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The potential for mass reduction of passenger cars and light commercial vehicles in relation to future CO2 regulatory requirements: Appendices

Report for the European Commission – DG Climate Action

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Appendices

Appendix 1 - Data sources used for assessing trends in the weights of passenger cars and light commercial vehicles

Sources of available data for car and LCV mass changes

We have collected and analysed several sources of data for vehicle sales and kerb masses in order to have a complete picture of recent trends in the sales-weighted average mass of passenger cars and light commercial vehicles. Some datasets were found to contain an insufficient level of detail for the analyses required and were therefore discarded. Key data sources used included the European Environment Agency's annual car CO_2 monitoring databases, data published by ACEA and vehicle data from previous studies carried out for the European Commission.

Passenger car data sources

European Environment Agency (EEA): Monitoring CO_2 emissions from new passenger cars in the EU

Coverage:

- Years: 2010, 2011, 2012, 2013
- Geographical areas: EU 27
- Details: Several parameters for each model sold, such as country of sale, mass, wheelbase, track width, fuel type, engine size.

Regulation 443/2009 on CO_2 emissions from new passenger cars requires Member States to provide a very detailed list of new car registrations as part of the annual monitoring and reporting process. Once member countries have submitted their entries (generally by June each year), the EC passes the database to manufacturers to check sales figures reported for their models. The validated database is usually published later during the year.

Since the first year it was released (2010), there have been a few changes in the information required. A particular problem with this dataset is that not every country has reported data in the same way (for example, there have been differing approaches to grouping of data, model names and levels of completeness). This resulted in the need to conduct some complex data cleaning before being able to confidently analyse and compare this data.

Database from previous DG CLIMA study: Effect of regulations and standards on vehicle prices (AEA, 2011)

Coverage:

- Years: 1995-2010
- Geographical areas: Germany, Great Britain, Italy, Slovakia, Slovenia and Sweden.
- Details: technical specification of 106 bestselling models for the countries above.

This database was purchased by Ricardo-AEA to support a study carried out for DG CLIMA in 2011.[1] The dataset provides detailed technical parameters for the top ten best-selling passenger cars in seven European countries from 1995 to 2010, plus 20 other popular vehicles from across the various automotive segment classification categories, for a total of over 100 models and more than 230,000 entries. Selecting various parameters, it has been possible to compare the same information reported for the EU regulation, although this dataset does not include sales data. For this reason, although many analyses could be extended back to 1995, the two datasets have generally been kept separate.

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[1] Assessment with respect to long term CO_2 Emission targets for passenger cars and vans, http://ec.europa.eu/clima/policies/transport/vehicles/docs/2009_CO2_car_vans_en.pdf

Data published by ACEA

Coverage:

- Years: 2003-2012
- Geographical areas: EU 27+
- Details: monthly sales data, broken down at member state and manufacturer level.

ACEA, the European Automobile Manufacturers' Association, collects information on vehicle sales at both the Member State and manufacturer level. While its datasets do not provide the details necessary for this study, it has been used to assess the reliability of other sources analysed and how much information has been lost, in terms of market coverage, due to data cleansing operations carried out on the EU dataset.

Van data sources

Data sources for analysis of mass change trends in vans are much less readily available. The primary source - European monitoring data relating to Regulation 510/2011 is only available from the year 2012. However this has been compared to a dataset from 2009 and it has been possible to draw some conclusions based on a comparison of the two datasets.

EEA Monitoring CO_2 emissions from new light commercial vehicles in the EU

Coverage:

- Years: 2012, 2013
- Geographical areas: EU 27
- Details: Several parameters for each model sold, such as country of sale, mass, wheelbase, track width, fuel type, engine size.

Analogous to Regulation 443/2009 for passenger cars, Regulation 510/2011 on CO_2 emissions from light commercial vehicles requires Member States to report their annual LCV registration data for monitoring purposes, starting in 2013 for vehicles sold in 2012. The first such database was published in June 2013.

Data from a previous European Commission study: Support for the revision of regulation on CO_2 emissions from light commercial vehicles (2012)

Coverage:

- Years: 2009
- Geographical areas: France, Germany, Italy, Spain, Poland, Romania, United Kingdom
- Details: Several parameters for each model sold, including country of sale, mass, wheelbase, track width, fuel type, engine size.

Ricardo-AEA has previously analysed registrations of LCVs at EU level using a dataset purchased for the above named previous study for the Commission. Using the same methodology used for passenger cars, the database was organised to be comparable with data from the EEA for 2012.

Data published by ACEA

ACEA provides sales data at Member State and manufacturer level for several categories of vehicles, including LCVs. This has been used for comparison purposes to estimate the loss of market coverage in our analysis due to data cleansing activities carried out on the EEA dataset, and to assess the coverage of other data sources available.

Data preparation and cleaning

In order to ensure the accuracy of the various analyses conducted on the datasets used, it was necessary to prepare (clean) the data to filter out erroneous data, ensure reliability and in some cases reduce the complexity of the datasets. In particular the EEA monitoring datasets required rather complex cleaning steps as they failed many quality checks. For example, it was necessary to check that values entered for various fields were reliable, as numerous entries appeared to have unrealistic values and, if used, these could have noticeable effects on overall averages.

For this analysis it was also particularly important to decide on a clear and consistent system of vehicle market segmentation. This needed to provide greater granularity than the more common high level segmentations of the market in order to allow analysis of the impact of new market sub-segments such as multi-purpose vehicles (MPVs) and cross-over vehicles to be assessed.

Preparation and cleaning of the data on passenger cars

The data the EEA releases to the public has several issues. These include:

- **Incomplete entries:** data line entries do not specify which model they refer to or are missing information for one or more parameters;
- **Erroneous values:** e.g. vehicles with mass values below 300 kg or a mass difference of over 50% with respect to specific model average;
- **Inconsistent details:** Data from different Member States were found to be inconsistent in the level of details entered. For example, while the CO_2 regulations require numbers of registrations to be indicated for each specific model and version, several entries included only the general model name. As a result registrations were found to be grouped for different versions. The database also included over 420,000 entries with only one single sales registration or where the model name had been left blank. These had to be excluded (a loss of 1.1% of registrations for the period considered). Other problems encountered were data entry errors such as: erroneous make-model matches and multiple brands (e.g. Chevrolet GMC Buick Pontiac Holden Daewoo). Fortunately these problems generally related to niche brands and models. However a particular case concerned BMW’s X models. BMW currently sells the following crossover vehicles: X1, X3, X5 and X6. Although they are all cross-overs, they are very different vehicles, with different sizes and features. However in many instances they have been entered only as “X series” without specifying which model and it is thus impossible to separate out these registrations to identify which of these vehicles the datasets relate to.
- **Country-specific names:** several brands and models are country-specific, or are branded specifically for the country: e.g. Opel trades as Vauxhall in UK;
- **Spelling and language:** as the database has been filled in using different alphabets, several entries for the same make or model have been entered differently. These have had to be reallocated (e.g. “┼áKODA” to “Skoda”);
- **Other factors that affect analysis:** during the timeframe under consideration there have been acquisitions and mergers. This resulted in the need to group various brands belonging to the same industrial groups. The dataset lacks a field to clearly indicate model types, so we had to extract it from the version name.

The analyses on this data required a very clear indication of the manufacturer and required that model variants were grouped under a single model for them to be allocated to a specific vehicle segment. Several rounds of cleaning and renaming have been necessary to bring the dataset to a more manageable size and in order to allow detailed analyses. Whenever possible, incomplete entries have been retained, and clearly erroneous values have been corrected using the field “version name” to validate other fields.

The original databases contained over one million line entries and included just over 38 million registrations for the three years combined; ACEA sales data have been used to validate these registration figures at country and manufacturer level. After removing erroneous entries and filtering out minor brands, the final dataset analysed included 500,000 entries, covering 35,600,000 registrations or 94% of ACEA reported sales. Table A1-1 highlights the main cleaning steps and how they have affected dataset size and percentage of sales.

Table A1-1: Car data cleaning steps

Step	Items	Registrations	Cleaning operated
Initial datasets (years 2010,2011 and 2012)	998,282	38,030,154	Joined in a single spread sheet.
Remove erroneous items	576,585	37,571,332	Filtered out items with only a single registration and items for which both manufacturer and model were not provided.
Allocate main manufacturers	567,692	37,354,146	Allocated entries to 33 main manufacturers (in appendix).
Allocate main model	498,466	35,822,846	Entries were allocated to 343 models. The majority of data losses are due to the lack of clear indication of model name.
	Items affected	Registrations affected	
Mass check	4,284	115,236	Items for which vehicle mass was over 30% lower or higher than the model average have been allocated the average mass for that model.
	Number of entries	Usable registrations	
Final dataset	498,466 (50% original dataset)	35,822,846 94% of original dataset	

For each of the selected brands, entries have been allocated to specific models, and each model to a vehicle segment. In total, 343 different models have been identified and allocated to 18 segments as shown in Table A1-2.

It should be noted that there is no definitive way of allocating vehicles to segments. In particular, the size boundaries between A, B, C, and D-segment vehicles are not clear and there are differences of opinion regarding which segment a given vehicle falls into. In reality the range of models available on the market results in a continuous spectrum of vehicles, with models available at almost every length from two and half to five metres.

The long term trend for a given model to get larger each time it is updated further complicates the issue. For example the 2012 Mercedes A-Class is almost 0.7 metres longer than the original 1997 version (a 20% increase), effectively moving it from B-segment to C-segment and making comparisons across time difficult.

Table A1-2: Allocation of models to segments

Segment	Segment name	Description	Example
A	Mini	City and micro-car	Smart ForTwo, Peugeot 107
B	Small / supermini	Conventional segment B	Renault Clio, Fiat Punto, Peugeot 206
BM	Small MPV	Mini MPV	Ford B-Max, Nissan Note
BX	Small crossover	B segment derived crossover	Mini Countryman, Nissan Juke
C	Medium	Conventional segment C	Volkswagen Golf, Ford Focus
CM	Medium MPV	Medium MPV	Peugeot 5008, Ford C max
CX	Medium crossover	C segment derived crossover	Peugeot 3008, Dacia Sandero, Nissan Qashqai
D	Large	Conventional segment D	BMW 3-series, Mercedes C Class
DM	Large MPV	Medium MPV	Ford Galaxy, Kia Carnival
DX	Large crossover	D segment derived crossover	BMW X3, Mazda CX-7
E	Executive	Conventional segment E	Audi A4, BMW 5-series
EM	Executive MPV	Large MPV	Mercedes R Class, Lancia voyager
EX	Executive crossover	E segment derived crossover	BMW X6, Audi Q7
F	Luxury	Luxury Saloon	Audi A8, Mercedes S Class
J	Sport Utility vehicles	Defined for the purpose of this study as an off road capable vehicle with body-on-frame construction.	Land Rover Defender, Toyota Land Cruiser
LAV	Leisure activity vehicles	Smaller, typically van-derived cars, with rear windows, and two or three rows of seats	Citroen Berlingo
S	Sport	Sports cars, from low to high end models	Porsche 911, Mazda MX-5
V	Van-derived	People carrier, adapted from vans	Fiat Ducato, Mercedes Viano

The classification devised reflects the introduction of new typologies of cars beside traditional segments (A, B, C, D, and E) and avoids the influence of non-traditional segments on average mass. In detail:

- **Multi-Purpose Vehicles (MPVs)** are also known as ‘people carriers’ or, in the USA, minivans. There is no clear definition of exactly what constitutes a vehicle being an MPV; however they are typically designed to maximise interior volume. Some designs are bespoke models while others are car derived vehicles. In both cases they can be allocated to a relative conventional class according to their size or to the model they relate to. For example, the Golf Plus is a medium size MPV related to the Volkswagen Golf, it is therefore allocated to the segment CM.
- **Crossovers** are also sometimes known as crossover utility vehicles (CUVs). As with MPVs, there is no clear definition, however they are typically built on a car platform and combine features of a sport utility vehicle (SUV) with features from a passenger car. Due to the difficulty in differentiating between crossovers and SUVs, for the purposes of this study it was decided that all vehicles in these two categories should be classified as crossovers, provided they feature a monocoque (or “unibody”) construction. As with MPVs, crossovers have been allocated to the specific segment according to their size or the base model they are derived from.
- **Sport Utility Vehicles (SUVs)** are typically designed to be off-road capable and generally feature four-wheel drive. For the purposes of this study, any vehicle of this type with a body-on-frame construction has been designated an SUV, otherwise it has been labelled a crossover. This was done due to the difficulty in consistently allocating vehicles between these two categories, and in the particular context of this study, to reflect the fact that body-on-frame construction typically results in a heavier vehicle. It was therefore felt important to separate out this construction technique to gain a better understanding of the underlying causes for changes in mass for these types of vehicles.
- **Leisure Activity Vehicles (LAVs)** are shaped like a small van but feature rear windows and two or three rows of seats. They are most commonly derived from conventional vans (for example the VW Caddy Life) but can also be a bespoke design (for example the Skoda Roomster).
- **Van-derived vehicles** are vehicles which are essentially adapted from Class II or Class III commercial vehicles for carrying 5+ passengers. They typically feature three rows of seats as well as having rear windows.

The 1995-2010 dataset required less cleaning, but in order to compare the two different sources, it was “converted” to the EU configuration, grouping specific model variants together and allocating models to the classes above. Since this dataset is primarily assembled from records of bestselling models in a selection of European countries, its coverage of the various vehicle segments defined above is more variable. It offers good data availability for the conventional passenger car segments, and therefore represents a good picture of average fleet values, but it has relatively little data for crossovers and MPV segments. It is also rather inconsistent in terms of data availability for the remaining classes (A, S, J, LAV, F). In order to assess the overall composition of this database, Table A1-3 shows the difference in terms of entries versus sales data. As the 1995-2010 dataset does not include sales data, the average is calculated as a simple average of every version included in the database.

Table A1-3: Segment distribution of the two datasets[2]

Segment	Database share 1995-2010	Market Share 2010-2012	Difference
A	0.8%	5.2%	-4.4%
B	20.3%	31.5%	-11.2%
BM	0.3%	3.1%	-2.7%
C	30.5%	21.1%	9.4%
CM	1.1%	5.6%	-4.6%
CX	0.2%	8.0%	-7.8%
D	31.4%	11.5%	19.9%
DM	0.8%	1.0%	-0.2%
DX	0.4%	3.3%	-2.9%
E	9.2%	3.9%	5.3%
EM	1.0%	0.1%	0.8%
EX	0.6%	1.0%	-0.4%
F	2.3%	0.3%	2.0%
J	0.1%	0.3%	-0.2%
LAV	0.3%	2.6%	-2.3%
S	0.7%	1.4%	-0.7%

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[2] 2010-2012 market shares have been calculated excluding segments BX and Van derived cars as they are not present in the 1995-2010 dataset.

