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Für Mensch und Umwelt

Estimate of the Technological Costs of CO_2 Emission Reductions in Passenger Cars

- Emission Reduction Potentials and their Costs-

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1 Background

On December 19 2007 the European Commission proposed a regulation on the reduction of CO_2 emissions from cars. According to this regulation, maximum permissible emissions in grams of CO_2/km will be calculated for all vehicles – depending on their mass – from 2012. Each manufacturer that, in the sum of its newly licensed vehicles for each year, has higher specific emissions than the sum of maximum permissible emissions has to pay a so-called excess emissions premium for each gram of excess CO_2/km to the Commission. In 2012 the premium will amount to 20 euros per g/km, increasing gradually to 95 euros per g/km in 2015.

The size of the premiums has been criticized by different parties. The Commission derived the premium from a report by TNO et al.[1] [8] and developed avoidance cost curves from the costs and CO_2 emission reduction potentials of individual technologies for increasing fuel efficiency. Cost data concerning such technologies reflects, however, the situation in or around the year 2004.

TNO assumed that the voluntary commitment of car manufacturer associations will be met, and that in 2008/9 a level of 140 grams of CO_2/km would be achieved.

In a report of 19 April 2007, the German Federal Environment Agency (UBA) gave its views on the additional costs that manufacturers would incur were they to design new vehicles that were 20% more efficient. It concluded that additional costs of a few hundred euros per vehicle could be expected, as opposed to the more than 1,000 euros forecast by TNO.

This report contains updated estimates of the costs of these measures and sets cost curves of a kind comparable to those of TNO. Only those technologies have been considered that have their effect in the measurement of fuel consumption according to the New European Driving Cycle (NEDC).

[1] Hereafter TNO

2 Procedure

This report goes on from the UBA report of 19 April 2007. CO_2 emission reduction potentials and the accompanying costs of all technologies that are employable in the short term – up to 2012 – are updated. The obtained data distinguishes between cars with otto and diesel engines, and differentiates, where possible, small, medium-sized and large vehicles.[2] Where size-related differentiation has not been possible, it has been estimated with the help of cost spreads for the respective technology as given in TNO [8, p. 50/51].

Greater increases in fuel efficiency can be demonstrated at – in part, lower – costs with packages of measures than with individual measures. Useful packages have therefore been created from individual measures, and their overall reduction potentials and costs ascertained. The scatter graph for each package of measures provides the basis for setting the cost curves of manufacturers.

Analogous to TNO, we set a continuous curve in the form of a third-degree polynomial, which determines additional manufacturing costs per car (in euros) as a function of CO_2 reduction (in gCO_2/km). From this, those costs can be deduced that are to be assumed for achievement of a given fuel efficiency level on the average of all cars of the respective class.

2.1 Reduction potentials and costs of individual measures

In order to determine current reduction potentials and costs of measures for improving fuel efficiency in cars, the UBA conducted extensive bibliographical research. In addition, we obtained expert opinions from research institutes and the automotive supply industry.

Prices and potentials are based on present (2007/2008) standard technological developments in cars of the above-mentioned classes (see Table 1). Individual measures can already be realized in a number of cars, but not, however, in the majority of cars of the respective class. This simplification is necessary in order to be able to set generally applicable cost curves. It is then not possible, however, to infer additional costs for a manufacturer for a particular vehicle or model.

The technical specifications of reference vehicles of each class and their average specific CO_2 emissions per kilometre are shown in Table 1.

[2] Cars with otto engines (small, medium-sized, large) and cars with diesel engines (small, medium-sized, large) are designated below in classes. Size-related differentiation is based on engine displacement: <1.4 l; 1.4-2.0 l; >2.0 l.

Table. 1: Technical specification of reference vehicles. Compilation of the best-selling models of the classes in Germany (including imported vehicles).

	Otto, small	**Otto, medium-sized**	**Otto, large**	**Diesel, small**	**Diesel, medium-sized**	**Diesel, large**
Engine	4 cylinder series	4 cylinder series	4 cylinder series	4 cylinder series	4 cylinder series	V6-, V8-cylinder
Pressure-charging	No	No (in part, turbo-charging)	No (in part, turbo-charging)	Turbo-charging	Turbo-charging	Turbo-charging
Fuel injection	Multipoint (in part, direct)	Multipoint (in part, direct)	Multipoint (in part, direct)	Direct injection	Direct injection	Direct injection
Gear change	5 gear, manual control	5 / 6 gear, manual control	6 (7) gear, automatic, (in part, infinitely variable)	5 (6) gear, manual control	6 (5) gear, manual control	6 (7) gear, automatic, (in part, infinitely variable)
CO_2 (g/km) 2006 in Germany	144.4	176.9	222.6	121.9	156.1	214.7
CO_2 (g/km) 2006 in EU[3]	143.9	179.0	230.6	122.3	150.1	211.0
Newly-licensed cars 2007, Germany[4]	746,392	718,587	157,297	47,237	998,646	455,683

Technologies shown in brackets are found in some models

All direct costs of the car manufacturer (costs of materials, tools, components and personnel) are included in the following examination of manufacturing costs. The costs refer to Germany. They can deviate from costs in other EU Member States, for instance, due to differences in tax rates, other consumer incentives (e.g. effect of CO_2 label, price and image) and different national promotion policies (e.g. government bonuses for new cars with a certain CO_2 level).

Cost degression through economies of scale and the related optimization of industrial processes as well as material substitution are considered in the estimate of costs. As to future developments in costs, economies of scale, in particular, hold great uncertainties. Mass production of certain technologies in connection with intensive research and development can greatly cut costs.

Published retail price data has been converted, analogous to TNO, to additional manufacturing costs with the factor 1/1.44.

[3] [43] Zierock and DLR, 2007. Classification according to the systematics of Polk Marketing Systems Data GmbH.

[4] [42] KBA, 2007

Potentials and additional manufacturing costs of individual measures to increase the fuel efficiency of cars with spark-ignition engines are summarized in Annex 1, those for cars with diesel engines in Annex 2. The sources of statements are noted in square brackets (see Section 5).

Many measures serve not only the improvement of fuel efficiency; they also contribute, for example, to the reduction of noise, improved drivability or increased comfort. TNO therefore attributes only a part of the costs of a measure to CO_2 reduction. For variable valve timing, for instance, TNO charges 25% of total costs to the reduction of exhaust gas pollutants, whose emission is regulated by statute, so that only 75% of the costs of the measure are chargeable to CO_2 reduction. Our analysis proceeds similarly. The shares of costs charged to CO_2 reduction are shown in Annexes 1 and 2 in line with the TNO procedure.

2.2 CO_2 emission reduction potential and costs of a package of measures

To identify possible packages of measures, interdependencies of individual measures have been determined. Annex 3 displays such interdependencies for cars with otto engines, Annex 4 those for cars with diesel engines. Their potentials were combined by multiplication when the measures had an effect independent of each other. They are marked in the Annex tables with "**+**". The calculation corresponds to the TNO approach:

$$CO_2^{package} = CO_2^{baseline} \times \prod_{i=1}^{n} (1 - \delta_i)$$

Combinations of individual, mutually exclusive measures are marked with "**-**", and they are not included in further calculations.

Finally, there are also measures that influence each other, since they exploit the same potential. For instance, a latent heat accumulator restricts the CO_2 emission reduction potential of low-friction oil, since its consumption-reducing effect occurs during the cold running phase. Such dependencies are marked with "**!**". The strength of mutual influencing depends on the particular combination. Specific reduction potentials have been estimated for these combinations (see Annexes 1 and 2). There is no clear indication of how TNO dealt with packages of measures that are impractical.

Manufacturing costs are calculated analogous to TNO for all packages of measures with "**+**" or "**!**" as the sum of the manufacturing costs of the individual measures:

$$\cos t^{package} = \sum_{i=1}^{n} \cos t_i$$

2.3 Combinatorics of individual measures

The multitude of technical measures that can be employed to increase fuel efficiency leads to a large number of possible packages. Merely considering individual measures from the areas of "engine" and "other", of the 13 measures for cars with otto engines and 10 measures for cars with diesel engines, with in each case two possible interpretations (with / without), one arrives at 2^{13} = 8,192 and 2^{10} = 1,024 possible combinations. If one includes the five possible gearing features (basic / optimized gearing / CVT / dual-clutch transmission (DCT) / optimized gearing with dual-clutch transmission) the numbers of possible combinations increase five-fold. Including the four hybrid forms (without / start-stop system / mild hybridization / full hybridization) results in a further four-fold increase. In all, there are 163,840 different packages of measures for cars with otto engines and 20,480 for cars with diesel engines.[5]

Due to the large number of variants, computer-aided calculation was indispensable. This was realized with the aid of VBA macros, providing reduction potentials and manufacturing costs according to predetermined specifications for all variants. Annexes 5 to 10 display the results for the six vehicle classes (cars with otto / diesel engines) * (small, medium-sized, large) in the form of scatter graphs. The TNO report uses similar scatter graphs.

