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TNO report

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Trends in energy efficiency of conventional petrol and diesel passenger cars

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Samenvatting

In de loop van de tijd zijn voertuigen zuiniger geworden door technologische ontwikkelingen en innovaties. Tegelijkertijd zijn er andere veranderingen geweest, die deze CO_2 reducties deels teniet doen. Een goede vergelijking van brandstofefficiëntie van vergelijkbare voertuigen van verschillende leeftijden zal gecorrigeerd moeten worden voor de veranderende fysieke eigenschappen, zoals massa of vloeroppervlak. Dit rapport is het resultaat van het onderzoek van de lange-termijn verbeteringen van brandstofverbruik, voor vergelijkbare voertuigen, op basis van Europese registratiegegevens. De Nederlandse registraties zijn minder geschikt omdat ze sterk beïnvloedt worden door belastingmaatregelen en daardoor fluctueren.

De brandstofefficiëntie verbetert al decennia lang, al ver voordat er Europese doelen waren vastgesteld. De recente Europese doelen, lijken deels ingevuld te worden door fabrikanten met aandelen PHEV's (plug-in) en BEV's (batterij elektrisch), waarbij het brandstofverbruik van conventionele voertuigen langzamer verbetert. Er zijn twee duidelijke momenten waarin deze trend onderbroken lijkt. De nieuwe emissiewetgeving, WLTP en RDE, gaf een verschuiving naar boven vanaf 2018, en voorafgaand aan de 2020 en 2021 afrekening op de Europese doelen, lijken er meer onzuinige voertuigen verkocht te zijn, waarna in 2020 de neergaande trend weer gecompenseerd is in de Europese data.

Het vloeroppervlak, als fysieke maat om voertuigen te vergelijken, laat een snellere verbetering van het brandstofverbruik zien dan het massa. In het bijzonder, het massa van voertuigen is de laatste jaren, zeker vanaf 2014, toegenomen. Daardoor is de gemiddelde verbetering van het brandstofverbruik over de vloot beperkt geweest. Voor voertuigen van hetzelfde massa is er een lange, monotone trend van verbeteringen. Dit is daarom ook de basis van de extrapolatie van de trend naar de jaren 2022 tot 2025. Dus, per definitie, een vergelijkbaar voertuig is in deze studie een voertuig van hetzelfde massa en brandstoftype. De sterke afhankelijkheid van massa is daarmee gecompenseerd, en grote en kleine voertuigen zijn langs dezelfde maatstaf gemeten.

De resultaten van brandstofverbruiksverbeteringen zijn gebaseerd op de NEDC waarden van 2010 tot 2016, ondersteunt met informatie van 2020 en van Nederlandse registraties van 2000 tot 2021, ook voor de overgang naar de WLTP. De correlatie van Europese NEDC and WLTP data maakt het beeld complete, en een extrapolatie mogelijk, zoals hieronder in de tabel is samengevat.

Table 1: WLTP CO_2 waarden voor 2020, 2022, en 2025 gebaseerd op de extrapolatie van CO_2/M trends.

WLTP		**Jaar**		
CO_2 [g/km]	**massa**	2020	2022	2025
	1000 kg	117	113	105
	1300 kg	131	122	108
Benzine	1700 kg	166	154	136
	1300 kg	110	103	93
Diesel	1700 kg	144	135	121

Summary

Technological developments and innovations lead to lower fuel consumption and CO_2 emissions on newer vehicles with the same physical characteristics. Newer vehicles are therefore not really the same, and comparisons should be based on known physical characteristics, like mass or footprint. This report investigates the long-term trends of fuel-economy improvements and uses European registration data to do so, since Dutch data is affected by changes in the trends due to varying tax incentives.

The long-term trend goes back well beyond the introduction of European targets. European targets do drive the trend partially through the registrations of PHEVs and BEVs, keeping the improvements in fuel efficiency of conventional technology rather monotonous. The only two clear deviations from the trend are from the introduction of WLTP and RDE legislation, that shifted the fuel consumption upward, and the seemingly strategic sales of less fuel-efficient vehicles ahead of the 2020 registrations. The years 2020 and 2021 are used by Europe to assess the manufacturers' targets, instead of a continuous assessment of all years.

Based on footprint, the same vehicles show a more rapid improvement in fuel efficiency than based on vehicle mass. The mass increases over the last years have been substantial, in particular from 2014, also in Europe, leading to a reduced net improvement of fuel efficiency, since the overall fuel efficiency is roughly proportional to the mass of the vehicle. The eventual estimates for 2022 to 2025 of improvements of fuel efficiency from 2020 onwards are based on the extrapolation of the European trend in CO_2 in g/km per kilogram vehicle mass. The same vehicle is assumed, in this study, to be an average vehicle of the same mass and fuel type.

The results of the fuel efficiency improvements is based on the European NEDC results from 2010 to 2016, which is supported by additional evidence from the results for 2020, and from the Dutch registrations, with trendlines for Dutch WLTP data. This is combined with the correlation between the NEDC and the WLTP, based on European data from 2020. These results provide an average and an extrapolation for WLTP CO_2 based on 2020, as shown in the table.

Table 2: WLTP CO_2 values for 2020, 2022, and 2025 based on extrapolating CO_2/M trends.

WLTP		**Year**		
CO_2 [g/km]	**Mass**	2020	2022	2025
	1000 kg	117	113	105
	1300 kg	131	122	108
Petrol	1700 kg	166	154	136
	1300 kg	110	103	93
Diesel	1700 kg	144	135	121

Contents

1 Introduction

1.1 CO_2-based purchasing tax in the Netherlands

The tax on passenger cars and motorbikes (BPM - *Belasting van personenauto's en motorrijwielen*) is paid in the Netherlands when new vehicles are registered. Since 2010, the BPM for passenger cars is calculated based on the type approval CO_2 emissions of the vehicle and the position of these emissions in a number of tax brackets. Every year the thresholds of the tax brackets are evaluated and adjusted. Underlying the adjustments in tax brackets is the “autonomous development” of fuel efficiency of conventional vehicles. This report addresses solely the question of trends in fuel efficiency of conventional vehicles, in order to extrapolate them to 2025 with the best possible level of confidence.

Over the years vehicle and engine technology has improved. This has been seen over the period 2010 to 2015 when the introduction of the European CO_2 target for manufacturers of 95 g/km may have stimulated increase in the fuel efficiency of vehicles and reduction in CO_2 emissions. The same model of a vehicle, of a later date, can have lower CO_2 emissions for this reason. Therefore the tax brackets based on CO_2 emissions should be adjusted to account for the change in fuel efficiency so that the same amount of BPM is paid on the same vehicle. To support these adaptations of the BPM, the Ministry of Finance requires an estimation of the expected average CO_2 emission of new petrol and diesel vehicles over the next four years. TNO has been asked to provide an estimated reduction of CO_2 emissions of new vehicles sold in the Netherlands over the period 2022 - 2025.

1.2 Scope: trends in fuel-efficiency of conventional passenger cars

This study addresses principally one question based on one definition: **What is the change in fuel efficiency of conventional diesel and petrol passenger cars over the period 2022 – 2025, based on historic trends and recent developments? Fuel efficiency is defined as fuel consumption, and CO_2 emission, per kilometre driven given the same physical vehicle.**

Considering the above definition of fuel consumption, the physical properties of the vehicle play an important role in this analysis. These properties determine the work the engine has to perform and therefore strongly influence the fuel consumption and CO_2 emissions. The only readily available physical property is vehicle mass, of which the legal definition (reference mass, and mass in running order) has not changed over the last decade, since it is part of the framework regulation Euro 5/6 from 2007. Additionally, the footprint, i.e., width times length (axle distance), is commonly known, although, the definition seems less fixed given the variation in the data. Other properties which also influence fuel consumption and CO_2 emissions such as the size, or volume, of the vehicle are not commonly known. If a consumer buys a new car, it can be bigger, and therefore heavier, or has more options and therefore heavier, or has a bigger engine and therefore heavier. Even if options become more standard and a smaller and lighter car of the same model no longer exits, it still is a different vehicle. The mass is a rough indication of the different options for the consumer which are a change with respect to the previous vehicle, to which a higher fuel consumption is associated.

This report will therefore focus on only vehicle mass as the reference for the same vehicle. Simply said, in this report changes in fuel efficiency are investigated for vehicle groups identified by the same mass.

Note that mass reduction is also a means to reduce fuel consumption, which is thereby not factored into the improved fuel efficiency in this definition. However, it seems vehicle mass is mainly related to comfort, drivability, frontal area, safety, and status. The increasing demand for these aspects should not be mixed up with fuel efficiency. The variation in mass, and associated CO_2 emissions, in the year-by-year registrations of new cars in the Netherlands, led to the idea that the European registrations are a more stable basis for determining the fuel efficiency and the changes therein. The European trend incorporate all aspects little affected by national policies. This is a central approach in this study.

1.3 Recent developments and considerations in the analysis

Over the past 2 years, 2018 and 2019, the increase in fuel efficiency and CO_2 emission reduction appears to have slowed. In part this may be linked to a shift in sales, towards larger, heavier, and more powerful vehicles. This sparked a lengthy and complex debate on the right CO_2-based BPM brackets, in which many further nuances were raised. In particular, the improvement in fuel efficiency seems less for the lower market segments, making these vehicles relatively more expensive. Another issue raised was the comparability of vehicles, in particular with the transition from the NEDC testing cycle to the WLTP testing cycle, which was another added complexity in an already rather difficult discussion.

There are several other issues raised in 2020, which are taken into account in this study. Firstly, the European CO_2 targets as a driver for improving fuel efficiency. It is often argued that the European targets are the design targets for fuel efficiency. With the wide introduction of PHEVs and BEVs in the fleet, by several manufacturers, the fuel efficiency of conventional cars is largely decoupled from the European targets. A relatively small fraction of PHEVs and BEVs will offset the average in such significant amounts, especially with the extra credits, that the targets are often reached on a strategy based on the mix of petrol, diesel, PHEV, and BEV vehicles, rather than the specific performance of each group.

For 2020 every vehicle below 50 g/km counts for two in the determination of the targets. So, a 3% share of BEV in sales will effectively lower the target CO_2 emissions by 6%. For 3% PHEV sales with 45 g/km, the reduction is about 4.5%. With manufacturers less than 10% away from meeting the targets, a share of BEV and PHEV will help to meet these targets.

Secondly, following this argument, if the PHEV and BEV are the means to meet European targets, the question arises if improvements in fuel efficiency in conventional vehicles is “worth the effort”, and the fuel efficiency is stalled with the increasing fractions of PHEVs and BEVs. This is investigated, based on the differences among manufacturers and their PHEV/BEV sales, in the last couple of years.

Thirdly, fuel efficiency improvement may be expensive, and may also not be needed for smaller vehicles.

Already in 2009, the first compact cars met the European targets for 2020. The question is if fuel efficiency improvements have to be the same over the whole vehicle market. The fact that CO_2 values are in a smaller range nowadays than ten years ago seems to suggest that compact cars had less improvements in fuel efficiency than the larger, heavier cars in higher market segments. The fuel efficiency trends have been investigated for different vehicle segments separately.

A fourth issue, taken in consideration in this study, is the possibility to extrapolate the trend in fuel efficiency towards the future, i.e., 2022-2025. In order to do so, the variations in the trends are to be understood and compensated for, so that a clear monotonous trend remains over a longer period that can be extrapolated with confidence. These, compensations, or corrections, are to be explained clearly and preferably simple in nature, such that they can be incorporated into possible policy decisions.

Fifthly, the transition from NEDC to WLTP, which was the main subject of debate in 2020, should not matter much for the analyses of fuel efficiency, since the intrinsic fuel efficiency comparisons should not depend much on the way it is measured, i.e., the test procedure. The NEDC will be the basis, as it was implemented for a longer period and there has more data, on which a stable trend can be established. The WLTP should follow a similar trend for the period that data is available, if the appropriate, intrinsic results are found.

Sixthly, previous reports[1] have been an attempt to provide a complete and illustrative picture, and to compare different perspectives on these issues. The Ministry of Finance has later elucidated[2] this as macro-perspectives (national taxes) and micro-perspectives (individual cases). Given the complexity of the matter at hand, the current report is more restrictive and clearer in the goals and definitions. This study does not look at individual vehicle models, cases, and specific market segments, thus hoping to avoid entering into semantic discussions about the essence and being of vehicles. And avoid also second discussion on the representativeness of specific vehicles used or grouped. Moreover, this report focusses only on the conventional vehicles, and their aspects, like mass and fuel, that may influence their trends. Furthermore, this study addresses the national and European averages, on the largest possible sets of vehicles, and the physically relevant differentiations, i.e., the macro-perspective, as is deemed relevant for national policies. Naturally, vehicle registration and sales are linked to consumer behaviour and marketing, with tools and issues like market segmentation and options. Why people buy certain cars, and the popularity of certain models, is not addressed in this study.

[1] Actualisatie CO_2-waarden nieuwe personenauto's en inschatting CO_2-waarde 2021, TNO 2020 R10826;
Aspects of the transition from NEDC to WLTP for CO_2 values of passenger cars - Phase 3: After the transition, TNO 2019 R10952;
Aspects of the transition from NEDC to WLTP CO_2 values of plug-ins hybrid vehicles. Aanvullend rapport, TNO 2019 R11310;
Aspects of the transition from NEDC to WLTP for CO_2 values of passenger cars - phase 2: Preliminary findings, TNO 2018 R11145;
Aspecten van de NEDC-WLTP overgang in relatie tot CO_2 waarden van personenauto's. Fase 1: De probleemschets, TNO 2018 R10732.

[2] Maatregelen op het gebied van autobelastingen, Kamerbrief 16 oktober 2020. Tweede Kamer, vergaderjaar 2020–2021, 32 800, nr. 69.

Such shifts in sales, and ranking of vehicles into market segments, is considered out-of-scope of the question limited to the trends in fuel efficiency of conventional vehicles.

And, finally, the seventh issue considered here is the large changes, also in the European market, where diesel vehicle registrations have increased and decreased over the last decade. It may therefore well be that shifts in vehicles occur where the other, less known and registered physical characteristics play a role. Specifically, the sales of SUVs, with large frontal areas and high air drag can cause variations in fuel efficiency. Moreover, the popularity of PHEV versions of SUVs may shift market shares. This aspect and the other aspects above are taken into consideration. However, the report will not meander into these aspects, but it will focus on the narrow and most robust approach, with the figures to support it. Aspects are only included in detail if they can be correlated to observed variations in the data regarding CO_2 emissions.

Engine manufacturing and design of the vehicle transmission and driveline are separate engineering teams within the car manufacturing industry. Although the amount of effort to improve these elements may vary, it is not expected that fuel efficiency worsens with time. Incremental improvements are always expected, unless business is discontinued. If vehicles have higher fuel consumption, the cause lies probably elsewhere: with considerations of comfort, drivability, safety, and status, included the marketing and wishes of consumers. But it is important to realize this detrimental effect of CO_2 emissions is the result of other choices and forces overruling the need to reduce CO_2 emissions, thus unrelated to the fuel efficiency considered here. The autonomous development of fuel efficiency is a natural, technical evolution, with occasional revolutions, stimulated by European policies. The only exception to this trend is a fuel penalty for environmental requirements to engines and exhaust gas after treatment systems. With the introduction of RDE legislation in late 2018, diesel vehicles have substantially lower NO_x emissions. This is related to the use of selective catalytic reduction (SCR) systems and thermal management to keep the catalyst warm. This may be linked to a single jump upward in CO_2 emissions, which should not be interpreted as a trend, since the environmental requirements on vehicles will not change between 2019 and 2025.