Figure A1-1:- Composition of the two datasets

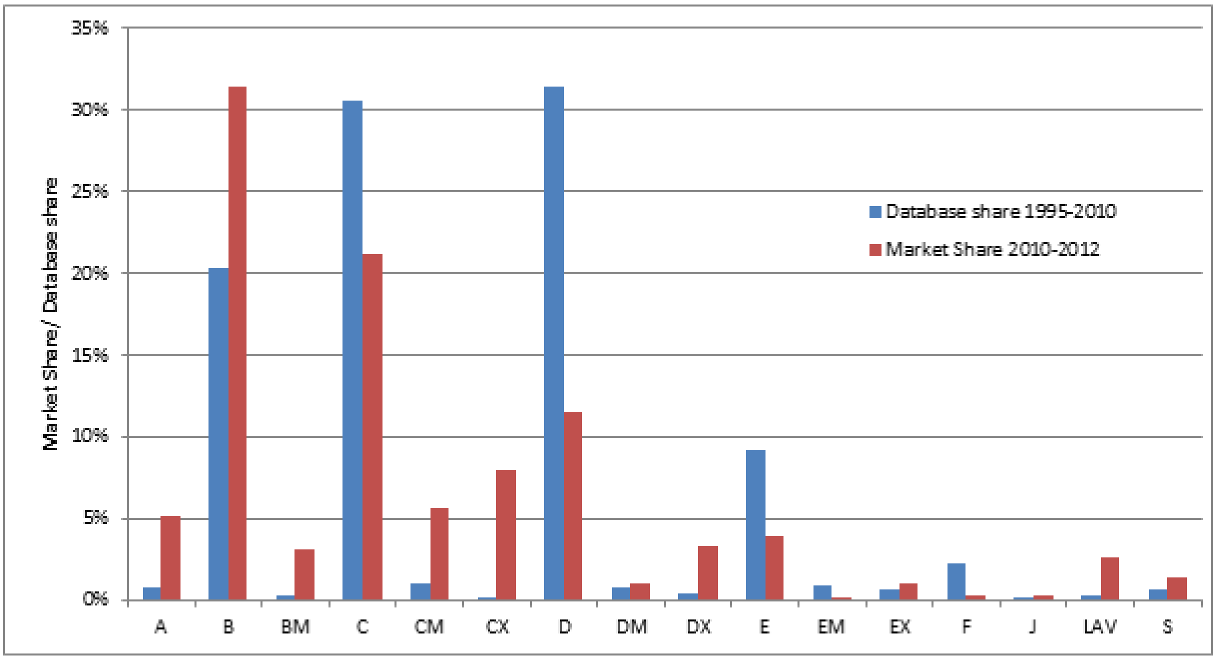


Table A1-3 and Figure A1-1 show that the 1995-2010 dataset is somewhat biased towards heavier segments, with C, D, E, and F segments having a higher proportion of entries in comparison to market share data, while A and B classes are underrepresented. Crossovers and MPVs, which tend to be heavier than average are less present in the 1995 to 2010 dataset as growth of these vehicle segments has occurred comparatively recently.

The relative differences between database share and overall market share will not have an impact on analysis of single class trends and on variation expressed in percentage terms, but may result in absolute overall mass values appearing higher than the true market average when examining this data. For this reason, when examining overall mass values the focus has been on the 2010-2012 dataset.

LCV data cleaning

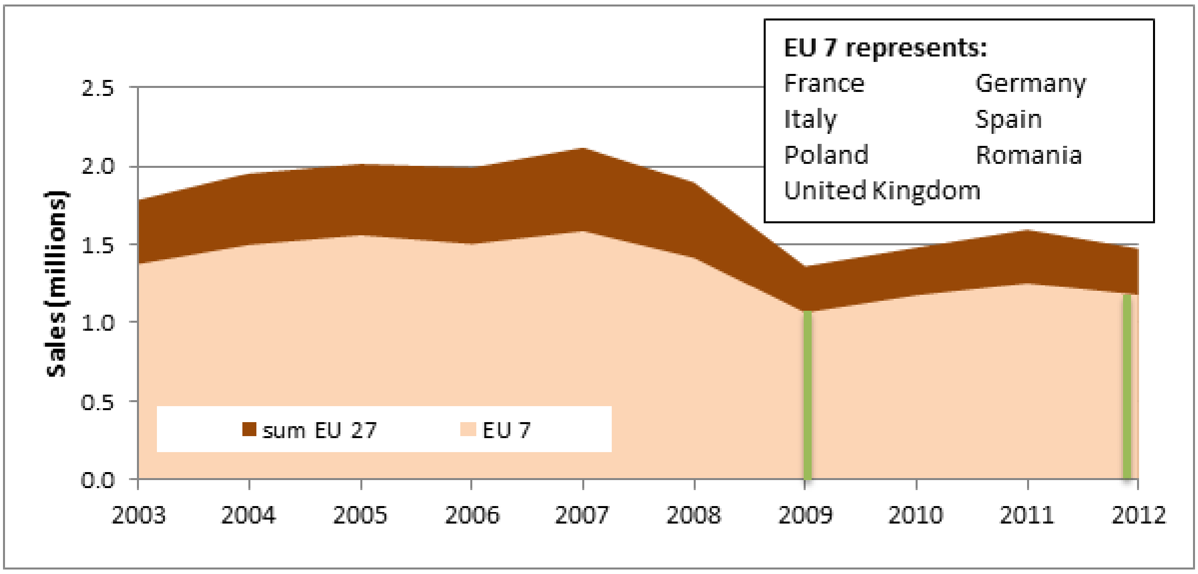
The EU database of LCV registrations compiled for Regulation 510/2011 presents similar issues, in terms of entries, to the passenger cars dataset. However, while allocating passenger cars to different segments required the identification of make and model, LCV classification is based exclusively on mass, which made data cleaning operations much simpler. Light Commercial Vehicles (N1 vehicles) are in fact classified in the following segments:

TableA1-4: LCV classification system

Class	Segment mass
Class I	below 1305 kg
Class II	between 1306 and 1760 kg
Class III	between 1761 and 3500 kg

Data preparation has been dictated by the need to compare different datasets with different coverage. Since the geographical coverage of 2009 data is confined to seven countries (France, Germany, Italy, Spain, Poland, Romania, United Kingdom), the EU dataset has been filtered to provide the same coverage. Analysing market share using ACEA sales data, it was possible to establish that these seven countries account for 77% of LCV sales in Europe in the past 10 years and 80% of 2012.

Figure A1-2: LCV market share of seven countries included in the analysis



We found that 95% of LCV sales in the selected countries can be traced back to eleven manufacturers. After incomplete or clearly erroneous entries had been removed, a comparison with ACEA sales data showed that our dataset covers 73% of 2012 registrations. This is due to very poor completeness by France and Italy, reporting respectively 60% and 50% of sales compared with ACEA figures. This problem reflects the fact that it is the first year that Regulation 510/2011 was applied; passenger car registrations in 2011 had very similar issues at the provisional release, which were mostly addressed with the release of the final data.

Although the 2009 dataset presented a more complete picture of LCV sales in the countries analysed, several entries had to be discarded as they do not include the indication of mass of the related vehicle. The final database used for analyses covered 89% of 2009 sales in the seven selected countries.

Appendix 2 - Additional figures relating to Section 4: “Implications of changes to the mass of vehicles on individual manufacturer CO₂ targets under the car and LCV CO₂ Regulations”

Part 1: Additional figures relating to Section 4.2

The figures below represent the results for Scenarios 1, 3 and 4 for an ‘average’ manufacturer.

Figure A2-1: Representation of, and results for, Scenario 1 for an ‘average’ manufacturer

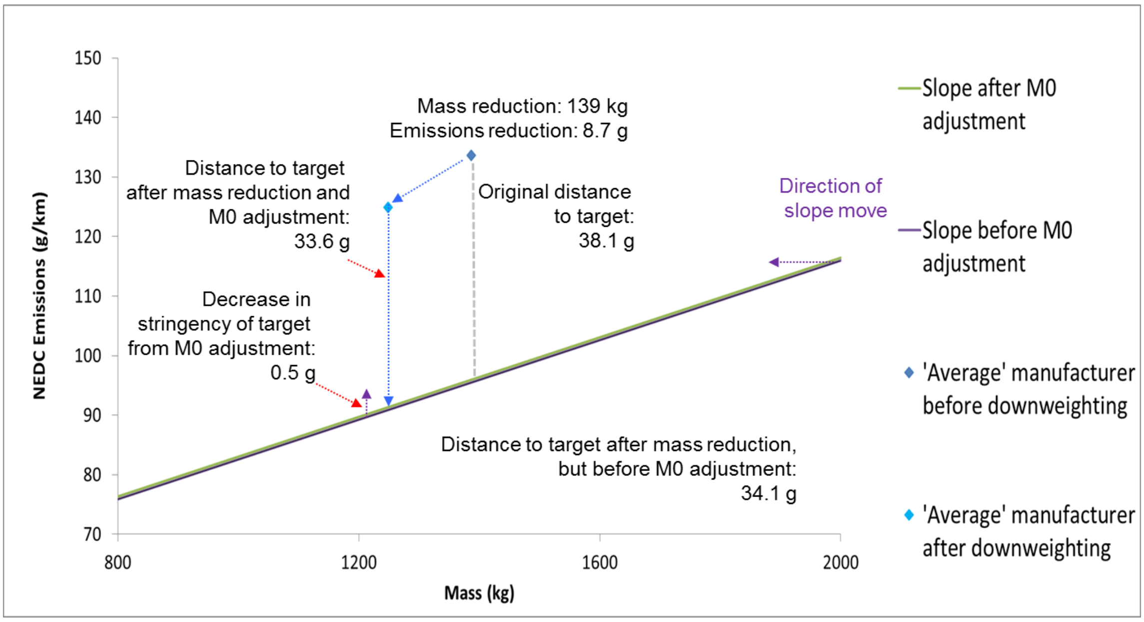


Figure A2-2: Representation of, and results for, Scenario 3 for an ‘average’ manufacturer

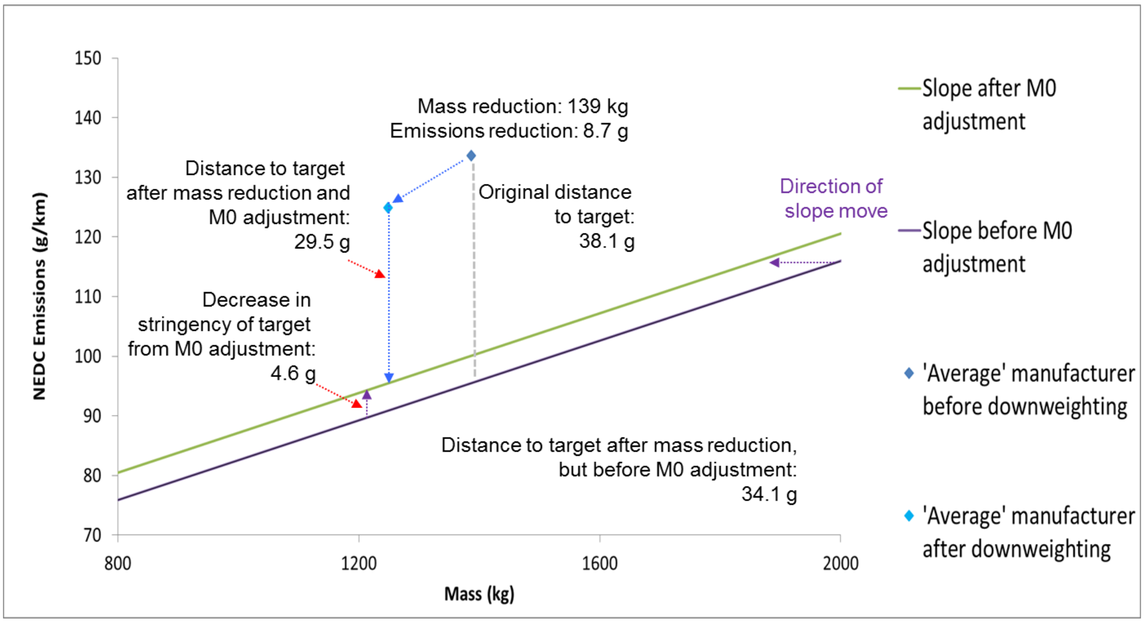
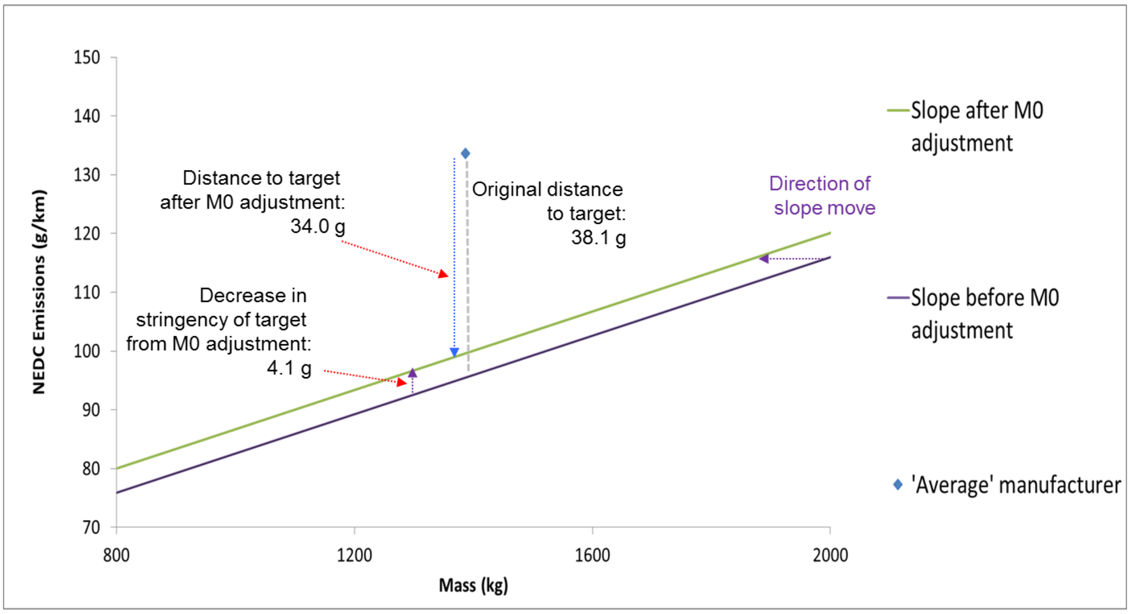


Figure A2-3: Representation of, and results for, Scenario 4 for an 'average' manufacturer



Part 2: Additional figures relating to Section 4.4

Figure A2-4 and Figure A2-5 represent the results for Manufacturer A and its competitors where the respective average masses change in accordance with the scenarios set out in Section 4.4, and where, respectively, Manufacturer A is a 'heavier' and a 'lighter' manufacturer. The blue bars in Figure A2-4 and Figure A2-5 are equivalent to, respectively, the blue and red bars in Figure 4-5.

