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TNO report

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Potential CO_2 reduction technologies and their costs for Dutch passenger car fleet

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Summary

PBL uses and maintains the Dutch passenger car fleet model DYNAMO to forecast the vehicle fleet development. This allows PBL to project the effects of policies on the fleet. The original model has to be adapted to the new issues that arise, such as the developments in CO_2 emissions of vehicles. In particular, in the Netherlands, the average CO_2 emissions of newly-sold vehicles have decreased more rapidly than in other European countries, partly due to European CO_2 emissions regulations and the fiscal climate.

The Dutch vehicle fleet projection has been made for over a decade now based on the same underlying data. To update the DYNAMO fleet model, PBL has asked TNO to provide PBL with input on, amongst others, future technologies which may be used to achieve the 95 g/km European CO_2-related targets for passenger cars in 2020 and possible more stringent targets thereafter, and associated cost curves.

The costs for CO_2 reductions are based on cost curves developed by TNO in 2011 for the impact assessment of the 95 g CO_2/km target for the European Commission. Currently the process of post 2020 in ongoing and new cost curves are being developed. However, as these are not available within the timeframe of this project, the 2011 cost curves are used in this study.

Compared to other European countries, the share of vehicles with CO_2 reducing technologies in the Netherlands is relatively high. The CO_2 reductions in the Netherlands are partly the result of the Dutch fiscal system.

In this study, the technological options for reducing type approval (TA) CO_2 emissions for passenger cars are discussed separately for the period up to 2020, and for the period beyond 2020. Additionally, cost curves for diesel and petrol cars are derived for the Netherlands based on these reduction technologies. The cost curves are based on work from (TNO, 2011) and translated vehicle weight categories as used in DYNAMO. The full potential of the cost curves, about the last 3% for petrol vehicles and 8% for diesel vehicles, can only be achieved with full hybridization.

Furthermore, the vehicle categories plug-in hybrids and fully electric vehicles are added to the analysis. The cost curves show a clear discontinuity between ICEVs, PHEVs and EVs, which indicates that reaching overall targets is normally not achieved in one step, but in several steps into the right direction.

Effectiveness to reduce real-world CO_2 emissions in the current climate, with the European CO_2 targets based on type approval values, will be limited. The current NEDC test is not fit-for-purpose and it will drive low-load improvements with limited relevance for real-world emissions. The new WLTP test is a compromise with many ineffective ways to achieve the targets on the type approval tests. The whole WLTP text has surprisingly few references to the fact the test is meant to be representative to real-world driving. The expected reductions on the type-approval test, NEDC and WLTP alike, will, very likely, correspond to two third to a half these effects for real-

world fuel consumption of modern fuel efficient vehicles. This means that a reduction of 30% on the type-approval results in 20% to 15% reduction in real-world fuel consumption.

Consequently, the reductions in type approval CO_2 from 2012 and beyond are expected to yield half these reductions or less for real-world emissions. As the problem is not appropriately acknowledged by the stakeholders, it is unlikely this situation will improve in the foreseeable future, i.e., prior to 2025.

Contents

Summary **2**

1 Introduction **6**

2 International developments **8**
2.1 European targets 8
2.2 International developments 8

3 Technological options for reducing type approval CO_2 emissions from passenger cars **10**
3.1 Technological options with relevance in the year 2020 10
3.2 Technological options with relevance in the years post-2020 11

4 Cost curves for technological options **13**
4.1 Cost curves as previously developed for the impact assessment of 2020 European CO_2 emission targets 13
4.2 Adjusted cost curves to be relevant for the post-2020 period 13
4.3 Caveats 20

5 Effectiveness of type approval CO_2 reductions for real-world CO_2 emissions **22**
5.1 Type approval test under-represents real-world variations 23
5.2 Effectiveness of reductions on the test for real-world CO_2 reductions 24
5.3 Total effectiveness 26
5.4 Conclusions 28

6 Drawbacks of type approval testing **29**
6.1 NEDC 29
6.2 WLTP 29
6.3 Flexibilities 31
6.4 Unwanted effects 31
6.5 Improvements aftermarket 31
6.6 Conclusions 32

7 Conclusions **33**

8 References **34**

9 Signature **35**

Appendices

A Technology options
B Additional costs for PHEVs and EVs in 2020
C Weight class inter- and extrapolation

The costs for CO_2 reductions are based on cost curves developed by TNO in 2011 for the impact assessment of the 95 g CO_2/km target for the European Commission. Currently the process of post 2020 in ongoing and new cost curves are being developed. However, as these are not available within the timeframe of this project, the 2011 cost curves are used in this study.

1 Introduction

PBL uses and maintains the Dutch passenger car fleet model DYNAMO to forecast the vehicle fleet development. This allows PBL to project the effects of policies on the fleet. The original model has to be adapted to the new issues that arise, such as the developments in CO_2 emissions of vehicles. In particular, in the Netherlands, the average CO_2 emissions of newly-sold vehicles have decreased more rapidly than in other European countries, partly due to European CO_2 emissions regulations and the fiscal climate.

The Dutch vehicle fleet projection has been made for over a decade now. To update the DYNAMO fleet model, PBL has asked TNO to provide PBL with input on, amongst others, future technologies which may be used to achieve the 95 g/km European CO_2-related targets for passenger cars in 2020 and possible stringent targets thereafter, and associated cost curves.

This study provides the necessary data to update the DYNAMO model for forecasts up to 2050, in particular regarding the potential for reduction of CO_2 emissions in cars and the associated costs. Three aspects are important:

1. the cost curves for technologies that can be combined to achieve CO_2 reductions on the type approval test;
2. technical developments of the fleet till 2020 and beyond, where distinction is made in the types of CO_2 reduction technologies which will be available in the different market segments;
3. the development of the increasing gap between the official type approval CO_2 emissions of vehicles, and the likely CO_2 emissions in real-world, on-road use of the vehicles.

As mentioned above, the (type approval) average CO_2 emissions of newly-sold vehicles in the Netherlands have reduced rather quickly, also compared to other European counties. Many energy efficient, and low emission vehicles are already present in the current fleet. The development of real-world CO_2 emissions differs from the type approval emissions due to the utilisation of test flexibilities[1] as well as differences between the driving conditions and behaviour during the lab-based type approval test and on the road. This is also the case for new drivetrain technologies, such as Plug-in Hybrid Electric vehicles (PHEVs), which may be applied by certain manufacturers as a strategy to reduce (type approval) CO_2 emissions even more, already anticipating more stringent regulations beyond 2020.

TNO is involved in a number of activities concerning the future developments in vehicle CO_2 emissions:

1. the new type approval test procedure; the WLTP, which will probably be applied from 2017 onwards. It will have an effect on the gap between type approval value and real-world CO_2 emission and on the flexibilities available to the industry to perform the type approval test in a manner to their advantage.
2. the cost assessments of future energy efficient technologies, which may be applied to achieve the future European CO_2 targets.

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[1] SR6

3. the monitoring of fuel consumption, in specific tests and from the real-world fuel consumption of large groups of motorists.
4. the assessment and monitoring of new vehicle technologies.

In this study projections are made for the effects of CO_2 emission reduction of Dutch passenger cars in terms of potential additional costs. These CO_2 emissions are expected to decrease within certain boundaries set by market demands and technological feasibility. The following data will be supplied:

1. the costs to achieve future European CO_2 targets for various vehicles segments;
2. the effectiveness of the different technologies on the type approval tests, NEDC and WLTP, and the gap between type approval and real-world emissions;
3. the assessment of additional flexibilities available with the old and new test procedures.

Caveats

The costs for CO_2 reductions are based on cost curves developed by TNO in 2011 for the impact assessment of the 95 gCO_2/km target for the European Commission. Currently the process of post-2020 is ongoing and new cost curves are being developed. However, as these are not available within the timeframe of this project, the 2011 cost curves are used in this study. More information on this matter is provided in section 4.3.1.

2 International developments

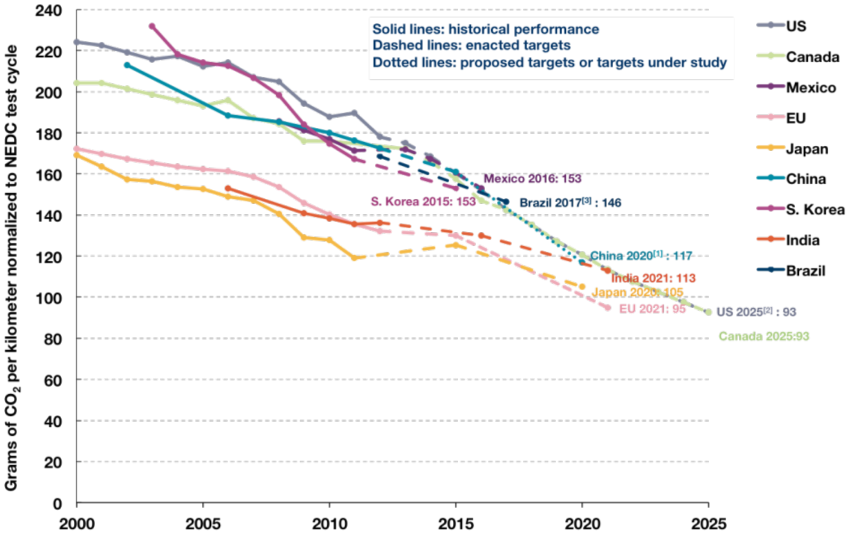
Compared to other European countries, the share of vehicles with CO_2 reducing technologies in the Netherlands is relatively high. Vehicles with downsized engines or (plug-in) hybrid powertrains are sold in large numbers. Despite the relatively large fraction of petrol vehicles in the total sales, the average type approval CO_2 value is low. The reductions in type approval CO_2 emission are well ahead of the schedule to reach the 2015 and 2020 European targets. This is largely due to the Dutch fiscal system.