2.4 Setting cost curves

TNO sets a continuous curve for each class, which indicates additional manufacturing costs for each car (in euros) as a function of CO_2 reduction (in grams of CO_2/km). Its approach was a third-degree polynomial

$$y = ax^3 + bx^2 + cx$$

with the restriction that the curve runs through the co-ordinate origin. The following computations also use this approach. Complete setting of the cost curve requires that coefficients a, b and c be determined. Their derivation is not clearly indicated in the TNO report.

Determination of degree of latitude by means of restrictions

Three degrees of latitude for the setting of cost curves arise from the three coefficients of the approach. In order to be able to set a specific cost curve it is therefore necessary to define three restrictions that limit the degree of latitude.

The *first restriction* arises, analogous to the TNO report, from the assumption that the manufacturer, in implementing packages of measures, does not tend towards the lower – cheaper – edge of the curve (of the package), but might rather choose more expensive packages should these be more in line with market requirements. The TNO report quantifies this by determining that one-third of the scatter-graph points are below and two-thirds above the curve. We proceed in exactly the same way.

The *second restriction* is that the slope of the curve at the co-ordinate origin should be 0. This restriction is practical, since individual measures exist for which no costs arise. As far as concerns the coefficients, this restriction means that c is given the value 0. In the TNO report c has values that are greater than 0. Its package of measures contains none that involve no cost.

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[5] The "measure" that requires that nothing is changed in the reference vehicle is included.

The *third restriction* lays down that the curve should run through the package of measures with the greatest reduction potential. The manufacturer can only realize this CO_2 emission reduction potential through the implementation of all individual measures. There is therefore no latitude in setting the course of the curve.

Computation of coefficients

Coefficient c can be directly derived from the second restriction. The slope at the co-ordinate origin should be 0. The following applies:

$$\frac{dy}{dx} = 0$$
$$\frac{d\left(ax^3 + bx^2 + cx\right)}{dx} = 0$$
$$3ax^2 + 2bx + c = 0$$
$$c = 0$$

The third restriction provides a connection between *a* und *b*, which enables the de-termination of *b* from a given *a*. The following applies:

$$y_{\max} = ax_{\max}^3 + bx_{\max}^2$$
$$y_{\max} - ax_{\max}^3 = bx_{\max}^2$$
$$b = \frac{y_{\max} - ax_{\max}^3}{x_{\max}^2}$$

It therefore only remains to determine *a* by means of the first restriction. This was realized with VBA macro. The macro conducts a target value search, during which the coefficient is changed until the curve (with constantly adjusted *b* according to the above equation) is such that one-third of the scatter-graph points are below and two-thirds over the curve.

2.5 Results

The coefficients *a* and *b* have been determined for each class, and *c* is per definition 0 (see Table 2). If the coefficients are employed in the third-degree polynomial in Section 2.4, one obtains the curves for additional manufacturing costs per car (in euros) as a function of CO_2 reduction (in grams of CO_2/km).

Engine displacement	**Otto engine**			**Diesel engine**		
	a	*b*	*c*	*a*	*b*	*c*
<1.4 l	0.001887	0.282310	0	0.004124	1.042238	0
1.4…2 l	0.00138	0.199462	0	0.002541	0.787621	0
>2 l	0.000948	0.124012	0	0.000860	0.455337	0

Table 2: Resulting coefficients for setting cost curves for additional manufacturing costs

The cost curves of each class set in this manner are displayed in Annexes 5 to 10. With predefined emission reduction – in grams of CO_2/km – costs are directly read-able or calculable by means of the coefficients.

2.6 Restrictions

The widely-spread scatter graphs of Annexes 5 to 10 illustrate a restriction in interpretation of cost curves. Should it be intended, for instance, to reduce the average specific CO_2 emissions of medium-sized vehicles with otto engines (Annex 6) of 176.9 g/km (cf. Table 1) by 37 g/km to 140 g/km, the manufacturer could incur costs, depending on the selected package of measures, of about 50 to 2,000 euros. A wide range of costs arises for all CO_2 emission reductions between 20 and 90 g/km.

Merely the approximate order of magnitude of actual costs can be determined. Cost curves are suitable, however, for comparing classes.

If cost curves are applied to the Commission's Proposal a further aspect has to be borne in mind. Since the Proposal relates permissible CO_2 emissions to the mass of the respective vehicle, measures that result in weight changes have to be differently assessed on the part of the manufacturer.

As a result of a "5% weight-reduction" measure, for instance, a medium-sized car could become about 70 kg lighter.[6] The maximum permissible emission value for this car, according to the Proposal, would at the same time fall by 3.2 g/km. If light-weight construction is to be employed, the measure must at the same time offset the excess emissions premium, which, for 2012, is 20 euros per gram of CO_2/km). The result would be an additional burden of 64 euros, which would have to be added to the 80 euros that the measure actually costs.[7] A 5% reduction in weight would thus "cost" the manufacturer in 2012 about 144 euros.

Downsizing and, perhaps, the choice of gearing, could also lead to a reduction in weight, so that they become relatively expensive for the manufacturer. Mild and full hybridization at the same time increases vehicle weight and are more attractive for the manufacturer. IAV [39] gives the additional weight resulting from full hybridization of a car with a diesel engine as well as a 50 kW electric motor and adequate dimensioning of the battery at about 300 kilograms. At the same time, downsizing the spark-ignition engine and a reduction in tank volume then enable weight savings of about 100 kilograms. The additional 200 kilograms increase the maximum permissible emission value by 6.4 g/km, which, taking into account the avoided excess emission premium, amounts to a positive equivalent value for the manufacturer of 128 euros. Since only 75% of the costs of full hybridization, according to TNO, are attributable to CO_2 emission reduction, such a configuration for large diesel vehicles would cost not 3,000 euros, but rather 2,872 euros (2012). Considerable cost reduction potentials for full hybridization are particularly to be found in energy storage and power electronics [39, 40].

Were newly licensed vehicles over a wide range to be full hybrids, this would push up the average increase in vehicle kerb weight. As a result, the European target of 130 grams of CO_2/km per new car could be missed.

The analysis does not cover:

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[6] According to our calculations, the average kerb weight of all cars newly registered in 2006 in Germany was approximately 1,392 kg.

[7] The additional burden arises only when the manufacturer lies above its maximum permissible emissions with respect to its total number of new vehicles.

- Market reactions to the Commission's Proposal. This means that the quantity and shares of classes of newly licensed vehicles is assumed – analogous to TNO – to be constant.

- Possible additional CO_2 emissions from Euro 5/6 regulations and the costs that arise through their compensation.

3 Discussion of results

We cannot carry out specific cost comparisons for individual manufacturers. For this, EU-wide data on the number and distribution of newly registered vehicles of the respective manufacturers according to the classes selected in this report would have to be available. Such data is not at our disposal. Annexes 11 and 12 provide an impression, however, of the average CO_2 emission level of each manufacturer in 2006 and of manufacturer-related reduction demands to preclude excess premiums as laid down in the new Proposal.

Since most manufacturers would have to reduce the specific CO_2 emissions of their new vehicles by about 20%, the estimated additional manufacturing costs for cars with otto and diesel engines as well as the resulting benefits for the economy are shown in Tables 3 and 4.

The determination of costs differentiates vehicle classes, analogous to the TNO report, in the same way for all manufacturers. This report does not consider the cost minimization potential for the particular fleet of a manufacturer, which arises from optimized distribution of reduction measures and costs to large and small vehicles of varied numbers in compliance with the manufacturer-specific fleet limit value. A number of manufacturers also have the opportunity to create a pool, linked with the potential of further cost minimization. Actual costs will therefore be lower than those shown in the following tables.

As mentioned at the beginning, only CO_2 emission reduction potentials are shown related to NEDC.

3.1 Cars with otto engines

The following measures can be carried out on cars with otto engines without appreciable additional costs:

- Direct fuel injection -> 5% potential
- Optimized gear design -> 4% potential
- Low-rolling-friction tyres -> 4% potential
- Improved aerodynamics -> 1% potential

Other measures that cost a maximum of €25 per percentage point of CO_2 savings are:[8]

Downsizing, exhaust-gas recirculation (EGR), reduction of engine friction, improvement of engine temperature control, variable valve timing, variable compression and weight reduction.

Most of these cost-effective measures concern the spark-ignition engine. The greatest potential lies in this area. Hybrid technology is presently relatively expensive. In

[8] Related to engine displacement class of 1,400 to 2,000 cm^3.

the short term, it is likely that from the hybrid area only start-stop systems will have an increasing impact on the market in new vehicles. Full hybrids will remain restricted in the short term to the top vehicle segment.[9]

Additional manufacturing costs are shown in Table 3 exemplarily for a 20% CO_2 emission reduction in vehicles with otto engines.