Figure A2-4: Distance closer to target as a proportion of original distance to target for a 'heavier' manufacturer and its competitors after mass reduction and M_0 adjustment (where relevant)

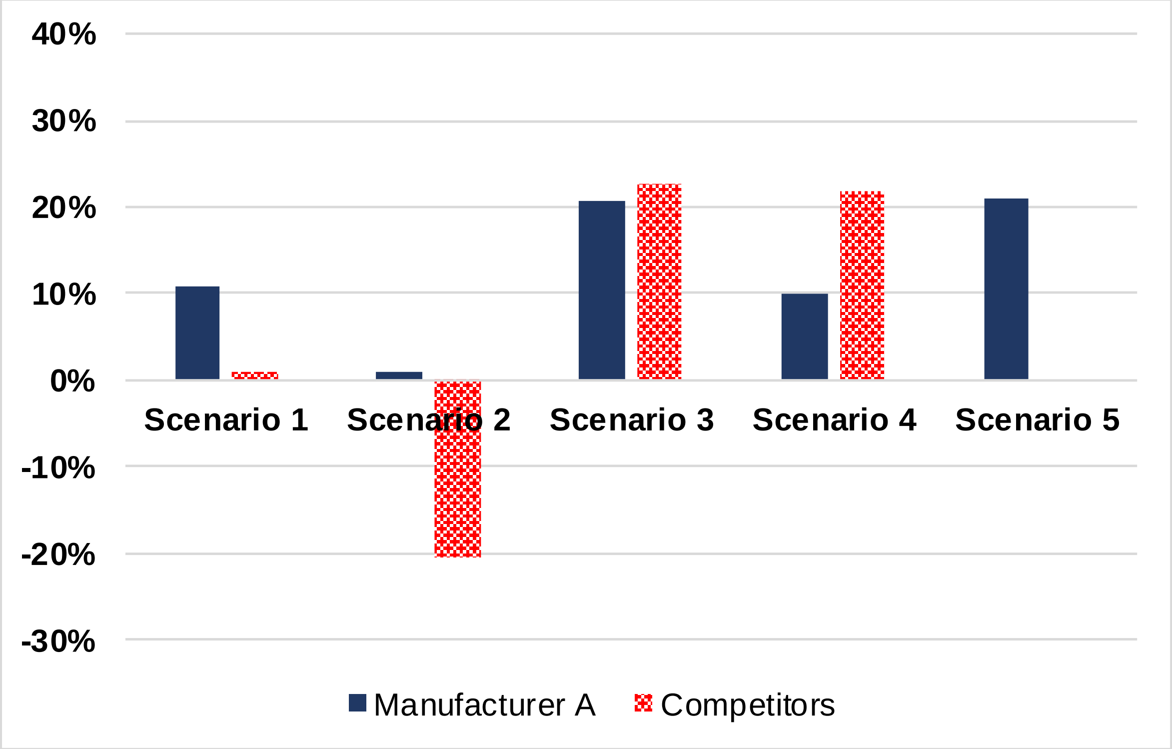
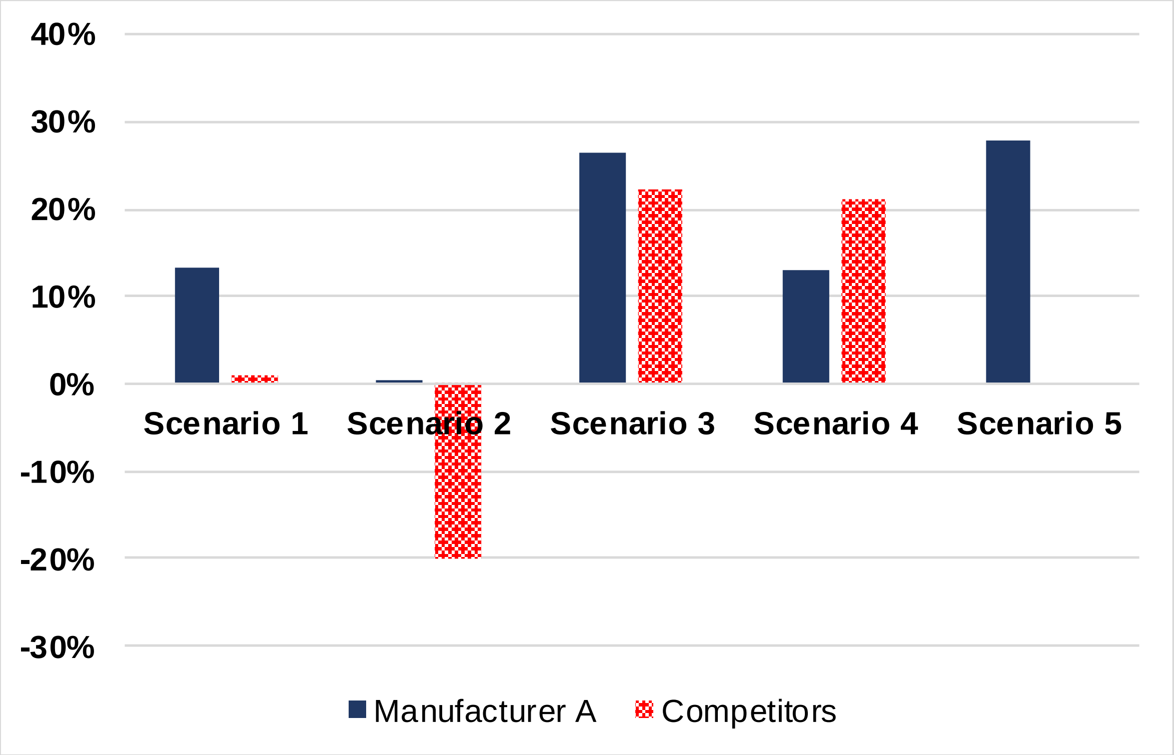


Figure A2-5: Distance closer to target as a proportion of original distance to target for a ‘lighter’ manufacturer and its competitors after mass reduction and M_0 adjustment (where relevant)



Appendix 3: Additional detail with respect to the Lotus Engineering (2010) study on the Toyota Venza

The table below provides a summary of the Lotus (2010) study results; the high development vehicle achieved a 38.4% weight reduction with a 3% increase in cost to the baseline vehicle, whilst the low development vehicle achieved a 21.8% weight reduction, with a cost saving of 2.1% against the baseline vehicle. Quite significant cost savings were achieved in areas where large mass reductions were made; notably the interior and suspension/chassis, although weight savings in the suspension/chassis were secondary weight savings (meaning the savings could only be achieved as a result of mass reductions achieved elsewhere).

Table A3-1 Summary of mass reductions and associated costs

System	Base	Low development			High development		
	Mass (kg)	Mass (kg)	% saving	Cost factor	Mass (kg)	% saving	Cost factor
Body	382.50	324.78	15.1%	0.98	221.06	42.2%	1.35
Closures/ fenders	143.02	107.61	24.8%	1.02	83.98	41.3%	0.76
Bumpers	17.95	15.95	11.1%	1.03	17.95	0.0%	1.03
Thermal	9.25	9.25	0.0%	1.00	9.25	0.0%	1.00
Electrical	23.60	16.68	29.3%	0.95	15.01	36.4%	0.96
Interior	250.60	182.00	27.4%	0.97	153.00	38.9%	0.96
Lighting	9.90	9.90	0.0%	1.00	9.90	0.0%	1.00
Suspension/Chassis	378.90	275.50	27.3%	0.96	217.00	42.7%	0.95
Glazing	43.71	43.71	0.0%	1.00	43.71	0.0%	1.00
Misc.	30.10	22.90	23.9%	0.99	22.90	23.9%	0.99
Totals	1289.53	1008.28	21.8%		793.76	38.4%	
Percentage compared to baseline	**100.0%**	**78.2%**		**97.9%**	**61.6%**		**103.0%**

The following sections describe the approaches used by Lotus Engineering to achieve the weight savings outlined in the above table.

Body system

The body system is comprised of the frame of the vehicle without bumper or closures. Benchmarked vehicles (such as the 2007 Acura and the 2008 Hyundai Santa Fe) show that the Toyota Venza's body system is, on average, 20 kg heavier than for these vehicles systems. A review of technologies available for this system shows that aluminium may be used extensively, as applied in the Jaguar XJ series, whilst different grades of steel may be used (as in Honda and Volvo).

Different manufacturing techniques may also be used such as tailor rolled blanks (TRB). This is a cold rolling process which allows the thickness of steel sheet to be continuously varied in the longitudinal direction. This allows the optimum thickness to be used for different sections of a given component, reducing weight while retaining strength. The process has a number of advantages over the alternative tailor welded blanks process (in which sheets of differing thickness are welded together):

- Continuous transitions in thickness can be achieved with a homogenous surface
- There are no detrimental effects on microstructure caused by welds
- The cost of production is unaffected by the number of sheet thickness variations
- Shorter production times and reduced costs with the raw material coil being transformed into the flexibly rolled component in one plant with no requirement for stacking of blank sheets, and less material wastage.[3]

High strength steels (HSS) are identified as being well suited to body system manufacture, although no vehicles are cited. The 'low development' vehicle used HSS and stamped medium strength steel of a reduced gauge for the majority of the components. The 'high development' vehicle used long glass fibre reinforced polypropylene developed by Bayer[4] for a large part of the underbody assembly, using magnesium over-moulded with structural plastics for the side body and stamped aluminium for the roof.

The 'low development' vehicle's use of HSS is credible as there are examples of extensive use of this material in production vehicles to reduce weight[5] and the qualities of the material are well described and are well-known as a feasible alternative to standard steel. Although magnesium is not currently used extensively in automotive manufacture, the report provides examples of magnesium castings being used in other production vehicles: roof frame in the Chevrolet Corvette Z06, the dash of the Dodge Viper, the liftgate inner for the Lincoln MKT and the front end module of the Land Rover LR3 (known as the Land Rover Discovery in Europe). Aluminium is used extensively for bonnets[6] and roofs, therefore the use of this material would appear to be reasonable for the 'high development' vehicle. No current mass production examples comparable to the proposed use of structural plastics and reinforced polypropylene are cited within the Lotus report.

Closures, fenders and bumpers

Closures and bumper systems include front and back doors, the rear hatch, bonnet and the fender and bumper systems. Benchmarking activities for all of these Venza components shows that they are considerably heavier than best practice production examples from several other vehicles. Compared to the average of best practice production benchmarks, the front and back doors in the Toyota Venza are 43% (8.7 kg) and 22% (3.1 kg) heavier, whilst the rear hatch is 26.1% (3.8 kg) heavier. Several production examples use aluminium, however the majority use steel, indicating that the Toyota Venza closure designs are significantly heavier than best practice.

The low development vehicle uses stamped aluminium for the bumper/fender system. The bonnet is also stamped aluminium, whilst the doors adopt a design change to facilitate weight reduction. There are examples of other production vehicles already using these materials demonstrating production feasibility. Since the Venza closures have benchmarked poorly (27.4 kg could be saved using other average benchmarked sub-systems), then it should be noted that production vehicles which already follow best practice lightweight design would not be able to achieve all of the identified weight savings.

The high development vehicle uses stamped aluminium for the same parts as the low development vehicle whilst adopting a cast magnesium frame for door closures, with a single injection moulded thermoplastic part to fit and finish. Magnesium casting is used in other production examples, however the single moulded thermoplastic part to fit the frame results in considerable functionality loss the lumbar support has been removed. To address this, the locking system had to be moved to the A frame. However, if side and rear crash tests can verify the use of these materials it is likely considerable weight saving may be achieved using magnesium.

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[3] Mubea (2006), Flexible Rolling of Tailor Rolled Blanks

[4] See http://www.bayermaterialsciencenafta.com/products/index.cfm?mode=grades&pp_num=EB7C464B-C3D0-7EE4-1E40B9794231F64C&o_num=14

[5] A 55% weight saving been achieved in the new Ford Fiesta as a result of HSS. See http://www.ford.co.uk/experience-ford/AboutFord/News/VehicleNews/2010/HeartOfSteel

[6] International Aluminium Institute (2006) Improving Sustainability in the Transport Sector through Weight Reduction and the Application of Aluminium, outlines that 20% of European vehicles sold in 2005 used aluminium bonnets.

Interior and parking brake

The interior consists of various parts which are outlined in Table A3-2. This shows that the majority of the weight reductions have occurred in the seating, instrument panel and controls systems. For the purpose of brevity our analysis will concentrate on these systems.

Table A3-2: Weight reductions in the interior system for low and high development vehicles

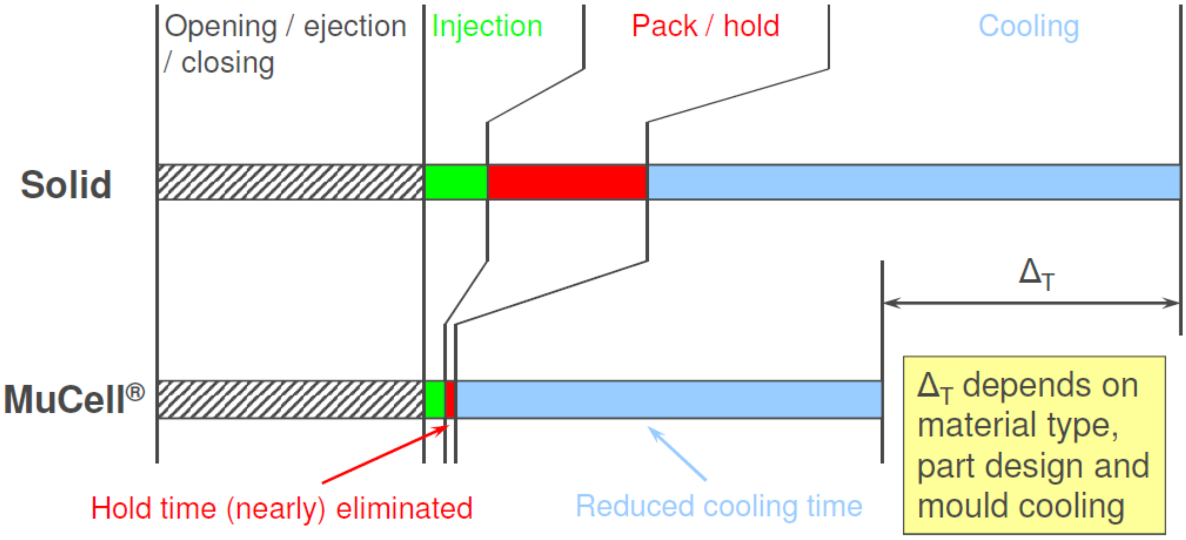
	Mass (kg)			Mass reduction (kg)		% reduction achieved	
Subsystem	Base vehicle	Low development	High development	Base vehicle	Low development	High development	Base vehicle
Seats	97.9	61.6	55.2	36.3	42.7	37.1%	43.6%
Instrument panel & centre console	43.4	28.7	25.8	14.7	17.6	33.9%	40.6%
Interior trim	41.4	36.7	24.3	4.7	17.1	11.4%	41.3%
Controls system	22.9	16	16	6.9	6.9	30.1%	30.1%
Safety	17.9	17.9	17.9	0	0	0.0%	0.0%
HVA/C & ducting	13.7	10.3	11.3	3.4	2.4	24.8%	17.5%
Closure trim	13.3	10.7	2.4	2.6	10.9	19.5%	82.0%
Total	**250.6**	**181.8**	**152.8**	**68.6**	**97.6**	**27.5%**	**39.0%**

The normalised benchmarking of the Venza seating revealed that all seating weight was comparable to other vehicles (5% heavier than the lightest benchmarks), however a considerable weight saving was achieved for both high and low development vehicles.

