Support for the revision of the CO_2 Regulation for light duty vehicles

Service request #1 and #3
for Framework Contract on Vehicle Emissions - No ENV.C.3./FRA/2009/0043
Richard Smokers, Maarten Verbeek, Jordy Spreen

ICCT-workshop, Brussels, April 27, 2012

Framework Contract on Vehicle Emissions ENV.C.3./FRA/2009/0043 Service request #1

Objectives of projects

- Assist European Commission with carrying out review clauses in
  - Regulation (EC) No 443/2009 wrt CO_2 emissions from passenger cars
  - Regulation (EU) No 510/2011 wrt CO_2 emissions from LCVs
    - review costs curves for 2020
    - assess costs for meeting the 2020 targets
      - 95 g/km for passenger cars
      - 147 g/km for vans
    - defining the modalities for implementing the 2020 targets

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Construction of cost curves for passenger cars in 2020

- Potential and costs of CO_2 reducing technologies
- Construction of cost curves for 2020

Cost and potential of CO_2 reduction options for the longer term – passenger cars

- Quantification of costs and reduction potential of technical options to reduce CO_2 emissions in passenger cars on petrol and diesel
  - Collection of data from:
    - **Recent literature, in-house expertise**
    - **Automotive manufacturers, suppliers and trade associations**
      - **Detailed questionnaire + consultations**
  - Consolidation of data set
- Electric and plug-in vehicles modelled separately
  - In collaboration with recent study by CE Delft / ICF / Ecologic

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Reduction technologies for petrol cars in 2020

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
	Mild downsizing (15% cylinder content reduction)	4	200	5	250	6	300
	Medium downsizing (30% cylinder content reduction)	7	400	8	435	9	510
	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
	Low friction design and materials	2	35	2	35	2	35
Transmission options	Optimising gearboxratios / 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	2	128	2	160	2	192
	Medium weight reduction	6	320	6	400	6	480
	Strong weight reduction	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

- Relative to 2002 reference vehicles

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Reduction technologies for diesel cars in 2020

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	400	7	450	7	500
	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 gearboxratios / 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 weight reduction	1.5	128	1.5	160	1.5	192
	Medium weight reduction	5	320	5	400	5	480
	Strong weight reduction	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

- Relative to 2002 reference vehicles

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Construction of cost curves for 2020

- Combine compatible options into packages:
  - $$E_{package} = E_{baseline} \times \prod_{i=1}^{n} (1 - \delta_i)$$
    - Subtract "safety margin" to avoid overestimation of combined reduction potential of options targeting the same energy loss
  - $$C_{package} = \sum_{i=1}^{n} C_i$$
- Safety margin assumed to increase linearly with reduction potential:
  - maximum value
    - 15% for petrol cars
    - 5% for diesel cars
  - based on available simulations from Ricardo + extrapolation of existing advanced vehicles + expert judgement

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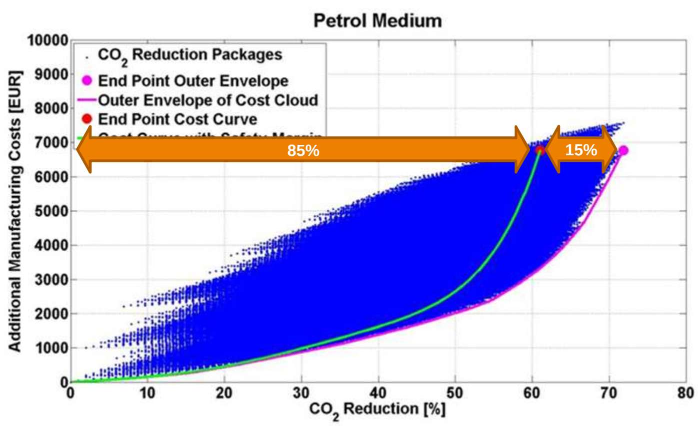
Definition of cost curves for 2020 - petrol



- Additional manufacturer costs as function of reduction percentage
- 6th to 9th order polynomials necessary to describe non-linearity of cost curve