2.1 European targets

The 95 g/km CO_2 target for 2020 has led to difficult negotiations on many related topics, such as the new test procedure WLTP, and the conversion of the current CO_2 target based on the NEDC to the WLTP. Currently, it seems that in the conversion of the targets, the benefits achieved and practice accepted are included in a paper conversion. Hence, the NEDC is still the standard against which CO_2 type approval value is to be determined. Effects are translated back to the NEDC in the period 2017-2020 using a complex mathematical model for specific vehicle technologies. This allows for the comparison with the old European 95 g/km target. Furthermore, additional effects on the WLTP can be added to the paper CO_2 reduction benefits, which can still be claimed for NEDC. For example: a stop-start system has a reduced effect on the WLTP, however, its effect on the NEDC can be taken into account for the type approval value till 2020.

2.2 International developments

Different parts of the world have CO_2 emission targets for motorized vehicles. These targets as well as the test procedure used to determine the CO_2 emissions vary substantially (see Figure 1).



[1] China's target reflects gasoline vehicles only. The target may be higher after new energy vehicles are considered.
[2] US standards GHG standards set by EPA, which is slightly different from fuel economy stadards due to low-GWP refrigerant credits.
[3] Gasoline in Brazil contains 22% of ethanol (E22), all data in the chart have been converted to gasoline (E00) equivalent
[4] Supporting data can be found at: http://www.theicct.org/info-tools/global-passenger-vehicle-standards.

Figure 1: Global comparison of passenger vehicle GHG emission standards normalized to NEDC gCO_2/km.

For instance, in contrary to Europe the US Environmental Protection Agency (EPA) not only checks the type approval values, but also does service conformity testing. About 15% of all the vehicle models are tested independently every year. In part these vehicles are randomly selected, in part the vehicles are follow-up of concerns or complaints. Such testing is performed to prevent manufacturers from optimizing the CO_2 emissions of their vehicles on the type approval cycle, since such optimizations result in relatively large differences between the CO_2 emissions during the test procedure and in the real world. In the last decade this difference has become larger and larger in Europe. This will be discussed in more detail in chapter 5. Currently the test value is in line with fuel consumption observations from private owners. A fixed 8% gap between test results and monitoring data is explained due to variation in conditions, driving behaviour, and vehicle state.

3 Technological options for reducing type approval CO_2 emissions from passenger cars

Over the last ten years, type approval fuel consumption of passenger cars has improved a lot. This is especially the case for petrol cars. As a result, the difference in fuel consumption between petrol and diesel cars has become much smaller. The main reason for the lower fuel consumption of diesel cars is no longer engine-related, but mainly the result of its higher (energy) density of the fuel. However, in terms of CO_2 emissions petrol and diesel cars hardly differ.

As mentioned previously, the CO_2 emissions reduction on the type approval test does not mean equally much CO_2 reduction in the real world. In the last two decades, manufacturers have utilised the flexibilities within the type approval test to reduce CO_2 emissions, by optimising the vehicle and other conditions. As a result technology has only partially been the cause for CO_2 reductions. This is discussed in more detail in chapter 5.

In this chapter, technological options for reducing type approval (TA) CO_2 emissions for passenger cars will be discussed separately for the period up to 2020, and for the period beyond 2020.

3.1 Technological options with relevance in the year 2020

Technological options as well as the cost curves for reducing TA CO_2 emissions of passenger cars in the period up to 2020 are discussed and documented in (TNO, 2011). As a starting point for the assessment, the reduction potential of individual options was assessed relative to a baseline vehicle. In order to determine the effect of these options, baseline vehicles were defined for petrol and diesel cars in three different weight categories, i.e. small, medium and large. The six baseline vehicles correspond to models from the year 2002 in which no CO_2 reduction technologies had yet been applied. The baseline vehicles are specified in Table 1. Further specifications of the baseline vehicles are shown in Table 2.

Table 1: Baseline technologies for reference vehicles in 2002 (TNO, 2011)

	ICEV Petrol			**ICEV Diesel**		
Weight category	Small	Medium	Large	Small	Medium	Large
Engine layout	4 cylinder in-line	4 cylinder in-line	4/6 cylinder in-line	4 cylinder in-line	4 cylinder in-line	4/6 cylinder in-line
Fuel system	Multi point injection	Multi point injection	Multi point injection	Common rail direct injection	Common rail direct injection	Common rail direct injection
Gearbox	5 speed manual	5 speed manual	5 speed manual (automatic)	5 speed manual	5 speed manual	5 speed manual (automatic)

Table 2: Specifications of baseline vehicles 2002, CO_2 emissions represent TA values (TNO, 2011)

	ICEV Petrol			**ICEV Diesel**		
Weight category	Small	Medium	Large	Small	Medium	Large
Total CO_2 [g/km]	149	189	264	123	157	213
Vehicle mass [kg]	956	1282	1698	1046	1396	1816

Based on the baseline vehicles a number of technological options for CO_2 reduction have been identified and grouped as follows:

- engine options
- transmission options
- hybridization options
- driving resistance reductions
- other

A concise list of each option's reduction potential and expected costs for the year 2020 is given in Annex A, respectively for diesel and petrol cars.

3.2 Technological options with relevance in the years post-2020

The list above and in Annex A take into account technologies that are likely to be marketable in the year 2020. In a current project for the European Commission, a list of viable technologies beyond 2020 is yet to be developed, with specification of CO_2-reduction potentials and costs for application of these technologies in different vehicle types / segments. As in previous studies for the European commission, cost curves are derived describing the increasing additional vehicles costs as function of an increasing reduction potential achieved by combining different technologies.

A concise list of these options has not yet been published, however the options are expected to focus on alternative fuel options [R-AEA, 2014]:

- gas: LNG / CNG and bio-derivatives LBG / CBG;
- plugin-Hybrid Electric Vehicles (PHEVs) and Range-Extended Electric Vehicles (REEVs);
- battery Electric Vehicles (EVs) and Fuel-Cell Electric Vehicles (FCEVs) as well as
- technologies with real-world savings not captured in test-cycles (e.g. eco-innovations or other)

The success of hybridization in European cars may be partly due to the NEDC test cycle, rather than on-road benefits. The NEDC test contains a substantial amount of stopping time and is moderate both in the velocity and acceleration. Consequently, optimisations of part-load efficiency are beneficial to achieve low CO_2 test values.

A new development is the introduction of plug-in vehicles, which have an internal combustion engine, but can also drive on an electric motor with a battery which can be charged from the power grid. Such vehicles have high benefits in low CO_2 emissions due to the particular way the type approval CO_2 emission is determined. Both the laboratory test, performed at 20-30^o Celsius, and the way the electric range plays a central role both in the current as well as in the new type approval determination is unlikely to be met with average conditions and vehicle usage on the road. In particular, since these vehicles are more expensive than a compact or a medium car, the annual mileage is expected to be higher to achieve an appropriate balance between the annual costs and costs per kilometre to warrant the ownership and use of such plug-in vehicles.

Except for gas vehicles, these options are discussed separately in the following chapter and included in the cost curves presented below. Apart from the alternative energy carriers, some options from (TNO, 2011) are still relevant in post-2020 cost curves, since the full potential of these options will not yet have been used.

4 Cost curves for technological options

With the accumulation of technological options in a reference vehicle, the effectiveness of the each individual option is reduced. Apart from this, not every option is applicable for all market segments. For example, in the last years multiple trends have been observed that do not apply to all market segments:

1. in the low-price market segment downsizing and weight reduction have been popular reduction measures;
2. in the high-price market segment the largest reductions have been reached by hybridization and the introduction of plug-in technology.

Engine-downsizing is also typical for the middle-class market segment. In comparison to other European countries, in the Netherlands many large cars have been sold with a very small engine of up to one litre displacement per ton vehicle weight.

In this chapter, the cost curves for diesel and petrol cars are derived for segments as defined in DYNAMO for modelling the Dutch fleet, based on the reductions options discussed in the previous chapter. The cost curves are based on work from (TNO, 2011) and translated vehicle weight categories as used in DYNAMO. Furthermore, the vehicle categories plugin hybrids and fully electric vehicles are added to the analysis.

4.1 Cost curves as previously developed for the impact assessment of 2020 European CO_2 emission targets

The cost curves as determined in (TNO, 2011) are presented in Figure 3. The origin of the cost curves are the baseline vehicles as defined above in Table 2.

Cost curves of the specific scenario c) of (TNO, 2011) have been used since this scenario takes account of the flexibilities that have been used by car manufacturers to reduce type approval CO_2 emissions. These reductions were assumed to come at zero costs and only have an effect on the type approval emissions and not on real world emissions. In (TNO, 2011) increased utilisation of these flexibilities between 2002 and 2020 was assumed to result in 10% CO_2 reduction for petrol vehicles relative to the 2002 emissions and 9% for diesels. More recent estimations forecast the maximum use of flexibilities to be 20 g/km between 2002 and 2020. This is within the same order of magnitude as 9-10% with reference to the baseline vehicles in 2002, which has been accounted for in this study. Chapter 5 of this study deals with the deviation between type approval and real world CO_2 emissions in more detail. This does not only include the use of flexibilities as mentioned above, but also deviations resulting from e.g. differences in vehicle use between the type approval test (NEDC) and the real world.

The maximal reduction potential is indicated by pink squares.

4.2 Adjusted cost curves to be relevant for the post-2020 period

As already discussed above, cost curves are currently being developed for the post-2020 period. Due to a delay in the delivery, these curves are not yet published.

In this section, currently available information will be used to make an educated estimate of how cost curves will most probably evolve. For this purpose, results from (TNO, 2011) will be used together with the historic developments and trends in CO_2 reductions. The following steps are taken and will be further detailed below:

- translation of cost curves from baseline vehicles 2002 to baseline vehicles 2012
- translation of (TNO, 2011) cost curves to DYNAMO weight categories
- addition of cost curves for PHEVs and EVs

4.2.1 Translation of cost curves from baseline vehicles 2002 to baseline vehicles 2012

Over the last years CO_2 type approval values in the Netherlands have decreased from 160 g/km in 2005 to roughly 120 g/km in 2012. The historical development of the norm values is shown in Figure 2. In the beginning of 2012, the CO_2 norm for petrol cars was on average 122 g/km, in comparison to 112 g/km for diesels. The dip in 2013 is related to a high share of plug-in sales in the end of the year (e.g. model Outlander).