Table 3: Manufacturing costs for 20 % CO2 emission reduction in otto vehicles

	Otto		
Engine displacement	**< 1.4 l**	**1.4 to 2.0 l**	**> 2.0 l**
Average CO_2 emissions, 2006	144 g/km	177 g/km	223 g/km
Average fuel consumption in litres/100km	6.1 litres/100km	7.5 litres/100km	9.4 litres/100km
Manufacturing costs accord. to UBA 20% CO_2 reduction	**281 €**	**311 €**	**329 €**
20 % CO_2 emission reduction	29 g/km	35 g/km	45 g/km
20% fuel saving in litres/100km	1.2 litres/100km	1.5 litres/100km	1.9 litres/100km
Price per litre of fuel before taxes 03/08	0.530 €	0.530 €	0.530 €
Price per litre of fuel after taxes 03/08	1.410 €	1.410 €	1.410 €
Service life of vehicle according to TREMOD	12 years	12 years	12 years
Fuel saving in litres over 12 years	1,368 litres	2,018 litres	2,925 litres
Savings in tonnes of CO_2 over 12 years	3.2 tonnes	4.8 tonnes	6.9 tonnes
Performance according to TREMOD	9,300 Km	11,200 Km	12,900 Km
Benefit for the economy	725 €	1,070 €	1,550 €
Benefit for the consumer	1,929 €	2,846 €	4,124 €
Cost to the economy	281 €	311 €	329 €
Cost to the economy per tonne of CO_2 savings	**87 €/tonne CO2**	**65 €/tonne CO2**	**48 €/tonne CO2**
Benefit for the economy per tonne of CO_2 savings	225 €/tonne CO2	225 €/tonne CO2	225 €/tonne CO2
Savings for the economy per tonne of CO_2	**-138 €/tonne CO2**	**-160 €/tonne CO2**	**-177 €/tonne CO2**
Manufacturing costs according to TNO et al	720 €	760 €	910 €

A 20% increase in fuel efficiency accordingly costs manufacturers an average of 280 to 330 euros.

The benefit to the German economy – which is here simply shown with savings in fuel costs before tax over the 12-year service life of a vehicle, depending on engine displacement class – lies between 725 and 1,550 euros.[10] This benefit involves higher costs, namely manufacturing costs, so that the balance is 280 to 330 euros lower. Were they to keep their car for 12 years, consumers could save between 2,000 and 4,000 euros in fuel costs. Other factors would have to be taken into account, such as the higher purchase price of the car and resulting interest charges as well as the effects of the planned CO_2-related car tax.

The higher additional costs, compared to the UBA report of 19 April 2007, result from TNO systematics concerning the setting of cost curves. The TNO specification that one-third of the scatter-graph points derived from packages of measures should lie below the curve prevents the "tying up" of the cheapest package of measures, as happened in the earlier UBA report.

A comparison of UBA and TNO results (Table 3, last line) for a 20% reduction is restricted since

- the technical specifications of reference vehicles are slightly different; this arising from the different base years (TNO: 2002, UBA: 2007/8),

[9] Image and marketing strategy considerations will have the effect that hybrid technology will penetrate the market and spread to other classes at a faster pace than is reasonable from the point of view of cost-efficient CO_2 reduction. Virtually all major manufacturers intend to hybridize at least a part of their new fleets.

[10] Calculations exclude external costs of passenger car traffic.

- reference CO2 emissions are therefore also different (in giving reduction potentials as a percentage, reduction potentials in grams of CO2/km are different), and
- the potentials and costs of measures have changed between 2002 and 2007/8.

The costs determined in this report amount to only 36 to 41 per cent of additional costs according to TNO.

3.2 Cars with diesel engines

The following measures can be carried out on cars with diesel engines without appreciable additional costs:

- Optimized fuel injection -> 3% potential
- Optimized gear design -> 4% potential
- Low-rolling-friction tyres -> 4% potential
- Improved aerodynamics -> 1% potential

Other cost-effective measures that cost a maximum of €25 per percentage point of CO_2 savings are low-friction oil, reduction of engine friction, improvement of engine temperature control and weight reduction. [11]

Fewer cost-effective possibilities exist for the further development of diesel cars than in the case of cars with otto engines. Furthermore, the potential of measures is, in part, much smaller, since, for example, downsizing in connection with pressure-charging has largely already been realized. So far as hybrid technology is concerned, the picture is essentially the same as for cars with otto engines.

Additional manufacturing costs are shown in Table 4 exemplarily for a 20% CO_2 emission reduction in vehicles with diesel engines:

Table 4: Manufacturing costs for 20 % CO_2 emission reduction for diesel vehicles

	Diesel		
Engine displacement	**< 1.4 l**	**1.4 to 2.0 l**	**> 2.0 l**
Average CO_2 emissions, 2006	122 g/km	156 g/km	215 g/km
Average fuel consumption in litres/100km	4.6 litres/100km	5.9 litres/100km	8.1 litres/100km
Manufacturing costs accord. to UBA 20% CO_2 reduction	**679 €**	**845 €**	**908 €**
20 % CO_2 emission reduction	24 g/km	31 g/km	43 g/km
20% fuel saving in litres/100km	0.9 litres/100km	1.2 litres/100km	1.6 litres/100km
Price per litre of fuel before taxes 03/08	0.648 €	0.648 €	0.648 €
Price per litre of fuel after taxes 03/08	1.330 €	1.330 €	1.330 €
Service life of vehicle according to TREMOD	12 years	12 years	12 years
Fuel saving in litres over 12 years	1,197 litres	2,980 litres	4,099 litres
Savings in tonnes of CO_2 over 12 years	3.2 tonnes	7.9 tonnes	10.8 tonnes
Performance according to TREMOD	10,800 Km	21,000 Km	21,000 Km
Benefit for the economy	776 €	1,931 €	2,656 €
Benefit for the consumer	1,592 €	3,964 €	5,451 €
Cost to the economy	679 €	845 €	908 €
Cost to the economy per tonne of CO_2 savings	**215 €/tonne CO2**	**107 €/tonne CO2**	**84 €/tonne CO2**
Benefit for the economy per tonne of CO_2 savings	245 €/tonne CO2	245 €/tonne CO2	245 €/tonne CO2
Savings for the economy per tonne of CO_2	**-30 €/tonne CO2**	**-138 €/tonne CO2**	**-162 €/tonne CO2**
Manufacturing costs according to TNO et al	1,020 €	1,090 €	1,200 €

[11] Related to engine displacement class of 1,400 to 2,000 cm^3.

A 20% increase in fuel efficiency accordingly costs manufacturers an average of 680 to 900 euros.

The benefit to the economy from cars with diesel engines, depending on engine displacement class, is between 780 and about 2,600 euros. With costs to the economy of between 680 and 900 euros there remains a balance of between 100 and 1,700 euros. The benefit for consumers in reduced fuel costs can amount to up to 5,000 euros.

The higher additional costs, compared to the UBA report of 19 April 2007, result – as with otto engines – from TNO systematics. Moreover, the potentials of a number of measures vary only slightly from those mentioned in the earlier UBA report.

The costs determined for cars with diesel engines amount to about 67 to 78 per cent of additional costs according to TNO.

4 Summary and conclusion

Proceeding from the UBA report of 19 April 2007 we updated the costs and potentials of technologies that improve the fuel efficiency of cars. For this purpose, extensive research was carried out. The results for six car classes (diesel and otto engines, and in each case small, medium-sized and large cars) are displayed in Annexes 1 and 2.

We created practical packages of measures out of individual measures with their costs and fuel efficiency potentials, from which we deduced cost curves in accordance with TNO systematics (Annexes 5 to 10).

The cost curves are third-degree polynomials and are defined by the coefficients in Table 5. By setting the coefficients in the polynomial one obtains the curves for additional manufacturing costs per car (in euros) as a function of CO_2 reduction (in grams per CO_2/km).

Table 5: Resulting coefficients for the determination of cost curves for additional manufacturing costs.

Engine displacement	Otto engine			Diesel engine		
	a	*b*	*c*	*a*	*b*	*c*
<1.4 l	0.001887	0.282310	0	0.004124	1.042238	0
1.4…2 l	0.00138	0.199462	0	0.002541	0.787621	0
>2 l	0.000948	0.124012	0	0.000860	0.455337	0

The informative value of cost curves has to be qualified, however, by the possible range of costs – that is, the spread of points in the scatter graphs in Annexes 5 to 10 – for a given increase in fuel efficiency in g/km. Moreover, the weight-related reference of permissible CO_2 emissions in the Commission Proposal has the effect that, for manufacturers, weight-increasing measures will be relatively cheaper and measures involving lightweight construction more expensive. This could lead to higher average mass of new vehicle fleets and to the European emission target of 130 grams of CO_2/km being missed.

Cost-effective measures for otto and diesel cars are theoretically in the areas of lightweight construction and engines, whereby the engine-related potential, based on the present standard of diesel vehicles, is less than that of vehicles with otto engines. Full hybridization is relatively expensive for both engine systems.