1.4 Data sources and approach

Two datasets formed the basis for the analysis in this project. These are the database of the European Environment Agency (EEA) for the European fleet and the RDW registration database for the Dutch fleet. Additionally, these two data sets were supplemented with data from the Dutch Certificates of Conformity (CoC).

These datasets were analysed to determine the trends in CO_2 emissions of conventional diesel and petrol passenger cars in Europe, in the Netherlands and for various manufacturers over the period 2010 – 2019. The Dutch registration data allows a further extension of the period from as early as 2000 till June 2021. These trends were then extrapolated to determine the average CO_2 emissions of conventional diesel and petrol passenger cars over the period 2021 – 2025. During the course of the project the provisional European data of 2020 became available. This data was included in part of the analyses redone.

1.5 Report structure

This report has the following structure:

- Chapter 2 - Overview of the European Environmental Agency data used in this study
- Chapter 3 - The trends in CO_2 emissions and vehicle characteristics over the period 2011 – 2019
- Chapter 4 – Trends extrapolated to 2021 and WLTP values
- Chapter 5 – Trends extrapolated till 2025
- Chapter 6 – Discussion of results in the context of the Dutch purchasing tax
- Appendices with supporting material

2 European Environmental Agency data

In order to monitor progress towards targets for CO_2 emissions per manufacturer group, the member states report vehicle registration data to the European Environmental Agency, in Copenhagen. In this reporting, key parameters, relevant for CO_2 emissions and for the manner in which the target is determined, are included. With changing legislation, some changes in the reporting took place from 2010, till the last reported year available now, 2019. In particular the WLTP CO_2 emission is added, but this data is underreported and therefore not very useful.

Not all data were complete, and some data were inconsistent. For example, in some cases the fuel type was “electric” but CO_2 emissions of up to 180 g/km were reported. Also, the manufacturer pools were partly empty. The focus is on conventional vehicles, so data of petrol and diesel vehicles (also denoted as petrol/electric) and a CO_2 emission above 50 g/km are used, consistent with super credits. The EU manufacturer names (and the common pooling) were used to group vehicles.

2.1 Data quality and availability

The following information is available for the last set, and the data used in the analyses in **bold face** in the table below. The data in *Italic* were examined and used for selections, grouping and screening, removing implausible data and misidentifications. See Table 3.

Table 3: The recent data columns descriptions.

Field name	**Field Definition**
ID	Identification number
MS	Member state
Mp	*Manufacturer pooling*
VFN	Vehicle family identification number
Mh	**Manufacturer name (EU standard denomination)**
Man	Manufacturer name OEM declaration
MMS	Manufacturer name (MS registry denomination)
TAN	Type approval number
T	Type
Va	Variant
Ve	Version
Mk	Make
Cn	Commercial name
Ct	Category of the vehicle type approved
Cr	Category of the vehicle registered
m (kg)	**Mass in running order**
Mt	WLTP test mass
Enedc (g/km)	**Specific CO_2 Emissions (NEDC)**
Ewltp (g/km)	Specific CO_2 Emissions (WLTP)

W (mm)	*Wheel Base*
At1 (mm)	*Axle width steering axle*
At2 (mm)	*Axle width other axle*
Ft	**Fuel type**
Fm	Fuel mode
ec (cm3)	Engine capacity
ep (KW)	Engine power
z (Wh/km)	Electric energy consumption
IT	Innovative technology or group of innovative technologies
Ernedc (g/km)	Emissions reduction through innovative technologies
Erwltp (g/km)	Emissions reduction through innovative technologies (WLTP)
De	Deviation factor
Vf	Verification factor
r	**Total new registrations**

Much of the data is used to determine the average final CO_2 emission and vehicle mass to compare against the targets and monitor the reported values. This value is not a simple average, to corrected for eco-innovations, i.e., CO_2 reducing technologies not tested in the standard procedure, and super credits, i.e., the higher weighing of BEV and PHEV vehicle registrations.

2.2 Used data definitions and groups

The manufacturers can pool registrations in the targets. The famous example in Tesla teaming up with FCA for these targets in 2019. But with many mergers over the last years, pools are not fixed. The solution designed for this is to consider the pooling of 2019 as the basis and all the previous years were mapped to this pooling to avoid any manufacturers changing the pool over the years and create other hidden trends within the pool. A notable exception; Tesla was part of the FCA pool in 2019, which may have affected trends in FCA temporarily.

There are 25 manufacturer pools considered in the study and each of them contain certain manufacturers. They are shown in Table 4. It is to be noted that some manufacturers have a country specific name, for example, Honda, could be manufactured under Honda UK or under Honda Motor Corporation. These differences are not elaborated in the table.

Table 4: The different manufacturer pools.

Manufacturer Pools	Manufacturer Name
AA-IVA	AA-IVA
BMW	BMW
DAIHATSU	Daihatsu Motor Co
DAIMLER	Daimler Ag
FCA	Alfa Romeo, Chrysler Group LLC, Fiat Group, Tesla
FORD	Ford Motor Company, Ford Werke GMBH
FUJI	Fuji Heavy Industries Ltd

GM	Opel Automobile, GM, Chevrolet, GM Daewoo Auto U Tech Comp
HONDA	Honda Motor Co
HYUNDAI	Hyundai
JLT	Jaguar Cars Ltd, Jaguar Land Rover Limited
KIA	Kia
MAZDA	Mazda Motor Corporation
MG	MG Motor
MITSUBISHI	Mitsubishi Motors Corporation MMC
NISSAN	Nissan
PSA	PSA, Automobiles Citroen, Automobiles Peugeot
RENAULT	Dacia, Renault
SAAB	Saab Automobile Ab
SSANGYONG	Ssangyong
SUBARU	Subaru
SUZUKI	Maruti Suzuki, Suzuki Motor Corporation, Magyar Suzuki Corporation Ltd
TOYOTA	Toyota
VOLVO	Volvo
VW GROUP	Audi AG, Porsche, Seat, Skoda, Volkswagen

2.3 General results from the EEA data

The total sales of vehicles in Europe is around 14 million per year, with small fluctuations. Notably, the number of diesel vehicles in the total sales has declined. The aggregated results of the dataset can be seen in the table below:

Table 5: Aggregated results of the EEA-dataset, all data combined, excluding eco-innovations.

Year	Number of registrations	Average mass [kg]	Average Emissions [g/km]	Average CO_2/M [g/(km*kg)]
2010	13121084	1361.10	139.91	0.102796
2011	12736031	1386.32	135.32	0.097614
2012	11988037	1400.43	131.81	0.094121
2013	11804465	1389.14	126.49	0.091053
2014	12513611	1374.43	123.12	0.089579
2015	13744477	1379.38	119.30	0.086485
2016	14678463	1384.23	117.80	0.085099
2017	15091935	1387.58	118.26	0.085228
2018	15131093	1389.79	120.50	0.086706
2019	15418745	1420.22	121.76	0.085732
2020	10818325	1442.59	106.59	0.073891

It can be seen from Table 5 that the number of registrations has been increasing steadily in the EU (European Union). The average emissions seem to be decreasing until 2016 and then increasing again. The CO_2/M had been decreasing until 2016 and then has been almost steady.

Following this, the fuel number of registrations per fuel type look as follows:

Table 6: Distinction of the number of registrations per fuel-type.

Year	Diesel	Electric	Other	Petrol
2010	6,730,452	5,334	465,809	5,919,489
2011	7,047,957	14,299	167,258	5,506,517
2012	6,591,814	12,950	248,565	5,134,708
2013	5,904,890	23,046	805,449	5,071,080
2014	6,645,655	36,659	237,351	5,593,946
2015	7,139,996	55,585	230,879	6,318,017
2016	7,268,540	62,795	353,463	6,993,665
2017	6,737,941	97,295	209,846	8,046,853
2018	5,517,097	149,889	244,278	9,219,829
2019	4,934,402	342,509	252,119	9,889,715
2020	2,981,437	669,297	205,630	6,961,961

As can be seen, Table 6 has only 4 fuel types. The “Electric” column contains all vehicles that are electric and PHEV’s (Plug-in Hybrid Electric Vehicles) mainly based on CO_2 below 50 g/km, or empty field in combination with “electric” as fuel type, while “Other” includes LPG, CNG, LNG, biomethane and the absent data. Since these fuel types had less vehicles compared to the other fuel categories, they have been grouped. It can be seen that the number of diesel vehicles has been decreasing since 2016 while petrol vehicles see an increase along with the electric and PHEV.

3 Trends from 2010 till 2019

3.1 European trends

From 2012 the average CO_2 emission of petrol vehicles in the Netherlands is constantly 10 g/km lower than the European average. Only in 2013 the Netherlands seemed to be ahead of Europe in the trend with a difference of 12 g/km – prior to 2013 the difference was approximately half of this value. Both averages have an upward trend from 2017. With a few exceptions most manufacturers followed the same trend.

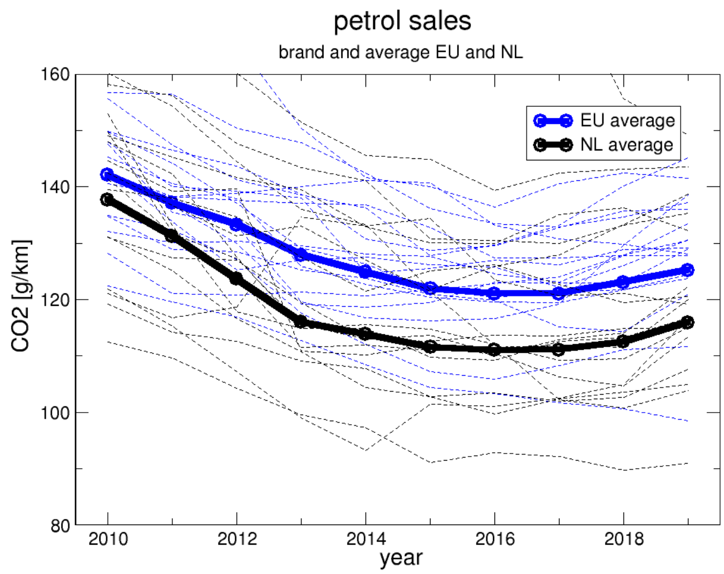

Figure 1: Average CO_2 emissions per kilometre of new petrol passenger cars per year in the EU and NL over the period 2010 - 2019.

For diesel vehicles over the period 2012 to 2015, the differences between the Dutch average and the European average was 8 g/km more than in the rest of the period between 2010 and 2019. The difference in the rest of the period was also a steady gap of 10 g/km, while the trend of the Dutch average followed the changes in the European average very closely. The exception is the last year, 2019, where the difference decreased from 10 to 7 g/km.

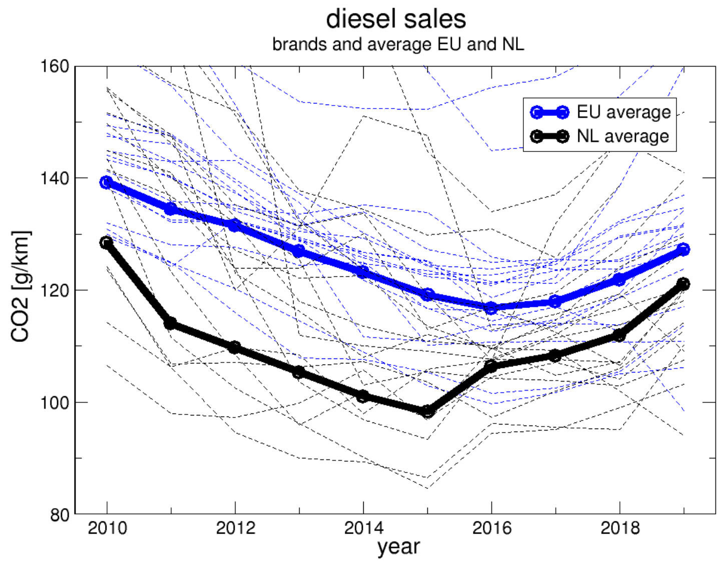

Figure 2: Average CO_2 emissions per kilometre of new diesel passenger cars per year in the EU and NL over the period 2010 – 2019.

For diesel and petrol vehicles the Dutch averages follow the European trend with a standard gap of 10 g/km, increased by 8 g/km in the period, from 2011 – 2015, of strong tax incentives for fuel efficient cars, affecting diesel vehicles more than petrol vehicles. Manufacturers with high CO_2 emissions showed a sharper decrease in CO_2 emissions over this period, but generally, all other manufacturers fluctuated around this European average.

Both petrol and diesel vehicles show an increase in average CO_2 in g/km from 2017. In earlier studies, it was shown to be linked to the changing properties of vehicles like mass and power. Higher engine power is a consumer demand and a marketing feature and not related to the physical characteristics, therefore, excluded from the analyses. In the previous report, engine power was included in the fits, for a better prediction. If the fuel efficiency is defined as the fuel consumption per vehicle mass, thereby correcting for the size of the vehicle, the upward trend disappears completely for petrol cars. Also, the trends per manufacturer smoothens out. From the start in 2010, the CO_2 in g/km per ton mass in running order, decreases about 5 g/(km*ton), but the decrease has been reduced to almost zero in 2019.

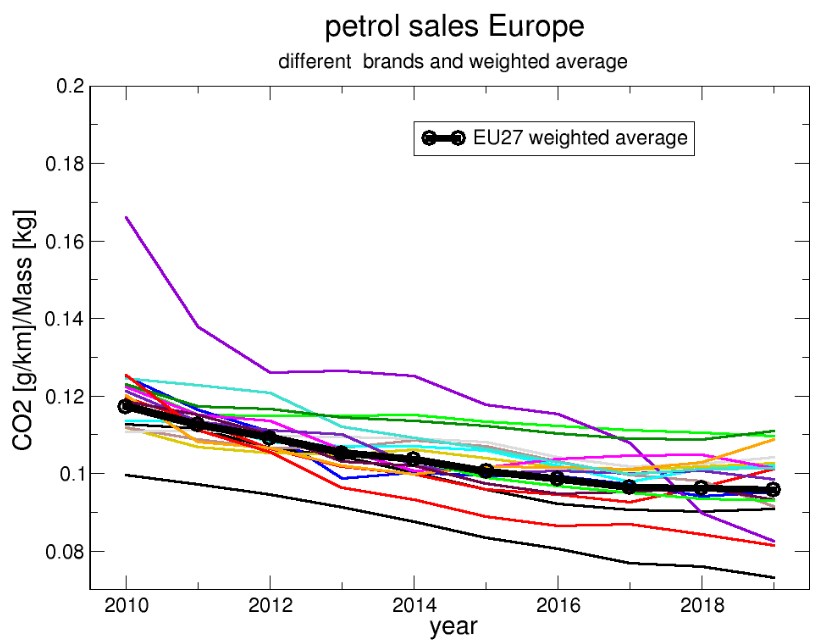

Figure 3: Average CO_2 emissions per kilometre per unit of vehicles mass for new petrol passenger cars per year in the EU in black over the period 2010 - 2019. Various manufacturer groups are shown in the coloured lines.