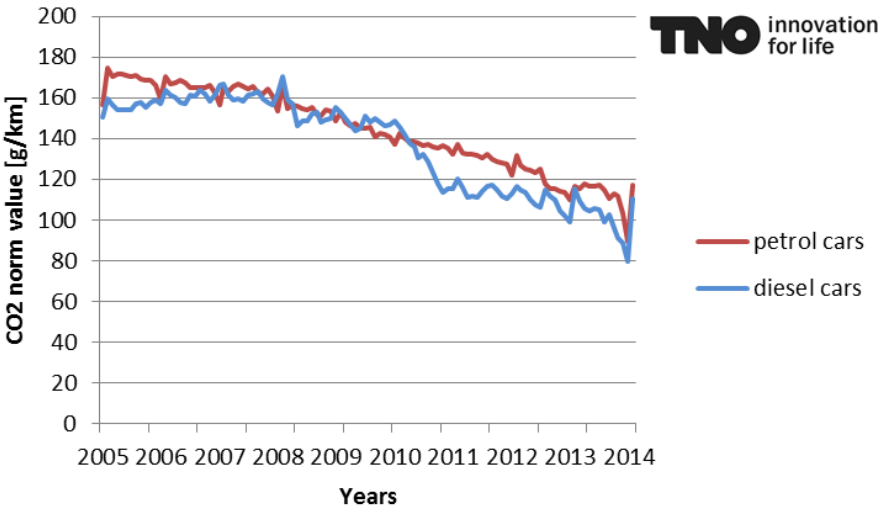


Figure 2: Historical development of CO_2 norm values for newly sold petrol and diesel cars in the Netherlands

CO_2 values can be split up into the baseline weight categories as shown in Table 3.In general, it can be observed that the larger the vehicle, the larger the reduction in CO_2 relative to 2002.

Table 3: Specifications of Dutch baseline vehicles 2012, CO_2 emissions represent TA values

	ICEV Petrol			ICEV Diesel		
Weight category	Small	Medium	Large	Small	Medium	Large
Total CO_2 [g/km]	114	128	152	95	103	135
Relative CO_2 2012 wrt. 2002	-23%	-32%	-43%	-23%	-34%	-37%
Vehicle mass [kg]	1033	1239	1507	1113	1253	1634
Relative mass 2012 wrt. 2002	+8%	-3%	-11%	+6%	-10%	-10%

The specific baseline vehicles 2012 are presented by red crosses in Figure 3. Additionally, the maximum reduction potential apart from hybridization are indicated by black circles. This means the full potential of the cost curves, about the last 3% for petrol vehicles and 8% for diesel vehicles, can only be achieved with full hybridization. This is not to be confused with plug-in hybridization.

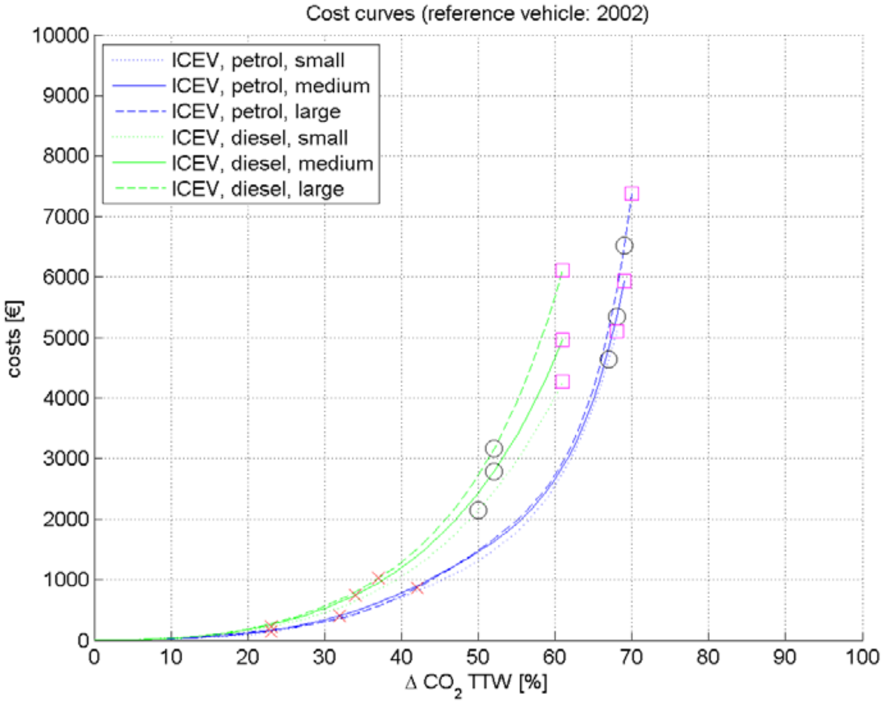


Figure 3: Cost curves relative to baseline vehicles in 2002 (TNO, 2011) - pink squares indicate the maximal reduction potential based on the considered technology options, red crosses indicate baseline vehicles in 2012, black circles indicate the maximum abatement potential that can be reached without any hybridization

When accounting for the reductions utilised between 2002 and 2012, new cost curves can be generated with baseline vehicles 2012 in the origin of the x-y-axis, see Figure 4. Saving potentials are plotted with reference to 2012 baseline vehicles.

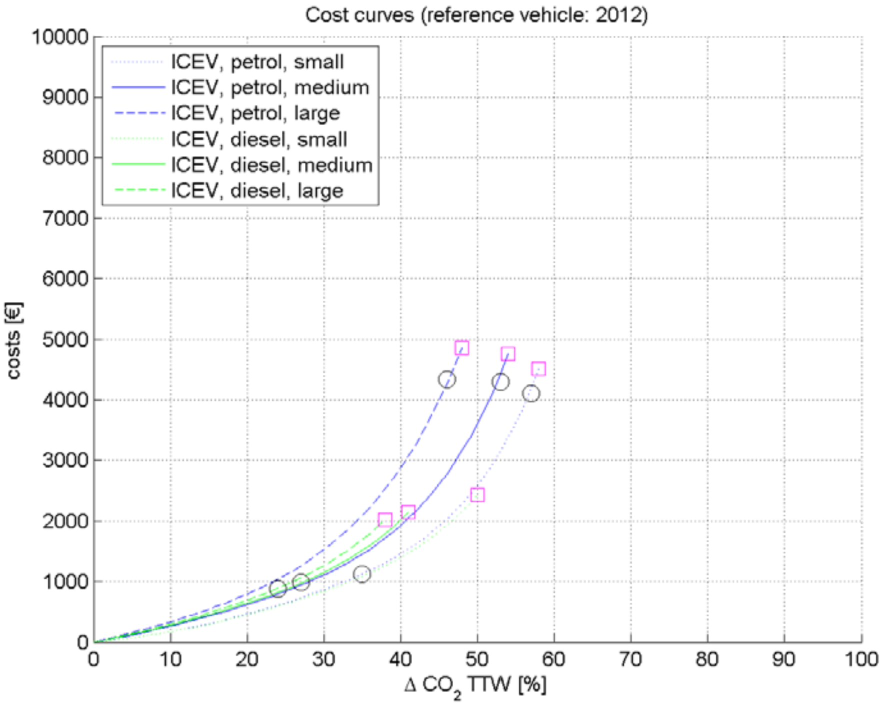


Figure 4: Cost curves relative to baseline vehicles 2012 - pink squares indicate the maximal abatement potential based on the considered technology options, black circles indicate the maximum abatement potential that can be reached without any hybridization

4.2.2 *Conversion of 2020 cost curves to DYNAMO weight categories*

DYNAMO uses other vehicle categories than the study in which the 2020 cost curves were developed (TNO, 2011). In that 2011 study three segments were distinguished, based on market segments (small = ‘A’ and ‘B’, medium = ‘C’ and large = ‘D’ and ‘E’),. In contrary, DYNAMO uses weight categories. These weight categories are given in Table 2. For each category the average CO_2 type approval value and vehicle mass is calculated for the baseline vehicles in 2012 by use of data of the yearly vehicle sales database from RDW.

Table 4: Specifications of baseline vehicles 2012 using DYNAMO weight categories, CO_2 emissions represent average TA values of the European fleet

	ICEV Petrol					ICEV Diesel				
Weight categories [kg]	< 951	951-1150	1151-1350	1351-1550	> 1550	< 951	951-1150	1151-1350	1351-1550	> 1550
Total CO_2 [g/km]	102	118	128	143	177	91	95	103	117	146
Vehicle mass [kg]	910	1072	1239	1434	1722	773	1131	1253	1442	1759

In order to determine cost curves for each weight category, the original cost curves above are inter- respectively extrapolated as described in Appendix C. For this purpose a 3rd grade polynomial is used. The result of this extrapolation is shown in Figure 5.

The maximum reduction potential of the DYNAMO classes are determined as a function of the weight difference between DYNAMO classes and SR1 weight classes.