For low and high development vehicles the design of the front driver and passenger seats was altered to a normalised Ford Fiesta seat design but with the use of a cast magnesium frame instead of the steel design, as used in the Hyundai Azera. Both also connected seats using seat runners moulded into the floor system, reducing the need for attachment systems.

For the rear seats a different design was adopted for both high and low development models using the Nissan Qashqai design, which utilises an all foam lower seat, with the back compiled of a roll formed and laser welded steel frame with foam insert. The high development vehicle opted to use a NuBax single foam insert into the driver and passenger seats, allowing for further weight savings. The instrument panel and centre console (as well as closure trim) uses MuCell technology extensively. This process produces air bubbles in resin, to develop a reduced-weight instrument housing and centre console. During our literature review further information regarding this process was obtained which highlights how use of this technology may result in reduced times for manufacturing processes, which may be expected to contribute to cost reductions (see Figure A3-1).

FigureA3-1: Reduction of cycle time through use of MuCell versus solid moulding[7]



Other systems used in both the high and low development vehicle include the use of a single LCD screen to control heating, audio, mirrors, windows, parking brake and car monitoring systems. The control system in both the high and low development vehicle adopted lighter weight pedal systems (plastic replacing steel), an electronic parking brake (replacing mechanical) and electronic gear shift. More advanced steering wheel technology was adopted for the high development vehicles whereas the low development vehicles used an aluminium design.

Seating weight reductions appear realistic and are likely to be applicable to other vehicles, especially as magnesium is not widely used but there are production examples and availability of such technology is expected to grow.[8] The use of MuCell provides extensive weight savings across the interior. This technology is beginning to be adopted by a number of vehicle manufacturers already, so these weight reductions may not be applicable to some vehicles.[9] Weight savings made through adoption of an electronic parking brake system are applicable in the EU context as only around 6% of new vehicles registered in the EU in 2012 were fitted with such a system, and hence it clear that there is significant scope for this technology to be applied more widely.

Further weight reductions may be achieved through combining this technology with electronic stability control (which will be mandatory on all new vehicles sold in Europe by the end of 2013). Combining the two eliminates the need for a separate electronic control unit.[10] Additional weight savings can be made through the use of an integrated electronic brake control system. This is an electric motor driven mechanism to eliminate the necessity for a vacuum booster (saving over 3 kg).[11] For hybrid and battery electric vehicles which currently have to rely on an electric vacuum pump to provide vacuum assist when there is insufficient vacuum generated by the engine, such systems can save an additional 3 kg.

There are fewer examples of a single LCD system to control the majority of the functions in the car, with only the Mercedes Benz S-Class, which uses such a system to engage parking brakes and audio, being mentioned in the study.

Suspension and chassis

Suspension and chassis benchmarking results as shown in Table A3-3 show that the suspension system in the Venza is particularly heavy compared with light weight examples (44.9% heavier), particularly in the suspension and wheel systems. The systems adopted in the low and high development vehicles reflect the ability to use other high production lighter weight parts.

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[7] Source: Trexel

[8] For example Faurecia, one of the largest seat suppliers announced in July 2013 it would be developing magnesium seat structures at the biggest automotive foundry in China: http://www.faurecia.com/en/faurecia-starts-developing-magnesium-seat-structures

[9] Trexel website (http://www.trexel.com) lists a large number of automotive manufacturers who have already adopted MuCell, including; Mercedes, VW, BMW, Ford, Mazda and General Motors

[10] TRW, EPB integrated. Available online here: http://www.trw.com/braking_systems/electric_park_brake/epb_integrated

[11] TRW, Integrated Brake Control system. Available online here: http://www.trw.com/braking_systems/integrated_brake_control

Table A3-3: Suspension and chassis benchmarking results (Lotus, 2010)

	Mass (kg)	Venza system to benchmarked vehicles (Normalised to 1700 kg kerb weight)			
	Toyota Venza	2005 VW Passat	Toyota Venza	2005 VW Passat	Toyota Venza
Front suspension	90.5	52.5	52.9	57.0	54.8
Rear suspension	67.9	47.4	53.6	54.7	51.9
Brakes	64.8	**2008 Fiat 500** 52.0	**2005 Toyota Sienna** 52.7	**2008 Toyota Prius** 55.0	53.2
Tyre and Wheel	140.2	**2008 Kia Carens** 93.0	**2003 Citroen C5** 89.8	**2008 Toyota Prius** 87.5	90.1
Total	**363.4**				**250.8**

Suspension systems for the low and high development vehicles were selected from the 2005 VW Passat for the front and the 2005 Alfa Romeo for the rear. The low development vehicle used different materials in the 2005 VW Passat suspension system including cast magnesium subframes, hollow steel stabiliser arms, aluminium knuckles and HSS springs. The high development vehicle included nylon spring seats, aluminium strut top mounts and foam reinforced control arms.

The brake systems for both were selected from the 2008 Toyota Prius, with no alterations made in the low development vehicle, but further detail mass reductions made in the high development vehicle.

Normalised 2008 Toyota Prius wheels were also selected for the low and high development vehicles, which resulted in an immediate weight saving and cost reduction in both models. For the high development vehicle the spare wheel was removed and thickness of the tyre and rim reduced to reflect reduced functional requirements achieved through weight reduction.

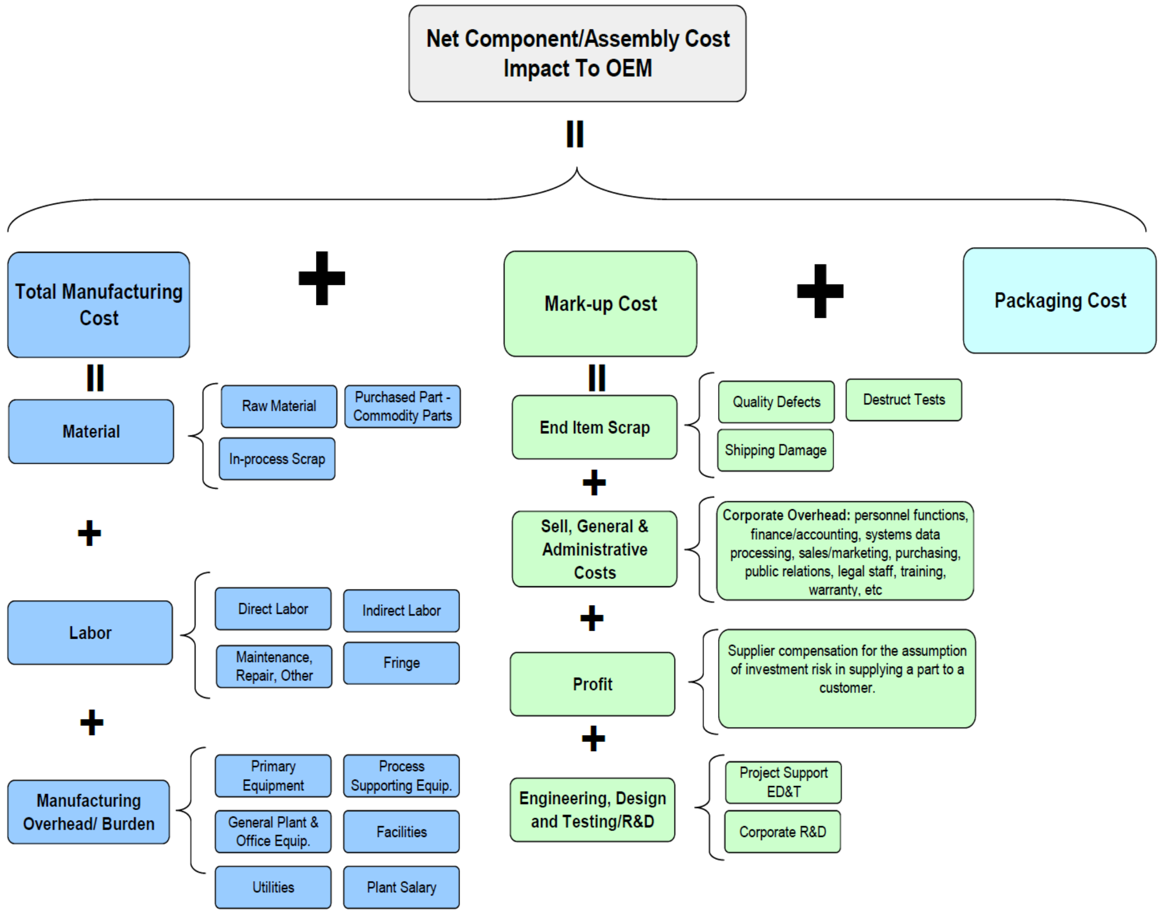
The weight saving approaches used in the suspension/chassis system appear credible due to the number of production examples available used for substitution. However, benchmarking shows that the base Venza is 167.7 kg heavier than existing best practice examples. This suggests that the savings found (103.4 kg for low development, 161.9 kg for high development) may not be achievable on all other vehicles.

Appendix 4: Additional detail with respect to the US EPA study (FEV, 2012) on the Toyota Venza

Assessment of costs

FEV adopted the use of a manufacturing assumption and quote summary spread sheet (MAQs), which was developed for the EPA in a pilot study.[12] Figure A4-1 details all factors used to determine the system part manufacturing costs for both the baseline and weight-optimised vehicle.

Figure A4-1: Detail of costs included in cost analysis[13]



The costs of component part manufacture were calculated using a methodology analogous to that used in the automobile industry. The gauge, size and geometry of each part were used to determine the machining processes required.

Process flow charts were developed to catalogue the step by step manufacture of each part, assigning tasks (e.g. metal stamping, drilling a hole) and machinery required (e.g. metal press). The cycle time of machinery provides a time factor for each machine operator, providing a multiple for; labour, materials and manufacturing overhead and burden.

Three levels of process parameter models were used to develop these flow charts:

1) **Simple serial** – These are single input models. They take basic component part input data and generate part specific output data (for example weld time; length of weld; cutting time; drilling

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[12] Light-Duty Technology Cost Analysis Pilot Study (2009), available from http://www.epa.gov/otaq/climate/420r09020.pdf
[13] Extract from FEV, 2012, report.

time etc.). These were created using Design Profit® software to produce and manage the process flows, and integrate costing information. This ensured a consistent approach.

2) **Generic moderate –** Used where the process requires multiple input parameters in generic types of operations and processes (for example injection moulding; stamping; die casting). Again part input data (material specifications, mass, volume, part geometry, part features, etc.) are used to generate key output parameters (e.g. equipment type, equipment size, operation cycle times, material usage, etc.).These were created in Microsoft Excel to allow greater flexibility and application to a wide variety of parts. Key output parameters are entered into the process flow charts.

3) **Custom complex –** Similar to the ‘generic moderate’ approach, but these process parameter models are more complex and are more specific to a particular component or sub-assembly. For example they might be used to model the manufacture of a radiator unit for a specific vehicle, engine size and body configuration.

Having used these approaches to develop process flow charts, costs associated with each process were calculated using databases previously developed by FEV for the EPA.

Once costs were assigned to the manufacture of each sub-system a mark-up was applied to the total manufacturing costs to factor in other external costs not considered. Following this a packaging cost was applied determined by the size, weight and fragility of component parts. Although this work was conducted, no costs were assigned for packaging of any sub-systems. Details of shipping costs were not applied as these were presumed to be covered by total mark-up or manufacturing overhead, or through an indirect cost multiplier.

The study does not include indirect OEM costs. These include corporate and selling operations, such as; salaries, heath care for corporate staff, or transportation, marketing and dealer support. The report also states that for production indirect OEM costs can include R&D and tooling costs. However these costs could also extend to changes in material handling and storage requirements (for example when an OEM is producing body structures from thinner gauge steels). An indirect cost multiplier detailed by the EPA in other studies[14], may be applied to the total manufacturing costs to obtain the final cost of vehicle production, but this was done by EPA themselves and so is outside the scope of the report. It should be noted that since indirect costs are applied as a multiplier, then where an overall cost saving is identified, the saving may be increased when an indirect cost multiplier is applied.

Learning factors are also applied by EPA – again details of this process is not included in the report and so they have not been reviewed here. However learning factors will be another important area of the costs to OEMs of adopting new lightweight technologies. The impact of indirect costs and learning factors is explored further in the stakeholder interviews.

Details of the factors used to determine costs are outlined through the database and cost multipliers used to determine costs:

Labour database

The direct labour costs for each task (e.g. press operator) were determined from the Bureau of Labour Statistics. The data provides categories of labourer within each industry breaking down skilled and non-skilled labours in the manufacture of particular materials, providing numbers and average pay of labourers under specific categories in the US. Each task was assigned to relevant categories available. Indirect labour costs (other labourers indirectly involved in the process; supervisors, quality control technicians, shipping and receiving personnel) and ‘maintenance, repair and other’ costs, were also determined from this data set: Using data on the number and pay of labourers in each category by industry, each category was assigned to; direct, indirect, operation, maintenance and other, helping determine the industry cost of labour as a ratio. This allowed the study to assign an indirect and ‘maintenance, repair and other’ cost as a proportion of direct labour costs. Fringe labour costs were also included in labour costs; this includes company medical and insurance benefits, pension/retirement

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[14] EPA carried out this analysis using Indirect Cost Multipliers determined from benchmarking industry results (Incremental Direct +indirect costs)/(incremental direct manufacturing costs), determining an indirect cost multiplier near to 1.5 in the following study; Automobile Industry Retail Price Equivalent and Indirect Cost Multipliers, EPA 2009

benefits, government-directed benefits, vacation and holiday benefits, shift premiums, and training. A multiple was used to include this cost, determined as 52% for suppliers and 160% for OEM costs.

Materials database

Material costs are derived from several sources to understand current and possible future trends. The sources used include:

- For metals: U.S. Geological Survey, Metal-Pages, London Metal Exchange, estainlessteel.com and Longbow.
- For resins: Plastic News, Plastics Technology, Online, Rubber and Plastics News and IDES.

‘In scrap’, determined as a proportion of all materials used, was a cost assigned for material lost through production. A subsequent $/kg cost was assigned to each material used in the study unless purchase parts were used. Purchase parts-commodity part cost was determined by: industry cost knowledge and experience (FEV and Munro); surrogate component costing databases; Tier 1 supplier networks; published information; or service part cost information. Alternative parts, composed of new materials of the value $10-15, were scaled from the baseline costs sourced.