Manufacturing costs are calculated exemplarily with a 20% increase in fuel efficiency, which is realizable in cars with otto engines, depending on class, for an average of 280 to 330 euros, and in cars with diesel engines for 680 to 900 euros. The difference, compared to earlier estimates, has primarily to do with TNO systematics specified for this analysis.

In practice, however, actual costs will be lower than those stated above, since the potential for minimizing costs for the particular fleet of a manufacturer and the possibilities for pooling on the part of several manufacturers have not yet been considered.

5 Sources

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6 Annex

Annex 1: Measures for the reduction of CO2 emissions in petrol vehicles - efficiency potential and manufacturing costs

	Measure	Published data on CO2 reduction potential	Assessed CO2 reduction potential	Published data on costs in €	Costs according to cylinder capacity in € (estimated)			Share of attributable costs	Proportionate costs according to cylinder capacity in € (estimated)		
					< 1.4 l	*1.4 - 2 l*	*> 2l*	%	*< 1.4 l*	*1.4 - 2 l*	*> 2l*
Engine	Downsizing with pressure-charging	20-30% [1]; 14-18% [10];	20%	200 [10]	180	200	220	100%	180	200	220
Engine	Direct fuel injection	5-20% [1]; 5% [10]; 8%[35]	5%	0	0	0	0	100%	0	0	0
Engine	Exhaust-gas recirculation (EGR)	5% [1]; 5-7% [2]	5%	approx. 10 (UBA)	10	10	10	100%	10	10	10
Engine	Reduction of engine friction	7-11 % [2]; 3-5% [8]; 5.4% [26]	4.5%	40-60 [8]	30	40	50	100%	30	40	50
Engine	Latent heat accumulator	5,7% [22]	3%	600-650 for customers [15]	420	440	450	100%	420	440	450
Engine	Optimized cooling circuit	3% [6]; 3% [8]; 6% [21]; 3%[34]; 4%[38]	3%	45 [8]; 55[38]	45	45	45	100%	45	45	45
Engine	Variable compression ratio (VCR)	8-9% [10]; 2-6% [11]; 7% [31]; bis	6.5%	111-261 [11]; 140 [31]	120	150	180	100%	120	150	180
Engine	Variable valve timing	12% [1]; bis 10%[26]	11%	300 (UBA)	250	300	350	75%	187.5	225	262.5
Engine	Cylinder deactivation	3-6 % [11]; 4% [12]	1% (< 1,4 l) 2.5% (1,4 - 2l) 4% (>2 l)	210-350 [12]; 59 to 133 [11]	130	150	170	100%	130	150	170
Gearing	Optimized gearing	1-1.5 % [8]; bis 4% [13]; 3% [44]	4%	0 [44]	0	0	0	100%	0	0	0
Gearing	Continuous variable transmission (CVT)	4,4 - 9.2% [2]; 2% [11]; 4-8%[1, S 68]	5%	190-460 [11]	200	250	300	100%	200	250	300
Gearing	Dual clutch transmission (DCT)	up to 10% [5]; 4-5% [8]; 4%[37]	5%	600-900 [8];	750	800	850	75%	562.5	600	637.5
Hybrid	Start-stop system	max. 6% [4]; ca. 3.5% [7];	3%	140-240 [12];	200	250	300	100%	200	250	300
Hybrid	Mild hybrid	15-18% [4]; > 20% [10]	10-15%	1200-2000 [8]; 1000 [23]	800	1000	1200	75%	600	750	900
Hybrid	Full hybrid	30% [1]	max. 30%	2800-4200 [8]	2500	3200	4000	75%	1875	2400	3000
Other	Low-rolling-friction tyres	max. 5% [2]; 3-4%[28]; 4%[44]	4%	0 [44]	0	0	0	100%	0	0	0
Other	Improved aerodynamics	1-2% with 10% improvement of the cw value [2]; 1-2% [11]	1%	0	0	0	0	100%	0	0	0
Other	Low-friction oil	1% [3]; 1% [11]; 1%[44]	1%	4-6 [11]	6	6	6	100%	6	6	6
Other	Weight reduction of 5%	3-4% [11]; 3-4%[29]	3.5%	110-185 [11]; 27[27]	50	80	110	100%	50	80	110
Combinations	Optimized cooling circuit + latent heat accumulator		4%		465	485	495		465	485	495
Combinations	Latent heat accumulator + low-friction oil		3.5%		426	446	456		426	446	456
Combinations	Optimized cooling circuit + latent heat accumulator + low-friction oil		4.5%		471	491	501		471	491	501
Combinations	Downsizing, pressure-charging + start-stop		22%		380	450	520		380	450	520
Combinations	Downsizing, pressure-charging + mild hybrid		27%		980	1200	1420		780	950	1120
Combinations	Downsizing, pressure-charging + full hybrid		35%		2680	3400	4220		2055	2600	3220

Annex 2: Measures for the reduction of CO2 emissions in diesel vehicles - efficiency potentials and additional manufacturing costs

	Measure	Published data on CO2 reduction potential	Assessed CO2 reduction potential	Published data on costs in €	Costs according to cubic capacity in € (estimated)			Share of attributable costs	Proportionate costs according to cubic capacity in € (estimated)		
					< 1.4 l	*1.4 - 2 l*	*> 2l*		*< 1.4 l*	*1.4 - 2 l*	*> 2l*
Engine	Optimized cooling circuit	3% [8]; 6% [21]; 3%[34]; 4%[38]	3%	45 [8]; 55[38]	45	45	45	100%	45	45	45
	Optimized fuel injection (Piezo injectors)	3% [17]	3%	0	0	0	0	100%	0	0	0
	Reduction of engine friction	9-14 % [2]; 3-5% [8]; 5.4% [26]	5%	40-60 [8]	30	40	50	100%	30	40	50
	Downsizing	2% [18]; 3-5 % [8]; bis 6% [9]	5%	120-350 [8]	150	200	250	100%	150	200	250
	Latent heat accumulator	5.7% [23]	3%	600-650 for customers [15]	420	440	450	100%	420	440	450
	Cylinder deactivation	4% [12]	1% (< 1.4 l) 2.5% (1.4 - 2l) 5% (>2 l)	210-350 [12]; 59 - 133 [11]	130	150	170	100%	130	150	170
Gearin	Optimized gearing	1-1.5 % [8]; bis 4% [13]; 3%[44]	4%	0 [44]	0	0	0	100%	0	0	0
	Continuous variable transmission (CVT)	4.4 - 9.2% [2]; 4-8%[1, p.68]	5%	190-460 [11]	200	250	300	100%	200	250	300
	Dual clutch transmission (DCT)	p to 10% [5]; 5% [8]; 4% [9]; 4%[3	5%	600-900 [8];	600	700	900	75%	450	525	675
Hybrid	Start-stop system	5% [9]; 5% [16]	5%	140-240 [12]; 100+300 Batt. [14]	200	250	300	100%	200	250	300
	Mild hybrid	6% [20];10% [19]	10-15%	1200-2000 [8]; 1000 [23]	800	1000	1200	75%	600	750	900
	Full hybrid	35% [1]	max. 30%		2500	3200	4000	75%	1875	2400	3000
Other	Low-rolling-friction tyres	max. 5% [2]; 3-4%[28]; 4%[44]	4%	0 [44]	0	0	0	100%	0	0	0
	Improved aerodynamics	1-2% with 10% improvement in the cw value [2]; 1-2% [11]	1%	0	0	0	0	100%	0	0	0
	Low-friction oil	1% [3]; 1% [11]; 1% [44]	1%	4-6 [11]	6	6	6	100%	6	6	6
	Weight reduction of 5%	3-4% [11]; 3-4%[29]	3.5%	110-185 [11]; 27[27]	50	80	110	100%	50	80	110
Combinations	Optimized cooling circuit + latent heat accumulator		4%		465	485	495		465	485	495
	Latent heat accumulator + low-friction oil		3.5%		426	446	456		426	446	456
	Optimized cooling circuit + latent heat accumulator + low-friction oil		4.5%		471	491	501		471	491	501
	Downsizing, pressure-charging + start-stop		7%		350	450	550		350	450	550
	Downsizing, pressure-charging + mild hybrid		17%		950	1200	1450		750	950	1150
	Downsizing, pressure-charging + full hybrid		32%		2650	3400	4250		2025	2600	3250