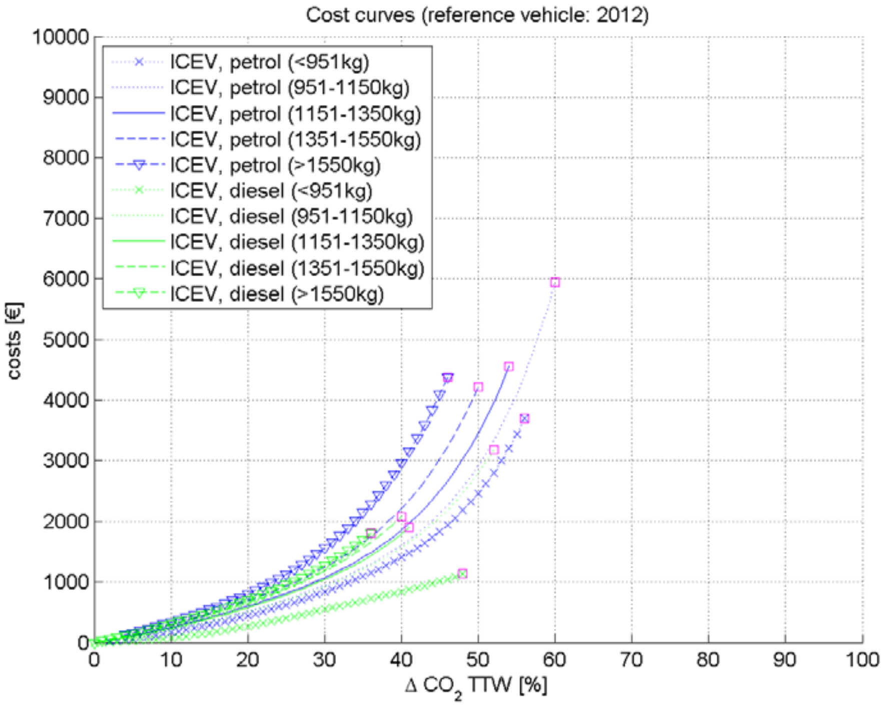


Figure 5: Cost curves for baseline vehicles 2012, using DYNAMO weight classifications - pink squares indicate the maximal abatement potential based on the considered technology options

4.2.3 *Addition of cost curves for PHEVs and EVs*

Apart from the technological options for ICEVs, plugin hybrids (PHEVs) and electric vehicles (EVs) will become more and more relevant to achieve CO_2 reductions beyond 2020. The cost curves for PHEVs and EVs have been determined based on the differences in vehicle prices and CO_2 reduction potentials as determined in (Policy Research Corporation, 2015) and are shown in Figure 6. In order to translate additional prices into additional manufacturer costs, the prices are divided by a mark-up factor of 1.235, which was determined in [TNO 2007]. More detailed information on real world retail price effects of tougher CO_2 regulations is provided in section 4.3.2.

For PHEVs, a type approval value of 45 g/km was assumed. Since many of the reduction measures for ICEVs are also applicable for PHEV (excluding hybridization). The cost curves for PHEVs follow the same gradients as ICEVs. For EVs no actual cost curves are developed as their emissions are already 0 g/km, equivalent to 100% CO_2 emission reduction compared to the reference vehicle. The relative EV emission reduction compared to the reference vehicle are plotted vertically at 100%, Extra price for EVs range from €1000 to €15000 (as shown in Table 5).

Table 5: Estimated price differences of plug-in hybrid and battery-electric cars with reference to a petrol and a diesel car in 2020 (based on battery costs of 300 €/kWh)

Vehicle type	**Fuel type**	**Segment**	**Additional vehicle prices [€]**	**Additional vehicle costs [€]**
PHEV	Petrol	A	7073	5727
		B	9781	7920
		C	14350	11619
		D	14276	11560
		E	61142	49508
	Diesel	A	5959	4825
		B	7863	6367
		C	11343	9185
		D	11395	9227
		E	73782	59743
BEV	Petrol	A	7560	6121
		B	4507	3649
		C	3823	3096
		D	3835	3105
		E	1466	1187
	Diesel	A	6446	5219
		B	2588	2096
		C	816	661
		D	954	772
		E	14105	11421

Results show that EVs on average have lower additional costs and a higher associated maximum reduction potential compared to PHEVs. It has be kept in mind that this benefit comes at the expense of a lower operational driving range. It can be seen that especially large PHEVs (>1550kg) are quite expensive in comparison to the ICEV version in the same weight category. At the same time the remaining savings potential of these vehicles that is related to any other options than hybridization is low.

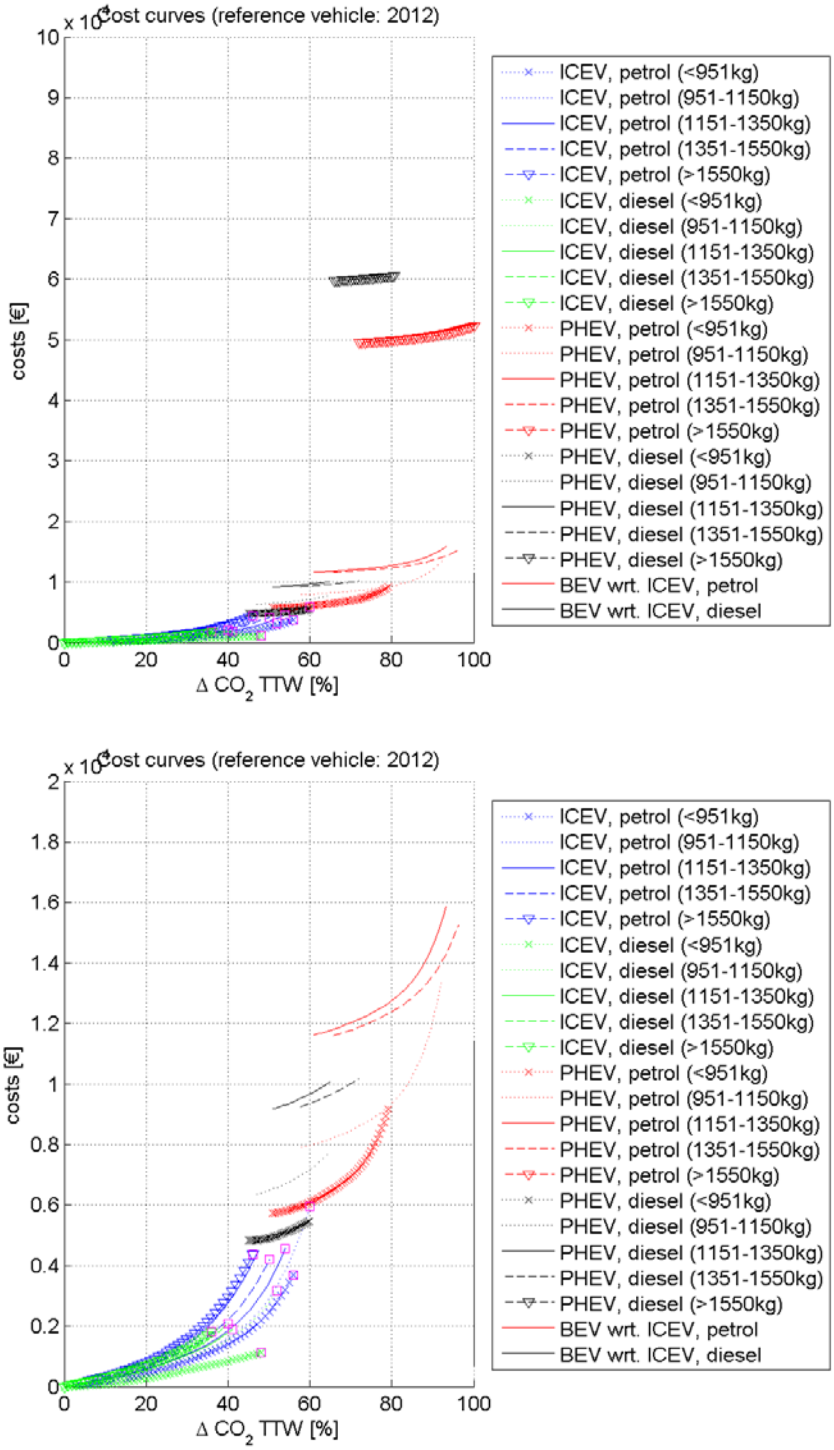


Figure 6: Cost curves for baseline vehicles 2012 including PHEVs and EVs, using DYNAMO weight classifications (top: full view, bottom: zoom) - pink squares indicate the maximal abatement potential based on the considered technology options. For EVs, cost curves are plotted vertically at 100% reduction.

The zoomed-in view of Figure 6 displays nicely the discontinuity between ICEVs, PHEVs and EVs and shows that reaching overall targets is normally not achieved in one step, but in several steps into the right direction. For EVs, it has to be reflected whether a TTW CO_2 approach is the right way to display the savings potentials. A MJ/km or gCO_2/km WTW might be a better approach that reflects the overall energy efficiency and the origin of the energy.

4.3 Caveats

4.3.1 Newer cost curves are currently being developed

The cost curves developed in this study are derived from (TNO, 2011). Currently new cost curves are being developed for a study for the European Commission in which TNO is not involved. In comparison to the 2011 TNO study, the new cost curve study will include dedicated PHEV and EV cost curves. However, since it was not possible to wait for these new cost curves, TNO’s 2011 cost curves are used instead.

Especially for PHEVs and EVs the cost curves could possibly deviate significantly from the curves generated in this study. This is expected because the PHEV cost curves in this study are derived from the ICEV curves (as explained in section 4.2.3), as dedicated PHEV and EV cost curves were not generated in 2011.

The methodology for deriving the PHEV and EV curves is based on the assumption that technologies have the same relative emission reduction effect on PHEVs as on ICEVs. However, certain technologies that do not target engine losses, e.g. light weighting, also have an effect on the electric energy use of PHEVs. Therefore such technologies increase the share electrically driven distance in the type approval procedure. As a result the distance weighted CO_2 emissions of PHEVs will actually reduce relatively more than the relative emission reduction defined for ICEVs. This effect is not taken into account for this study.

Moreover technologies that do not affect the CO_2 emissions on ICEVs but that do affect the type approval emissions of PHEVs, e.g. battery capacity, are not taken into account in this study.