Manufacturing overhead and burden (burden)

The list of costs includes: all premises and machinery rent, maintenance, depreciation, insurance and tax, intra-company shipping costs and all other plant wages. Due to a lack of publicly available data on manufacturing overhead rates for the relevant industry sectors, overhead rates were estimated using expert knowledge and some bottom-up estimates. A ‘Manufacturing Overhead Calculator Template’ was subsequently created which broke down costs associated with premises, machinery, and plant wages. As the machinery is the largest cost associated with burden, each machine group was assigned an hourly burden rate calculated from: purchase cost, life expectancy, yearly operating capacity, operating efficiency and equipment utilization (both as a percentage of yearly operating capacity) and cost of money (interest assigned at 8%). A depreciation cost for machinery was also factored in, a percentage of which was used to determine additional plant and office hardware/equipment costs. Facilities costs are assigned per square footage utilized for the equipment, with utility expenses per hour being assigned to process support equipment.

Mark-ups

After calculating total manufacturing costs (labour, materials and burden cost) for each subsystem, a mark-up was applied to the total. The multiple is applied according to the complexity and size of equipment used in manufacture. Manufacturing processing groups (e.g. injection moulding, aluminium die casting) were assigned to each piece of machinery used, followed by a sub categorisation, based on size and complexity of the part produced. Alternatively, if parts were sourced a mark-up to the supplier cost is applied. The following mark-ups were used:

Table A4-1: Mark ups applied to total manufacturing costs

	Mark up (%)				
Primary Manufacturing Equipment Group	End Item Scrap[1]	SG&A[2]	Profit[3]	ED&T[4]	Total
Large size, High Complexity	0.7	7	8	2	17.7
Medium Size, Moderate Complexity	0.5	6.5	6	1	14
Small Size, low complexity	0.3	6	4	0	10.3
Complete System/Subsystem Supplier	0.7	7	8	6	21.7
High Complexity Component Supplier	0.7	7	8	4	19.7
Moderate Complexity Component Supplier	0.5	6.5	6	2.5	15.5
Low Complexity Component Supplier	0.3	6	4	1	11.3

[1] This accounts for failure rates of manufacture (e.g. 1 in 200 (0.5%) stamped metal bonnets are faulty).

[2] This accounts for; corporate facilities, corporate salaries, insurance on non-manufacturing buildings and equipment, legal and public relation expenses, insurance and warranty, patent fees, marketing and advertising, corporate travel.

[3] Investment risk is applied as a factor in determining the profit mark up; the newer the technology the higher the investment risk, and therefore a higher mark up.

[4] Traditionally ED&T and research and development (R&D) activities in automotive manufacture are grouped, therefore this approach was adopted. Royalty fees are also included in this mark-up, with estimations provided on a part specific basis.

Detailed review of weight saving potential for individual subsystems

The following sub-systems were reviewed in more detail due to the substantial labour cost savings made.

Seating

Significant weight and cost savings were made through the seating subsystem via:

- Thixomolding of magnesium compared with stamp cast moulding of seat frames.
- Use of a whole seat foam insert system which had orthopaedic benefits
- Use of a foam process which removes the need for a frame at the bottom of the seat.

Thixomolding may only be used in the moulding of magnesium and although die casting of plastics, aluminium and zinc were considered by FEV, Thixomolding of magnesium provides the biggest cost and weight saving. Thixomolding of magnesium was used for the back of the seat frames for both the front and rear seating, but it was only used for the base of the front seating as a whole foam piece was used for the base of the rear seat. This moulding process is yet to be widely used as a result of wariness over the fluctuating price of magnesium and the slow change of manufacturing processes due to the need to invest in equipment. The use of Thixomolding resulted in significant weight savings, due to the change in material from steel to magnesium. It also achieves labour cost savings through reducing the welding requirements of the frame and reducing the time taken for assembly. However in this study the use of this process resulted in an overall additional cost to the frame due to the significantly increased material cost.

FEV also chose to use ProBax©, an innovative foam-based seating technology which has been in production on the Lotus Elise and Exige sports cars since 2006. Although this is currently the only automotive application, according to the manufacturer's website, *"ProBax development projects are* *currently progressing with a number of major OEMs".* This resulted in a one piece seat allowing the removal of the active head rest and lumbar system. The seating system improves posture of the passenger, and claims to have health benefits. It allows removal of additional components from the seat and reduces manufacture time, by the addition of one foam insert that may be trimmed to specification. The technology may be introduced into any frame with a cost and weight saving benefit, however there may be concerns around consumer acceptance of the overall seat proposed by FEV given the removal of the separate head rest assembly and lumbar system.

The very heavy steel welded rear seat bottom frame, a carryover part from the Toyota Highlander, was replaced by a polyurethane / elastic polyether polyurethane (PU/EPP) foam structure. This also provided significant cost and weight savings. This system has been used by Kia, Chevrolet and Porsche and may therefore be seen as a proven method, with significant weight and labour savings.

Braking

There are significant material and labour cost savings identified in the analysis of the brake system. Labour, materials and mass reduction savings have been found through the use of an electronic parking brake system, where calipers are electronically engaged when a parking button is pressed on the dashboard.

The front and rear rotor/drum and shield subsystems (calliper, brake discs, brake pad and relevant housing) have undergone significant design changes. These result in increased machining for parts (e.g. insertion of holes for increased cooling), whilst not increasing labour costs. This may be through use of Toyota Prius components as substitutes but the methods used to determine labour costs should reflect in-house machining, which would be more complicated with these parts. There is a potential error in the FEV report - the analysis of the front rotor/drum and shield subsystem, which substitutes a large proportion of calliper and brake disc parts from cast iron or steel to aluminium and uses more machined parts, identifies a decreased material cost ($10.70), whilst a seemingly identical approach used for the rear rotor/drum and shield subsystems results in an increased material cost ($10.90). This apparent error suggests an increase in costs as opposed to a decrease in costs of up to $35.91 (with mark up as 98% of costs are materials). An enquiry regarding this possible error was made with FEV but no reply was received. Again, the analysis of both the rotor/drum and shield does not explain where labour cost reductions have been made.

The electronic parking brake actuation subsystem results in cost savings (as in the Lotus Study) by eliminating the use of a hand brake cable and allowing reduced brake hosing. This again results in large reductions in labour and material costs. As highlighted earlier, electronic parking brakes are currently only fitted to a very small proportion of new EU-market vehicles, so there is significant potential for such systems to be fitted more widely as a means for reducing both weight and cost.

Suspension

Changes made in the suspension system (which includes connection arms and rods for suspension, shock absorbers, and wheels and tyres) result in a reduction in labour and material costs of $22.15 and $74.13 respectively (before applying burden and markups).

Front and rear suspension subsystem materials were changed from steel to aluminium or magnesium, high strength steel and use of hollow connecting rods. The increased material costs are offset by slightly decreased labour costs resulting in an improved design whilst not greatly altering costs.

Shock absorber systems benefitted from significant reductions in materials and labour costs of $29.87 and $9.23 (before markup) respectively. It is not clear why the changes made have resulted in labour cost reductions; parts are downsized but there is no reduction in the number of components involved in the manufacture of shock towers or piston shafts. There may be potential labour reductions associated with the spring system but little detail is provided to assess how these might be achieved. The use of the Alfa Romeo shock tower assembly as a result of the secondary benefits of weight reduction results in big material cost reductions, and market place validation may have resulted in cost reductions in excess of materials, however insufficient information is provided about how this leads to labour cost reductions.

Wheel and tyres were substituted for the upsized Toyota Prius design. The Toyota Prius wheels, like the Toyota Venza wheels, are made from aluminium, but are of a slightly different design, which had no significant difference in the type of tyre used. Although this was the case, significant weight savings

(32.83 kg) with cost savings of $48.69 in materials and $11.18 in labour (before mark-up) were found; these cost savings may have been sourced through market place validation exercises, but they are not justified in the report.

The analysis of the suspension system provides well justified weight reductions in suspension subsystems and shock absorbers, but those for wheels and tyres may be questionable. The justifications for the cost reductions for shock absorber subsystems, wheels and tyres are not clear. This is commented on by Joost in the peer review of the FEV study where he states that the technology employed in the Prius wheel is not different from the standard Venza wheel, so it is not clear why a scaled up Prius wheel should weigh less.

Frame and Mounting

The frame and mounting system includes the mounting attachments for the engine, engine under cover and the front and rear strut frame which encase the engine. Mass reductions have been found by utilizing different materials and downsizing parts due to engine size reductions. Mass reductions of 16.3 kg were found in this area by altering the design and mounting of the front and rear strut frames, which made up a large proportion of the weight for this system. Reductions in labour and material costs of $11.03 and $3.86 respectively were achieved (before markup).

The labour costs are justified as many of the base vehicle parts were formed from welded stamped steel constructions (e.g. the rear frame was made of six individual steel stampings welded together). Adopting a single-part magnesium stamped front strut frame allows for large reductions in labour costs, although burden costs increased. The reduced size of the rear strut frame, still manufactured from stamped steel, leads to reduced material costs, helping justify the reduction in material costs overall.

Changes to the frame and mounting resulted in increased burden costs associated with machinery for the new stamping process for the front strut frame, which would be similar if a different material was to be used other that magnesium.

Fuel system

The fuel system is composed of the fuel tank and lines, and fuel vapour management sub systems. Here plastic replaced many steel components and, together with a new mounting system, this resulted in a 58% (12.21 kg) reduction in the weight of the system. Materials costs increased by $18.32, but this was more than offset by a labour cost reduction of $6.28 and a $14.79 decrease in burden costs.

A blow moulded HDPE plastic fuel tank replaced a multi-component steel fuel tank. This accounted for by far the largest part of the physical weight reduction achieved. However, as FEV themselves note, while steel fuel tanks are common for Toyota, some industry reports indicate more than 95% of the fuel tanks produced in Europe are made from plastics. The other major source of weight reduction was that the design reduced the fuel held by 12%, justified by the improved fuel consumption of the overall vehicle. The reduced-weight mounting system eliminated a number of parts reducing labour costs. It is presumed that burden costs are reduced due to the use of plastic moulding rather than steel stamping of the fuel tank, combined with the reduction in parts required (hence assembly line processes) to manufacture the system; however detail on this is not provided.

Appendix 5: Additional detail with respect to the NHTSA study (Electricore, 2012) on the Honda Accord

The Electricore (2012) study for the US National Highway and Transportation Safety Administration (NHTSA) achieved a mass reduction of 327.2 kg compared to the base vehicle mass of 1,410 kg[15]. This amounts to a 23.2% reduction in mass at a cost increase of $319 or $1.03 per kg, against a baseline cost of $21,980. The main cost savings were in the secondary weight-optimised systems such as the engine and transmission, drive shaft, and parts of the suspension and steering systems. These systems were downsized to those currently used on the smaller Honda Civic model, while maintaining similar or increased performance to that of the benchmark vehicle, with cost savings coming from reduced material usage on the smaller components. A summary of the results is provided in the table below.

Table A5-1: Summary of mass reductions and associated costs

	Base vehicle	Light weight vehicle			
System	Mass (kg)	Mass reduction (kg)	Cost ($)	% saving on baseline vehicle	Cost $ / kg
Engine / Powertrain	331.39	68.89	-118.29	4.9%	-1.72
Body	328.00	72.80	147.00	5.2%	2.02
Closures / fenders	92.04	43.97	153.70	3.1%	3.50
Bumpers	15.80	7.10	1.22	0.5%	0.17
Thermal	0.00	0.00	0.00	0.0%	-
Electrical	34.10	5.40	0.00	0.4%	0.00
Interior	150.60	39.23	112.27	2.8%	2.86
Lighting	9.40	2.34	0.00	0.2%	0.00
Suspension / Chassis	279.89	85.72	27.59	6.1%	0.32
Glazing	33.50	0.00	0.00	0.0%	-
Miscellaneous	135.35	1.75	-3.97	0.1%	2.27
Totals	**1410.1**	**327.2**	**$319.5**	**23.2%**	
% against baseline	**100.0%**	**23.2%**	**1.45%**		

The following sections review the approaches used in the NHTSA study for realising weight savings in each of the main vehicle systems.

Body system

The baseline Honda Accord uses a 328 kg HSS unibody monocoque structure. As with both the US EPA and Lotus studies, the NHTSA study looks at multiple options for mass reduction of the body system. Aluminium intense and multi-material approaches were both considered but rejected due to

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[15] These numbers differ slightly as the NHTSA study includes the mass of the fuel and the savings related to the reduction of fuel with a smaller fuel tank. As neither the FEV or Lotus studies include fuel, it has been removed for the calculations in this review of the NHTSA study

higher costs and limitations in terms of manufacturing and assembly. Recyclability was also noted as an issue, with multiple aluminium grades and multi-material approaches requiring separation of material at the end-of-life.

The other two options looked at were a full AHSS approach and an AHSS body structure with aluminium roof panel and glass fibre reinforced floor. This second approach was deemed to carry risks of not being compatible with high volume production, partly due to the un-conventional joining methods required for such a body. The selected option was that of maximising use of AHSS, using multiple grades of steel so as to select the best option in terms of strength and formability. This differs from the US EPA approach which involved optimisation based on three variables: gauge (thickness of part), grade (material grade) and geometry (part shape). The US EPA study made less use of high strength steels, more often simply opting for thinner gauges to achieve weight reductions. However the continuing importance of steel for body structures is clear, with all the studies reviewed selecting various grades as being affordable, effective choices for reducing weight while maintaining strength and safety, and meeting manufacturing requirements.

Closures, fenders & bumpers

The original closures and fenders were produced mainly from stamped steel. Aluminium stamping instead of steel was chosen for the front and rear doors (as used on Audi A6, A8 and BMW 5 series vehicle currently in high volume production), as well as the bonnet and boot lid. Although more costly per kg saved than using AHSS, it was felt the additional mass savings (over three times as much) made this option the most desirable. The stamping process remains the same as used for the baseline steel doors. This is the same option as used on the low development Lotus vehicle. MuCell plastic was selected for the interior trim of the doors.

Aluminium stamping was also chosen for the fenders over other options including a plastic composite, with the report noting “mass savings of aluminium versus plastic fenders were also verified in a 2011 Mercedes-Benz study for the SLK roadster”. Aluminium stamping was thus chosen across all three studies (low development for the Lotus study) and with examples of high volume vehicles already in production using such designs it can be seen that such a change is likely to occur in more cars in the future.

For the bumpers AHSS offered a greater mass saving than aluminium. AHSS is a more expensive material than the steel used in the baseline vehicle. However the reduced amount of material required due to its greater strength results in little or no cost increase.

Interior

As in in the US EPA study, aluminium was chosen to replace copper for much of the wiring. Also as with both the US EPA and Lotus studies, MuCell was used extensively to replace conventional plastic mouldings, such as parts of the instrument panel, trim, wiring harnesses and lighting systems. The study does highlight that it is not suitable for Class-A surfaces (those needing to have the highest quality surface finish) as the finish is not quite as smooth as standard plastics. For this reason it was decided that MuCell would not be used on surfaces visible to the consumer in this study. However the study notes that the manufacturer, Trexel, is working to improve the surface appearance, and MuCell is used in current production for the Ford Escape / Kuga instrument panel moulding (which is visible to the consumer).

