020. See Figure 8-2. If this effect is to be incorporated in the fuel consumption and CO_2 emission analyses in the future, it will require some further study of fuel properties, like density and carbon content, to establish the new relation between these aspects.[11]

[11] Petrol fuel and blending ethanol analyses, TNO report 2020 R10138, and Dutch market fuel consumption for GHG emissions, TNO report 2016 R10700.

9 Conclusions and discussion

The real-world CO_2 emissions and energy consumption of passenger cars and light commercial vehicles were studied from different angles. Fuel consumption monitoring data was primarily obtained from Travelcard B.V., and augmented for the analysis with data from RDW and the TNO contribution to the LIFE-MILE21 project.

Petrol and diesel passenger cars
The type approval CO_2 emission values of newly registered vehicles in the Travelcard database in 2020 are lower than those registered in 2019, while the real-world emissions have remained stable for petrol cars, and have slightly increased for diesel cars. The increase for diesels is likely to be related to the fast increase of empty weight of the diesels sold, which coincides with a strong decrease in sales. At the same time, the WLTP type approval values have decreased slightly.

WLTP values remain closer to real-world emissions than the old NEDC values were. The result of the trends is that the real-world-to-WLTP gap has increased, and approaches 20 g CO_2 per km for both diesel cars and petrol cars (both excluding plug-in hybrids); thereby the gap is 13%. If plug-in hybrids are included, the gap for petrol vehicles is close to 25 g/km or 17%.

For the vehicles in the Travelcard database the average real-world CO_2 emission of new passenger cars in 2020 was 156 g/km for petrol including (plug-in) hybrids, and 164 g/km for diesel including (plug-in) hybrids. New petrol plug-in hybrids in 2020 had an average real-world CO_2 emission of 147 g/km: a gap of 240% to the average WLTP type approval value of 43 g/km.

An analysis was made of the fuel consumption per tonne of empty vehicle weight, to cancel out the changes in average mass over time. This was done for new registrations. For petrol cars, this fuel efficiency (litre per 100 km per tonne) has improved considerably for the lightest cars, over the last 10 years. For heavier petrol cars, including plug-in hybrids, as well as for diesel passenger cars, the improvement is limited.

Electric passenger cars and hydrogen fuel cell passenger cars
For electric passenger car models the average electricity consumption was calculated from charge pass records and odometer registrations. The numbers include charging losses. The most efficient models consume 16 kWh per 100 km, the least efficient up to 30 kWh/100 km. The values have decreased quite a bit for some models. Possible reasons include the fact that the amount of data has doubled compared to the previous report, changes in the speed limit on the highway and potential effects of the lockdown. The Travelcard fleet average has not changed over time: 20.2 kWh/100 km. Reweighted to the Dutch EV fleet composition does not change this number much: 20.1 kWh/100 km.

The gap of these real-world numbers with the WLTP declared value is 19% on average, the real-world number being higher. Some models are very close to, or even below WLTP-value, while others have an upward deviation of 40% or more.

A prediction model was made to estimate the real-world electricity consumption of battery electric cars. It is based on mass, air drag and battery capacity, and is fitted to the actually observed electricity consumption averages in the abovementioned dataset. The average deviation of the model is 8%, and the maximum is 20%, so the model is a better predictor than the WLTP value.

Data on charging losses from other projects point out that these are significant, in the order of 10-20%.

The relation between annual driven distance and electricity consumption (kWh/100 km) was investigated. Although driving on the highway is relatively energy consuming for electric cars, and high mileage usually means a high share of highway driving, the trend is the other way. The higher the annual distance, the lower the average energy consumption. At 40,000 km/year the five most common car models in the dataset have an electricity consumption that is around 12% lower than for vehicles of the same models which are driven 10,000 km/year. It cannot be derived from the data why this occurs. Possibly experienced drivers optimize their driving style, or the lower amount of braking losses offsets (partially) the extra energy needed to drive higher speeds. The mode and speed of charging might play a role as well, through differences in losses.

For fuel cell electric vehicles for the first time an average real-world hydrogen consumption value was calculated based on tank pass data for 23 vehicles. The hydrogen consumption was found to be 1.24 kg/100 km. In terms of energy content in hydrogen this is roughly twice as much as the energy in charged kilowatt-hours for battery electric vehicles.

Plug-in hybrid passenger cars
The real-world fuel consumption data of plug-in hybrids was analysed over time to derive an indication of the share of electrically driven kilometres. The results have not changed significantly since the previous analysis: the electric share ranges from 12% to 34% of the driven kilometres.

Light commercial vehicles
The first trend observed for light commercial vehicles is that the empty mass of new vehicles increases quickly: 6 or 7% in two years’ time. In the same time, the fuel efficiency (litre diesel per 100 km per tonne of empty vehicle weight) has improved considerably as well: around 1.25% per year, ever since 2010.

The WLTP regulation reduced the type approval-to-real-world gap for vans as well. However, the numbers are not stable yet because of limited WLTP-approved vehicles in the dataset. The real-world average CO_2 emissions seem unchanged at around 220 g/km.

Weather effects
Almost half of the seasonal variation in fuel consumption can be predicted using variations in temperature, wind and solar irradiation, whereby the three factors are ordered by magnitude of contribution. A part of the effect is indirect, by changes in the way people use their vehicles and changes in driving behaviour as a result of the variation in temperature, wind and sun.

The remaining variation can have many causes, including nonlinear effects of weather that were not explored yet, and seasonal variation in fuel composition and tyres.

Fuel composition

The effect of an increasing admixture of ethanol in petrol was estimated by analysing the trends in seasonal variation in fuel consumption between petrol and diesel cars. The petrol vehicles on average showed an increase in fuel consumption of 2% ever since summer 2020, after compensation for the expected seasonal variation. This increase can most likely be attributed to the introduction of E10.

To incorporate the effect of E10 in the analyses of real-world CO_2 tailpipe emissions, further study of fuel properties, including density and carbon content and variations therein, will be required.

10 Signature

The Hague, 4 March 2022

Geoff Holmes
Project manager

TNO

René van Gijlswijk
Author