For diesel vehicles there has been a decrease in reduction, from the initial 5 g/(km*ton) per year, to an increase from 2017 onward. In 2019, the trend seemed to have turned, but still an increase of about 0.0008 g/(km*kg) per year from 2018 can be observed, down from a maximum increase of 0.0014 g/(km*kg) per year.

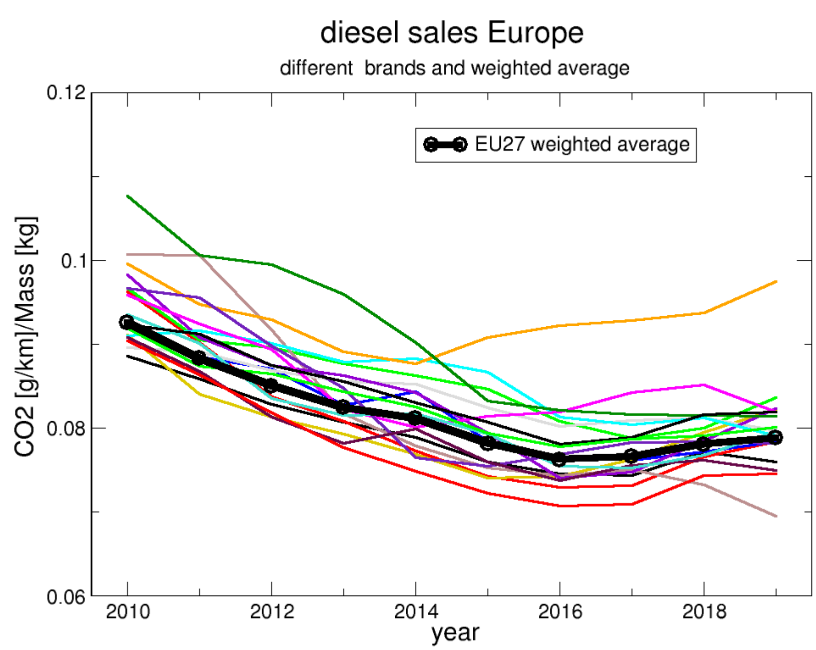

Figure 4: Average CO_2 emissions per kilometre per unit of vehicle mass for new diesel passenger cars per year in the EU in black over the period 2010 - 2019. Various manufacturer groups are shown in the coloured lines.

With the shift upwards for 2018 and 2019, related to the introduction of the WLTP and the RDE legislation, and the registrations ahead of the target years 2020 and 2021, these years are considered a temporary deviation. The trends are there based on the years 2010 to 2017. In the appendices of this report alternative approaches are analysed as well.

3.2 CO_2 per footprint

The footprint (average axle width times the distance between the axles) has been considered as parameter to normalize manufacturer data. This analysis is included here for completeness. Eventually, it was decided that some mass dependence was introduced in the European targets. However, footprint remains an interesting concept, as it expressed the physical dimensions of the vehicle. The European data show similar trends for footprint-based fuel efficiency trends as for mass-based fuel efficiency trends.

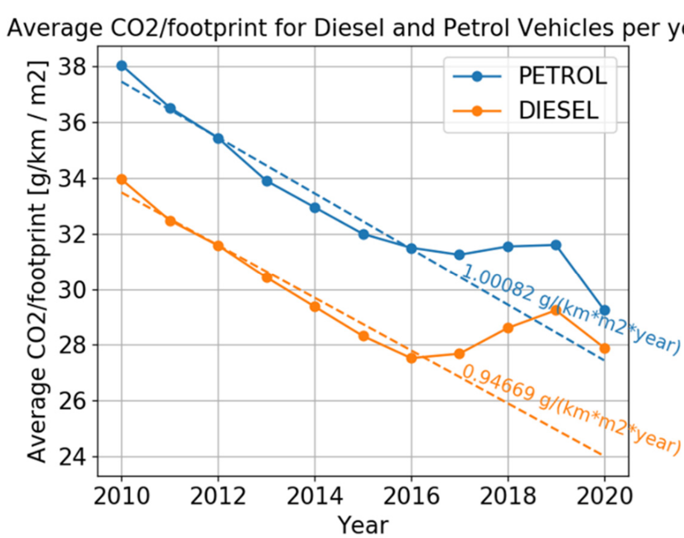

Figure 5: The trends in CO_2/A of CO_2 [g/km] per footprint area A[m^2] for the European registrations. The data up to 2017 is used to fit a trend.

The linear regression is modelled as :

$$y = C + B * x$$

Where,
y = CO_2/A
x = year

The parameters of this fit along with the R^2 value for the fit are as follows:

Table 7: Fit parameters of the CO_2/A of Diesel and Petrol vehicles.

Fuel	**C**	**B**	**R^2**
Petrol	2049.1043	-1.00082	0.7673
Diesel	1936.3262	-0.94669	0.4072

The decrease of CO_2/A over the years is substantial. If the same linear trend continues, the CO_2/A would reach zero in 22 year.

For mass-based trends that would be about 35 years. The footprint trend is therefore must faster. About 15 years ago it was argued that the footprint would be a better measure of the same physical vehicle over the years. Indeed, with respect to footprint vehicles have increased less over time than with respect to mass. Clearly, the consumer demand was not so much bigger vehicles but mainly heavier vehicles, with more equipment, power, and safety systems on board.

Another reason could be the mass-based correction, where part of the mass is corrected for in the European targets. So, increasing mass has not the same negative effect on meeting CO_2 target as has increasing footprint for which there is no correction. The mass is therefore the more conservative, or lower, estimate, of the fuel efficiency improvement over time.

The reduction rates are:
- Petrol: CO_2/A : -1.00082 g/(km*m^2*year) (EU)
- Diesel: CO_2/A: -0.94669 g/(km*m^2*year) (EU)

To show the consistency of the improvements across the fleet, a small, a medium, and a large vehicle are based on the quartiles of the data. These reference vehicles with regard to footprint are made on the basis of analysing the data. The data for diesel and petrol vehicles in terms of footprint and the quartiles of their distribution through the years looks as follows:

Table 8: The first and third quartile footprint of petrol and diesel vehicles in the period 2010-2019

Petrol [m^2]				Diesel [m^2]			
1st quartile (min)	1st quartile (max)	3rd quartile (min)	3rd quartile (max)	1st quartile (min)	1st quartile (max)	3rd quartile (min)	3rd quartile (max)
3.61	3.78	4.08	4.23	3.95	4.09	4.37	4.56

From the data obtained from the Table above, it was decided to have two reference vehicles, one, the low footprint vehicle with 3.75 m^2 as the footprint and the high footprint vehicle with a footprint of 4.25 m^2.

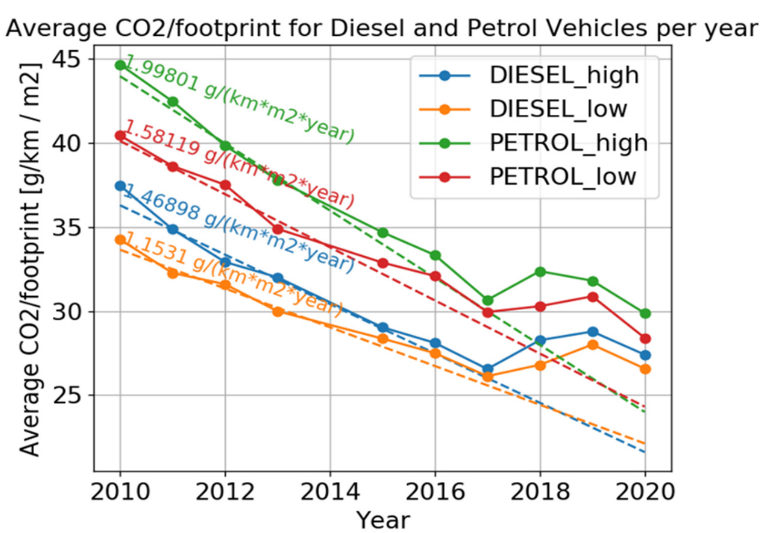

Figure 6: The difference in trends for vehicles with small and large footprints.

The parameters of this fit along with the R^2 value for the fit are as follows:

Table 9: Fit parameters of the CO_2/A of Diesel and Petrol reference vehicle

Fuel	**C**	**B**	**R^2**
Petrol_high_footprint	4059.9785	-1.99801	0.834
Petrol_low_footprint	3218.3230	-1.58119	0.860
Diesel_high_footprint	2988.9392	-1.46898	0.598
Diesel_low_footprint	2351.3747	-1.1531	0.610

Clearly, there seems to be a convergence in reduction rates. Smaller vehicle improve less but have a lower CO_2/A to start with. Even with the introduction of the WLTP, despite the offset, the data converge further.

3.3 Variations among manufacturers

The BEV and PHEV sales have been increasing over the last couple of years (2017 to 2019). The shares of PHEV and BEV vary between 0% and 15% over this period. There are large variations among manufacturers and between the years. It is, however, clear that large shares of BEVs and PHEVs are related to manufacturers with average CO_2 [g/km] of conventional vehicles of 120 g/km or more. In particular, the Jaguar-Land Rover group show an increased share from 2017 to 2019, from 0% to 5.7%, counteracting the increase in CO_2 emissions (from 152 g/km to 167 g/km) over the same period. The three datapoints are at the right-hand side of the graph.

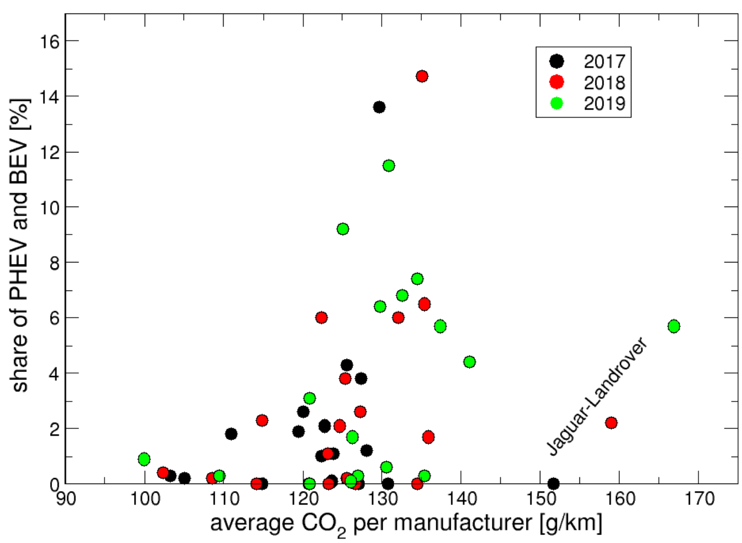

Figure 7: Share of PHEV and BEV and average CO_2 emissions per kilometre for various manufacturers over the period 2017 – 2019.

It could be possible that a large share of BEVs and PHEVs may lead to a reduced interest in improving fuel efficiency. However, limited correlations are found between the year-by-year change in fuel efficiency, expressed as CO_2/M, and the BEV/PHEV shares. It is more likely some manufacturers use, or need, both aspects to meet the European or sales targets.

In particular in 2020, in the provisional EEA data a large drop in average CO_2 emissions is observed. The drop of 14.5 g/km is for the greater part the result of in increased registrations of BEV and PHEV. The conventional vehicles also show a decrease but about two-third of the decrease of the fleet average CO_2 can be attributed to the registrations of BEV and PHEV. The BEV registrations increased from 3.5% in 2019 to 11% of the total. This would account for the total reduction, suggesting little change in conventional cars. However, conventional cars in term of CO_2/M showed an improvement, but partly compensated for by the mass increase of vehicles.

Albeit not consistent, the different manufacturers show that margins from BEV and PHEV sales are compensated by the sales of bigger and heavier vehicles. The margin is partly provided by the improved fuel efficiency of conventional cars.

3.4 Comparison with the Dutch registrations

The trends in the European registrations and the Dutch registrations are very similar for the g/km averages. The difference is constant, only with offsets related to periods of strong tax incentives. For CO_2 in g/km per kg vehicle mass, the differences between the European averages and the Dutch averages are less stable, indicating larger fluctuations in sales in the Netherlands. The European and Dutch averages are closer together, indicating a more stable result, but the differences between the two are far less constant that for the g/km. This is caused by variations in the average mass, year-by-year.

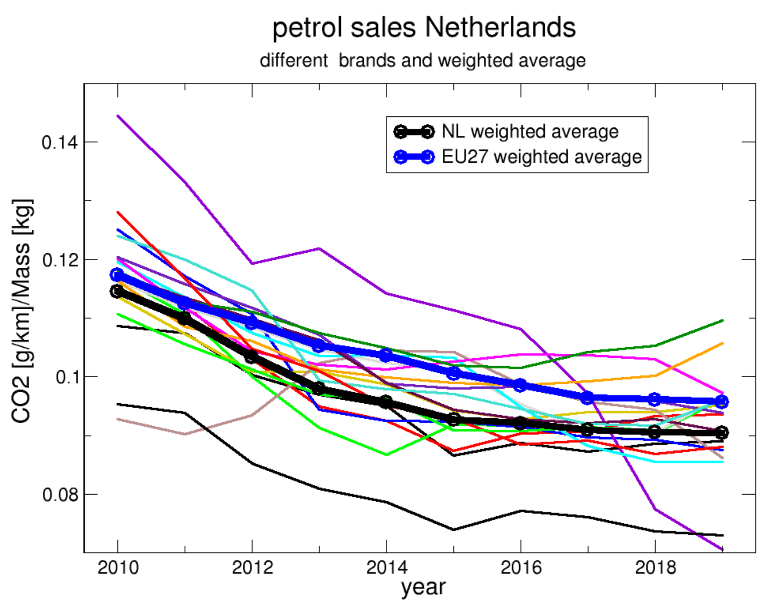

Figure 8: Average CO_2 emissions in g/(km*kg) for new petrol passenger cars per year in the EU and Netherlands over the period 2010 - 2019. Various manufacturer groups are shown in the coloured lines.

For diesel vehicles the variation in the CO_2 emissions is normalized to mass even larger for the Netherlands, suggesting a consistent upward trend from 2016 onwards, one year before the European change in trend.

In the Dutch sales manufacturers vary also more than at a European scale, indicating changes in sales in the Netherlands. In that respect, the Dutch data show fluctuations, within bounds, on the European trends of improved fuel efficiency which was monotonous up to 2016 and showed some stalling in the last years. Apart from RDE legislation from 2018 onward, from 1 September 2015 compliance with Euro 6 legislation was compulsory for all new registrations, which required, in particular for diesel vehicles the use of catalytic technologies, may be the reason for a shift backward in fuel efficiency. So, the quick succession of two, or three steps (distinguishing Euro-6d-Temp and Euro-6d-Final), in increased stringency in pollutant emission legislation may be the reason for the period of stalled fuel efficiency between 2016 and 2019 for diesel vehicles in particular.