4.3.2 Real world pricing effects of tougher requirements on the environmental performance of road vehicles

These cost curves as presented above are based on the assumption that more stringent environmental requirements will lead to higher production costs. As a first order estimate, it is assumed in many recent studies that these additional costs will consequently result in higher vehicle prices for consumers. However, in reality these additional costs are usually not simply transferred on to the vehicle for which the costs are made. Adding the substantial fragmentation on choice of models and variants makes it very difficult to link cost and profit margins. The actual way in which prices develop in times of more stringent environmental requirements heavily depend on

- individual OEM strategies to deal with additional costs, e.g.
  - cross-subsidising over different vehicle models of one brand,
  - cross-subsidising over different brands one manufacturer group or
  - (temporary) lower profit margins.

- other cost or price developments happening simultaneously, whether resulting from the more stringent environmental requirements or not, e.g.
  - growth of practices such as platform sharing and collaborative approaches to vehicle development and production, which have been key to cost reductions in the industry [AEA 2011],
  - production shift to areas with lower labour rates or
  - exchange rate developments.

As a result of all these factors and more, analyses of historical vehicle pricing datasets and features does not provide any definite relationship between vehicle emissions standards and car prices [AEA 2011].

Conclusively, on the long term additional costs have to be transferred to end users in some way. Since the exact way in which this occurs is not transparent, it is not possible to generate a general ratio between additional cost and the resulting additional price that will accurately reflect the actual price developments resulting from more stringent environmental requirements. However, in order to assess the effect the effect of such requirements on vehicle prices, usually a generally accepted multiplication factor is used to determine price additional based on additional costs clearly stating that such a factor will most likely not accurately reflect reality.

5 Effectiveness of type approval CO_2 reductions for real-world CO_2 emissions

The effectiveness of type approval CO_2 reductions for real-world CO_2 reductions depends on many factors. So far, from 2004 to 2008 the trend has been an increasing gap between the type approval value and the real-world fuel consumption. Nowadays, a rule of thumb is an average 50 g/km additional CO_2 emission in real-world compared to the type approval value across all vehicle makes and models. This value can be decomposed into several parts. However, it starts with the propulsion of the vehicle. The engine is there to provide energy to overcome driving resistance. This, again, can be decomposed into different parts:

1. The rolling resistance, which yield a certain CO_2 emission [g/km], more or less independent of the vehicle velocity.
2. The air-drag, which increases CO_2 emission with the velocity, where at velocities over 100 km/h the increase is rapid and substantial.
3. The braking losses, from fast deceleration and stopping. The kinetic energy in the vehicle is only lost if the vehicle brakes.
4. The engine losses, depending on the engine size, cold start, gear shifting, gear ratios, etc.
5. The auxiliary losses, from pumps, light, air-conditioning etc.

These effects ensure a car needs fuel and they are in part responsible for additional fuel consumption in real-world for aspects not, or not properly, covered in the test. Traditionally, the gap has been in the order of 15 to 20 g/km. Recently the gap has increase to twice this number, and for the latest vehicle models 50 g/km is the gap. In part it is due to the optimized testing, exploiting the flexibilities, the other part is due to the change in technology appropriate to achieve low test values, which are not as effective for reducing CO_2 in real-world driving.

All of the physical effects contribute to the type approval test and the real-world driving in different manners, which should be separated in order to determine the effectiveness of CO_2 type approval targets. However, some aspects are easily overlooked. In Europe cars are sold which must be able to accelerate on the motorway. This drivability determines the typical, ever-increasing engine power of passenger cars. With this engine power, also the engine losses increase. Engine losses account for almost half the CO_2 emission of the NEDC test, and less so on the WLTP test. The only appropriate means to reduce the engine size, and thereby the engine losses, is weight reduction. The European drivability requires a power-to-mass ratio of 40 kW/ton or more.

The force on the vehicle in Newton translates more or less in the additional CO_2 in g/km. Given an optimal small engine efficiency expressed as 700 g/kWh CO_2 for a diesel engine and 750 g/kWh CO_2 for a petrol engine, 1 Newton force yields at least 0.19 g/km and 0.21 g/km CO_2 emission to overcome such driving resistance. Additional CO_2 emission are to be attributed to a lower efficiency expressed as losses and auxiliary power usage.

Given a typical 500 Newton vehicle resistance for a compact car at 100 km/h, it requires 14 kW power, and a 700 Newton resistance at 120 km/h requires a more than proportionally higher power of 23 kW.

Even moderate accelerations of 0.3 m/s^2 adds for a 1200 kg vehicle weight an extra power need of 10 kW at 100 km/h and 12 kW at 120 km/h. This allows a driver to accelerate from 100 km/h to 120 km/h in 19 seconds. For most drivers this does not suffice nowadays. This power requirement is balanced against the downsizing needed to reduce CO_2 emissions. In Germany with unrestricted velocities on the autobahn, and Austria with the mountains the power demand for drivability is even higher. In the Netherlands, flat with well-observed maximal velocities of 100 to 130 km/h, depending on the region, the drivability puts a lesser strain on the CO_2 emission reduction targets.

Typically, the fixed engine losses are 3% to 4% of the rated power. This corresponds to about 2 kW and 0.4 g/s CO_2. Adding it up at 30 km/h it accounts for 48 g/km and at 120 km/h for 12 g/km. The engine losses increase somewhat with vehicle speed and engine speed, but such numbers show the relevance of the engine size for the total CO_2 emission. In particular, the low velocity, such as for the NEDC the contribution to the total is significant. The CO_2 emission in g/km varies only slightly for a modern vehicle over a wide range from the 30 km/h to 100 km/h. The balance or composition, however, changes dramatically. The resistance for constant velocity is typically only 200 Newton, for low-velocity, urban driving. Hence, with an electric vehicle the total work is much lower at low velocity. For an internal combustion engine, the losses and the lack of energy recuperation during braking yields the highest CO_2 emission at low velocity in congested urban driving.

The flow of air through an engine is an important aspect of the engine losses. With a higher engine speed the air flow increases more or less proportionally, as the piston strokes ensure the volume displacement. Given a CO_2 emission rate of 4 g/s, associated with an engine power of 20 kW, and a 120 g/km at 120 km/h, for a petrol engine the CO_2 concentration is 14% and average volume flow is 22 litres per second. For diesel vehicles the volume flow is higher, due to the excess air. For example, a DPF has a back pressure up to 10 kPa, which requires 0.3 kW to overcome. This is in the same order of the vehicle lights operation at night and 1.5% of the total engine output power.

Likewise the air through the radiator, for cooling, is an substantial part of the air drag of a vehicle. With some modern vehicles this internal air drag can be limited through adjustable vanes in the inlet grill.

5.1 Type approval test under-represents real-world variations

In many case the average value, such as average velocity, or average air flow, does not provide enough detail to determine the CO_2 emissions. For example, the air drag force increases with v^2. Therefore, an average velocity obtained by driving constantly 60 km/h or partly 30 km/h and partly 100 km/h will lead to doubling of the average air drag for the case of the two velocities. The latter case is generally the situation for the Netherlands. This is the result of the nonlinearity of the effect with the variation in vehicle usage.

The variation of the emission with vehicle usage requires therefore a detailed usage profile to compare the type approval test against the real-world vehicle usage.

For simplicity, the Dutch real-world usage is set at:

- 25% of the distance at 25 km/h (urban)
- 30% of the distance at 60 km/h (rural)
- 45% of the distance at 100 km/h (motorway)
- 9% of the time idling
- 12% of the total work at the wheels lost in braking

This corresponds to about half the time in urban driving and a quarter of the time at rural roads and motorway each.
Comparing this to the NEDC and the WLTP it results in the following table of comparable numbers:

Table 6: The comparison of typical driving characteristics on different test cycles. For example $<v^2>$ is the relevant velocity for the determination of the total air drag contribution.

	Velocity	**<v>**	**$<v^2>$**	**force**	**Braking**		**Idling time**
	km/h	km/h	km/h	N	N	[%]	[%]
NEDC	33.3	62.1	68.6	460	96.1	20.9%	20.7%
WLTP	46.5	74.4	81.5	563	109.1	19.4%	13.0%
CADC	60.9	91.6	97.4	688	80.0	11.6%	9.8%

The test cycles have more dynamics than typical for normal driving. This results in a larger variation of the moments of the velocity <v> and $<v^2>$ for test cycles than for normal driving. Likewise idling time (i.e. v < 0.2 km/h) is much smaller than the 10%-20% on test cycles. Test cycles are reconstructed realities which represent only a few aspects of the normal driving. In particular idling time, and stop-start systems, seem to generate an artificial CO_2 reduction benefit hardly obtained in real-world.

5.2 Effectiveness of reductions on the test for real-world CO_2 reductions

Basically the effects of CO_2 reduction, apart from autonomous trends can be grouped into three main categories, which are offset by effects not covered by the test procedure at all. These effects are, in order of effectiveness: weight reduction, rolling resistance reduction, low-load engine efficiency improvements, and plug-in vehicles. Test flexibilities are not considered in the section. They will be discussed in the next chapter.

5.2.1 Real-world effects not associated with type approval CO_2 reductions

A number of aspects of real-world fuel consumption are not likely to be reduced by type approval targets:

- Auxiliary power, which is mainly lights: 300 Watt of power demand from the engine continuously adds 8 g/km to the urban emission and 2 g/km to the urban emission
- Back pressure of the DPF is linear with volume flow and engine speed, which is a 3 g/km additional CO_2 likely to be minimized in the chassis dynamometer testing.
- Wind velocity of 3 m/s adds 1 g/km CO_2 on average, with 15 g/km more with headwind and down 14 g/km less with tail wind.

- Ambient temperature: 10 to 15 degrees lower than during the testing means a 4% higher air density in real world driving. At 100 km/h this adds 4 g/km CO2, at 25 km/h the CO_2 effect is negligible.
- The cold start requires additional fuel. The laboratory cold start is at a higher temperature than in ambient conditions, so the effect of the cold start will be less than in real world. However, the number of cold starts per kilometre are less in real world than with the NEDC and less than the WLTP.
- After-market changes and options on the vehicle, such as the presence of air-conditioning and the installation of different wheels and tyres.