Otto

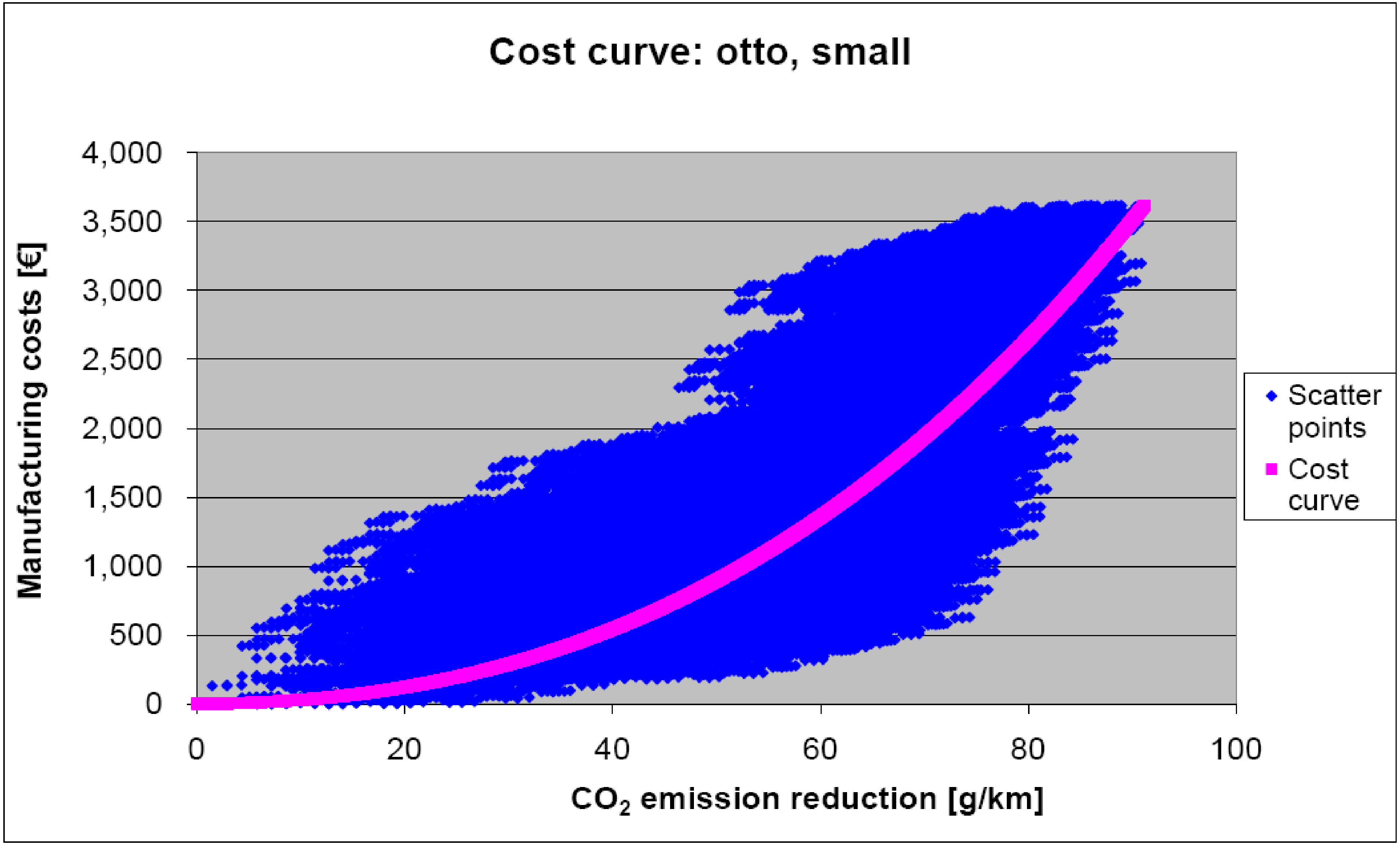
		Engine									Gearing			Hybrid			Other			
		Optimized cooling circuit	Direct fuel injection	Reduction of engine friction	Downsizing	Latent heat accumulator	Cylinder deactivatrion	Exhaust-gas recirculation	Variable compression ratio	Variable valve timing	Optimized gearing	Cont. var. transm. (CVT)	Dual clutch transmiss. (DCT)	Start-stop system	Mild hybrid	Full hybrid	Low-rolling-friction tyres	Improved aerodynamics	Low-friction oil	Weight reduction of 5%
Engine	Optimized cooling circuit		+	+	+	!	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	Direct fuel injection			+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	Reduction of engine friction				+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	Downsizing					+	+	+	+	+	+	+	+	!	!	!	+	+	+	+
	Latent heat accumulator						+	+	+	+	+	+	+	+	+	+	+	+	!	+
	Cylinder deactivation							+	+	+	+	+	+	+	+	+	+	+	+	+
	Exhaust-gas recirculation (EGR)								+	+	+	+	+	+	+	+	+	+	+	+
	Variable compression ratio (VCR)									+	+	+	+	+	+	+	+	+	+	+
	Variable valve timing										+	+	+	+	+	+	+	+	+	+
Gearing	Optimized gearing											-	+	+	+	+	+	+	+	+
	Continuous variable transmission (CVT)												-	+	+	+	+	+	+	+
	Dual clutch transmission (DCT)													+	+	+	+	+	+	+
Hybrid	Start-stop system														-	-	+	+	+	+
	Mild hybrid															-	+	+	+	+
	Full hybrid																+	+	+	+
Other	Low-rolling-friction tyres																	+	+	+
	Improved aerodynamics																		+	+
	Low-friction oil																			+
	Weight reduction of 5%																			

Annex 3: Possible efficiency-increasing technologies for vehicles with **otto engines**. Linking of potentials through creation of packages of measures. Key: "**+**" : measures do not exploit the same potential (no overlapping; combined by multiplication); "**!**": measures exploit the same potential (overlapping; separate estimate of potential); "**-**": measures are mutually exclusive (packages are not considered in further calculations).