Seating options were based on supplier expertise due to the complications arising for such a study in dealing with safety standards related to seating. Three options depending on generation of vehicle were stated, with the Generation 3 (2018-2020) using composite structural components, lightweight plastics, as well as the lighter foams and aluminium usage. Expected weight savings for this generation of seating over the front and rear seats is 20 kg, a saving of nearly 30% over the current mass of the seats.

Magnesium was used for the Instrument Panel beam replacing the current steel beam, again the same option as selected in the US EPA study. The main savings in the interior are summarised below in Table A5-2. As can be seen the use of MuCell is expected to be cost neutral while still offering reasonable savings of 13 kg.

Table A5-2: Summary of interior mass reductions and associated costs

Subsystem	Base (kg)	Mass reduction (kg)	Cost ($)
Seats	66.77	20.03	96.84
Plastic replaced with MuCell	69.95	13.03	0
Instrument panel beam	11.88	5.38	15.43
Audio system	2.00	0.79	0
Totals	**150.6**	**39.23**	**112.27**

Powertrain & engine

The weight reduction of the vehicle allowed for secondary downsizing in many areas. Rather than taking an approach of individual analysis, the NHTSA study replaced many systems in the Accord with lighter components taken from the Honda Civic. The engine, transmission, braking, battery, steering and radiator systems were all directly replaced with the smaller Civic components while maintaining equal performance to the baseline Accord model. This includes the downsizing of the engine from a baseline 2.4L engine to the naturally aspirated 1.8L Accord engine, while maintaining an equal power to weight ratio.

As a contrast to the US EPA and Lotus study, this highlights that redesign or new materials are not always required, and that secondary systems from other current production models can be used. Cost savings from reduced material usage in these smaller components apply, without any of the negative costs associated with retooling or introducing new processes. The mass savings from the use of Civic parts totalled 84.3 kg (25.7% of the overall mass reduction) while achieving estimated cost savings of $138.50. The savings in various subsystems due to downsizing to Honda Civic parts are detailed below in Table A5-3.

Table A5-3: Summary of mass reductions and costs by subsystem for those replaced by downsized Honda Civic parts

System	Base (kg)	Mass reduction (kg)	Cost reduction ($)
Suspension	16.66	3.75	0
Braking	30.92	10.57	23.45
Powertrain	111.90	31.40	72.58
Engine	184.69	30.49	31.31
Exhaust	20.75	1.75	3.97
Steering	22.80	5.25	7.20
Electrical Distribution and Electronic Control	12.40	1.10	0
Totals	**400.12**	**84.31**	**138.51**

Savings in the suspension due to downsizing and replacement of steel with both AHSS and aluminium accounted for a saving of 53.3 kg against an original mass of 134.6 kg, a saving of nearly 40%. This was calculated as having a total cost of only $33 due to savings made through reduced material usage. One of the greatest savings in this area was with the rear suspension K-frame and reinforcement, where steel was replaced with downsized aluminium parts, as used on the current production Audi A8.

Appendix 6: Comparison of the impacts and costs of using mass and footprint as a utility parameter – impacts on CO_2 emissions of replacing the NEDC with the WLTP

The aim of the translation of NEDC CO_2 emissions values to WLTP values was to replicate, as far as is possible, the conditions post 2020 in which any CO_2 regulatory regime for light duty vehicles will operate. As a more detailed and comprehensive translation from NEDC to WLTP values is being undertaken in another project, the values shown here should be taken only as a first approximation of the impact of translating CO_2 emissions values from the NEDC to the WLTP. TU Graz's PHEM simulation model was used for this purpose; a series of simulations for various vehicle sizes and powertrains were performed to identify CO_2 emissions values under the WLTP.

The key elements of this approach were as follows:

- PHEM simulations for 13 different vehicle models were set up to represent typical vehicle models from the following segments: conventional passenger cars from each of the A to E segments; multi-purpose vehicles from the BM and CM segments; and crossover vehicles in the CX and EX segments.
- Six different generic engine maps were used representing small, medium and large petrol and diesel engines. Manual transmission was modelled.
- Simulations were run for each vehicle on the NEDC and then again on the WLTP.
- For the B, C and E segment models, simulations were also run examining the impact of 10%, 20% and 30% vehicle weight reduction on both NEDC and WLTP tests. Engine power and gearing were adjusted to maintain equivalent full load performance.
- NEDC test simulations were primarily conducted *without* use of inertia classes to avoid artefacts created from jumps in inertia class when reducing vehicle mass. Instead vehicles were tested at their unladen mass plus 100 kg. Simulations were also run to check the impact of using inertia classes.
- For WLTP tests, due to changes in the test procedure compared to NEDC, rolling resistance was assumed to be 15% higher and aerodynamic drag assumed to be 5% higher.

The main findings of the simulations are presented in the tables overleaf. Table A6-1 shows that under NEDC test conditions, vehicle mass reduction delivers a greater reduction in fuel consumption when actual vehicle mass is used in the test procedure (as is the case in the WLTP) rather than using inertia classes as a proxy for vehicle mass (as is the case in the NEDC).

However, it must be remembered that for the NEDC simulations, we did not make use of the inertia classes that are used in real-world NEDC tests. In the NEDC test, actual vehicle mass is not used to simulate road loads on the chassis dynamometer used for conducting such tests. Instead, vehicles are assigned to one of a standard set of "inertia classes", with each inertia class covering a set range of actual vehicle mass values. This means that reductions in actual vehicle mass may not lead to improvements in CO_2 emissions and fuel consumption under the NEDC test procedure because the inertia class used to simulate road loads in the test procedure may not have changed. For example, from our PHEM simulation work, the percentage reductions in CO_2 emissions and fuel consumption that result from reducing vehicle mass are, in general, lower when inertia classes (as opposed to actual vehicle mass values) are used as the basis for road loads. This can be seen from the analysis of simulation results in the table below which presents the percentage change in fuel consumption divided by percentage change in mass for each vehicle simulated using (a) inertia classes and (b) actual vehicle mass values.

Table A6-1: Comparison of changes in fuel consumption in the NEDC in relation to changes in vehicle mass based on (a) actual vehicle mass and (b) inertia classes

Powertrain	Segment	Ratio: Percentage change in fuel consumption divided by percentage change in mass	
		NEDC simulation based on inertia classes	NEDC simulation based on actual vehicle mass
Petrol	A	0.669	0.672
	B	0.647	0.696
	BM	0.558	0.672
	C	0.544	0.656
	D	0.558	0.672
	E	0.561	0.665
Diesel	B	0.609	0.656
	C	0.857	0.700
	CM	0.704	0.699
	CX	0.587	0.699
	D	0.529	0.699
	E	0.638	0.742
	EX	0.685	0.699
Average		**0.63**	**0.69**

Based on these results, it can be inferred that on average, a 10% reduction in vehicle mass will give a 6.3% reduction in fuel consumption under the NEDC when inertia classes are used and a 6.9% reduction in fuel consumption when actual vehicle mass is used.

Appendix 7: Assessment of long-list of options against the conditions

Table A7-1: How might the options meet the conditions?

Key:	Condition would be met: ✓	Condition would not necessarily be met: ?	Condition would not be met: ×

	1. Deliver net CO_2 emissions reductions	**2. Reduce average mass of the new vehicle fleet**	**3. NOT provide benefits for applying technologies that would have been introduced anyway**	**4. Be clearly defined and verifiable**	**Other risks**	**Take forward as an option to incentivise mass reduction (if mass retained as the utility parameter)?**
A. Less stringent target for applying specified weight reduction technologies	× A weaker target would not lead to net CO_2 emissions reductions.	× There is nothing to guarantee that the average mass, or the mass of specific vehicles, would decline.	? This condition would be satisfied, as long as 'specified weight reduction' technologies would not otherwise have been applied. However, it is difficult to see what such a technology might be in practice.	? This condition would be satisfied, as long as relevant technologies can be sufficiently clearly specified (and therefore verified that they have been applied). However, it is difficult to see what such a technology might be in practice.	Potential to skew manufacturers' CO_2 reduction strategies in favour of the specified weight reduction technologies. Could not be considered to be technology-neutral.	Overall, these options are probably not feasible. The 'weaker' target option is only really workable (as it does not meet most of the conditions) if used with the 'more stringent' target option. However, the main challenge with both of these options is to identify the specified technologies to which they would apply, in particular to identify those that would not have been introduced anyway.

	1. Deliver net CO_2 emissions reductions	2. Reduce average mass of the new vehicle fleet	3. NOT provide benefits for applying technologies that would have been introduced anyway	4. Be clearly defined and verifiable	Other risks	Take forward as an option to incentivise mass reduction (if mass retained as the utility parameter)?
B. More stringent target for not applying specified weight reduction technologies	✓ A more stringent target would deliver net CO_2 emissions reductions.	? As it would not guarantee that the average mass, or the mass of specific vehicles, would decline. However, the increased stringency of the target would make mass reduction more likely.	? This condition would be satisfied, as long as 'specified weight reduction' technologies would not otherwise have been applied. However, it is difficult to see what such a technology might be in practice. (The 'benefit' would not be having a more stringent target.)	"Specified weight reduction technologies" might include fitting specified lightweight components, such as fuel tanks, doors or bonnets in all appropriate vehicles, or using a certain proportion of lightweight materials (e.g. high strength steels) across the fleet. However, for all of these, determining which technologies are able to count towards the benefit will be problematic and administratively complex.	Would probably be considered to be too much in the way of market interference, as it would dictate the weight reduction technologies to be used. Could not be considered to be technology-neutral.	It would not make sense to include options that are cost-effective unless perhaps no manufacturer had implemented introduced the technology. However, this would suggest that there are wider issues with the technology. If other manufacturers are applying the technology, it would be unfair to reward those that are not (and would also not meet condition 3). Hence, arguably the most appropriate focus of these options would be technologies that are not yet cost-effective. However, many issues still remain, not least in determining which technologies, or extent (i.e. %) of lighter materials, is not yet cost-effective and so should be rewarded..

	1. Deliver net CO_2 emissions reductions	2. Reduce average mass of the new vehicle fleet	3. NOT provide benefits for applying technologies that would have been introduced anyway	4. Be clearly defined and verifiable	Other risks	Take forward as an option to incentivise mass reduction (if mass retained as the utility parameter)?
C. Weight reduction credits for vehicles weighing less than a certain amount	? The potential to gain credits for weight reduction would reduce the incentive to reduce CO_2 emissions, as less CO_2 reduction would be needed as a result of the credits. However, the fact that these would only be given for lighter vehicles could deliver net CO_2 emissions reductions.	? The credits are directly linked to lighter vehicles, so it would ensure that the mass of the respective vehicles at least remained less than the specified amount. However, it would not guarantee that the average mass would decline.	? There is the potential that a credit could be awarded for the application of technologies that would have been introduced anyway.	✓ As option linked to a vehicle's mass, which is measured in the course of type approval, and reported. No need to specify specific technologies.	Would not cover the entire fleet, but would focus attention on weight reduction technologies for those vehicles that have the potential to reach the 'mass target'. The extent to which this would make weight reduction no less attractive as other CO_2 options would require detailed analysis. Not clear on what criteria the choice of mass under which vehicles would receive the credit might be based, as no mass is intrinsically better than any other.	Overall, this option is probably not desirable, as it does not meet many of the conditions.

	1. Deliver net CO_2 emissions reductions	2. Reduce average mass of the new vehicle fleet	3. NOT provide benefits for applying technologies that would have been introduced anyway	4. Be clearly defined and verifiable	Other risks	Take forward as an option to incentivise mass reduction (if mass retained as the utility parameter)?
D. Weight reduction credits for manufacturers demonstrating a downward mass trend (on the sales-weighted average)	? The potential to gain credits for weight reduction would reduce the incentive to reduce CO_2 emissions (as above), but the condition that there is a downward trend in mass could deliver net CO_2 emissions reductions across the fleet.	✓ The condition would not necessarily be met at the level of an individual vehicle. However, the guarantee of a downward trend would deliver mass reduction on average.	? There is the potential that a credit could be awarded for the application of technologies that would have been introduced anyway.	✓ As mass trends for each manufacturer can be calculated on the basis of the information on mass measured in the course of type approval. No need to specify specific technologies.	Equity re early movers. Rather uncertain as credits can only be given at the end of the period. The extent to which this would make reducing weight no less attractive as other CO_2 options would require detailed analysis. It would be important to clearly define what constitutes a “trend”. This would have to be sustained, rather than an anomaly.	The option has the potential to deliver lower emissions, if designed appropriately, as otherwise there is a risk of perverse incentives. Hence, it should be explored further.

	1. Deliver net CO_2 emissions reductions	2. Reduce average mass of the new vehicle fleet	3. NOT provide benefits for applying technologies that would have been introduced anyway	4. Be clearly defined and verifiable	Other risks	Take forward as an option to incentivise mass reduction (if mass retained as the utility parameter)?
E. Weight reduction credits for vehicles using a specified weight reduction technology	✗ The potential to gain credits for weight reduction would reduce the incentive to reduce CO_2 emissions (as above) and not deliver net emissions reductions.	✗ It would not guarantee that the average mass, or the mass of specific vehicles, would decline.	✓ As long as 'specified weight reduction' technologies would not otherwise have been applied.	✓ as long as relevant technologies can be sufficiently clearly specified (and therefore verified that they have been applied).	Potential to skew manufacturers' CO_2 reduction strategies in favour of the specified weight reduction technologies. Risks not being considered to be technology-neutral.	This option has the same challenge as options A and B. Hence, the option is probably not desirable for the same reasons.

	1. Deliver net CO_2 emissions reductions	2. Reduce average mass of the new vehicle fleet	3. NOT provide benefits for applying technologies that would have been introduced anyway	4. Be clearly defined and verifiable	Other risks	Take forward as an option to incentivise mass reduction (if mass retained as the utility parameter)?
F. Banking of CO_2 emissions reductions allowed where an annual target is exceeded and where downward mass trend is demonstrated (on the sales-weighted average)	? Marginally reduces incentive for CO_2 emissions reductions, as overachievement can be banked, whereas otherwise it would 'not count'. However, the condition that there is a downward trend in mass could deliver net CO_2 emissions reductions across the fleet.	✓ The condition would not necessarily be met at the level of an individual vehicle. However, the guarantee of a downward trend would deliver mass reduction on average.	? There is the potential that a credit could be awarded for the application of technologies that would have been introduced anyway.	✓ as average mass for each manufacturer can be calculated on the basis of the information measured in the course of type approval. No need to specify specific technologies.	Equity re early movers. Rather uncertain as the benefit can only be given at the end of the period. The extent to which this would make weight reduction no less attractive as other CO_2 options would require detailed analysis. It would be important to clearly define what constitutes a "trend". This would have to be sustained, rather than an anomaly.	The option has the potential to deliver lower emissions, if designed appropriately, as otherwise there is a risk of perverse incentives. Hence, it should be explored further.