Together it adds about 15 gram/km of CO_2 to real world driving with respect to the NEDC which is weakly dependent on the actual driving. With the introduction of the WLTP this will increase with about 5 g/km to a total of 20 g/km, mainly due to cold start and ambient temperature effect of air drag at higher velocity.

5.2.2 Weight reduction effects

Weight reduction effects are the most effective to achieve also real-world reduction of fuel consumption. Both the braking energy and the rolling resistance are more or less linear with the weight. However, the actual weight will be somewhat higher than the type approval weight, more so on the NEDC than on the WLTP. Moreover, with a weight reduction the engine power may also proportionally and still retain the same drivability, or power-to-mass ratio. All in all, it can be stated that for fuel efficient design the weight reduction affects all aspects of fuel consumption, except for air drag. However, the real-world additional weight may be higher than the test mass.

5.2.3 Low-load reduction

Low-load reductions are very effective on the NEDC and less so on the WLTP and only limited so in real-world driving. The increased engine efficiency, stop-start systems and hybridization are mainly relevant in urban driving, which covers about a quarter of the total distance. For a conventional engine the losses are about two-third of the total fuel consumption in these cases. Hence 17% of the real-world driving CO_2 can be attributed to engine losses, while on the NEDC, which is overall a tame test cycle to allow even the smallest engine to execute the NEDC test, the losses account for 50% of the CO_2 emissions. Hence low-load efficiency improvements will have only a third of the effect in real-world than in type approval testing.

5.2.4 Rolling resistance and air drag reductions

The largest resistance to air-drag reduction comes from the automotive marketing departments: low-air-drag cars look like ducks and toy cars, and they will not be sold to image-conscious consumers, who bring the money. Hence only some small improvements in air drag are to be expected. The rolling resistance allows for larger reductions with larger effects on the test cycle, as the amount of driving constantly a high speed, as on the motorway is extremely limited at the NEDC test and still limited at the WLTP test, which keeps the rolling resistance a significant part of the total power demand.

Typically rolling resistance is 150 N which is associated with 30 g/km CO_2. A 30% reduction in rolling resistance is extreme but feasible, removing 9 g/km from the CO_2 emission. Such effects are already visible on the NEDC where low type approval road loads are obtained from a combination of tyre choice and treatment, and a weight reduction. Forces of around 70-80 N are not uncommon in these cases. At least part of that could be obtained in real world. However, 30% reduction is expected to be the limit for real-world driving. In the WLTP this gap will be smaller, at least on paper. In that case, the improvements seen on the test are expected to translate for a greater part to the real-world result. However, since it is mainly a paper exercise, it is to be expected that the translated effect will be diluted somewhat with time, due to aftermarket changes to the vehicle and adaption of the user manual. So far, little provisions are taken to avoid aftermarket adaptions, however, in the case of fuel-efficient tyres the stimulation in aftermarket sales may be required.

5.2.5 Plug-in vehicles (PHEV's)

Plug-in vehicles are more-and-more high-end vehicles with an electric boost, which can drive the test cycle with moderate power, no auxiliary usage, and moderate conditions on the electric engine only. Hence, in this case test results and real-world results will start to deviate more and more. Nowadays, the real-world fuel consumption is almost threefold the real-world fuel consumption, discarding any Well-to-Tank emissions from the electric charging. It is not to be expected that the gap between type approval value and real-world emission will be smaller than 100% in any near future, unless there is a shift from PHEV to range-extender electric vehicles.

5.3 Total effectiveness

The translation based on the results in the previous section from the type approval result and reduction in real world, barring test flexibilities, will be:

- 15 g/km extra on top of the NEDC
- 20 g/km extra on top of the WLTP
- 90% effect of CO_2 reduction through weight reduction (of 60 g/km total)
- 35% effect of CO_2 reduction through low-load efficiency improvements (of 50 g/km on the NEDC and 30 g/km on the WLTP)
- 80% effect of CO_2 reduction through rolling resistance improvement on the WLTP (of 30 g/km total)
- 20% effect of PHEV technology (of 80 g/km reduction potential)

Both the percentages and the total contributions are rough estimates for modern, generic vehicles and technologies, but they show the decreasing effectiveness of reduction on the test cycle for real-world CO_2 emissions. Eventually the technology-mix will include many measures, to achieve the large CO_2 reduction. The CO_2 reductions so far have been a combination of low-load efficiency improvements and small weight reductions, combined with increasing flexibilities, which showed a combined, or average, effectiveness of around 50%. As the type approval values go down the real-world offset will become more important. With a 90 g/km on the WLTP and 20 g/km extra for real-world driving a 9 g/km reduction will be 10% of the type approval value and 8% of the real-world value.

Eventually the mix of technology to achieve substantial reductions is not that relevant, the effectiveness will decrease rapidly as values get below 95 g/km.

Table 7: The effectiveness for test cycles to reduce real-world CO_2 values decrease as the actual value is lower, as relatively more emission is outside the test protocol. The results are based on 15 g/km and 20 g/km outside the test protocol for the NEDC and WLTP respectively, combined with a rough estimate for effectiveness based on a 50 g/km gap.

	type-approval value [g/km]					
	110	100	80	70	60	50
assumed test effectiveness	60%	56%	52%	48%	44%	40%
real-world effectiveness NEDC	52.8%	48.7%	43.8%	39.5%	35.2%	30.8%
real-world effectiveness WLTP	50.8%	46.7%	41.6%	37.3%	33.0%	28.6%

Currently, with 110 g/km the additional real-world fuel consumption is 45-50 g/km higher. This will increase a little over time with a combination of high-end vehicles with reduced CO_2 emission and further exploitation of flexibilities. One-third is due to ambient conditions and usage outside the test regime (mainly related to ambient temperature). And two-third, or 30 g/km, is covered by the type approval test as reduction on the test cycle without effect on the real-world CO_2 emission. This means the starting position was 185 g/km CO_2 real-world emission, which is now down to 155 g/km. However, further reductions with the limited effectiveness for real-world fuel consumption make the barrier of 100 g/km real-world CO_2 emission very hard to brake, even with 50 g/km type approval values.

A simple, yet robust equation to relate type approval values to real-world emissions is:

$$CO_2^{\text{real-world}}[\text{g/km}] = 0.95*CO_2^{\text{type approval}}[\text{g/km}] + 55$$

It corresponds to the current findings over a longer period of changing type approval values, and a variety of technologies. For diesel, petrol, and hybrid alike, the formula applies. Currently the real-world emissions, for conventional technology, are slightly lower than this line, but this is expected to change in the future, when flexibilities are fully exploited. In part, this relation is based on the emission performance of existing novel technologies in the Dutch fleet. On the other hand, plug-in vehicles with type approval values of 27 to 44 g/km currently have a gap of 60-80 g/km, for which some improvements in real-world performances are expected to reach a 50-55 g/km gap.

A variation of a few percent is expected over time, however, this is in the bandwidth of the uncertainty of the future developments. The simplest assumption is that the WLTP post-2020 will not change this result. The real-world offset will increase due to the higher velocity (air-drag air-density effect) and the reduced cold start contribution. On the other hand, the test procedure is adapted. The test mass is higher and the tyres on the production model should match the test results. Both effects are expected to cancel each other out. However, the WLTP legislative text has not reached it final form, so some, yet limited, bandwidth exists. This is discussed in the next chapter.

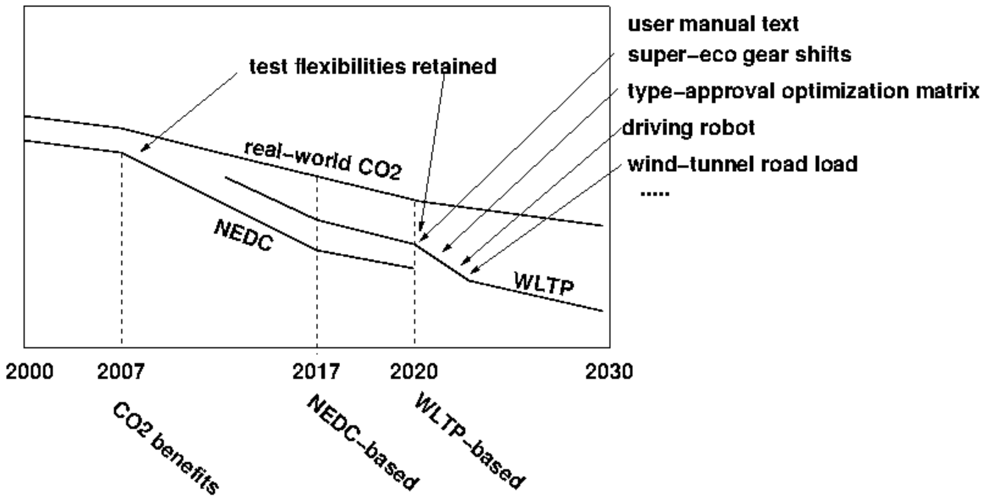


Figure 7: The likely scenario for the gap between real-world and type approval test values. The gap between NEDC and WLTP is maintained for a beneficial correlation factor, until the WLTP will be the reference for the type approval value. With the start of the WLTP-based CO_2 figures, the manufacturers will be able to use the procedure to their benefit.

5.4 Conclusions

In principle, energy is required to overcome the driving resistance. This cannot be avoided by physical principles. Hence some work must be done, and the associated CO_2 emissions are unavoidable for fuel-based technology. Real-world driving show a larger variation in driving and circumstances than any of the test cycles, type approval or real-world, and therewith associated emissions. For example, it is not possible to represent normal motorway driving well on a test cycle, as the typical duration is long and average velocity is high. This split is clear in Dutch driving where modern vehicle do half their distance at an average velocity of about 100 km/h, yielding a substantial contribution of air-drag absent in the test.
The effects outside the testing regime become increasingly important with the reduction of CO_2 emissions on the type approval test. In 2000 an additional 15 g/km CO_2 was only a small portion of the total CO_2 emission, nowadays it affects the gap between real-world and type approval emissions in a significant manner.
With the current target and the set-up of the test procedure, CO_2 reductions may be sought in measures which have a limited effectiveness in real-world CO_2 reductions. Some measures, such as weight reduction have a large effectiveness, on the other hand plug-in technology and even stop-start systems result in a small effectiveness in normal Dutch vehicle usage. Eventually, the reductions in CO_2 emissions on the type approval test will be less and less effective for real-world CO_2 reduction.