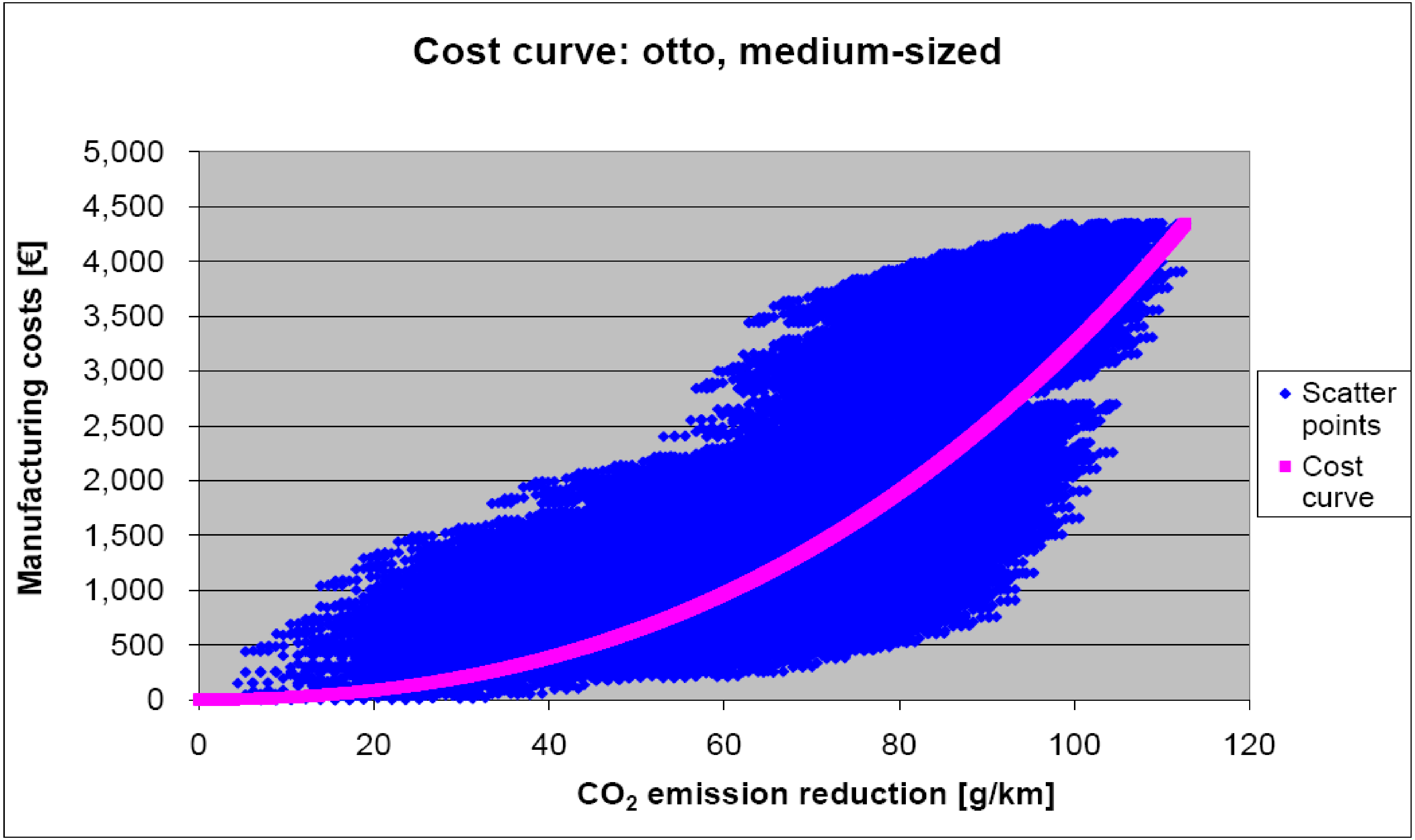
Diesel

		Engine						Gearing			Hybrid			Other			
		Optimized cooling circuit	Optim. fuel injection (piezo)	Reduction of engine friction	Downsizing	Latent heat accumulator	Cylinder deactivation	Optimized gearing	Cont. variable transm. (CVT)	Dual clutch transm. (DCT)	Start-stop system	Mild hybrid	Full hybrid	Low-rolling-friction tyres	Improved aerodynamics	Low-friction oil	Weight reduction of 5%
Engine	Optimized cooling circuit		+	+	+	!	+	+	+	+	+	+	+	+	+	+	+
	Optimized fuel injection (piezo injectors)			+	+	+	+	+	+	+	+	+	+	+	+	+	+
	Reduction of engine friction				+	+	+	+	+	+	+	+	+	+	+	+	+
	Downsizing					+	+	+	+	+	!	!	!	+	+	+	+
	Latent heat accumulator						+	+	+	+	+	+	+	+	+	!	+
	Cylinder deactivation							+	+	+	+	+	+	+	+	+	+
Gearing	Optimized gearing								-	+	+	+	+	+	+	+	+
	Continuous variable transmission (CVT)									-	+	+	+	+	+	+	+
	Dual clutch transmission (DCT)										+	+	+	+	+	+	+
Hybrid	Start-stop system											-	-	+	+	+	+
	Mild hybrid												-	+	+	+	+
	Full hybrid													+	+	+	+
Other	Low-rolling-friction tyres														+	+	+
	Improved aerodynamics															+	+
	Low-friction oil																+
	Weight reduction of 5%																

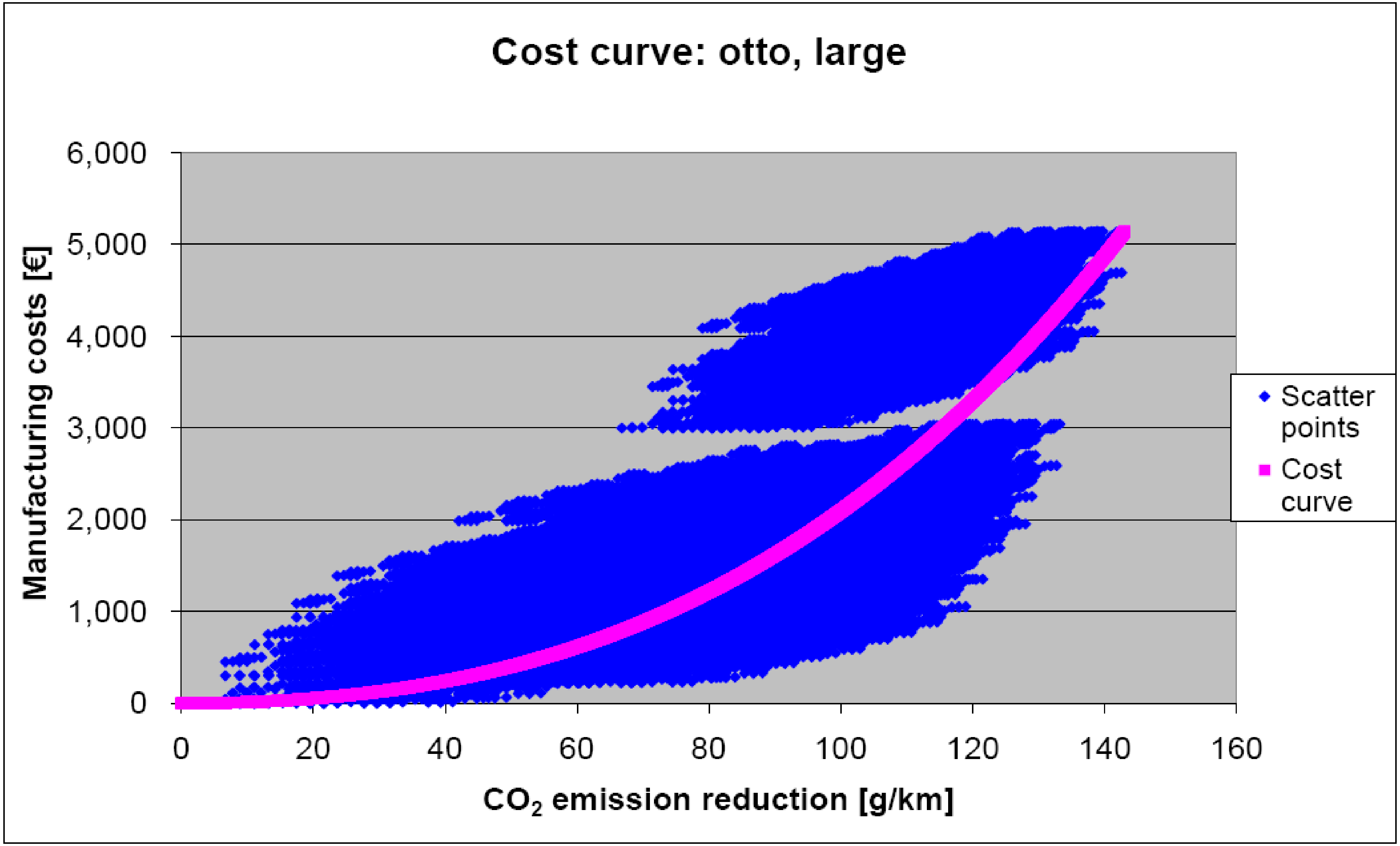
Annex 4: Possible efficiency-increasing technologies for vehicles with **diesel engines**. Linking of potentials through creation of packages of measures. Key: "**+":** measures do not exploit the same potential (no overlapping, combined by multiplication); "**!**": measures exploit the same potential (overlapping; separate estimate of potential); "**-**": measures are mutually exclusive (packages are not considered in further calculations).



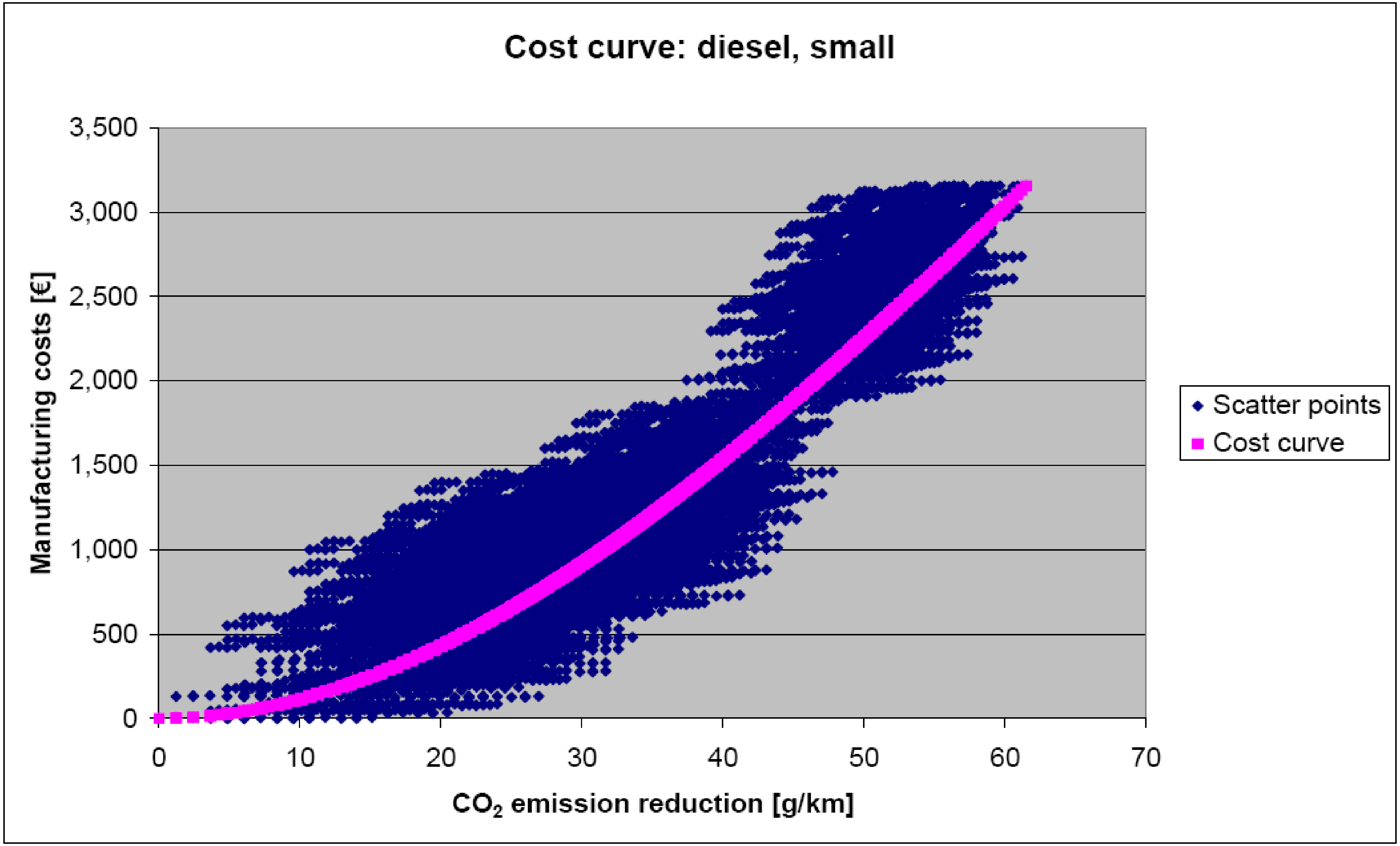
Annex 5: Potentials and manufacturing costs of all packages of measures, resulting additional cost curve. Cars with **small otto engines (capacity < 1.4 litres)**