	1. Deliver net CO_2 emissions reductions	2. Reduce average mass of the new vehicle fleet	3. NOT provide benefits for applying technologies that would have been introduced anyway	4. Be clearly defined and verifiable	Other risks	Take forward as an option to incentivise mass reduction (if mass retained as the utility parameter)?
G. Link targets to mass by setting less stringent targets for lighter vehicles, e.g. by introducing a floor that affects only the lightest vehicles	× A more lenient target would reduce the need, and therefore the incentive, to reduce CO_2 emissions. However, the fact that these would only be given for lighter vehicles could increase net CO_2 emissions.	× As would not guarantee that the average mass, or the mass of specific vehicles, would decline.	? There is the potential that a more lenient target could be set for the case where technologies that would have been introduced anyway are applied.	✓ As option linked to a vehicle's mass, which is measured in the course of type approval. No need to specify specific technologies.	Equity problem as not all manufacturers are in the market for smaller or larger cars. Will only impact a small proportion of vehicles. The extent to which this would make weight reduction no less attractive as other CO_2 options would require detailed analysis. It would be important to ensure that the ceiling is set at the appropriate level. Previous analysis has suggested that in the European car market, floors and ceilings only have significant impacts if they are set at unreasonable levels[16].	Most of the conditions would not be met, while there is a risk that it will encourage manufacturers to focus on weight reduction some cars rather than on overall CO_2 reduction (as with option C). Hence, reject the option, unless it is combined with option H.

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[16] TNO *et al* (2011) *Support for the revision of Regulation (EC) No 443/2009 on CO2 emission from cars*, Service request #1 under Framework Contract on Vehicle Emissions No ENV.C.3/FRA/2009/0043; http://ec.europa.eu/clima/policies/transport/vehicles/cars/docs/study_car_2011_en.pdf

	1. Deliver net CO_2 emissions reductions	2. Reduce average mass of the new vehicle fleet	3. NOT provide benefits for applying technologies that would have been introduced anyway	4. Be clearly defined and verifiable	Other risks	Take forward as an option to incentivise mass reduction (if mass retained as the utility parameter)?
H. Link targets to mass by setting more stringent targets for heavier vehicles, e.g. by setting a ceiling that affects only the heaviest vehicles	✓ Condition would be met, as the vehicles affected by the ceiling would be subject to a more stringent target.	? Would not guarantee that the average mass, or the mass of specific vehicles, would decline, although the more stringent the target the greater the chance of mass reduction.	? There is a risk that the benefit would be granted for technologies that would have been applied anyway. However, the more stringent targets would increase the chance of some technologies being introduced that would not otherwise have been applied. (The 'benefit' would be not having a more stringent target.)	✓ As option linked to a vehicle's mass, which is measured in the course of type approval. No need to specify specific technologies.	Equity problem as not all manufacturers are in the market for smaller or larger cars. Will only impact a small proportion of vehicles. The extent to which this would make weight reduction no less attractive as other CO_2 options would require detailed analysis. It would be important to ensure that the ceiling is set at the appropriate level. Previous analysis has suggested that in the European car market, floors and ceilings only have significant impacts if they are set at unreasonable levels	Setting more stringent targets (than otherwise would have been the case) for heavier cars would focus affected manufacturers' attention on the mass of such vehicles. While there is a risk that this would distract them from wider CO_2 reduction, this is lessened as only a relatively small sub-set (the heaviest) of vehicles would be covered. However, this would not guarantee an overall mass reduction, as smaller vehicles could increase in mass. Could be used in conjunction with Option G. Retain for further consideration combined with Option G.

	1. Deliver net CO_2 emissions reductions	2. Reduce average mass of the new vehicle fleet	3. NOT provide benefits for applying technologies that would have been introduced anyway	4. Be clearly defined and verifiable	Other risks	Take forward as an option to incentivise mass reduction (if mass retained as the utility parameter)?
I. Weight reduction credits (and debits) for vehicles having a ‘density’[17] of less (more) than a certain amount (compared to the overall average fleet density)	? The lower ‘density target’ could be achieved by either reducing mass or increasing footprint (or a combination of these two). The potential to gain credits for less ‘dense’ vehicles would reduce the incentive to reduce CO_2 emissions, as less CO_2 reduction would be needed as a result of the credits. However, the fact that these would only be given for less ‘dense’ vehicles could deliver net CO_2 emissions reductions. The debits would have a small positive effect on CO_2 emissions reductions	? The credits are directly linked to less dense vehicles, which is unlikely to be achieved completely by increasing footprint. Hence, it should ensure that the mass of the respective vehicles remains relatively low. The debits would have a small positive effect in reducing mass. However, together they would not guarantee that the average mass would decline.	? There is the potential that a credit could be awarded for the application of weight reduction technologies that would have been introduced anyway.	✓ As option linked to a vehicle’s mass and footprint, which are measured in the course of type approval, and reported. No need to specify specific technologies.	Would not cover the entire fleet, but would focus attention on weight reduction technologies (or measures to increase the footprint of) vehicles that have the potential to reach the ‘density targets’. The extent to which this would make weight reduction no less attractive as other CO_2 options would require detailed analysis. Not clear on what criteria the choice of ‘density’ under which vehicles would receive the credit might be based (and similarly for the debits), as no density is intrinsically better than any other.	Overall, this option is probably not desirable, as it does not meet many of the conditions.

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[17] ‘Density’ is used to refer to mass over footprint, so it is measured in kg/m^2

	1. Deliver net CO_2 emissions reductions	2. Reduce average mass of the new vehicle fleet	3. NOT provide benefits for applying technologies that would have been introduced anyway	4. Be clearly defined and verifiable	Other risks	Take forward as an option to incentivise mass reduction (if mass retained as the utility parameter)?
J. Weight reduction credits for vehicles having a 'density' of less than a certain amount (compared to other vehicles of their size/mass)	? The lower 'density target' could be achieved by either reducing mass or increasing footprint (or a combination of these two). The potential to gain credits for less 'dense' vehicles would reduce the incentive to reduce CO_2 emissions, as less CO_2 reduction would be needed as a result of the credits. However, the fact that these would only be given for less 'dense' vehicles could deliver net CO_2 emissions reductions. The debits would have a small positive effect on CO_2 emissions reductions.	? The credits are directly linked to less dense vehicles, which is unlikely to be achieved completely by increasing footprint. Hence, it should ensure that the mass of the respective vehicles remains relatively low. The debits would have a small positive effect in reducing mass. However, together they would not guarantee that the average mass would decline.	? There is the potential that a credit could be awarded for the application of weight reduction technologies that would have been introduced anyway.	✓ As option linked to a vehicle's mass and footprint, which are measured in the course of type approval, and reported. No need to specify specific technologies.	Would not cover the entire fleet, but would focus attention on weight reduction technologies (or measures to increase the footprint of) vehicles that have the potential to reach the respective 'density targets'. There would be many potential interplays when comparing average densities against vehicles of a similar mass or footprint, all of which would need to be explored in order to ensure that there are no perverse incentives.	Overall, this option is probably not desirable, as it does not meet many of the conditions. Furthermore, it would be more complex than Option I, which risks perverse incentives.

	1. Deliver net CO_2 emissions reductions	**2. Reduce average mass of the new vehicle fleet**	**3. NOT provide benefits for applying technologies that would have been introduced anyway**	**4. Be clearly defined and verifiable**	**Other risks**	**Take forward as an option to incentivise mass reduction (if mass retained as the utility parameter)?**
K. Weight reduction credits (and debits) for vehicles based on their ‘density’ relative to the overall average ‘density’	✓ A credit (or debit) would be given to a vehicle related to how its ‘density’ compared to the average: a credit (debit) would be given to a vehicle with a ‘density’ less (more) than average. The potential to gain credits for less ‘dense’ vehicles would be balanced by the debits for denser vehicles. Together, these could be designed to deliver net CO_2 emissions reduction.	✓ The credits and debits are directly linked to the density of vehicles to which differences in mass will contribute (although increasing footprint could also have a role to play). If balance of credits/debits designed appropriately, could reduce the mass of individual vehicles, as well as the average mass.	? There is the potential that a credit could be awarded for the application of weight reduction technologies that would have been introduced anyway.	✓ As option linked to a vehicle’s mass and footprint, which are measured in the course of type approval, and reported. No need to specify specific technologies.	The extent to which this would make weight reduction no less attractive as other CO_2 options would require detailed analysis. It would be important to ensure that the credits and debits are set to ensure that there is an incentive to reduce CO_2 emissions and that mass declines. However, there is a risk of perverse incentives, so the interplay between mass reduction and footprint increase with respect to benefiting from credits would need to be explored.	The extent to which this option will meet the conditions depends on its design and on the exploration of whether there is a risk of perverse or unintended consequences. Retain for further assessment.

	1. Deliver net CO_2 emissions reductions	2. Reduce average mass of the new vehicle fleet	3. NOT provide benefits for applying technologies that would have been introduced anyway	4. Be clearly defined and verifiable	Other risks	Take forward as an option to incentivise mass reduction (if mass retained as the utility parameter)?
L. Strengthening the target overall, i.e. lowering the overall target compared to what it otherwise would have been	✓ A more stringent overall target would deliver net CO_2 emissions reductions.	? It would not guarantee that the average mass, or the mass of specific vehicles, would decline although the more stringent the target the greater the chance that there would be a mass reduction.	? There is no additional ‘benefit’ in this option – all manufacturers will have a more stringent target.	✓ As emissions can be measured in the course of type approval. No need to specify specific technologies.	Would not be technology-neutral, as would maintain the current disincentive for weight reduction technologies. It would also be difficult to justify a more stringent target, as the retention of mass as the utility parameter would make targets more costly than would a target using footprint.	Reject option, as it does not make weight reduction no less attractive an option as other CO_2 reduction technologies. While the options would be the least complicated and interfere least in the market it would not be technology-neutral, as it would retain the status quo in which mass reduction is relatively less attractive than other CO_2 reduction technologies. Additionally as ‘mass’ will have been retained as the utility parameter, weight reduction technologies would appear to be less cost-effective to manufacturers, thus reducing the likelihood that this option could be justified by an Impact Assessment.

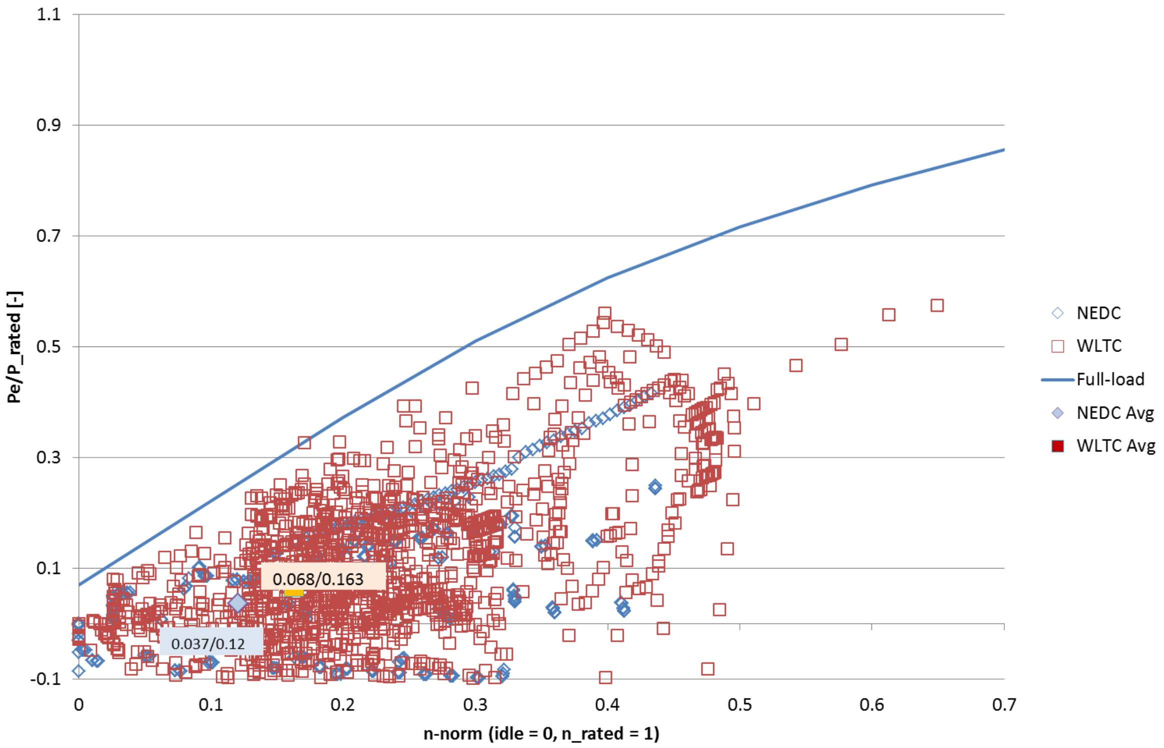
Appendix 8: Cost cloud analysis

List of technical options

A full list of technical options can be found in Table A8-1 and Table A8-2. This list is largely based on the list from TNO et al (2011) however the following modifications have been made:

1. **NEDC to WLTP** – As mentioned, previous CO_2 reduction potentials for different technologies were based on the NEDC testing procedure so it was necessary for this study to update these potentials based on the new WLTP. This was performed using the PHEM model. Differences in the fuel saving effects due to engine technology are mainly related to the different load points for a vehicle in the NEDC and in the WLTP. Figure A8-1 below shows the load points a C-segment car under the NEDC and under the WLTP. The WLTP covers a broader range of load points than the NEDC. This leads to the effect that technologies with higher fuel saving potential at lower engine loads than at higher loads have lower overall CO_2 reduction effects under the WLTP than they do under the NEDC.

Figure A8-1: Engine load points in the NEDC and in the WLTC for the segment C car. Each dot represents one second in the cycle



The simulation was carried out for all technologies using the same approach:

a. The fuel consumption was simulated for NEDC and for WLTP for baseline C-segment petrol and diesel cars (i.e. those without additional CO_2 abatement technologies).
b. The same simulations for both the NEDC and WLTP were repeated but with the engine map (or Willans equation) from the technology under consideration.
c. The ratio of the CO_2 reductions compared to the the baseline results were used to calculate the conversion factor CF = $\Delta FC_{WLTC} / \Delta FC_{NEDC}$

2. ***Updating of down weighting costs*** – Following on from the stakeholder consultation process of this study it was concluded that the costs used in TNO *et al* (2011) were too high. Weight reduction costs used in this study were therefore revised using the lower costs detailed in Appendix E of TNO *et al* (2011) but uplifted by 25%. This resulted in the cost of a 20% weight reduction for a medium car becoming EUR 250 and a large car becoming EUR 300. This approach was based on expert judgement as well as stakeholder opinion. Similarly, the costs of weight reduction for light commercial vehicles were also revised. These were calculated by taking the ratio of new and old costs for cars and applying this to the previous costs for light commercial vehicles detailed in the study for the European Commission (EC, 2012).[18] Revised costs for a 20% weight reduction varied between EUR 409 for small vans to EUR 886 for large vans.
3. ***Inclusion of REEV and EV for passenger cars*** – Unlike TNO et al (2011), the range extender technology has been included in the evaluation of the cost curve for passenger cars. This was decided under the assumption that in 2025 this technology will see a greater uptake of use and in ignoring it in this study; the possible post 2020/21 targets would become unattainable. An EV technology was also included but not used in defining the cost curve. This was included to illustratively show the cost of reaching 100% CO_2 reduction.
4. ***Removal of ineffectual technologies*** – TNO *et al* (2011) analysed a maximum of 29 different technology options in their analysis. Due to the scope and constraints of this work it was decided to reduce this down to a maximum of 26. This vastly decreases the high computational time of running the cost cloud tool. It was therefore ensured that technologies that were removed were of little to no significance of the final cost curve (i.e. packages including these technologies would not sit to the outer envelope of the cloud).
5. ***Re-evaluation of range extender CO_2 reduction potential and costs and EV costs*** – Reduction potential and costs for the range extender technology was reviewed as they were deemed inaccurate. Comparing existing range extender vehicles with their conventional equivalents yielded between 60%-79% reduction in CO_2 (previous work in this respect had that figure at 45%). Costs for range extenders and EVs were also reviewed. Recent work by Ricardo-AEA for TfL had improved estimates for the additional cost of these technologies. See Table A8-1 and Table A8-2 for details.