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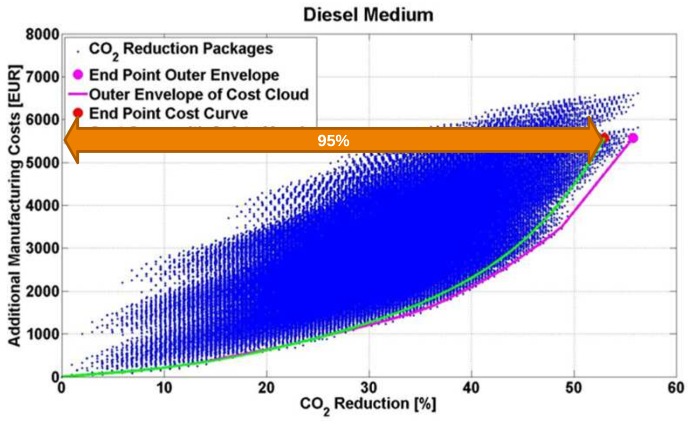
Definition of cost curves for 2020 - diesel



- Additional manufacturer costs as function of reduction percentage
- 5[th] to 6[th] order polynomials necessary to describe non-linearity of cost curve

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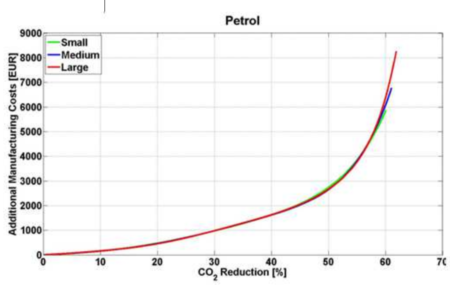
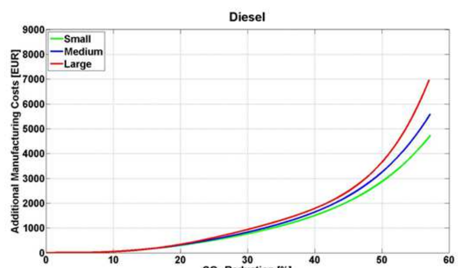
Cost curves for 2020 - overview





$$y = \sum_{i=1}^{9} a_i \cdot x^i$$

	a9	a8	a7	a6	a5	a4	a3	a2	a1	End %	End €
p,S				8.134E+05	-9.302E+05	3.859E+05	-6.922E+04	1.319E+04	6.453E+02	60.1%	5870
p,M				1.207E+06	-1.386E+06	5.381E+05	-7.426E+04	9.017E+03	9.985E+02	61.1%	6775
p,L	9.431E+07	-2.233E+08	2.180E+08	-1.121E+08	3.226E+07	-5.187E+06	4.602E+05	-1.672E+04	1.574E+03	61.9%	8265
d,S					2.193E+05	-1.757E+05	5.709E+04	9.584E+01	1.657E+03	53.0%	4711
d,M					4.147E+05	-3.757E+05	1.308E+05	-9.708E+03	2.151E+03	53.0%	5571
d,L				-1.549E+05	1.069E+06	-8.804E+05	2.701E+05	-2.236E+04	2.585E+03	52.8%	6946

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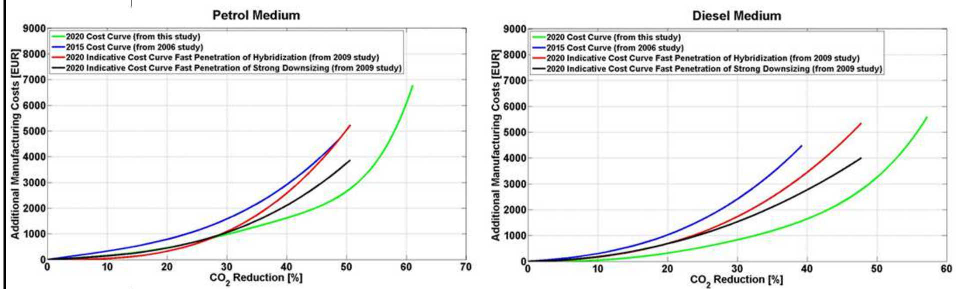
Comparison with previous studies



- 2015 cost curves from TNO/IEEP/LAT 2006
  - also used in IEEP/CE Delft/TNO 2007
- indicative 2020 cost curves from AEA/CE Delft/TNO/Öko 2009

- For petrol lower costs than 2009 study for high reduction levels
- For diesel lower costs than 2009 study over entire range

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Scenario variants

- In the course of the study two issues arose that justified critical evaluation of the cost curves as presented before:
  - Observed **progress** in CO_2 reduction in European new passenger car fleet **in the 2002-2009 period**
  - Technical **data** becoming available **from EPA studies** in support of the US legislation on CO_2 emissions from light duty vehicles
- These data seem to suggest that the costs of reducing CO_2 emissions in passenger cars could be lower than estimated in this study.