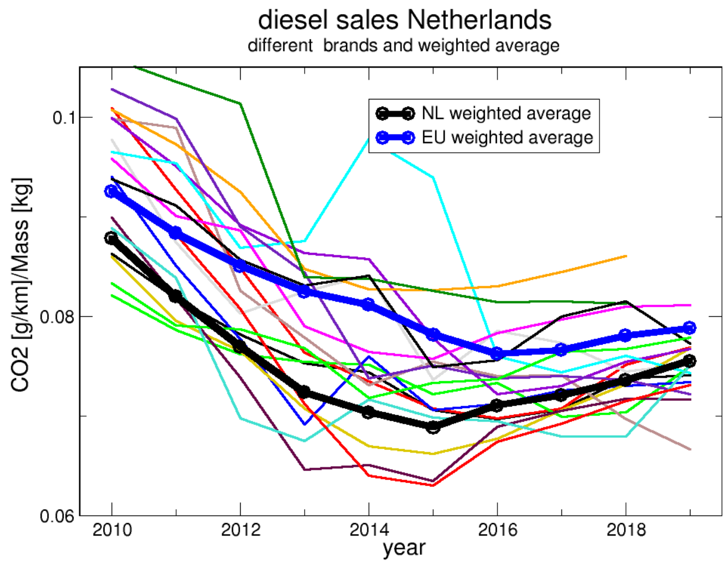

Figure 9: Average CO_2 emissions per kilometre per unit of vehicles mass for new diesel passenger cars per year in the EU and Netherlands over the period 2010 - 2019. Various manufacturer groups are shown in the coloured lines.

The next round of pollutant emission legislation, i.e., Euro-7, is not expected until 2026, which may leave room for the fuel efficiency improvements in the meantime. Compared to the European averages per manufacturer, the Dutch averages per manufacturer fluctuate much more, indicating a less stable market. In particular in the period 2013 to 2016 for diesel cars trends per manufacturer deviated significantly from the average downward trend.

3.5 Trends for different mass classes

The data for each year was split into different mass classes, namely; <=1100 kg, 1100-1300 kg, 1300-1500 kg, 1500-1700 kg and >1700 kg. It has to be known that the number of registrations in each mass category is different in each year and therefore contributes to the massed average differently. There seems to be two factors that play a role in determining the average CO_2/M; one, the mass of the vehicle and the other, the year of registration.

Both for petrol and diesel, the fuel efficiency, in terms of CO_2 [g/(km*ton)] is best for vehicles around 1500 kg. But, more importantly, for petrol vehicles there seem to have been little increase in the fuel efficiency in the last 5 years, while for heavier vehicles the improvements can be seen over the whole period. The CO_2 emissions of lighter and heavier petrol vehicles are closer together now than they were in 2010.

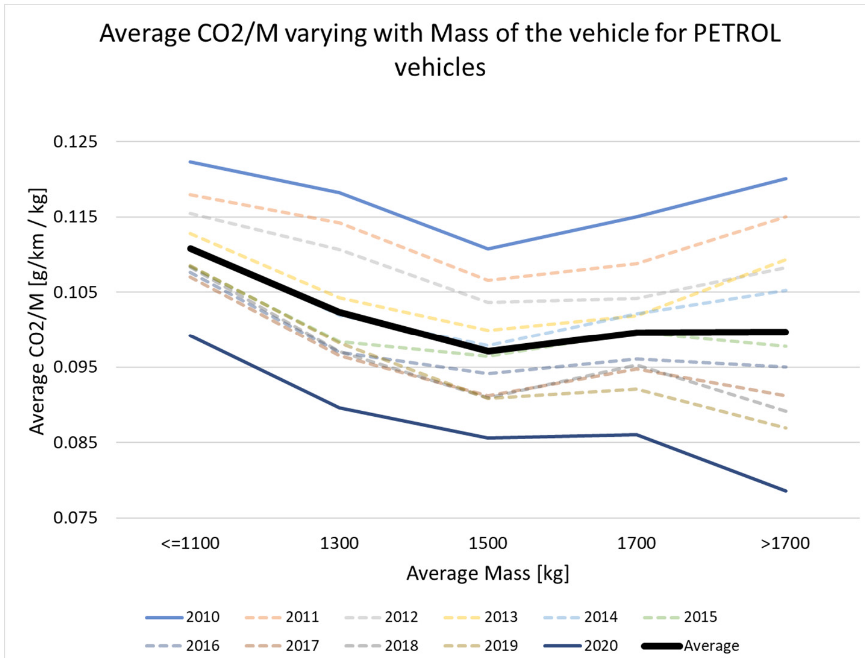

Figure 10: Average CO_2/M of petrol vehicles for mass categories per year, which show a stagnation for 2018 and 2019, with a large reduction in 2020 compensating the earlier stagnation.

In Figure 10 the initial and final year, and the average, are drawn solid, while the other years are dashed. This shows clearly that the fuel efficiency of compact petrol cars remains at 0.108 g/(km*kg) over the period 2016-2019, after substantial improvements in the years before. Moreover, the fuel efficiency of compact petrol cars, in terms of CO_2/M, is generally lower than that of larger vehicles, except for the largest and oldest petrol cars.

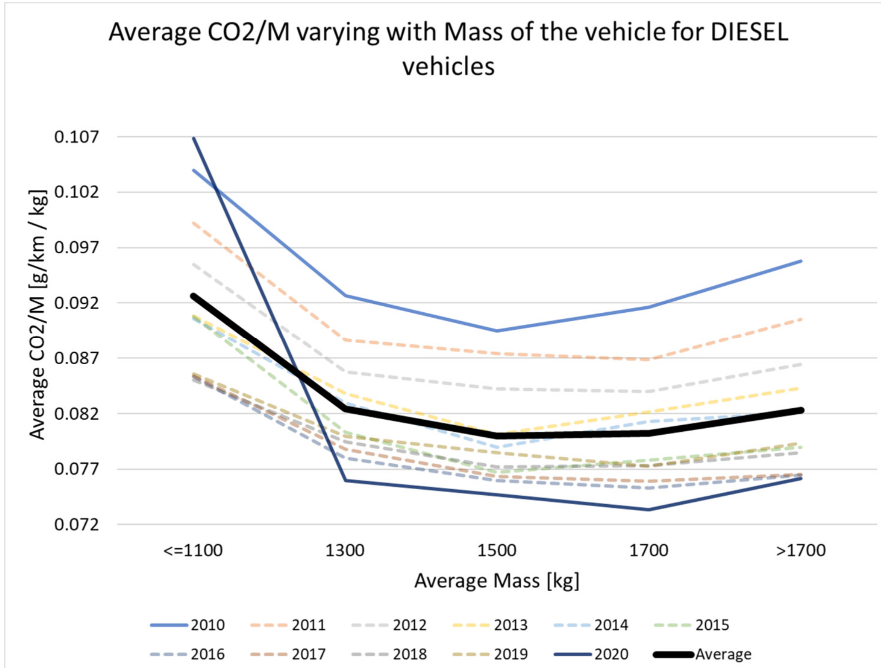

Figure 11: Average CO_2/M of diesel vehicles for mass categories per year. Diesel vehicles below 1100 kg is a very minor group, and the 2020 data for this group is of little relevance.

Figure 11 is a similar picture as the previous one but for diesel vehicles. This shows clearly that the fuel efficiency of compact diesel cars remains at 0.085 g/(km*kg) over the period 2016-2019, after substantial improvements in the years before. Furthermore, the fuel efficiency of compact diesel cars, in terms of CO_2/M, is generally lower than of larger vehicles and then it almost stabilizes for heavier vehicles, in the recent years from 2016-2019.

4 Extrapolating to 2021 and WLTP values

Fuel efficiency improvements occurred for as long as engines are built. The EEA data only covers the period in which European policies for CO_2 reduction came into place, suggesting implicitly that improvements are linked to these policies. However, looking beyond this period shows that fuel efficiency improvements in this period is roughly in line with a longer trend. The EEA data spans only the period 2010 till 2020. By comparing the European averages with the Dutch averages in this data, the limitations of the Dutch data are clear. The same trends are followed, but in the intermediate period, due to more progressive CO_2 based taxing, the Dutch fleet shifted quicker and more extensively to fuel efficient vehicles. Given these limitations, trends observed for the NEDC results also apply to the WLTP results, with a fixed difference.

4.1 RDW registration data July 2021

The data used for the analyses is mainly the open data of the RDW containing the vehicle registrations in the Netherlands. These are both the new registrations and the imported vehicles. The month-by-month averages show limited fluctuations, unlike the CO_2 g/km monthly averages that are influenced by the typically December or January peaks in sales in the business-oriented market.

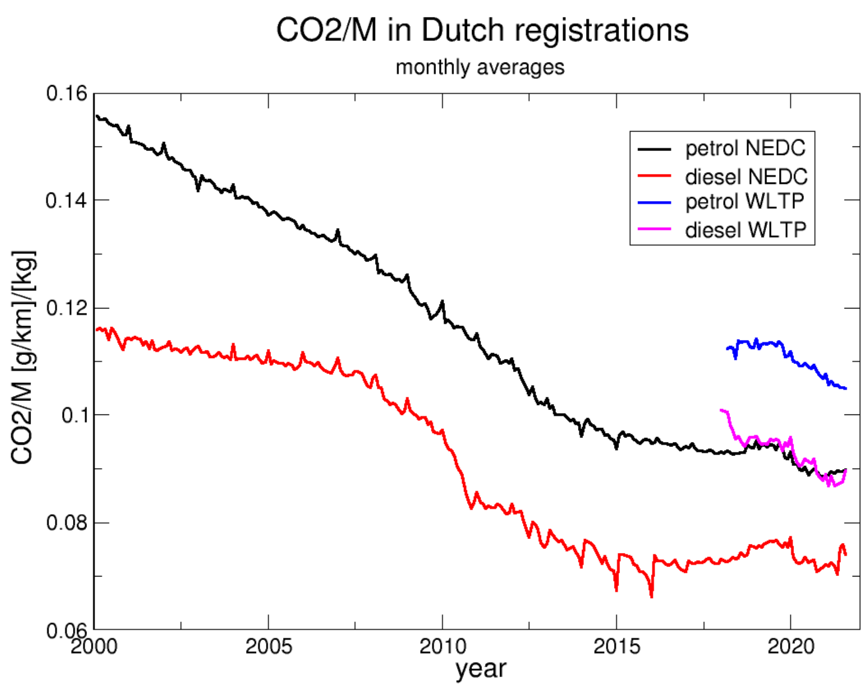

Figure 12: Monthly fleet average CO_2 emissions in g/(km*kg) for petrol and diesel vehicles based on the NEDC and WLTP test cycles in the Netherlands over the period 2000 – June 2021.

The same result for CO_2 itself, not normalized by mass, show the same trend but with larger monthly variations, especially for petrol cars.

On the other hand, the few dips in the diesel cars sales seem to be genuine fuel efficiency improvements, linked to tax incentives. However, more importantly, in the years 2000-2007 there seems little improvement of fuel efficiency, on the basis of CO_2 alone. For CO_2/M there is a clear downward trend. The increase is mass has kept pace with the improved fuel efficiency, with limited net effect.

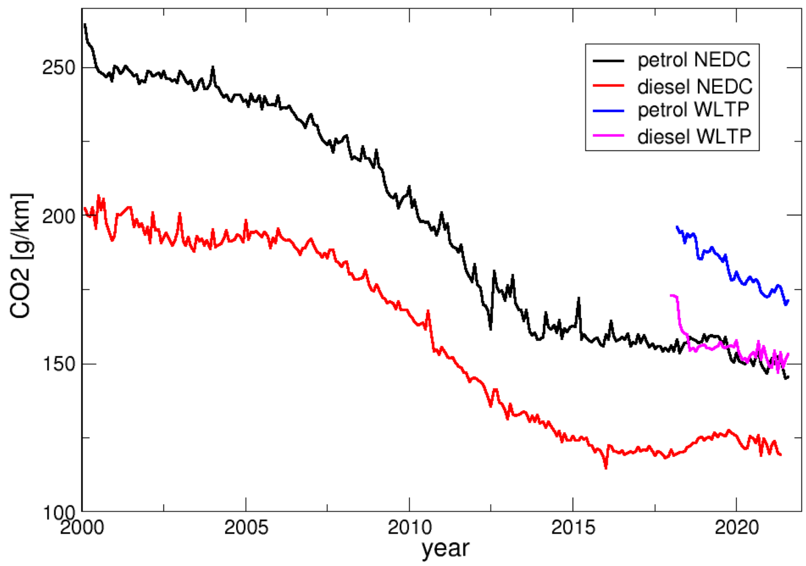

Figure 13: The monthly average CO_2[g/km] based on the RDW registration data on July 2021. The mass increase between 2000 and 2005 obscured somewhat the fuel economy improvements observed in the CO_2/M plots.

Improvements in fuel efficiency, visible already decades ago, predates the European targets, the EEA monitoring, and even the Dutch CO_2 based tax scheme from 2006. The long-term trend shows an improvement of fuel efficiency in terms of CO_2 in g/km per kg vehicle mass from 2000 onward with a slight interruption in the period 2017 to 2019. After 2019 the fuel efficiency improvements are again taken up.

Looking at the dependence on vehicle mass, the RDW data can give further indication of the differences in fuel efficiency, for different mass categories. Using a 200-kilogram bandwidth around a central reference mass shows variations in the trends in fuel consumption. Heavier vehicles, both petrol and diesel, had a sharper increase in fuel efficiency than lighter vehicles. Nowadays, vehicles of 1300 kg and 1700 kg have the same CO_2/M, while lighter and compacter petrol cars are lagging behind in improvements, by a fixed amount of about 0.01 g/(km*kg), or about 11 g/km for these vehicles. Smaller diesel vehicles show a substantially lower CO_2/M than bigger vehicles until the tax incentives ended in 2016. After that date, there seems little distinction in CO_2/M for different masses.

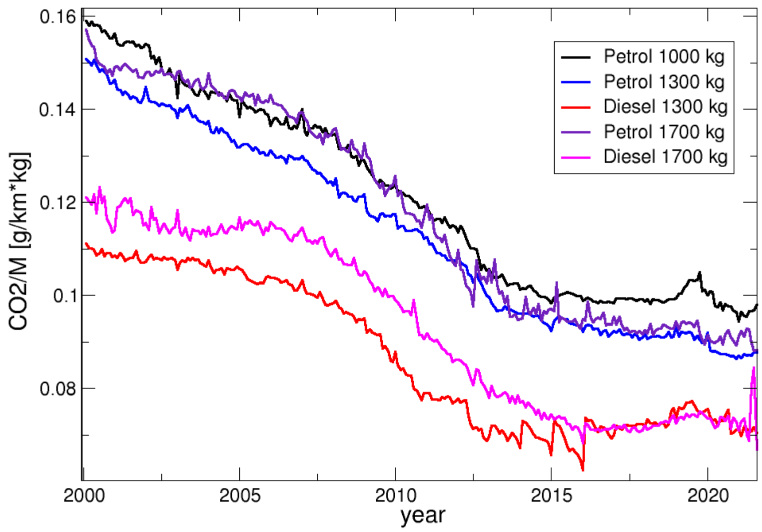

Figure 14: Monthly fleet average CO_2 emissions in g/(km*kg) for petrol and diesel reference vehicles based on the NEDC and WLTP test cycles in the Netherlands over the period 2000 – June 2021.