It should be noted here that a study to look at costs and reduction potential of the full list of technical options used in this study (and more) has recently been outlined by the European Commission. In light of this, learning rates have not been taken into account in this analysis as this work will be repeated in more detail in the near future. The purpose of this analysis is to simply look at the effect on manufacturers of the two utility parameters in an illustrative sense.

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[18] EC (2012) 'Support for the revision of regulation on CO2 emissions from light commercial vehicles', available at: http://ec.europa.eu/clima/policies/transport/vehicles/vans/docs/report_co2_lcv_en.pdf

Table A8-1: Costs and WLTP-based CO_2 reductions for passenger car technical options

Technology Name	Small, Petrol		Medium, Petrol		Large, Petrol		Small, Diesel		Medium, Diesel		Large, Diesel	
	Potential CO_2 Reduction (%)	Additional Cost (Euros)	Potential CO_2 Reduction (%)	Additional Cost (Euros)	Potential CO_2 Reduction (%)	Additional Cost (Euros)	Potential CO_2 Reduction (%)	Additional Cost (Euros)	Potential CO_2 Reduction (%)	Additional Cost (Euros)	Potential CO_2 Reduction (%)	Additional Cost (Euros)
Tyres: low rolling resistance	4.4%	30	4.4%	35	4.4%	40	4.4%	30	4.4%	35	4.4%	40
Low friction design and materials	1.4%	35	1.4%	35	1.4%	35	▨	▨	▨	▨	▨	▨
Reduced driveline friction	1.2%	50	1.2%	50	1.2%	50	1.2%	50	1.2%	50	1.2%	50
Aerodynamics improvement	3.0%	50	3.0%	50	2.3%	60	3.0%	50	3.0%	50	2.3%	60
Gas-wall heat transfer reduction	2.9%	50	2.9%	50	2.9%	50	▨	▨	▨	▨	▨	▨
Optimising gearbox ratios / downspeeding	0.8%	60	0.8%	60	0.8%	60	0.6%	60	0.6%	60	0.6%	60
Cam-phasing	3.0%	80	3.0%	80	3.0%	80	▨	▨	▨	▨	▨	▨
Mild hybrid - torque boost for downsizing	16.7%	1400	16.7%	1500	16.7%	1500	12.2%	1400	12.2%	1500	12.2%	1500
Start-stop hybridisation	2.0%	175	2.0%	200	2.0%	225	1.6%	175	1.6%	200	1.6%	225
Direct injection-homogeneous	4.5%	180	5.0%	180	5.5%	180	▨	▨	▨	▨	▨	▨
Thermodynamic cycle improvements e.g. split cycle PCCI/HCCI CAI	12.0%	475	12.9%	475	13.8%	500	▨	▨	▨	▨	▨	▨
Mild downsizing (15% cylinder content reduction)	2.7%	200	3.4%	250	4.1%	300	2.7%	50	2.7%	50	2.7%	50
Variable valve actuation and lift	4.0%	280	4.4%	280	4.8%	280	0.4%	280	0.4%	280	0.4%	280

Technology Name	Small, Petrol		Medium, Petrol		Large, Petrol		Small, Diesel		Medium, Diesel		Large, Diesel	
	Potential CO_2 Reduction (%)	Additional Cost (Euros)	Potential CO_2 Reduction (%)	Additional Cost (Euros)	Potential CO_2 Reduction (%)	Additional Cost (Euros)	Potential CO_2 Reduction (%)	Additional Cost (Euros)	Potential CO_2 Reduction (%)	Additional Cost (Euros)	Potential CO_2 Reduction (%)	Additional Cost (Euros)
Automated manual transmission	5.0%	300	5.0%	300	5.0%	300	4.0%	300	4.0%	300	4.0%	300
Full hybrid - electric drive	26.4%	2250	26.4%	2750	26.4%	3750	23.2%	2250	23.2%	2750	23.2%	3750
Micro hybrid - regenerative braking	8.2%	325	8.2%	375	8.2%	425	7.0%	375	7.0%	375	7.0%	375
Medium downsizing (30% cylinder content reduction)	4.8%	400	5.5%	435	6.2%	510	4.8%	400	4.8%	450	4.8%	500
Direct injection-stratified charge	6.9%	400	7.3%	500	7.7%	600	▨	▨	▨	▨	▨	▨
Strong downsizing (>=45% cylinder content reduction)	10.9%	550	11.6%	600	12.3%	700	10.3%	500	10.3%	600	10.3%	700
Dual clutch transmission	6.0%	650	6.0%	700	6.0%	750	5.0%	650	5.0%	700	5.0%	750
Mild weight reduction	6.3%	31	6.4%	39	6.4%	48	5.8%	31	6.2%	39	7.1%	48
Medium weight reduction	12.6%	200	12.5%	250	12.6%	300	11.5%	200	12.8%	250	14.2%	300
Strong weight reduction	18.9%	738	18.9%	923	19.0%	1106	17.7%	738	19.0%	923	21.3%	1106
Auxiliary systems efficiency improvement	12.0%	420	12.0%	440	12.0%	460	11.0%	420	11.0%	440	11.0%	460
Range extender	77.9%	9095	77.9%	10106	77.9%	11117	63.0%	8544	63.0%	9493	63.0%	10443
EV	100.0%	17728	100.0%	19698	100.0%	21668	100.0%	16954	100.0%	18838	100.0%	20722

Table A8-2: LCV technical options

Technology Name	Small, Diesel		Medium, Diesel		Large, Diesel	
	Potential CO_2 Reduction (%)	Additional Cost (Euros)	Potential CO_2 Reduction (%)	Additional Cost (Euros)	Potential CO_2 Reduction (%)	Additional Cost (Euros)
Optimising gearbox ratios / downspeeding	0.2%	0	0.0%	0	0.0%	0
Improved M/T Transmission	0.5%	0	0.0%	0	0.0%	0
Mild weight reduction	6.1%	38	5.7%	45	5.6%	83
Mild downsizing (15% cylinder content reduction)	2.7%	50	2.7%	50	2.1%	50
Aux thermal systems improvement	2.5%	70	2.8%	80	3.2%	80
Medium downsizing (30% cylinder content reduction)	4.8%	290	4.8%	290	4.1%	170
Combustion improvements	2.9%	90	2.9%	90	2.9%	90
Aux system improvements (lubrication, vacuum, FIE)	2.8%	85	3.5%	100	3.7%	115
Dual clutch transmission	4.0%	900	5.0%	1100	▨	▨
Downspeeding	0.6%	120	0.6%	120	0.6%	120
Start-stop hybridisation	1.6%	175	1.6%	200	2.0%	225
Variable valve actuation and lift	▨	▨	0.4%	50	0.4%	50
Micro hybrid - regenerative braking	7.0%	350	8.2%	375	9.3%	400
Tyres: low rolling resistance	5.9%	150	7.4%	200	7.4%	300
Aerodynamics improvement	2.3%	50	3.0%	100	2.3%	100
Medium weight reduction	6.1%	409	5.7%	477	5.6%	886
Automated manual transmission	6.0%	300	6.0%	300	6.0%	500
Reduced driveline friction - major	3.6%	210	3.6%	220	3.6%	250
Aerodynamics improvement	4.5%	150	4.5%	200	4.5%	250
Reduced driveline friction - minor	1.2%	80	1.2%	80	1.2%	90
Mild hybrid - torque boost for downsizing	12.2%	1400	12.2%	1500	12.2%	1600
Full hybrid - electric drive	26.4%	2550	26.4%	3050	26.4%	4250
Strong weight reduction	17.7%	2046	16.1%	2385	17.2%	4429
Range extender	71.6%	8280	71.6%	9200	71.6%	10121
EV	100.0%	30000	100.0%	32000	100.0%	33000

Table A8-3: Passenger car technical options – exclusion criteria

Technology Name	Tyres: low rolling resistance	Low friction design and materials	Reduced driveline friction	Aerodynamics improvement	Gas-wall heat transfer reduction	Optimising gearbox ratios / downspeeding	Cam-phasing	Mild hybrid - torque boost for downsizing	Start-stop hybridisation	Direct injection- homogeneous	Thermodynamic cycle improvements e.g. split cycle PCCI/HCCI CAI	ild downsizing (15% cylinder content reduction	Variable valve actuation and lift	Automated manual transmission	Full hybrid - electric drive	Micro hybrid - regenerative braking	Medium downsizing (30% cylinder content reduction)	Direct injection- stratified charge	Strong downsizing (>=45% cylinder content reduction)	Dual clutch transmission	Mild weight reduction	Medium weight reduction	Strong weight reduction	Auxiliary systems efficiency improvement	Range extender	EV
Tyres: low rolling resistance	▨																									
Low friction design and materials		▨																								
Reduced driveline friction			▨																						X	X
Aerodynamics improvement				▨																						
Gas-wall heat transfer reduction					▨																					
Optimising gearbox ratios / downspeeding						▨																			X	X
Cam-phasing							▨						X													
Mild hybrid - torque boost for downsizing								▨	X						X	X									X	X
Start-stop hybridisation								X	▨						X	X									X	X
Direct injection- homogeneous										▨	X							X								
Thermodynamic cycle improvements e.g. split cycle PCCI/HCCI CAI										X	▨							X								
Mild downsizing (15% cylinder content reduction)												▨					X		X						X	X
Variable valve actuation and lift							X						▨													
Automated manual transmission														▨						X					X	X

Technology Name	Tyres: low rolling resistance	Low friction design and materials	Reduced driveline friction	Aerodynamics improvement	Gas-wall heat transfer reduction	Optimising gearbox ratios / downspeeding	Cam-phasing	Mild hybrid - torque boost for downsizing	Start-stop hybridisation	Direct injection- homogeneous	Thermodynamic cycle improvements e.g. split cycle PCCI/HCCI CAI	ild downsizing (15% cylinder content reduction	Variable valve actuation and lift	Automated manual transmission	Full hybrid - electric drive	Micro hybrid - regenerative braking	Medium downsizing (30% cylinder content reduction)	Direct injection- stratified charge	Strong downsizing (>=45% cylinder content reduction)	Dual clutch transmission	Mild weight reduction	Medium weight reduction	Strong weight reduction	Auxiliary systems efficiency improvement	Range extender	EV
Full hybrid - electric drive								X	X						▨	X									X	X
Micro hybrid - regenerative braking								X	X						X	▨									X	X
Medium downsizing (30% cylinder content reduction)												X					▨		X						X	X
Direct injection- stratified charge										X	X							▨								
Strong downsizing (>=45% cylinder content reduction)												X					X		▨						X	X
Dual clutch transmission														X						▨					X	X
Mild weight reduction																					▨	X	X			
Medium weight reduction																					X	▨	X			
Strong weight reduction																					X	X	▨			
Auxiliary systems efficiency improvement																								▨	X	X
Range extender			X					X	X			X		X	X	X	X		X	X				X	▨	X
EV			X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	▨

Table A8-4: LCV technical options – exclusion criteria

Technology Name	Optimising gearbox ratios / downspeeding	Improved M/T Transmission	Mild weight reduction	Mild downsizing (15% cylinder content reduction)	Aux thermal systems improvement	Medium downsizing (30% size reduction)	Combustion improvements	Aux system improvements (lubrication, vacuum, FIE)	Dual clutch transmission	Downspeeding	Start-stop hybridisation	Variable valve actuation and lift	Micro hybrid - regenerative braking	Tyres: low rolling resistance	Aerodynamics improvement	Medium weight reduction	Automated manual transmission	Reduced driveline friction - major	Aerodynamics improvement	Reduced driveline friction - minor	Mild hybrid - torque boost for downsizing	Full hybrid - electric drive	Strong weight reduction	Range extender	EV
Optimising gearbox ratios / downspeeding	▨									X														X	X
Improved M/T Transmission		▨							X								X							X	X
Mild weight reduction			▨													X							X		
Mild downsizing (15% cylinder content reduction)				▨		X																		X	X
Aux thermal systems improvement					▨																				X
Medium downsizing (30% cylinder content reduction)				X		▨																		X	X
Combustion improvements							▨																		X
Aux system improvements (lubrication, vacuum, FIE)								▨																	X
Dual clutch transmission		X							▨								X							X	X
Downspeeding	X									▨														X	X
Start-stop hybridisation											▨		X								X	X		X	X
Variable valve actuation and lift												▨													
Micro hybrid - regenerative braking											X		▨								X	X		X	X
Tyres: low rolling resistance														▨											
Aerodynamics improvement															▨										
Medium weight reduction			X													▨							X		

Technology Name	Optimising gearbox ratios / downspeeding	Improved M/T Transmission	Mild weight reduction	Mild downsizing (15% cylinder content reduction)	Aux thermal systems improvement	Medium downsizing (30% size reduction)	Combustion improvements	Aux system improvements (lubrication, vacuum, FIE)	Dual clutch transmission	Downspeeding	Start-stop hybridisation	Variable valve actuation and lift	Micro hybrid - regenerative braking	Tyres: low rolling resistance	Aerodynamics improvement	Medium weight reduction	Automated manual transmission	Reduced driveline friction - major	Aerodynamics improvement	Reduced driveline friction - minor	Mild hybrid - torque boost for downsizing	Full hybrid - electric drive	Strong weight reduction	Range extender	EV
Automated manual transmission		X							X								▨							X	X
Reduced driveline friction - major																		▨		X				X	X
Aerodynamics improvement																			▨						
Reduced driveline friction - minor																		X		▨				X	X
Mild hybrid - torque boost for downsizing											X		X								▨	X		X	X
Full hybrid - electric drive											X		X								X	▨		X	X
Strong weight reduction			X													X							▨		
Range extender	X	X		X		X			X	X	X		X				X	X		X	X	X		▨	X
EV	X	X		X	X	X	X	X	X	X	X	X	X				X	X		X	X	X		X	▨

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