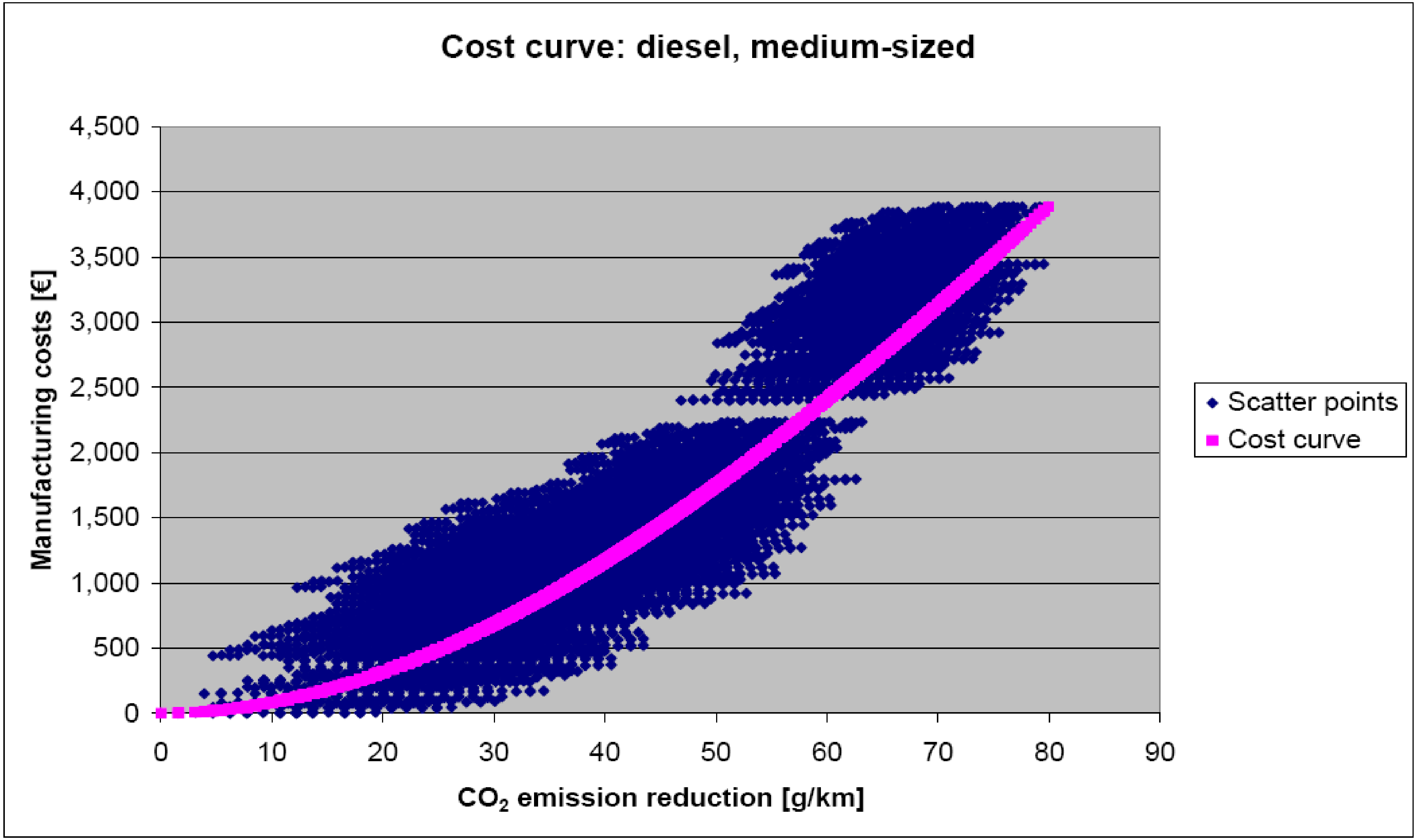
Annex 6: Potentials and manufacturing costs of all packages of measures, resulting additional cost curve. Cars with **medium-sized otto engines (capacity 1.4 - 2.0 litres)**



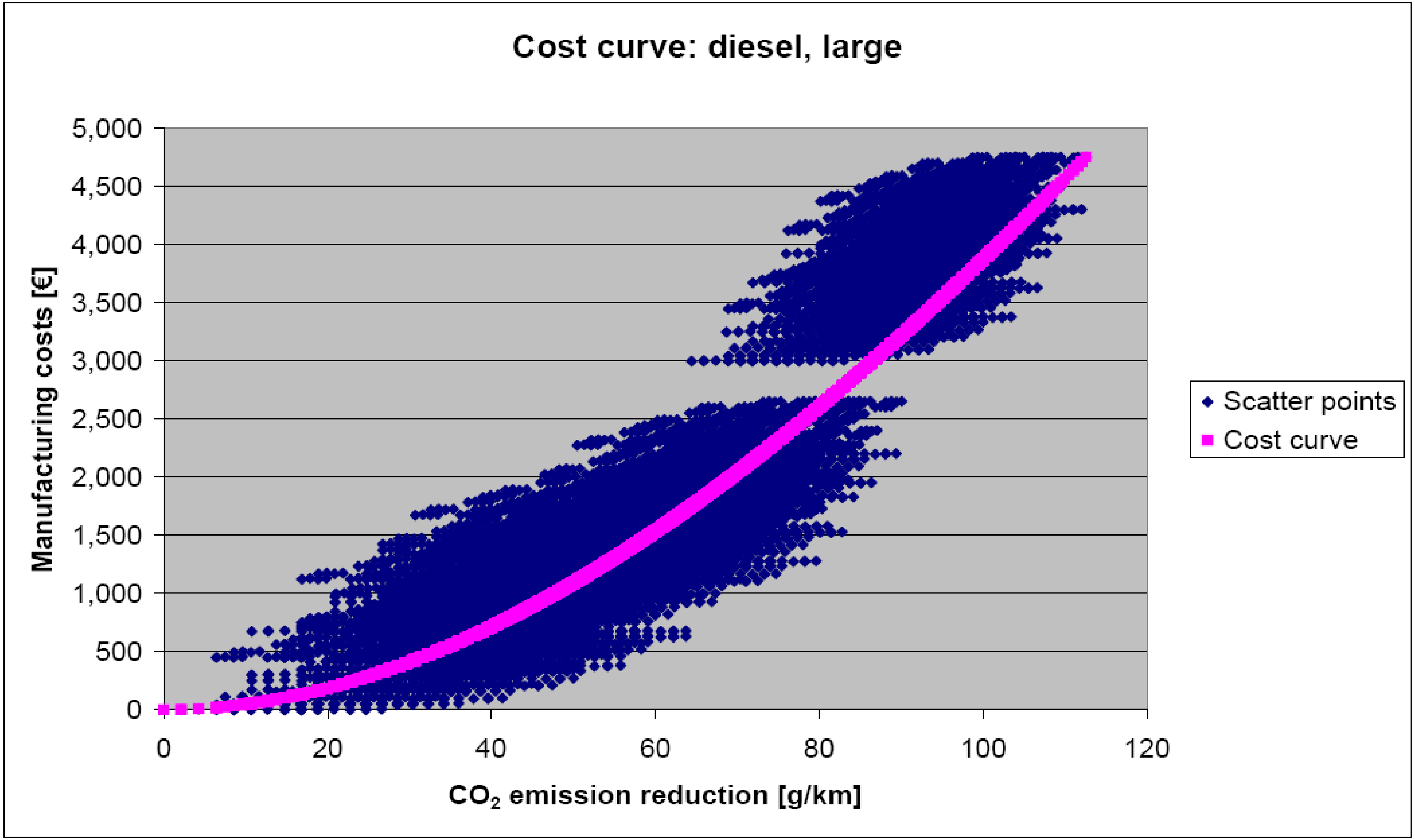
Annex 7: Potentials and manufacturing costs of all packages of measures, resulting additional cost curve. Cars with **large otto engines (capacity >2.0 litres)**