5 Extrapolating up to 2025

From the CO_2/M as a measure for fuel efficiency it is clear that fuel efficiency has been increasing monotonously over a long period. The introduction of WLTP and RDE legislation lead to a singular jump in this trend, but is not expected to change the long and consistent trend in fuel efficiency.

Without making reference to variations for vehicle mass the long-term monotonous trend of fuel-efficiency improvements are:

- Petrol: -0.0033 g/(km*kg*year) (NL data)
- Diesel: -0.0022 g/(km*kg*year) (NL data)

These results are interpolated between the endpoints 2000 and 2021, excluding the periods of Dutch tax incentives, but including the effect of the WLTP introduction. These changes are irrespective of the test procedure, either NEDC or WLTP. The upward jump of about 4 g/km of diesel vehicles is factored in into the change to WLTP CO_2 values.

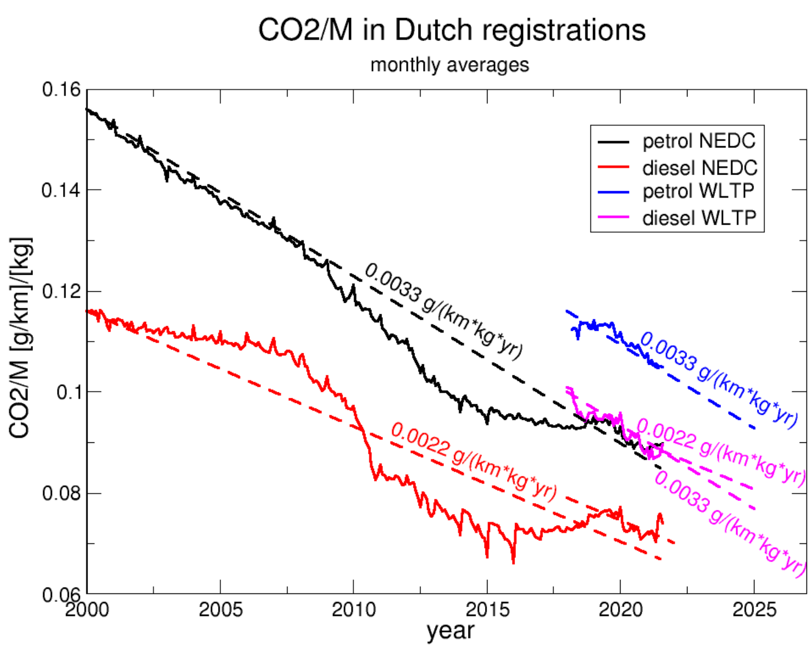

Figure 15: Monthly fleet average CO_2 emissions in g/(km*kg) for petrol and diesel vehicles based on the NEDC and WLTP test cycles in the Netherlands over the period 2000 – June 2021. Diesel vehicles had an upward jump in 2019, due to the RDE legislation.

Consequently, for the autonomous development these trends can be translated into reduction values for vehicle groups by setting a reference mass M. If mass M for petrol is set at 1200 kg and M for diesel is set at 1450 kg, representative averages for both groups, the change in fuel efficiency is 4.0 and 3.2 g/km per year, respectively.

Two possible scenarios exists for the diesel vehicles. Firstly, the continuation of the long-term 0.0022 g/(km*kg*year) trend, accepting the more recent trend for WLTP vehicles as a temporary adjustment, compensating for the upward jump with RDE. Or, secondly, using the new WLTP trend, similar to the trend for petrol vehicles. The long-term trend seems to be more appropriate, since the realignment of diesel vehicles with RDE legislation, with the shift upward is likely to be compensated in the years after.

For the long-term trend, the European data, not affected by changes related to tax policies, is more appropriate. This gives minor changes in the fuel efficiency trend for petrol and diesel: (See Figure 17)

- Petrol: -0.00289 g/(km*kg*year) (EU data)
- Diesel: -0.00228 g/(km*kg*year) (EU data)

The average fuel efficiency change depends on the mass of petrol cars. The low mass petrol cars, around 1000 kg has limited fuel efficiency improvement relative to the heavier cars. For diesel cars, the fuel efficiency improvements do not vary much with the mass of the vehicle. Ignoring the temporary disturbance 2017-2019.

The long terms trends, also supported by RDW data 2010-2021, are:

- Petrol vehicle of 1000 kg: 2.47 g/km CO_2 reduction per year.
- Petrol vehicle of 1300 kg: 4.55 g/km CO_2 reduction per year.
- Petrol vehicle of 1700 kg: 5.95 g/km CO_2 reduction per year.
- Diesel vehicle of 1000 kg: 2.67 g/km CO_2 reduction per year
- Diesel vehicle of 1300 kg: 3.47 g/km CO_2 reduction per year
- Diesel vehicle of 1700 kg: 4.54 g/km CO_2 reduction per year

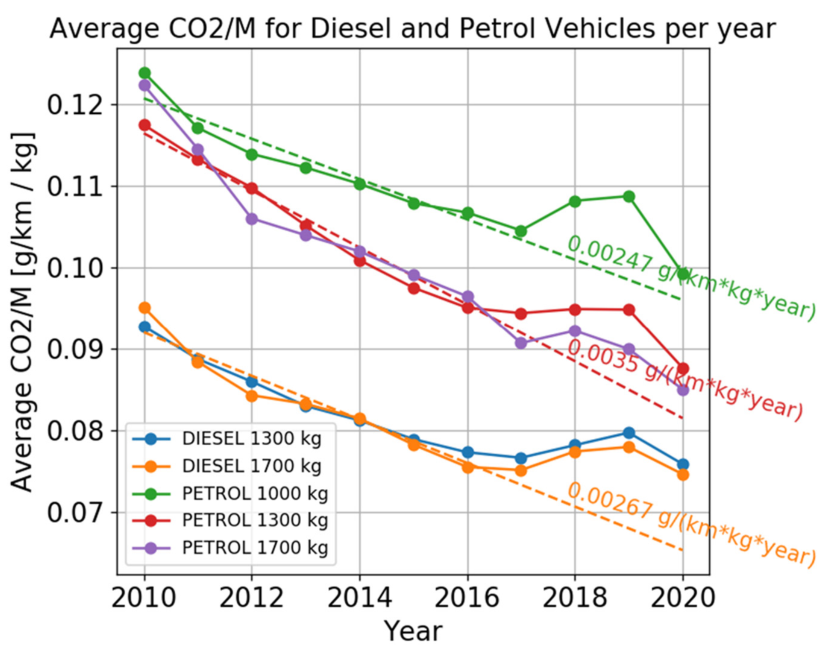

Figure 16: Yearly average of CO_2/M in g/(km*kg) in the EU for petrol and diesel reference vehicles based on the NEDC and WLTP test cycles in the Netherlands over the period 2000 – June 2021, based on EEA data.

The fitting parameters along with the R^2 of this fit is as follows:

Table 10: Fit parameters of the CO_2/M of Diesel and Petrol reference vehicle.

Fuel	**C**	**B**	**R^2**
Petrol 1000 kg	5.0920	-0.00247	0.565
Petrol 1300 kg	7.1492	-0.0035	0.781
Petrol 1700 kg	8.1336	-0.0040	0.858
Diesel 1300 kg	4.7135	-0.0023	0.378
Diesel 1700 kg	5.4630	-0.00267	0.378

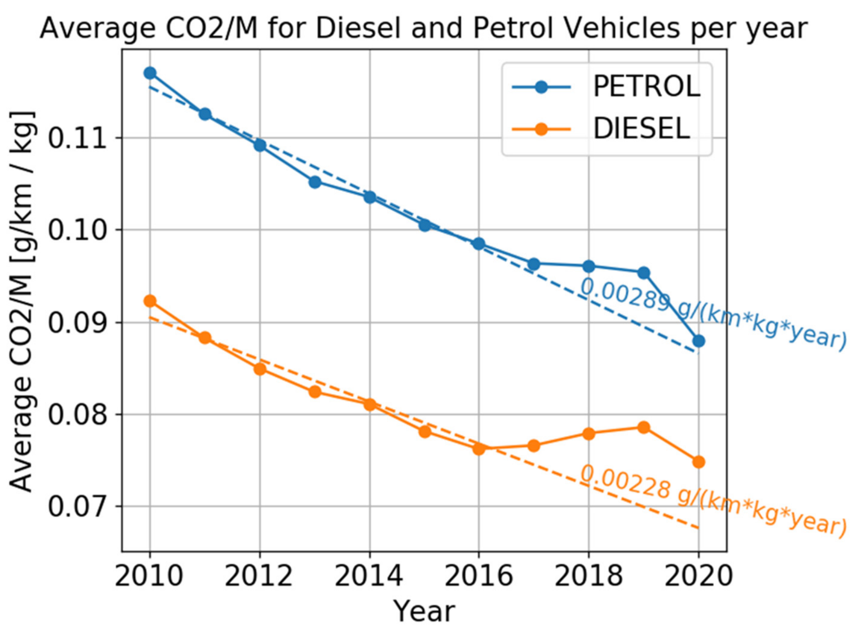

Figure 17: Yearly fleet average of CO_2/M in g/(km*kg) in the EU for petrol and diesel vehicles.

The fitting parameters along with the R^2 of this fit is as follows:

Table 11: Fit parameters of the CO_2/M of Diesel and Petrol vehicle.

Fuel	**C**	**B**	**R^2**
Petrol	5.9253	-0.00289	0.923
Diesel	4.6831	-0.00228	0.606

The consequence of the mass dependence of the CO_2 emission reduction is a shrinking bandwidth of CO_2 values, e.g., for petrol cars from 80 g/km in 2010 to 27 g/km in 2025. Take a fixed bandwidth of 700 kg between the smallest and the heaviest vehicle, the change of time brings all values together, and the distinctions in CO_2 of compact and medium size cars are negligible:

Table 12: The NEDC CO_2 [g/km] values, based on the trends in CO_2/M, incorporating a 5 g/km effect for diesel and a 1 g/km effect for petrol in 2019 with RDE/WLTP legislation.

CO_2 g/km	Year	2010	2020	2022	2025
Petrol	1000 kg	120	96	91	84
	1300 kg	152	108	99	85
	1700 kg	199	140	129	111
Diesel	1300 kg	121	91	84	74
	1700 kg	158	118	109	95

5.1 Expected effects of BEV and PHEV sales

There seems very little reason or indications that the trends of fuel efficiency of conventional vehicles is affected by the shares of BEV and PHEV vehicles sold in total or per manufacturer. There is little correlation between the two aspects.
The European targets, or autonomous developments, will increase these shares, but in the period from 2020 to 2025, it is expected that petrol and diesel vehicles will have a steady decrease in CO_2/M. Whether the absolute CO_2 emissions will go down depend very much on the size and mass of the vehicles.

Changing average masses are very common in the vehicle sales of different manufacturers, over the last years. Market segments and new models are meant to entice consumers to buy bigger and more expensive cars. The industry is very successful because vehicle models of 20 years ago are no longer acceptable to the current consumer. The trend to sell larger, i.e., heavier, vehicles is only sustainable with improved fuel efficiency and other means to meet European targets.

5.2 Uncertainties and confidence

Confidence is the support of the conclusions by facts and figures. It can be formalized mathematically, but a trend from 2000 to 2021 of an almost monotonous decrease of the CO_2/M, as an appropriate proxy for fuel efficiency, year by year, and month by month, should speak for itself, given the figures provided. Both the European data and the Dutch data are consistent, and the differences are explained. The Dutch data, until June of 2021, shows that the temporary change 2017-2019, likely related to new and more stringent pollutant emission legislation ended in 2020, and the improvements are now again following the same pace as before, but based on the WLTP CO_2 values. Given the different routes, like using EEA or RDW data, to arrive at the trend in fuel economy give slightly different answers this can form the basis of the uncertainty, which is within 15% on the cited CO_2/M in [g/(km*kg*year)] for petrol, and within 10% for diesel, with high confidence. For individual vehicles the deviations are much larger, but this report considers only fleet and mass bin average results, for which the deviations are small. Statistical approaches, e.g., standard deviations and R^2 will lead to even smaller errors. But it is expected that the systematic errors, i.e., the appropriateness of the data to perform the extrapolation is the larger source of uncertainty.
The RDW data is less appropriate for the extrapolation, given the effect of task incentives, still this data leads to a similar result.

There is limited data on the trend of the fuel efficiency for the WLTP. The fuel efficiency in terms of a fixed annual change of ΔCO_2/M is assumed to continue with the WLTP, as it did with the NEDC for over two decades. The shift upwards with the WLTP, seemed like a setback for 2018 and 2019, where 2020 is similar, slightly lower for petrol, as the 2017 results for conventional vehicles. The much higher WLTP values may suggest a faster reductions of CO2/M values. However, the slightly increasing gap in absolute difference between NEDC and WLTP, from 2019 to 2020 indicates the lack of convergence and new parallel trajectories of the same decreases in CO2/M. The transition to WLTP can best be interpreted as a four to five year shift back in time for the CO_2[g/km] values, for a fixed vehicle mass, where the hypothetical intersection with the zero axis, initially expected for 2044 is now set to 2049.

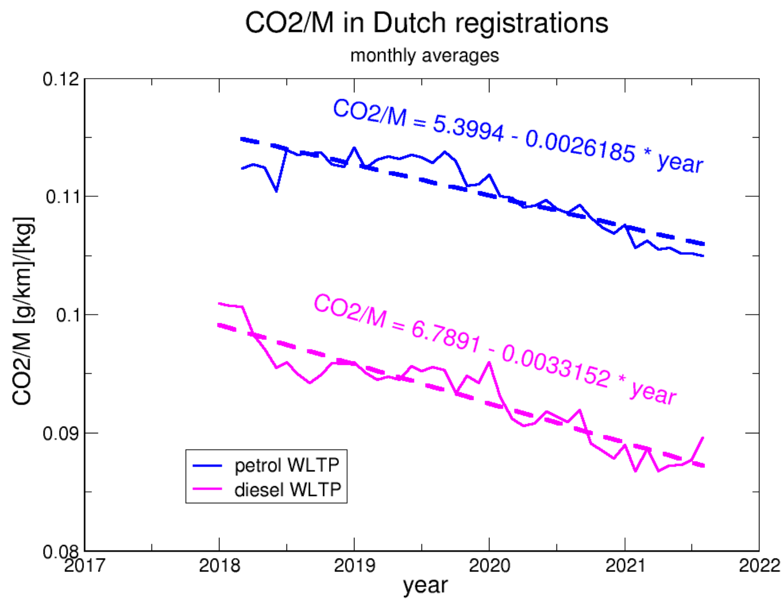

Figure 18: Details of the limited WLTP data of Dutch vehicle registrations from Figure 15, with the fit lines and formulas. The slope for petrol vehicles is consistent with the slope based on the NEDC values.