6 Drawbacks of type approval testing

The different type approval test and test procedure have different characteristics. However, all of the tests are meant for all European cars, with some small exception. This means the test procedure is designed for the weakest cars to be able to follow the test. Unlike in the case of heavy-duty engines where the ETC and WHTC tests are scaled with the rated power, the light-duty vehicle test does not take into account the power-to-mass ratio and the vehicle capabilities in terms of maximum velocity and acceleration. Hence the focus of the test cycles is on low load, which reflects the improvements in fuel-efficiency in mainly low load usage. This is not the common Dutch vehicle usage, with 50% motorway driving. It can be even argued that the engine downsizing has an adverse effect of high-velocity CO_2 emissions as the gear ratio changes, to maintain drivability with increasing engine losses on the motorway.

6.1 NEDC

The NEDC test is an old stylized test, with simple instructions and fixed velocities to shift gear. There is little flexibility in the way the test can be executed, and the test flexibilities are mainly in the state and condition of the vehicle not described in the test. Although the test is meant as representative for normal driving, the weight, the state of the tyres, and the state-of-charge of the battery is typically optimized for low CO_2 emissions. This is considered as acceptable practice by many.

The main advantage in the past of the NEDC was the low engine load. It has driven some major improvements. Actual optimizations of the engine, effective on the NEDC are improvements of the low-load engine efficiency. An engine is designed for the moments of high power demand: accelerations on the motorway. The normal operation is low load: 15% of the rated power is usually needed. The improvement of engine efficiency in this range has benefitted most vehicle usages. Hence the improvements in engine technology since 1992 are visible in both the NEDC test and in real-world fuel consumption. Moreover, the short cycle means the cold start (at 20^{o}-$30^{o}C$ laboratory temperature) has a major impact on the pollutant and CO_2 emissions. This is also relevant for the real-world operation.

6.2 WLTP

The WLTP was meant to be an improvement compared to the NEDC test. It is no longer the case. In the process the effectiveness and fit-for-purpose of the WLTP is largely lost. The average velocity is higher on the WLTP, more in line with real-world driving. In particular velocities above 100 km/h play a more significant role in the WLTP than in the NEDC, which may drive effective aerodynamic improvements, and frontal area reductions. Another positive feature is the attention for vehicle mass and payload. The total vehicle weight on the test will be substantially higher on the WLTP than on the NEDC. The type approval weight on the NEDC is commonly much lower than the actual weight of the vehicle. This is no longer the case on the WLTP. Moreover, no longer a generic vehicle weight is to be used, be the actual weight of the different production models.

Another important focus of the WLTP regulation text is to ensure that practices, not explicitly forbidden in the NEDC, but undesirable, are explicitly forbidden in the WLTP. For example, tyres must according to the WLTP have sufficient thread and may not be aged or heat-treated. No such provision was set in the NEDC. In what respect such practices are used at the moment is unknown. Moreover, it is unclear what the common interpretation of the NEDC protocol is, and how much it varies from one to the next of the eighteen witnessing authorities in Europe.

The WLTP regulation text is the result of long and difficult negotiations with many stakeholders. The current result, phase 1a, has some lacunas and placeholders for new regulation.

A few of the generic problems with the current status, Spring 2015, of the WLTP regulation:

1. “options”: rather than a prescribed procedure, the WLTP allows for several options in many cases, of determining road load, executing chassis dynamometer tests, etc.. This means the manufacturer can choose the options which generate the largest benefits. Stacking such optimized choices will lead to a substantial effect, compared to fixed procedures.
2. “calculations”: The amount of testing is limited, and many values are determined through calculations. Inserting such calculations together with a choice of underlying test data to be used can generate further benefits on paper, without any underlying measurements.
3. “obfuscations”: the WLTP text with the calculations and options is a complex procedure of which little information is shared. For example, the gear shifts are no longer fixed, but based on the engine characteristics which can be calibrated to improve engine load. Even errors in the calculations, yielding benefits, may go unnoticed.
4. “optimal is normal”: manufacturers find it no longer acceptable that the road-load values obtained in the test are higher due to wind. In normal driving this wind is present. The gap between test conditions and the test vehicle state, and normal conditions and vehicle state increases.
5. “user instruction”: What now is considered a large improvement over the NEDC, such as a tighter description of the state of the tyres during the coast-down test will very likely disappear with simple adaptions in the user instructions. Requiring a higher tyre pressure, with an associated lower rolling resistance, can be added to the instruction.
6. “exceptions”: generic testing is no longer standard, there are many exceptions and cases where at the request of the manufacturer there can be deviated from the prescribed test protocol.
7. “aftermarket”: if the production vehicle has features to reduce CO_2 affecting other aspects relevant for consumers, they are easily removed, added, or alter in the aftermarket sales. Fuel-efficient wheels tyres may be replaced in similar schemes which provide “sport wheels” to many car owners.

The current WLTP text reflects a large interference of the industry. The initial expectations for a better representation of the real-world situation by the test procedure is no longer fitting. In principle, only independent testing for all or proper sample of vehicles seems to be the only way to ensure appropriate test results.

6.3 Flexibilities

Next to the deviation between real-world fuel consumption and the type approval result as observed in independent testing, there is also an increasing gap between neutral test results, and the values declared by the manufacturer. The test execution for the type approval values is more and more optimized. Without any observed improvement in real-world fuel efficiency the reduction of type approval value is approximately 1%-2% a year. This has started in 2006 and some manufacturers started early, while others made a jump down later in the process. From 2011 all main manufacturers exploited the test flexibilities for all vehicle models (Kadijk 2012, Ligterink 2014). There seems so far no end in the optimization of the test procedure and the increasing gap between neutral testing and optimized testing. The gap between neutral testing and the declared value is expected to increase to 20 g/km in 2020, with the introduction of the WLTP this gap may decrease, maybe even by half. However, CO_2 emissions not covered by the test, mainly due to deviating ambient temperature and cold start will increase, more or less negating the effect of the reduced flexibilities on the WLTP. Hence the transition to the WLTP will not show an effect, once the WLTP is the normative test for CO_2 targets.

It is especially visible for type approval values with certain tax benefits. The declared CO_2 values are often below a threshold, while values just above the threshold do no occur. Vehicle models with no apparent change in engine or body have reductions in CO_2 from one month to the next.

6.4 Unwanted effects

Some technologies, such as PHEV’s, are stimulated. The calculated CO_2 reduction benefits are substantial, with little real-world benefit to show for. This gap is not closed in the WLTP. The test procedure is not adapted, because the European Commission means to stimulated PHEV’s vehicles in this manner. Such a mixed approach, where technology stimulation interferes with CO_2 targets, can only lead to reduced efficiency on both.

6.5 Improvements aftermarket

The WLTP will probably forces a shift to aftermarket adaption of the vehicle. The wheels and tyres are nowadays already changed from the original production model. In the future, the vehicle for the type approval CO_2 figure which rolls out of the factory may be a different one that is on sale.

Apart from vehicles sales, aftermarket plays a role in achieving CO_2 reductions. In particular the sales of fuel-efficient Triple-A tyre will reduce CO_2. On the other hand, the sales of auxiliaries increasing the weight or the electric power consumption are part of the aspects which widens the gap between type approval and real-world CO_2 beyond the control of the car manufacturers. In particular till 2020, when the NEDC is still the reference, this effect can be substantial.

6.6 Conclusions

There exists a considerable risk that the introduction of WLTP might not decrease the gap between real-world and type approval CO_2 emissions. Even more, there is a substantial risk the gap is larger, as some of the aspects that add CO_2 emissions to the NEDC type approval value per kilometre are reduced in the WLTP, such as cold-start and low engine load. In that respect the NEDC test may be more appropriate, yet for the wrong reasons. The removal of the exploitation of the “wrong reasons” for achieving a low CO_2 value on the test will make the improvements on the WLTP more “fit-for-purpose”. The limited effectiveness of the WLTP to achieve real-world reductions lies mainly in the wrong focus, the NEDC benchmark, and the manifold increased complexity of the procedure, with many optimization options, than in the general features of the test itself.

7 Conclusions

Compared to other European countries, the share of vehicles with CO_2 reducing technologies in the Netherlands is relatively high. The CO_2 reductions in the Netherlands are partly the result of the Dutch fiscal system.
In this study, the technological options for reducing type approval (TA) CO_2 emissions for passenger cars are discussed separately for the period up to 2020, and for the period beyond 2020. Additionally, cost curves for diesel and petrol cars are derived for the Netherlands based on these reduction technologies The cost curves are based on work from (TNO, 2011) and translated vehicle weight categories as used in DYNAMO. The full potential of the cost curves, about the last 3% for petrol vehicles and 8% for diesel vehicles, can only be achieved with full hybridization, not to be confused with plug-in hybridization.

Furthermore, the vehicle categories plug-in hybrids and fully electric vehicles are added to the analysis. The cost curves show a clear discontinuity between ICEVs, PHEVs and EVs, which indicates that reaching overall targets is normally not achieved in one step, but in several steps into the right direction.

Effectiveness to reduce real-world CO_2 emissions in the current climate, with the European CO_2 targets based on type approval values, will be limited. The current NEDC test is not fit-for-purpose and it will drive low-load improvements with limited relevance for real-world emissions. The new WLTP test is a compromise with many ineffective ways to achieve the targets on the type approval tests. The whole WLTP text has surprisingly few references to the fact the test is meant to be representative to real-world driving. Was it in the NEDC still possible to reduced fuel consumption by “real-world driving like in the NEDC”, with the WLTP there is no longer a driving style and vehicle usage prescribed which will bring the driver’s fuel consumption down. The expected reductions on the type approval test, NEDC and WLTP alike, will, very likely, correspond to half these effects in real world.