- As detailed assessments were not possible within scope of study and given limited availability of data, it was decided to deal with these issues in the form of scenarios
  - **a)** Alternative accounting for progress observed in 2002-2009 period
  - **b)** Alternative cost curves based on a modified technology table
  - **c)** Combination of a) and b)

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Scenario a) Alternative accounting for progress observed in the 2002-2009 period

- Variant including additional reduction step based on assumption that part of the reductions achieved in the 2002-2009 period are to be attributed to other causes than application of technologies as included in the technology tables:
  - technical options not included in cost curves
  - effects of optimising the powertrain calibration by improving trade-offs against other parameters
  - possible utilization of flexibilities in the test procedure
- Based on detailed comparison of base models in 2002 and 2010 and of average reductions per segment the following additional reduction potentials were chosen for the scenario analysis:
  - petrol: 10%
  - diesel: 9%

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Scenario b) Alternative cost curves based on a modified technology table

- Available results from EPA studies in support of US CO_2 target for passenger cars provide strong indications that costs for meeting the EU 95 g/km target for 2020 could be lower than the estimates based on the cost curves from this study.
- Due to large differences in technology definitions, baseline vehicles and drive cycles, however, the direct use of EPA data for the European assessment was considered not appropriate.
- To test the possible impact of the most striking differences between US and EU data a selection of data derived from the EPA studies, specifically for **full hybrids and the various levels of weight reduction**, has been used to construct a modified technology table. Alternative cost curves have been constructed on the basis of this table.
- More in-depth assessment needed as soon as complete EPA data are available.

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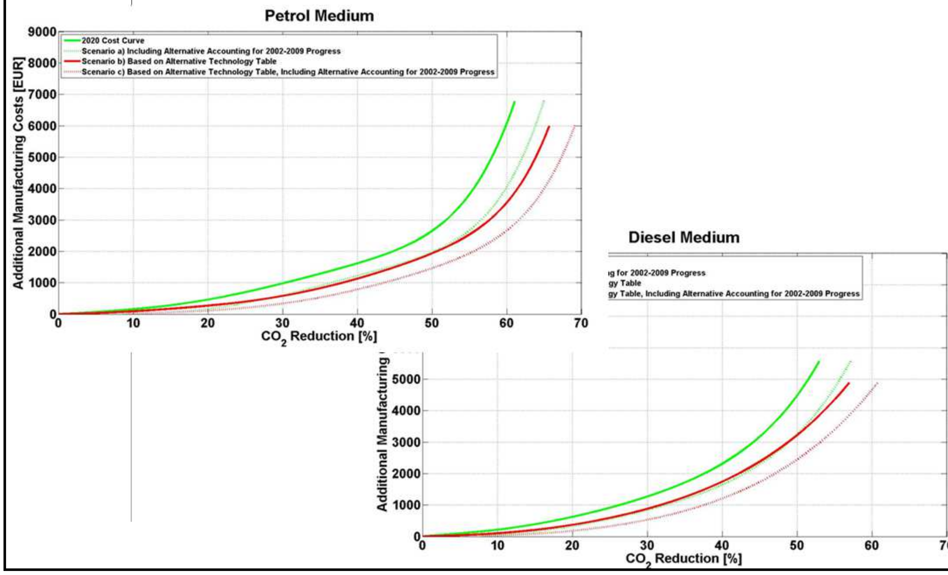
Scenario a), b) and c): Comparison of cost curves



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Costs for meeting the 95 g/km target in 2020

- a) Alternative accounting for progress observed in 2002-2009 period
- b) Alternative cost curves based on a modified technology table with data from EPA studies
- c) Combination of a) and b)

		Additional manufacturer cost relative to 130 g/km target [€]			
Utility parameter	Slope	based on 2020 cost curves	based on "Scenario a)"	based on "Scenario b)"	based on "Scenario c)"
Mass	60%	1748	1159	1280	765
	100%	1750	1158	1277	760
Footprint	60%	1754	1164	1290	775
	100%	1760	1168	1294	772

- Scenario a) and b) lead to ~ 500 - 600 € lower costs
- Scenario c) leads to ~ 1000 € lower costs
- Results for the scenarios a) to c) would change the conclusion from the assessment of impacts of introducing EVs by 2020.