The transition to the WLTP has made it harder to achieve low CO_2 values, and it is therefore not expected that the fuel efficiency in the CO_2/M metric is faster than it has been before. Given these findings, a fixed ΔCO_2/M is assumed independent of the test method. The appropriateness of this assumption is confirmed by Dutch registration data. The linear fit through Dutch month-by-month WLTP values are 0.00262 and 0.00332 g/(km*kg*year) for petrol and diesel vehicles respectively. The WLTP reduction rate for petrol, based on Dutch registrations is similar to the European NEDC, which lies in the bandwidth of 0.00246 to 0.0035, depending on vehicle mass. The value deviates only 9% from the average of 0.00289 g/(km*kg), well within the cited bandwidth of uncertainties of 15% from other sources. The reduction rate for diesel, based on the Dutch WLTP data, is higher than the long term trend of 0.00228 g/(km*kg*year), but this is affected by the limited number of registrations, which reduces the reliability of Dutch diesel registration data for overall fuel efficiency changes.

6 Discussion

There are many perspectives on CO_2 policies and the role of CO_2 values therein. Depending on the perspective the approach in a study will change. This report took the narrow path and deviated only from mass-based to footprint-based approach and back for illustrative purposes that mass is a conservative gauge to compare fuel efficiency over time. The footprint as a gauge does not take into account that recent changes in vehicles are mainly options for comfort and safety, increasing the mass, independent of the footprint. The faster downward trend of footprint is however somewhat surprising, indicating an even more substantial increase in car sizes across Europe than mass. It may also reflect a mass reduction on component basis is taken place, although compensated by the increase in both size, i.e., footprint, and options.

The first and foremost user of vehicle CO_2 values is the European Commission, which sets targets for manufacturers based upon them. If European targets would have driven the Dutch registration CO_2 values to the desired national level, no additional national policies would be needed. The Dutch CO_2-based tax policies are on top of these European policies; only a net effect, and therefore they need to be adapted to the effectiveness of European CO_2 policies on passengers cars. So a constant monitoring of the European baseline is needed, to adjust national policies accordingly.

The problem with this evaluation lies partly in the European targets themselves, which combine BEV, PHEV, and conventional cars in one particular manner, while Dutch policies make clear distinctions between these groups of vehicles, with separate policies. Hence, a translation from European targets to Dutch policies is not straightforward. European targets have had a shift in effect on CO_2 of conventional cars, with recent broader introduction of PHEV and BEV. From the data it is clear that the CO_2 trend of conventional cars is a monotonous trend over a long period, in particular when separated by fuel type and normalized by vehicle mass. The monotonous, long term trend provides the confidence that this trend can be extrapolated.

A simplistic approach to assume that the 95 g/km European target, for 2020, and subsequent targets for 2025 and 2030, is also the expected fuel efficiency improvements for conventional cars, is flawed, since an increasing part of this target is met by PHEV and BEV sales. So 95 g/km is a lower limit, which is missed by more than 10 g/km by conventional cars alone, independent of the precise perspective taken. The long-term autonomous trend of fuel economy, provides a much more stable answer, irrespective of manufacturers' sales mix.

Vehicle mass plays a complex role. It is part of the European targets, thus limiting slightly the need to reduce mass to meet the targets. Furthermore, vehicle mass seems to be a bit of a free variable. If possible within the requirements, manufacturers seem to want to sell more expensive and more heavy cars. This is consistent with the understanding that sales margins are higher of heavier, more luxurious cars, and any way to increase this share in the annual sales is welcomed.

This is probably the key driver in the CO_2/M decreases over the years, but will make the CO_2 in g/km vary, when improvements in fuel efficiency are “cashed in” by subsequently increasing vehicle mass.

This report does not provide any bandwidth on CO_2 values. For a vehicle of a given mass there is a large bandwidth in CO_2 values.
A small vehicle mass combines compact cars and sportscars. A large mass may include luxury cars, SUVs, and MPVs, all with their distinct CO_2 values. The sales mix of European cars is considered the reference of determining the averages. These averages are consequently the basis of the analyses. For the macroscopic view, the details of the underlying fleet are less relevant, and there is little need to zoom in on details. The change in registrations, and the averages, is captured in a single parameter: the change in vehicle mass. Since these trends are monotonous and well correlated with CO_2 itself, this is the basis of the study. The European fleet are a reflection of the European CO_2 targets. This lies, or should lie, at the basis of national policies, as it is the starting point of this report.

The results show a narrowing of the CO_2 bandwidth between the smallest, lightest, and the largest, heaviest cars, over the years. The CO_2 value is less and less a qualifying feature of the size or price of a vehicle. Hence, CO_2-based taxes may lead to similar taxes on compact cars and luxury cars, in particular in the full bandwidth of CO_2 values within a given mass class. Given the different catalogue prices of the vehicles, this is a significant deviation from value added tax principle.

7 Signature

The Hague, 17 September 2021

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A Alternative fits for the trends

In this section, other methods of fitting are used to describe and understand the effects of CO_2/M and CO_2/A over the years. This gives an indication of the bandwidth based on the underlying assumptions. The report used the fit 2010-2017 as the basis, as this data is not tainted by the WLTP transition and the pre-target registrations.

A number of methods include an estimate of the shift in CO_2 emissions from the introduction of the WLTP. In 2019 this was estimated to be 1 g/km for petrol and 7 g/km for diesel, excluding mass effects.[3] These effects should compare well with the offset in CO_2/M.

A.1 Method 1 – fit on 2010-2020

If all data is used the fuel efficiency improvements are about 20% lower. The effect of mass is similar. A fit for CO_2/M and CO_2/A was also made for a period of 2010 to 2020 in place of the previous fit made from 2010-2017. The results for that are as follows.

A.1.1. CO_2 per mass of the vehicle

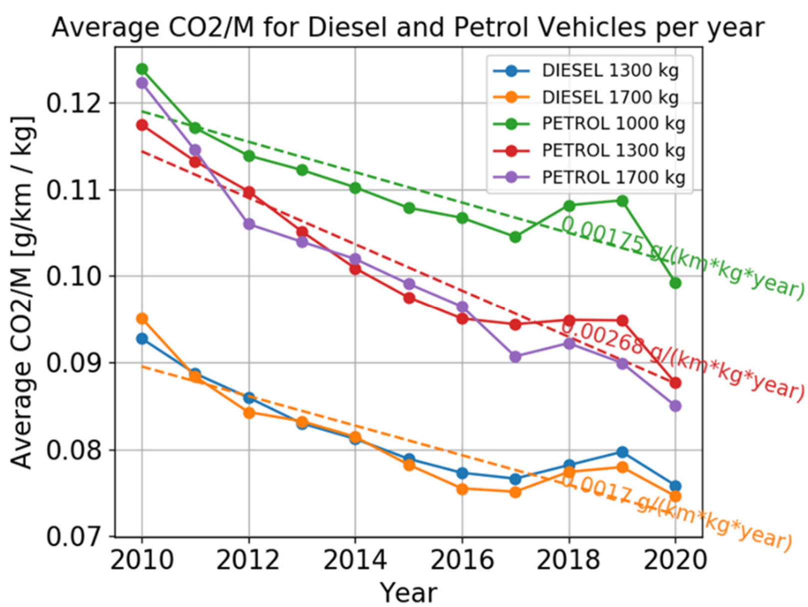

Figure 19: CO_2/M for reference Petrol and Diesel vehicles for a fit made from 2010 to 2020.

[3] TNO 2019 R10952 Aspects of the transition from NEDC to WLTP for CO2 values of passenger cars - Phase 3: After the transition.

The fitting parameters along with the R^2 of this fit is as follows:

Table 13: Fit parameters of the CO_2/M of Diesel and Petrol reference vehicle.

Fuel	A	B	R^2
Petrol 1000 kg	3.6463	-0.00175	0.788
Petrol 1300 kg	5.5091	-0.00268	0.918
Petrol 1700 kg	6.6733	-0.0033	0.933
Diesel 1300 kg	3.0266	-0.0015	0.794
Diesel 1700 kg	3.5103	-0.0017	0.785

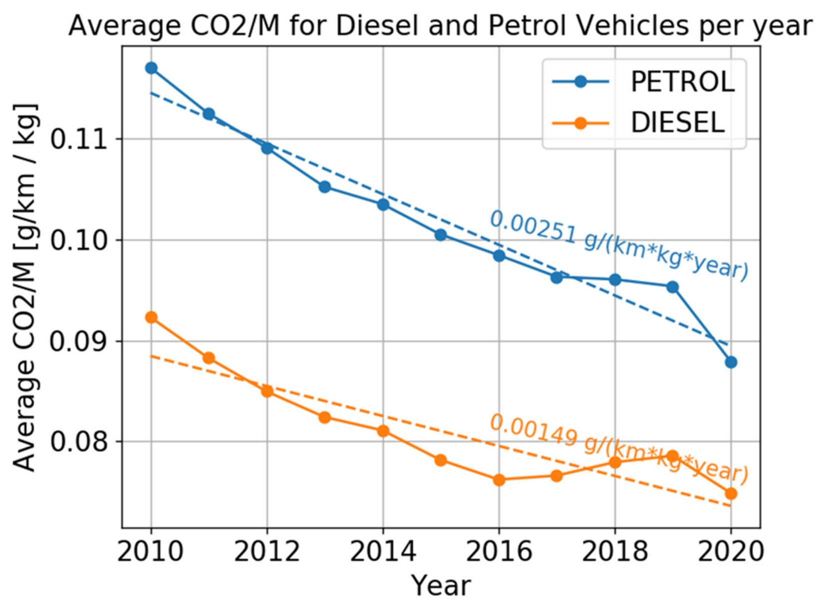

Figure 20: CO_2/M for Petrol and Diesel vehicles for a fit made from 2010 to 2020.

The fitting parameters along with the R^2 of this fit is as follows:

Table 14: Fit parameters of the CO_2/M of Diesel and Petrol vehicle

Fuel	A	B	R^2
Petrol	5.1612	-0.00251	0.957
Diesel	3.0753	-0.00149	0.806

A.1.2. CO_2 per footprint of the vehicle

The use of 2010 to 2020 data for the fit with footprint lead to similar results as with mass. The reductions in fuel efficiency are somewhat less.

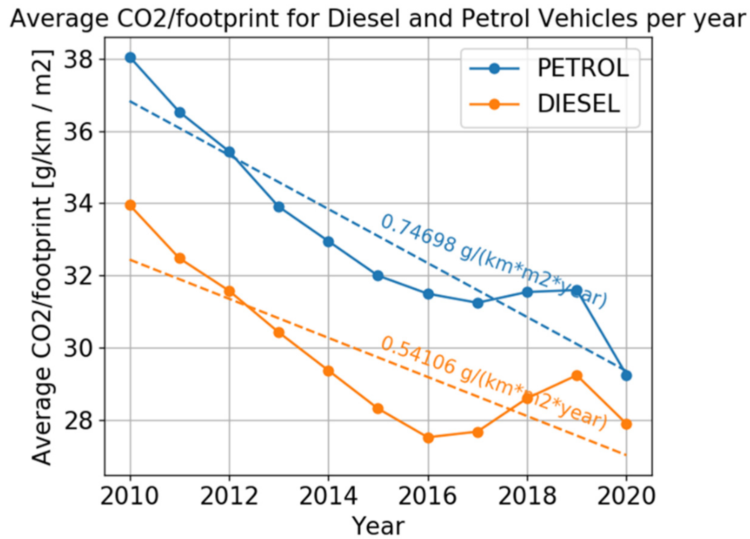

Figure 21: The trends in CO_2/A or CO_2 [g/km] per footprint area A[m2] for the European registrations. The data up to 2020 is used to fit a trend.

The parameters of this fit along with the R^2 value for the fit are as follows:

Table 15: Fit parameters of the CO_2/A of Diesel and Petrol vehicles.

Fuel	**A**	**B**	**R^2**
Petrol	1538.2466	-0.74698	0.888
Diesel	1119.9743	-0.54106	0.710

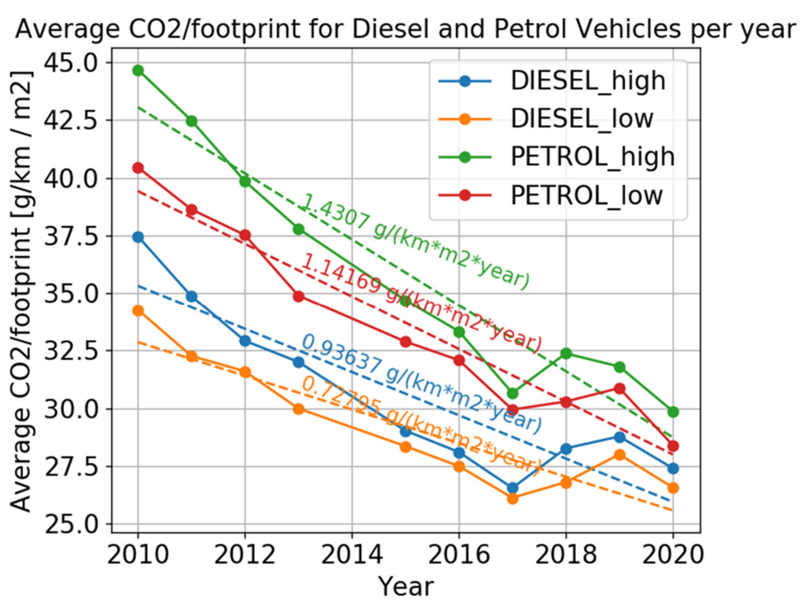

Figure 22: The trends in CO_2/A or CO_2 [g/km] per footprint area A[m2] of reference vehicles for the European registrations. The data up to 2020 is used to fit a trend.

The parameters of this fit along with the R^2 value for the fit are as follows:

Table 16: Fit parameters of the CO_2/A of Diesel and Petrol reference vehicles.

Fuel	A	B	R^2
Petrol_high	2918.7659	-1.4307	0.9279
Petrol_low	2334.2089	-1.14169	0.9416
Diesel_high	1917.4213	-0.93637	0.818
Diesel_low	1496.0512	-0.72795	0.8422

A.2 Method 2 – fit on 2010-2017 and 2018-2020 with a WLTP offset

Another method for analysis used was to fit the data from 2010-2017 and 2018-2020 with an offset to see the effects of the change in regulations from NEDC to WLTP. The results for that are as follows.

A.2.1 CO_2 per mass of the vehicle

A better way to include all years 2010 to 2020 is to accept an offset from the transition to WLTP and RDE. This yields a larger offset for petrol cars than found earlier. Also, the offset for diesel cars, already somewhat higher, is higher in this fit still.