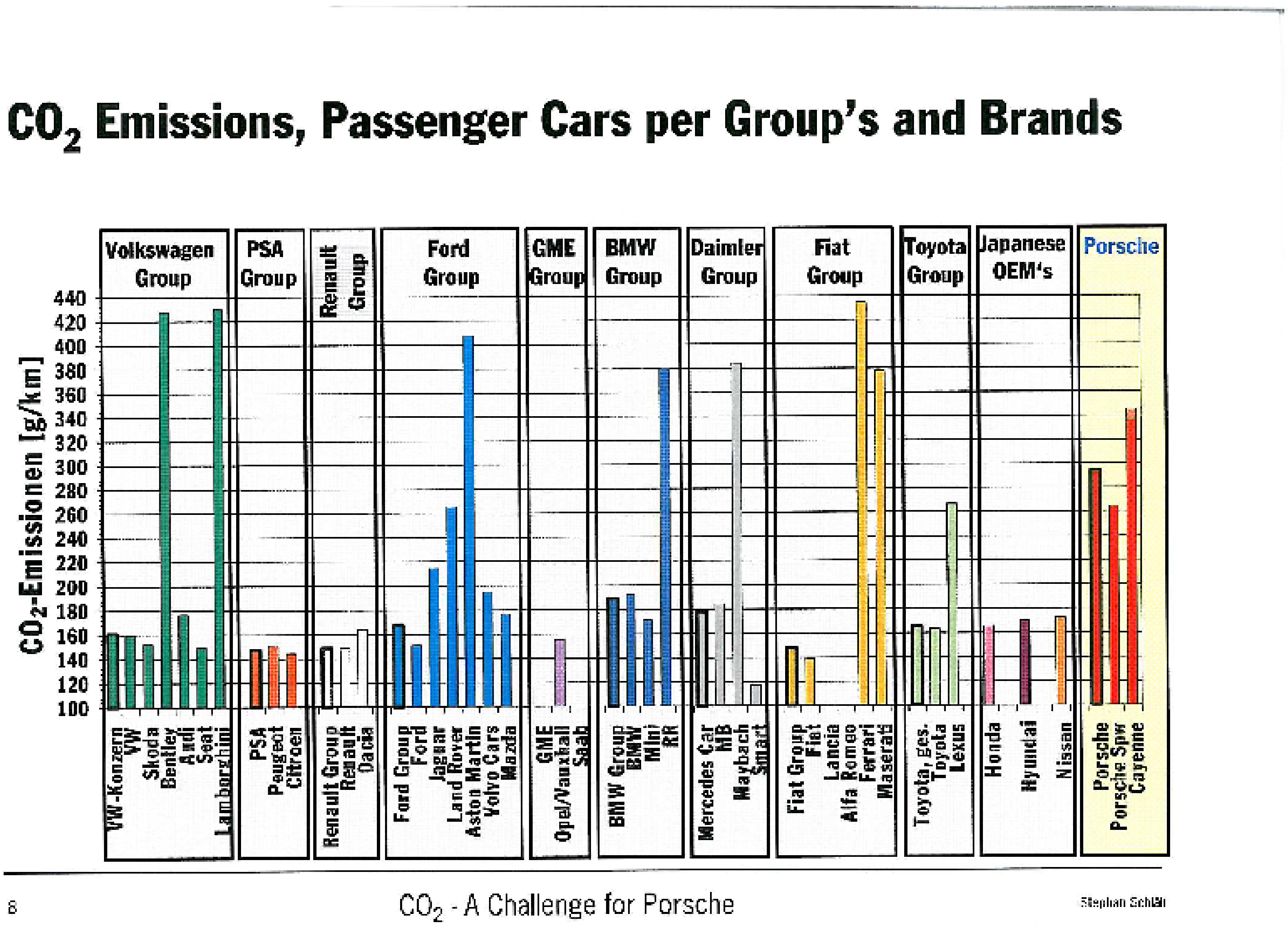
Annex 8: Potentials and manufacturing costs of all packages of measures, resulting additional cost curve. Cars with **small diesel engines (capacity <1.4 litres)**



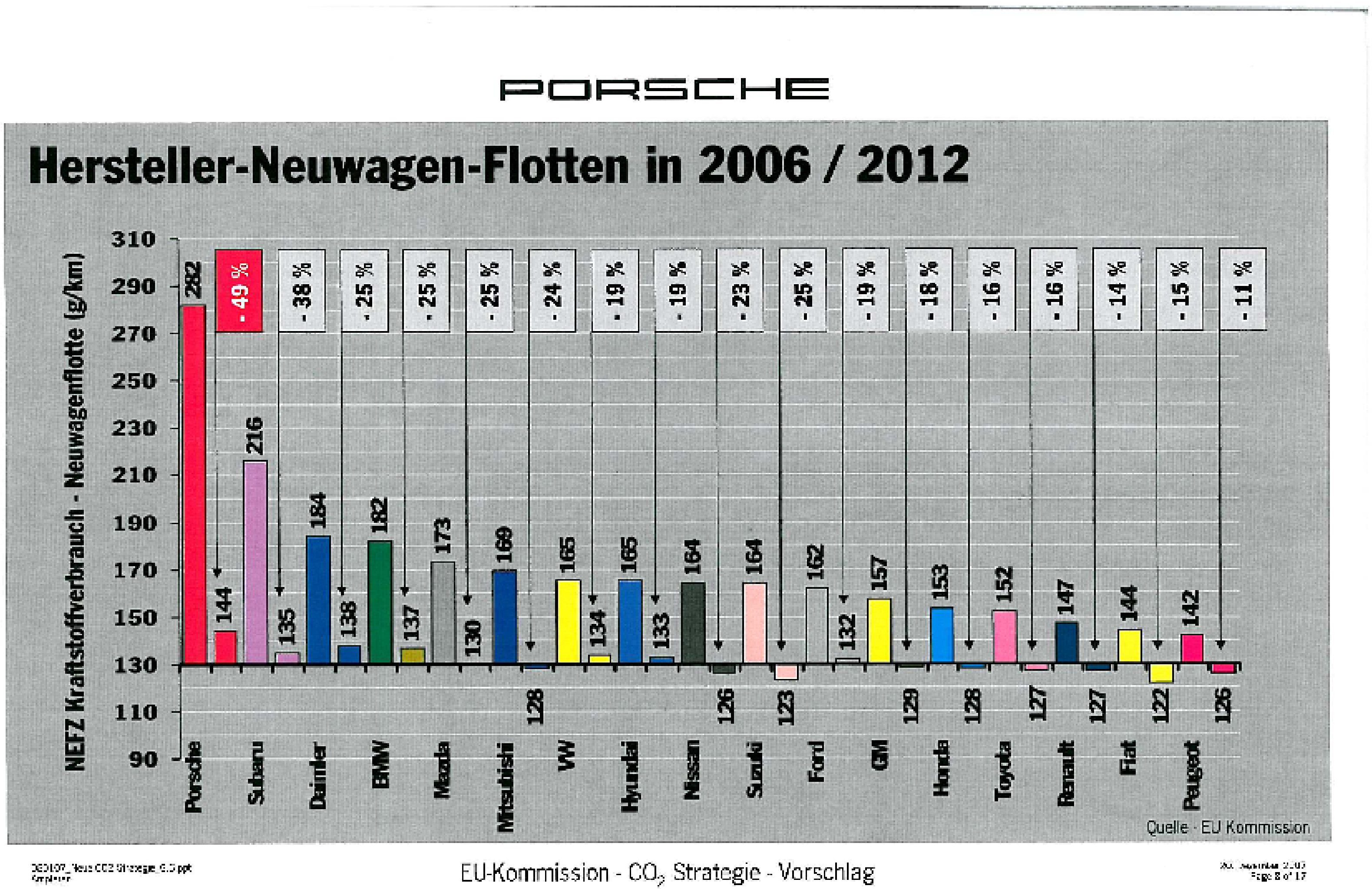
Annex 9: Potentials and manufacturing costs of all packages of measures, resulting additional cost curve. Cars with **med.-sized diesel engines (capacity 1.4-2.0 litres)**



Annex 10: Potentials and manufacturing costs of all packages of measures, resulting additional cost curve. Cars with **large diesel engines (capacity > 2.0 litres)**



Annex 11: Average specific CO_2 emissions according to manufacturer.



Annex 12: **New Vehicle Fleets in 2006 / 2012**

Specific CO_2 emissions per manufacturer 2006, required emission reductions up to 2012 in %.
y-axis: NEDC CO_2 emission of the new vehicle fleet (g/km).