Construction of cost curves for LCVs in 2020

- Potential and costs of CO_2 reducing technologies
- Construction of cost curves for 2020

Cost and potential of CO_2 reduction options for the longer term - LCVs

- Quantification of costs and reduction potential of technical options to reduce CO_2 emissions in diesel LCVs (app. 96% of 2010 LCV sales)
  - Collection of data from:
    - Service Request #1 on passenger cars
      - Recent literature, in-house expertise
      - Automotive manufacturers, suppliers and trade associations
      - Detailed questionnaire + consultations
    - Recent literature, **in-house expertise**
  - Consolidation of data set
    - Followed by industry consultation (little response received)
- Electric and plug-in vehicles modelled separately
  - In collaboration with recent study by CE Delft / ICF / Ecologic

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Service request #3

Reduction technologies for diesel LCVs in 2020

	Technology options for diesel LCVs	Small LCV		Medium LCV		Large LCV	
	Description	CO2 reduction potential [%]	Cost [EUR]	CO2 reduction potential [%]	Cost [EUR]	CO2 reduction potential [%]	Cost [EUR]
base engine	Combustion improvements	3,0	90	3,0	90	3,0	90
	Mild downsizing (15% cylinder content reduction)	4,0	50	4,0	50	3,0	50
	Medium downsizing (30% cylinder content reduction)	7,0	290	7,0	290	6,0	170
	Variable valve actuation	N/A	N/A	1,0	50	1,0	50
transmission	Optimising Gearbox ratios/downspeeding	1,0	0	1,0	0	1,0	0
	Improved M/T Transmission	0,5	0	0,5	0	0,5	0
	Downspeeding via slip controlled clutch and DMF deleted	3,0	120	3,0	120	3,0	120
	Automated manual transmission	6,0	300	6,0	300	6,0	500
	Dual (dry) clutch transmission	4,0	900	5,0	1100	N/A	N/A
Hybridisation/EV	Start stop	4,0	175	4,0	200	5,0	225
	Micro-hybrid (including regenerative braking)	6,0	350	7,0	375	8,0	400
	Mild hybrid (Torque boost for downsizing)	11,0	1400	11,0	1500	11,0	1600
	Full Hybrid (EV only mode)	25,0	2560	25,0	3060	25,0	4250
	Series Range extender with 40-50kW engine	46,0	10000	46,0	11000	46,0	11600
	Electric vehicle	100,0	30000	100,0	32000	100,0	33000
Driving resistance reduction	BIW lightweighting - mild (~10% reduction)	1,5	150	1,0	175	1,0	325
	BIW lightweighting - medium (~25% reduction)	4,0	750	2,5	875	2,5	1625
	BIW lightweighting - strong (~40% reduction)	6,5	2400	4,0	2800	4,0	5200
	Lightweight components other than BIW	1,5	150	1,0	175	1,0	325
	Aerodynamics improvement - minor	1,5	50	2,0	100	1,5	100
	Aerodynamics improvement - major	3,0	150	3,0	200	3,0	250
	Low rolling resistance tyres	4,0	150	5,0	200	5,0	300
	Reduced driveline friction (mild reduction)	1,0	80	1,0	80	1,0	90
	Reduced driveline friction (high reduction)	3,0	210	3,0	220	3,0	250
Other	Thermo-electric generation	N/A	N/A	2,5	300	4,0	400
	Secondary heat recovery cycle	N/A	N/A	4,0	400	5,0	600
	Auxiliary (thermal) systems improvement	2,5	70	2,8	80	3,2	80
	Auxiliary systems improvement (lubrication, vacuum, FIE)	2,8	85	3,5	100	3,7	115
	Other Thermal management	1,5	80	2,2	120	2,5	170
	Electrical assisted steering (EPS, EPHS)	N/A	N/A	N/A	N/A	3,0	150

- Relative to 2010 baseline vehicles

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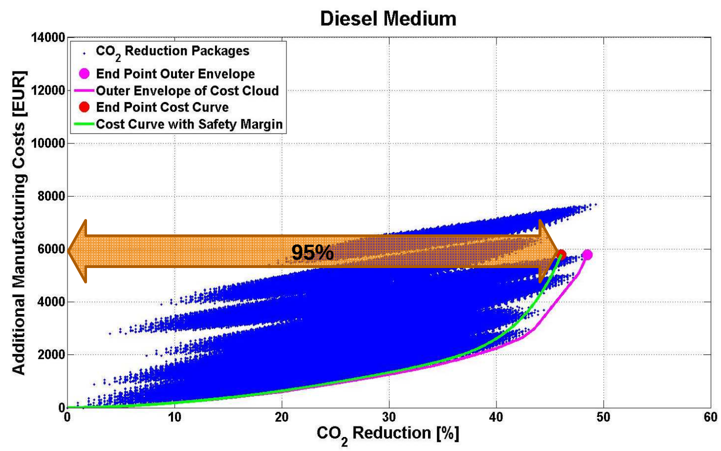
Definition of cost curves for 2020 - vans