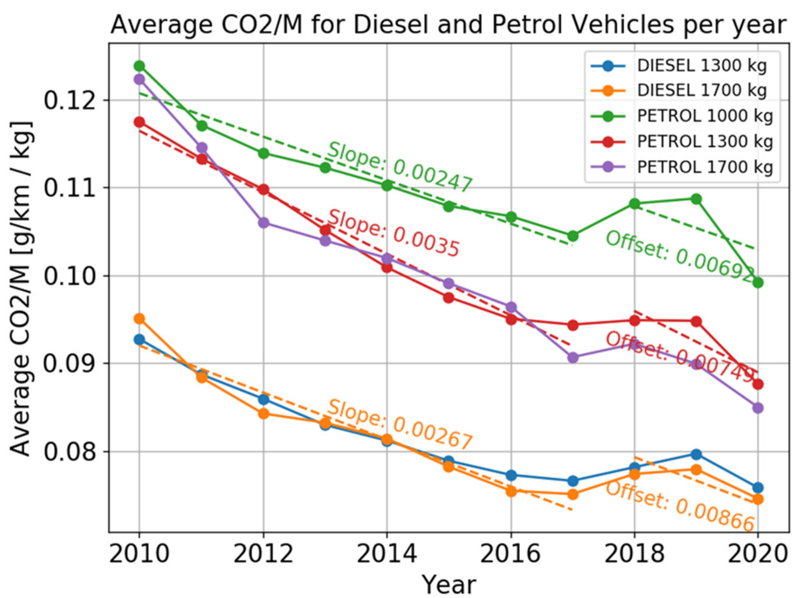

Figure 23: CO_2/M for reference Petrol and Diesel vehicles for a fit made for 2010-2017 and 2018-2020 with an offset depicting the change in regulations.

The slope is measured in g/(km*kg*year) while the offset is measured in g/(km*kg). The offset is similar to a shift back 2 to 3 years. For the averages themselves the shifts are less, indicating a shift across weight classes.

The fitting parameters and the R^2 along with the offset values are as follows:

Table 17: Fitting parameters, R^2 and offset values for the fit made on reference petrol and diesel vehicles for CO_2/M for 2010-2017 and 2018-2020 with an offset.

Fuel	**A (for 2010-2017)**	**A (for 2018-2020)**	**B**	**Offset**	**R^2**
Petrol 1000 kg	5.0920	5.0989	-0.00247	0.00692	0.8991
Petrol 1300 kg	7.1492	7.1567	-0.0035	0.00749	0.9757
Petrol 1700 kg	8.1336	8.1402	-0.0040	0.0066	0.9622
Diesel 1300 kg	4.7135	4.7210	-0.0023	0.0075	0.9474
Diesel 1700 kg	5.4630	5.4716	-0.00267	0.00866	0.9352

The offsets for the fleet averages, with no distinction in mass, is more in line with earlier findings. The slope is somewhat lower, for a smaller offset in return, for petrol vehicles. The offsets would for diesel vehicles the difference is less.

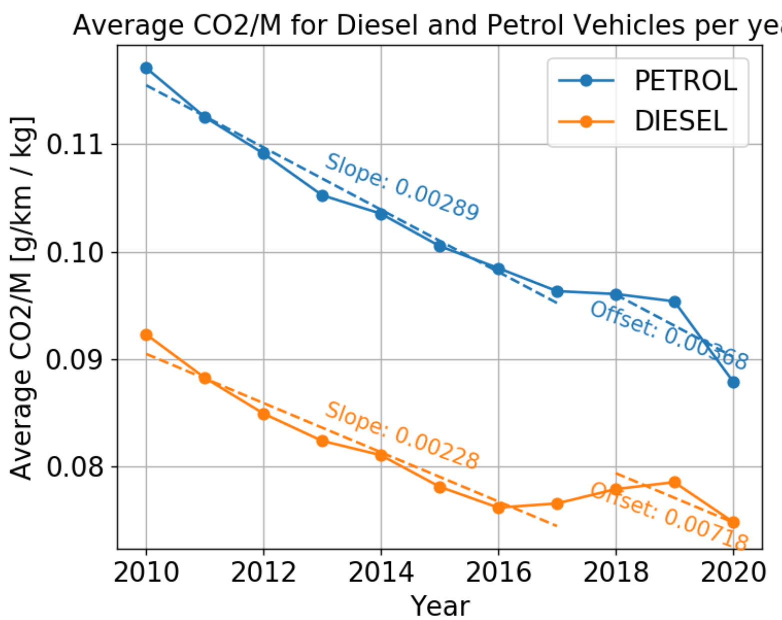

Figure 24: CO_2/M for Petrol and Diesel vehicles for a fit made for 2010-2017 and 2018-2020 with an offset depicting the change in regulations. The offset for petrol is comparable to a shift backward in the downward trend of 15 months, while for diesel the shift is about 3 years.

The fitted offsets translate into about 4 g/km for petrol, 3 g/km higher than the 2019 result, and 9 g/km for diesel, which is 2 g/km higher than the findings based on the limited data in 2019. These results, for European data differ somewhat from the Dutch registration data. The precise reason is unclear. The introduction to the WLTP can be interpreted for the NEDC values as a “delay” of 15 months for petrol, and three years for diesel, in the improvement of fuel efficiency.

The slope is measured in g/(km*kg*year) while the offset is measured in g/(km*kg).

Table 18: Fitting parameters, R^2 and offset values for the fit made on petrol and diesel vehicles for CO_2/M for 2010-2017 and 2018-2020 with an offset.

Fuel	**C (for 2010-2017)**	**C (for 2018-2020)**	**B**	**Offset**	**R^2**
Petrol	5.9253	5.9290	-0.00289	0.00368	0.976
Diesel	4.6831	4.6903	-0.00228	0.00718	0.9479

A.2.2 CO_2 per footprint of the vehicle

The change to the WLTP did lead to changes in the physical dimensions of vehicles. This has led to different shifts upward in 2018 for mass and footprint. The shift can be compared with the year-by-year change, captured in the slope. The shift is typically related to 1.6 to 2.5 years. For the CO_2/A, the results looks as follows:

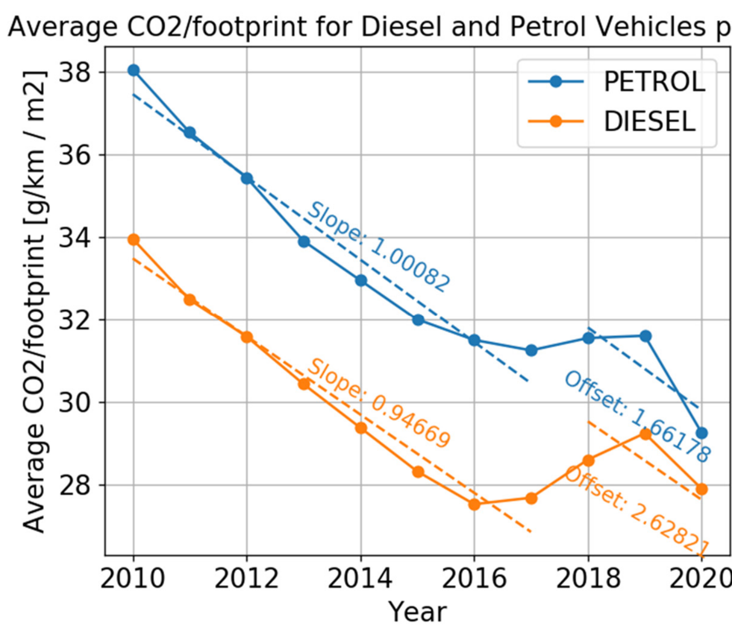

Figure 25: The trends in CO_2/A or CO_2 [g/km] per footprint area A[m^2] for the European registrations. The fit is made on 2010-2017 and 2018-2020 with an offset.

The shifts in years based on mass and footprint are similar for both diesel and petrol. The parameters of this fit along with the R^2 value for the fit are as follows:

Table 19: Fit parameters of the CO_2/A of Diesel and Petrol vehicles of all footprint combined per fuel type.

Fuel	**C (for 2010-2017)**	**C (for 2018-2020)**	**B**	**Offset**	**R^2**
Petrol	2049.1043	2051.4554	-1.00082	1.66178	0.96
Diesel	1936.3262	1939.9454	-0.94669	2.62821	0.941

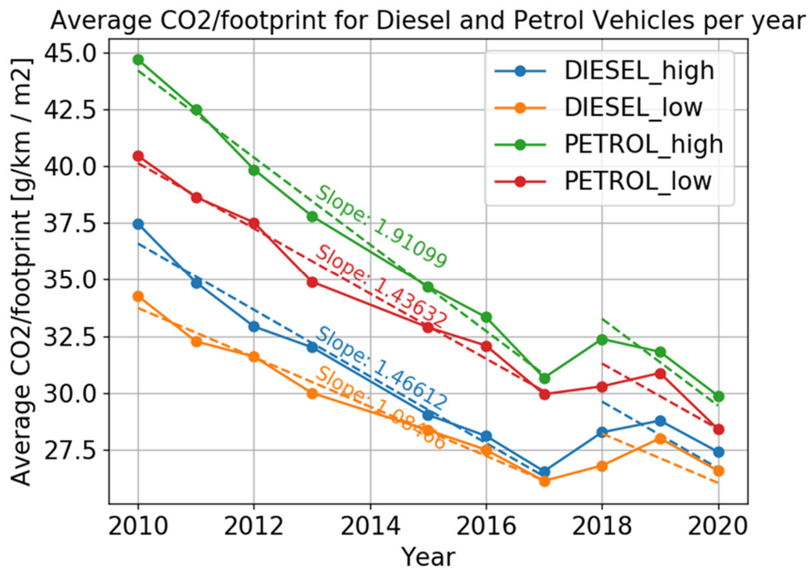

Figure 26: The trends in CO_2/A or CO_2 [g/km] per footprint area A[m2] of reference vehicles for the European registrations. The fit is made on 2010-2017 and 2018-2020 with an offset.

The parameters of this fit along with the R^2 value for the fit are as follows:

Table 20: Fit parameters of the CO_2/A of Diesel and Petrol reference vehicles for the different footprints.

Fuel	C (for 2010-2017)	C (for 2018-2020)	B	Offset	R^2
Petrol_high	3885.2809	3889.6382	-1.91099	2.0202	0.989
Petrol_low	2927.1231	2929.7814	-1.43632	1.5189	0.977
Diesel_high	2983.4880	2988.2419	-1.46612	2.6787	0.963
Diesel_low	2213.8928	2217.0470	-1.08466	2.1380	0.945

B NEDC-WLTP correlation revisited

Based on the EEA 2020 data, with for the first time WLTP data entered relatively complete and correct, it is possible to determine the correlation between the NEDC CO_2 values and the WLTP CO_2 values based on an average European fleet.

The difference between WLTP and NEDC is determined as a function of vehicle mass. This allows the combination of these results with the main results in the report.

- diesel: CO_2[WLTP] – CO_2[NEDC] [g/km] = 1.20 + 0.0176 * M[kg];
- petrol: CO_2[WLTP] – CO_2[NEDC] [g/km] = 15.8 + 0.0064 * M[kg].

Hence, for petrol vehicles there is a constant offset, with minor increasing trend with vehicle mass. For diesel vehicles the difference between WLTP and NEDC CO_2 values is roughly proportional with vehicle mass. Initially, a 15 g/km + 5% CO_2-related difference was determined, based mainly on petrol cars.[4] Given a CO_2/M of 0.09 g/(km*kg) for 2020, the same formula would now read 15.8 g/km and 7.1% of CO_2. For 2019 the CO_2 per kilogram vehicle mass was less, and the difference between WLTP and NEDC would be 15.8 g/km and 6.6% of the NEDC CO_2. It should be noted that these differences are small compared by the year-by-year reduction of CO_2 values.

Table 21: The WLTP CO_2 [g/km] extrapolation values, based on the trends in NEDC CO_2/M. Converted to the WLTP values based on mass-dependent trends in the EEA 2020 data.

WLTP		**Year**		
CO_2 [g/km]	**Mass**	2020	2022	2025
	1000 kg	117	113	105
	1300 kg	131	122	108
Petrol	1700 kg	166	154	136
	1300 kg	110	103	93
Diesel	1700 kg	144	135	121

One central question is, if the CO_2/M trend is different across the fleet for WLTP compared to NEDC. Looking at the dependencies on mass of the CO_2/M, the linear regression through the data shows:

- diesel: CO_2/M [g/(km*kg)] = 0.0904 + 1.89e-06 * M[kg];
- petrol: CO_2/M [g/(km*kg)] = 0.1450 - 2.82e-05 * M[kg].

which gives a range with vehicle mass between 1100 and 1700 kg, of 0.092 and 0.094 for diesel, and 0.114 and 0.097 CO_2/M [g/(km*kg)] for petrol. These WLTP results are well in line with the mass dependence of the CO_2/M results for the NEDC values. Diesel shows a limited dependency of the CO_2/M on the mass itself, while compact petrol vehicles have about 20% higher CO_2/M than the larger models, for NEDC and WLTP CO_2 values alike.

[4] Aspects of the transition from NEDC to WLTP for CO2 values of passenger cars - Phase 3: After the transition TNO 2019 R10952.

C Possible effects of Euro-7 legislation

Currently, new pollutant emission legislation is being discussed in Brussels. The European Commission is expected to submit draft Euro-7 emission legislation for consultation early 2022. The Euro-7 emission legislation is expected to come into force in 2026 at its earliest, given the needed lead time and steps to be taken. Possible CO_2 penalties have not yet been discussed in the Euro-7 legislation. Pollutant emission legislation is largely decoupled from CO_2 regulation.

It is currently not expected that car manufacturers will implement new emission control technologies before 2026. Depending on the stringency and test execution envelope some technologies may be applied from that date, that would lead to another, yet minor fuel penalty. In particular, the stringency of legislation regarding pollutant emissions during the cold start in cold weather, and the need for preheating catalysts may yield a CO_2 and fuel penalty. However, translated into the WLTP test of 23 kilometres the effect, spread over the full test, is expected to be minor, below 2 g/km.

The increase of CO_2 emissions in the WLTP of diesel vehicles could be attributed to more stringent pollutant emission RDE regulation. In particular the stringency of NO_x emission limits and the test design interplays with CO_2 emissions. This interplay has become important with RDE legislation because the vehicle can no longer have a different emission control strategies in the official test and in normal use. The thermal management of the aftertreatment system and the more and larger catalyst volumes will lead to more CO_2 emissions. The effect of the RDE was estimated in the order of 4 g/km. For Euro-7 legislation further large changes are not expected. From NEDC to RDE there has been the major step, and currently diesel vehicles emit only a fraction of the NO_x emissions compared to previous generations. From RDE to Euro-7 is expected to be a minor step in the trade-off between NO_x and CO_2.

D Effect of mass increases on the net CO_2 reduction in Europe

The average Dutch vehicle mass has fluctuated a lot and thus lead to variations in average CO_2[g/km], given the strong correlation between CO_2 and mass. Not only in the Netherlands, but all across Europe the vehicles mass is increasing. This is a long term trend, but from the EEA data the last 10 years can be analysed consistently.