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9 Signature

Delft, 10 June 2015 TNO

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A Technology options

Table 8: Reduction potential and estimated additional manufacturer costs of technical options to reduce CO_2 emissions of passenger cars on diesel, assuming large scale production by 2020 (TNO, 2011)

Technology options for diesel cars		Small		Medium		Large	
Description		Reduction potential [%]	Cost [€]	Reduction potential [%]	Cost [€]	Reduction potential [%]	Cost [€]
Engine options	Combustion improvements	2	50	2	50	2	50
	Mild downsizing (15% cylinder content reduction)	4	50	4	50	4	50
	Medium downsizing (30% cylinder content reduction)	7	450	7	450	7	450
	Strong downsizing (>=45% cylinder content reduction)	15	500	15	600	15	700
	Variable valve actuation and lift	1	280	1	280	1	280
Transmission options	Optimising gearbox ratios / downspeeding	3	60	3	60	3	60
	Automated manual transmission	4	300	4	300	4	300
	Dual clutch transmission	5	650	5	700	5	750
	Continuously variable transmission	4	1200	4	1200	4	1200
Hybridisation	Start-stop	4	175	4	200	4	225
	Micro hybrid - regenerative breaking	6	375	6	375	6	375
	Mild hybrid - torque boost for downsizing	11	1400	11	1500	11	1500
	full hybrid - electric drive	22	2250	22	2750	22	3750
Driving resistance reduction	Mild (~10% reduction on body in white)	1,5	128	1,5	160	1,5	192
	Medium (~ 25% reduction on body in white)	5	320	5	400	5	480
	Strong (~40% reduction on body in white)	11	800	11	1000	11	1200
	Lightweight components other than BIW	1,5	120	1,5	150	1,5	180
	Aerodynamics improvement	2	50	2	50	1,5	60
	Tyres: low rolling resistance	3	30	3	35	3	40
	Reduced driveline friction	1	50	1	50	1	50
Other	Thermo-electric conversion	2	1000	2	1000	2	1000
	Secondary heat recovery cycle	2	200	2	200	2	200
	Auxiliary systems improvement	11	420	11	440	11	460
	Thermal management	2,5	150	2,5	150	2,5	150

Table 9: Reduction potential and estimated additional manufacturer costs of technical options to reduce CO_2 emissions of passenger cars on petrol, assuming large scale production by 2020 (TNO, 2011)

Technology options for petrol cars		Small		Medium		Large	
Description		Reduction potential [%]	Cost [€]	Reduction potential [%]	Cost [€]	Reduction potential [%]	Cost [€]
Engine options	Gas-wall heat transfer reduction	3	50	3	50	3	50
	Direct injection, homogeneous	4,5	180	5	180	5,5	180
	Direct injection, stratified charge	8,5	400	9	500	9,5	600
	Thermodynamic cycle imporvements e.g. split cycle, PCCI/HCCI, CAI	13	475	14	475	15	500
	Scale down architecture, 4-->3 cylinder	0	0	0	0	0	0
	Mild downsizing (15% cylinder content reduction)	4	200	5	250	6	300
	Medium downsizing (30% cylinder content reduction)	7	550	8	600	9	700
	Strong downsizing (>=45% cylinder content reduction)	16	550	17	600	18	700
	Cam-phasing	4	80	4	80	4	80
	Variable valve actuation and lift	9	280	10	280	11	280
	EGR	0	0	0	0	0	0
	Low friction design and materials	2	35	2	35	2	35
Transmission options	Optimising gearbox ratios / downspeeding	4	60	4	60	4	60
	Automated manual transmission	5	300	5	300	5	300
	Dual clutch transmission	6	650	6	700	6	750
	Continuously variable transmission	5	1200	5	1200	5	1200
Hybridisation	Start-stop hybridisation	5	175	5	200	5	225
	Micro hybrid - regenerative breaking	7	325	7	375	7	425
	Mild hybrid - torque boost for downsizing	15	1400	15	1500	15	1500
	Full hybrid - electric drive	25	2250	25	2750	25	3750
Driving resistance reduction	Mild weight reduction (~10% reduction on body in white)	2	128	2	160	2	192
	Medium weight reduction (~ 25% reduction on body in white)	6	320	6	400	6	480
	Strong weight reduction (~40% reduction on body in white)	12	800	12	1000	12	1200
	Lightweight components other than BIW	2	120	2	150	2	180
	Aerodynamics improvement	2	50	2	50	1,5	60
	Tyres: low rolling resistance	3	30	3	35	3	40
	Reduced driveline friction	1	50	1	50	1	50
Other	Thermo-electric waste heat recovery	2	1000	2	1000	2	1000
	Secondary heat recovery cycle	2	200	2	200	2	200
	Auxiliary systems efficiency improvement	12	420	12	440	12	460
	Thermal management	2,5	150	2,5	150	2,5	150

B Additional costs for PHEVs and EVs in 2020

Table 10 shows the additional vehicle costs for plug-in hybrids and battery-electric vehicles with reference to petrol and diesel vehicles in the year 2020. The additional vehicle costs have been determined as a function of the estimated battery costs in 2020 and corresponds to the central scenario as determined in (Policy Research Corporation, 2015). In this scenario the battery costs correspond to 300€/kWh.

The required CO_2 reduction per segment can be found in [TNO 2011].

Table 10: Estimated price differences of plug-in hybrid and battery-electric cars with reference to a petrol and a diesel car in 2020 (based on battery costs of 300 €/kWh)

Vehicle type	Fuel type	Segment	Additional vehicle prices [€]	Reference vehicle prices [€]
PHEV	petrol	A	7073	10084
		B	9781	14329
		C	14350	21518
		D	14276	28837
		E	61142	63908
	diesel	A	5959	11198
		B	7863	16248
		C	11343	24525
		D	11395	31719
		E	73782	51269
BEV	petrol	A	7560	10084
		B	4507	14329
		C	3823	21518
		D	3835	28837
		E	1466	63908
	diesel	A	6446	11198
		B	2588	16248
		C	816	24525
		D	954	31719
		E	14105	51269

C Weight class inter- and extrapolation

The cost curves determined in SR1 (TNO, 2011) are applicable to different weight class categories than used in DYNAMO. DYNAMO cost curves are determined through inter- and extrapolation of SR1 by use of a 3rd grade polynomial fit. The results are shown in Figure 8 and Figure 9.

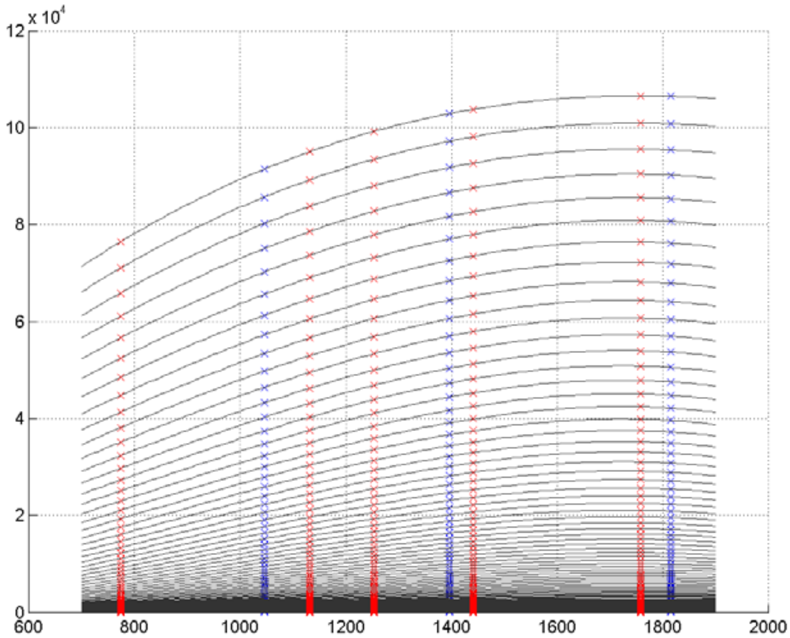

Figure 8: Weight class inter- and extrapolation of ICEV diesel vehicle costs.

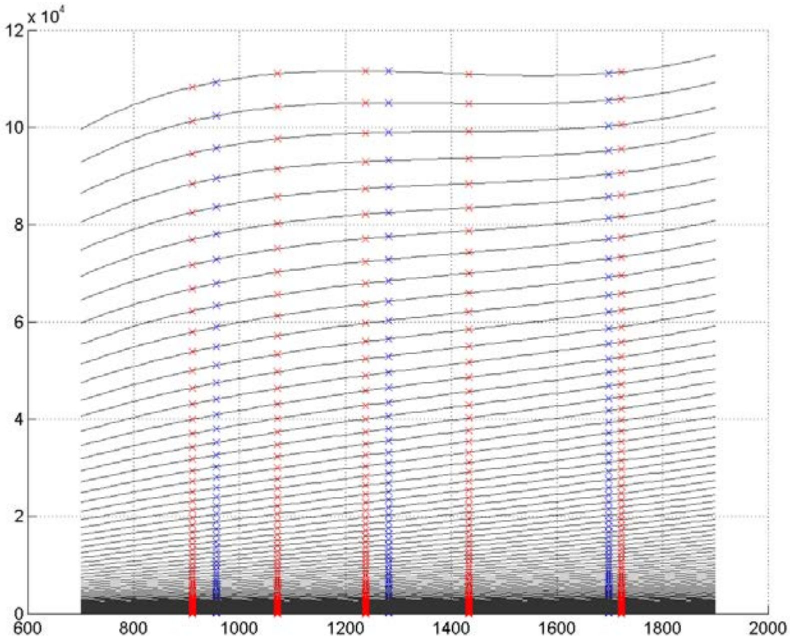

Figure 9: Weight class inter- and extrapolation of ICEV petrol vehicle costs.