- Additional manufacturer costs as function of reduction percentage
- 5th to 8th order polynomials necessary to describe non-linearity of cost curve

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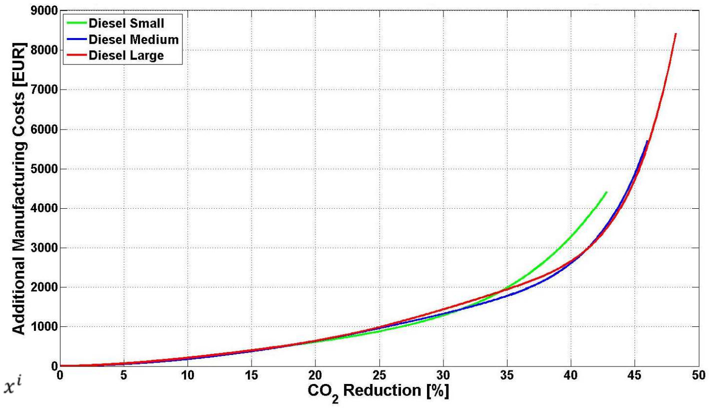
Cost curves for 2020 – overview - vans



$$y = \sum_{i=1}^{8} a_i \cdot x^i$$

	a_8	a_7	a_6	a_5	a_4	a_3	a_2	a_1	End %	End €
Diesel Small				8.07E+05	-3.30E+05	1.78E+04	1.48E+04	6.87E+02	41.9%	4455
Diesel Medium	2.89E+07	-2.53E+07	6.93E+06	-8.68E+04	-2.95E+05	5.06E+04	1.13E+04	4.48E+02	46.1%	5780
Diesel Large	6.38E+07	-6.13E+07	1.66E+07	5.03E+05	-6.95E+05	5.16E+04	1.58E+04	5.64E+02	48.2%	8475

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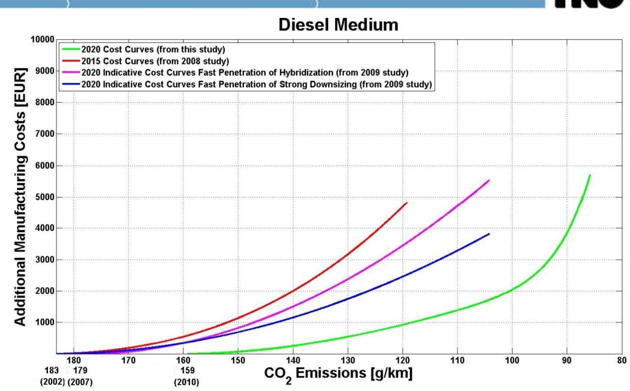

- 2015 cost curves from TNO/CE Delft/AEA 2008
- indicative 2020 cost curves from TNO 2009
- Reasons for lower costs than 2009 study over entire range
  - TNO 2009 based on simplified methodology
  - **New insights w.r.t. costs and potentials**

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Costs for meeting the 147 g/km target for LCVs in 2020

- Cost for meeting 147 g/km (additional manufacturer costs):
  - ~450 €/vehicle relative to maintaining 175 g/km between 2017-2020
    - equivalent to ~2% relative price increase
  - ~540 €/vehicle relative to 2010

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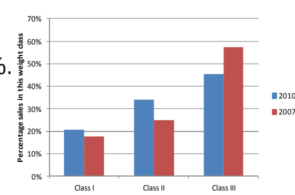
Service request #3

Effort to meet 147 gCO_2/km lower than previously estimated

- Two reasons:
  - **2010 average CO_2 emissions much lower than 2007 average**
    - **2007: 203 g/km**
      - The 2007 database was missing CO_2 data for a large share of – especially larger – vehicles. These were estimated using statistical fits on available data for same model.
    - **2010: 181 g/km**
      - Share of vehicles with CO_2 data now 98%.
      - Lower average CO_2 value partly caused by shift to smaller vans
      - But also by CO_2 emissions for large vans being lower than estimates made in 2007 database.
        - Caused by test procedure.