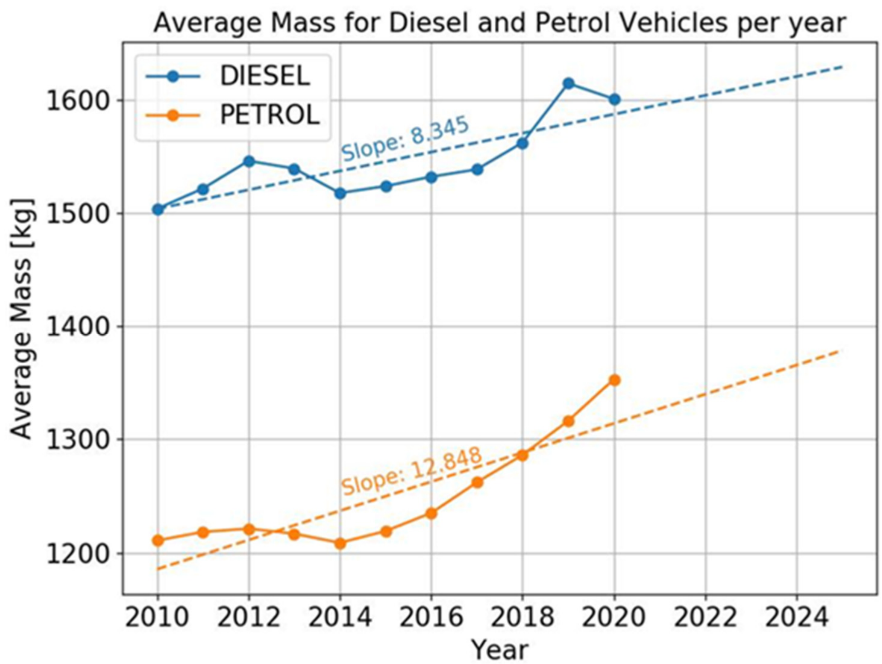

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Figure 27: The fit through the whole period from 2010 to 2020, shows and increase for diesel vehicles of 8.3 kilogram per year, and for petrol vehicles 12.8 kg/year.

In Europe there seems a varying trend for the average mass, but that is mainly the result of the fleet composition of diesel, petrol, PHEV, and BEV, which all have their distinct average masses. For conventional vehicles, separated by fuel type, the trends are much more stable. However, the monotonous increase of vehicle mass has picked up since 2014. So we fit two trend lines: one over the whole period from 2010 to 2020, and one over the period 2014 to 2020, with the larger increase. This provides a bandwidth for the extrapolation to 2025.

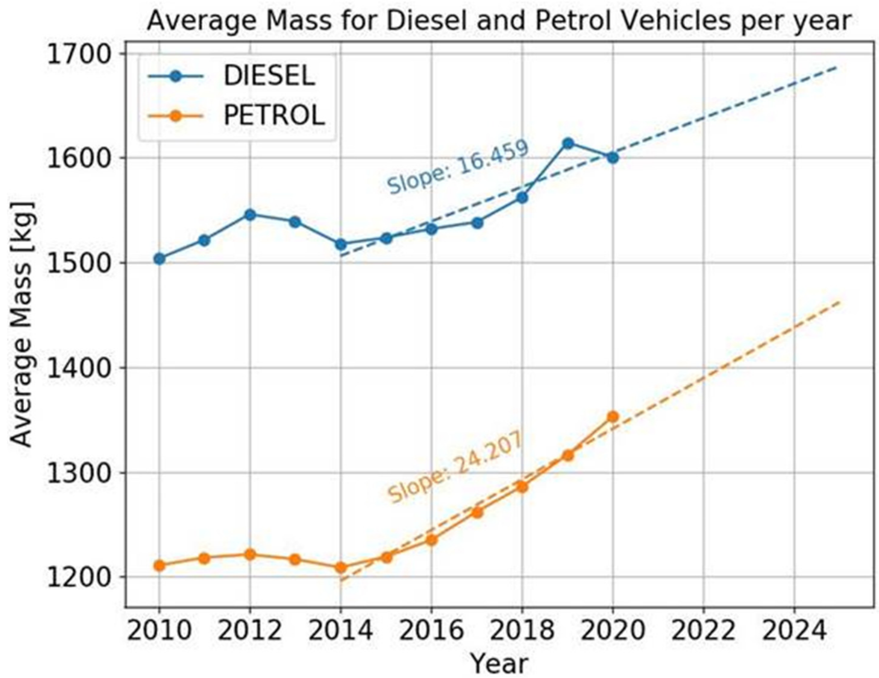

Figure 28: The linear fit from 2014 to 2020 has a better correlation with the data, due to the specific trend in the latter years. The increases a roughly double the values of the 2010-2020 fit, with 16.5 kg/year and 24.2 kg/year for diesel and petrol respectively.

The fit coefficients are for the 2010-2020 fit:
The model is: $y = C + B * (year - 2010)$
The correlation is limited, since there is no consistent trend in the data from 2010 to 2020.

Table 22: The regression coefficients of the fit 2010-2020.

Fuel	C [kg]	B [kg/year]	R^2
Petrol	1185.52	12.847	0.7639
Diesel	1503.76	8.344	0.6426

Starting with average masses in 2010 of 1186 and 1504 kg for diesel and petrol respectively.

For the 2014-2020 fits the R^2 values are higher, suggesting a better fit on more limited data. However, the mass increase is a long trend dating back many decades, with a typical increase of 10 kilogram per year. The pause in mass increase in 2010-2014 is likely compensated in the years 2014-2020 after. Therefore, it is expected that for the 2022 to 2025, the short term trend of the last years is less relevant than the long term trend, best represented by the 2010-2020 data fit.

In the initial years from 2010 to 2014, the mass increases over the first four years were limited to 3 kg and 10 kg, for diesel and petrol vehicles respectively, based on the two fits, which excluded some annual fluctuations.
The model from 2014: $y = C + B * (year - 2014)$

Table 23: The regression coefficients of the fit 2014-2020.

Fuel	C [kg]	B [kg/year]	R^2
Petrol	1195.97	24.207	0.9717
Diesel	1506.28	16.459	0.8572

If these values are taken into account in the change in fuel efficiency, the net fuel efficiency improvement will be smaller. Assuming the change to be proportional to the actual mass, the mass increase of diesel is in the bandwidth of 0.6% to 1.0%, and the mass increase of petrol is in the range 1.1% to 2.0%, at the start 2010 and at 2014. Given the fact that CO_2 [g/km] is roughly proportional to mass (i.e. CO_2/M is constant in a given year), the improvement of fuel efficiency is on average 0.8% less for diesel and 1.6% less for petrol, if mass increase is accepted as part of the autonomous trend. The full bandwidth suggests that fuel efficiency improvement of compact petrol vehicles can be almost absent in the worst case, if mass increases are not compensated for. For diesel vehicles the effects are smaller, both due to the larger CO_2 reduction, compared to compact petrol cars, and the limited mass increase. In the period 2015 to 2019, close to the maximal effect of mass increases on average CO_2[g/km] is indeed observed in the European data, although somewhat obscured by the transition to the WLTP.

Table 24: The annual CO_2 reductions and mass increases for 2022-2025, based on vehicles in 2020, converted to relative effect, showing the substantial effect of mass increases on the net CO_2 reduction rates. For compact petrol cars fuel efficiency improvements can be almost fully compensated by the increase in mass, if both trends are extrapolated from 2020 onwards.

Annual changes 2022-2025			Mass increases		Net CO_2 reduction	
WLTP	**CO_2 [g/km]**	**CO_2 reduction**	**Minimal**	**Maximal**	**Minimal**	**Maximal**
Petrol	1000 kg	2.59%	0.98%	1.80%	1.61%	0.79%
	1300 kg	4.27%	0.98%	1.80%	3.29%	2.46%
	1700 kg	4.27%	0.98%	1.80%	3.29%	2.46%
Diesel	1300 kg	4.03%	0.53%	1.03%	3.50%	3.00%
	1700 kg	4.03%	0.53%	1.03%	3.50%	3.00%

E European CO_2 regulation

This report shows that the European targets have some, yet limited, influences on long term improvements of fuel efficiency of conventional vehicles. The increase in mass is used to fill the available margins that become available with the improvements. However, there are a number of observations that directly link to the specific details of this European legislation.

European legislation seems a patchwork of measures and countermeasures. Some elements, like on-board fuel meters, could be a good idea, but the implementation is currently neither useful nor effective for climate goals. Despite the general outcry on the increasing gap between type-approval and real-world fuel consumption, the European system does not enable car users and owners to pinpoint deviations in real-world fuel consumption from the norm. The CO_2 legislation is mainly a big bookkeeping scheme with perpetually changing rules, to counteract adverse effects of existing regulations that could have been avoided if legislation was more purposeful from the start. The general audience has lost track and experts, with detailed knowledge, still have different perspectives on the matter.

Below some key elements are addressed briefly, from the authors singular perspective.

E.1 Target years

The years leading up to 2020 showed clearly a backlash in registrations of less fuel-efficient vehicles ahead of the manufacturers need to comply with targets partly in 2020 and fully in 2021. The sharp drop in 2020, 15 g/km overall, and a few g/km more than the autonomous trend for conventional vehicles, was the result.
The same situation will occur ahead of the targets with 15% reduction in 2025. It is expected that less fuel-efficient vehicles will be sold in 2024, when no targets apply. The year 2024 will likely show a stalling of fuel efficiency trends, because of the need to sell the more fuel-efficient vehicles in 2025, when the targets apply.

E.2 Threshold values and credits

The 50 g/km threshold for super-credits till 2022 has turned into a design-criteria for plug-in vehicles. Many have battery capacity just meeting this standard, with only a few g/km CO_2 emissions to spare. In the analyses in this report, the 50 g/km is taken as a separation between “conventional” vehicles and plug-ins. A very small number of plug-in vehicles (Off-Vehicle Charging Hybrids) have higher than 50 g/km CO_2 emissions, but this, rather irrelevant, distinction is not easily made in the EEA data.

Additional credits can also be gained by eco-innovations. These aspects do not change the CO_2 result of the type-approval test, but they are included in the evaluation of the targets. It is not generally known which vehicles have which eco-innovations and in which situations they provide a benefit over other vehicles. Or why consumers should buy them.

E.3 Changing metrics

The transition from NEDC to WLTP, and the translating back to NEDC values for the 2020 target, is only one of the confusing aspects of CO_2 emission legislation.

The shift from reference mass to test mass, in combination with the interpolation method, to provide individual CO_2 values add another layer of complexity to evaluating the true change in vehicle fuel efficiency for years to come. Furthermore, the reference value for 2025 based on the emission test results, on prototype vehicles, separate from the actual, declared CO_2 value on the certificate of conformity will lead to very complex discussions, for any legislation based on CO_2 values of registered cars.

New items and alternatives are added frequently. The vehicle registration data are extended. However, very little information is shared outside the type-approval process and people are generally none the wiser on the meaning and use of the data that is provided.

E.4 Decoupling of pollutant and CO_2 emission legislation

With pollutant emissions being controlled mainly in on-road testing, and CO_2 emissions determined in the laboratory, the two parts move in different directions. The legally required transparency on environmental impact, the details shared and public involvement in pollutant emissions, is not the same for CO_2 emissions. The CO_2 targets are considered a largely internal matter, despite the many protests urging more, and more effective, climate actions.

F Linear fits

In this report only straight lines are fitted through the data. The R^2 value is reported in many cases, but the reader can judge for themselves, from the figures, if the fits make any sense, because the data and the trendlines are presented throughout the report.

The choice for a linear fit is robust. Many other fits, like higher order polynomials or non-linear functions typically magnify some marginal effects in the last data points while extrapolating it beyond the initial data range. This report is intended to provide an extrapolation to the period 2022 to 2025. The linear fits are conservative estimates on the trends.[5]

The coefficient of determination, R^2 is the well-known indication of the appropriateness of the fit. The R^2 is defined as the difference of the initial sum square errors, or spread in the data, and the spread of the data around the line:

$$R^2 = 1 - \frac{\sum(y_i - (C + B * x_i))^2}{\sum(y_i - y_{average})^2}$$

Other coefficients and aspects of the fit are occasionally used, but are less common as the R^2 value and with varying definitions and underlying assumptions of the statistics. The human eye, however, is a very good judge of appropriate conclusions whether a trendline is a faithful representation of the data. Therefore, this report is filled with plots so the reader can judge for themselves.

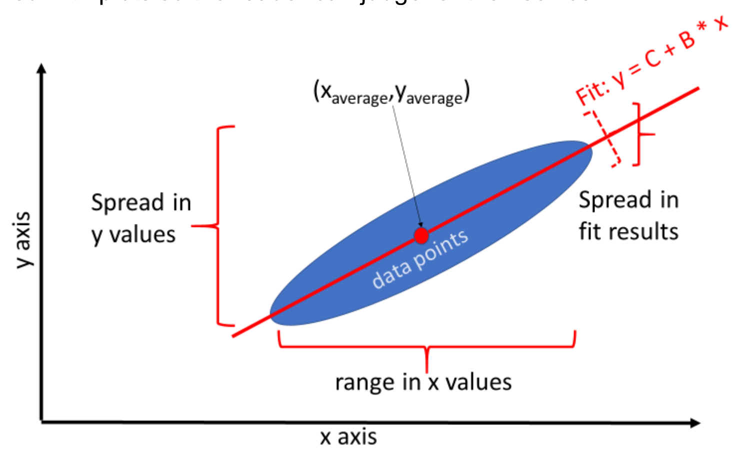

Figure 29: Key aspects of a linear fit through data points represented by the blue ellipse. The spreads in y and the fit results determine R^2.

We draw little conclusions from the fit coefficients themselves. The coefficients of a linear fit have straightforward meanings as the starting value and the slope. Therefore, no sensitivity analysis is carried out on the coefficients separately, which is usually the source of additional econometrical parameters for fit quality.

[5] Tweede Kamer der Staten-Generaal 2019-2020 35302 nr. 8181 reflects a discussion on the details of the fit procedures and reporting by TNO. This appendix is added to avoid such misunderstandings for this study.

In principle, most of these parameters could be derived from the range and the R^2 themselves, and assumptions on probabilities of the underlying data, and contain little extra information in the case of a least-square error fit of a straight line.

Occasionally, alternative methods like an orthogonal fits are used in the literature, treating the x-values and y-values the same. This may improve the visual representation in the case of a poor correlation in the data. This is not considered appropriate in this study, because the x-values are the independent values, without error or change, like years, while the y-values are investigated. Therefore, errors, and the approach to minimize them are only part of the y-values.

Key aspects of a least square error fit, as carried out in this report are: First, the line will intersect to average y value at the average x value of the data. Second, as the name indicates, this fit minimizes the sum square error and thus maximizes the R^2. Mathematically, the least square error fit is the solution vector **b =** (C,B)**'** from **b = (A'A)**$^{-1}$ **A' y** of the function **y = b x**, where **A** is the matrix consisting of rows of **x** values. The fit minimizes, **e'e;** the sum square error **e = y – b x.** The matrix **A** for a linear fit has the shape:

$$\mathbf{A} = \begin{pmatrix} 1 & x_1 \\ 1 & x_2 \\ \vdots & \vdots \end{pmatrix}$$

The matrix **A'** is the transposed of the matrix **A**, and the vector **b** consist of the constant C and slope B of the fit line. The comparison of data and the fit results are then given by **y = A b**:

$$\begin{pmatrix} y_1 \\ y_2 \\ \vdots \end{pmatrix} \approx \begin{pmatrix} 1 & x_1 \\ 1 & x_2 \\ \vdots & \vdots \end{pmatrix} \cdot \begin{pmatrix} C \\ B \end{pmatrix}$$

The coefficients C and B that provide best result, i.e., the smallest deviation between the data and the line is the result of the least square error fit.