  - **New cost curves predict lower costs for given level of reduction**

Problems with test procedure for LCVs

- Inertia level in TA test does not increase beyond 2270 kg for vehicles weighing above 2210 kg.
- Dynamic coefficients do not change for vehicles > 2610 kg.
- For large vehicles “cook book values” are lower than real resistance factors (as derived in coast down test)
- For vehicles, other than passenger cars, with reference mass > 1700 kg the dynamometer settings should be multiplied by 1.3. This introduces a step function, increasing the CO_2 emissions when testing LCVs of which the mass in running order is greater than 1700 kg.

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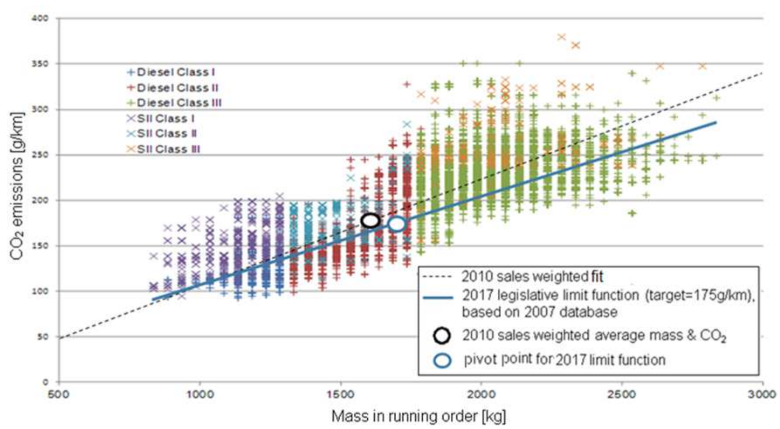
Mass as utility parameter - LCVs



- Levelling off of CO_2 emissions for mass > 1900 kg

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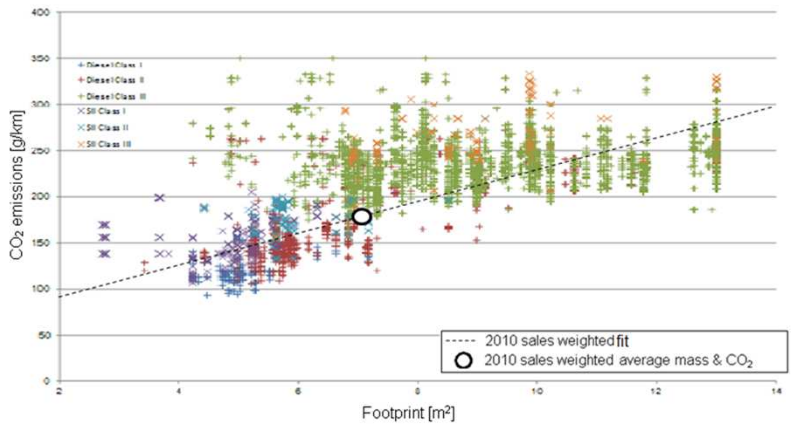
Footprint as utility parameter - LCVs



- Levelling off of CO_2 emissions for footprint > 7 m^2

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Reflections on EU vs. US process in preparing CO_2 regulation

- EU
  - budgets: probably 2.5 M€ in sequence of 10 projects since 2004
  - industry consultation part of assignment
    - to create buy-in from industry
  - limited amount of cost data available in public domain
    - assumptions under available data not well documented

- US activities for CO_2 regulation
  - budgets: 15 M$ budget for support studies, 4 M$ on assessment of technology costs and potentials alone, 50 person staff
  - crisis in Detroit facilitated availability of expert staff and willingness of consultants to participate and share expert knowledge

Challenges for next round of CO_2 regulation

- The tighter the target the more important it is to get the numbers right
  - Post 2020 targets should be based on more detailed technical assessments
  - Current EPA / ICCT are valuable input
  - But progress in technology performance and costs needs to be monitored and included into cost curves
  - Can EPA / ICCT approach be reproduced 5 years from now?

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Challenges for next round of CO_2 regulation

- But detailed cost assessment may not be biggest challenge
  - Test procedure needs to be updated to meet demands of CO_2 regulation
    - NEDC => WLTP
    - reducing flexibilities in the test procedures
      - road load determination, test conditions, vehicle conditioning
  - Alternative metric needed to cater for new powertrains and energy carriers

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