

RICARDO-AEA

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

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Executive summary

Overview

The European Commission's Directorate General Climate Action (DG CLIMA) commissioned Ricardo-AEA and its partners TEPR, the Technical University of Graz (TU Graz) and the Centre for Automotive Industry Research (CAIR) at Cardiff Business School to undertake detailed analysis to improve the understanding of 'downweighting' – i.e. vehicle mass reduction – for passenger cars and light commercial vehicles (LCVs, commonly known as vans). The overall objective of this study was to understand the potential for mass reduction in the EU market, the associated costs and the subsequent implications for the development of the passenger car and van CO₂ regulations for the period beyond the year 2020. Vehicle mass reduction is important in the context of cutting CO₂ emissions from light duty vehicles as a 10% reduction mass can give between 6% and 7% reduction in fuel consumption and CO₂ emissions. However, it is possible that the design of the car and van CO₂ Regulations penalises the adoption of mass reduction measures. This study was also tasked with investigating this issue.

A fundamental challenge in the design of a CO₂ regulation for new cars and LCVs is the need to accommodate a wide diversity of powertrain packages, product designs and vehicle specifications without unduly penalising individual manufacturers or distorting the market. During the development of the initial phase of the CO₂ regulations for cars and LCV (i.e. the legislation covering the period up to 2020), the European Commission evaluated a range of options that would maintain this diversity using a meaningful and cost-effective measure of utility. Of the two most appropriate measures of utility, vehicle 'mass' (measured in kg) was chosen rather than a vehicle's 'footprint' (defined as the product of a vehicle's 'vehicle wheelbase' and 'track width', measured in m²) as it was more understandable, more consistent data was then available and it was more internationally compatible at the time.

In the EU, data to calculate 'footprint' are now collated in a consistent manner, while legislation regulating the CO₂ emissions of light duty vehicles in North America now uses 'footprint', so two of three original arguments in favour of 'mass' are no longer valid. In the studies developed in support of the passenger car CO₂ Regulations, 'footprint' was considered to be a better measure than 'mass' of the actual utility of a car, to be less likely to cause perverse effects and not to discriminate against some CO₂ reduction options (i.e. those that reduce mass). The extent to which 'mass' as the utility parameter discriminates against the adoption of mass reduction options for reducing CO₂ emissions, the implications of this and thus the suitability of retaining mass as the utility parameter beyond 2020 are all explored within this report.

In both the passenger car CO₂ Regulation and the light commercial vehicle CO₂ Regulation, there are two mechanisms that relate manufacturers' CO₂ targets to mass. First, having 'mass' as the utility parameter in the Regulations until 2020 effectively relates a manufacturer's CO₂ emissions target in any year to the average mass of its new vehicle fleet that year. Second, to ensure that any increases in the average mass of the car and LCV fleets do not lead to an increase in the CO₂ emissions of the new EU vehicle fleet as a whole, there is a second mechanism. Every three years, this second mechanism adjusts M_0 , i.e. the average mass of the EU new vehicle fleet (which is used to calculate manufacturers' annual targets), to the average mass of the vehicle fleet over the preceding three years. This means that if the average mass of the EU's new car (or LCV) fleet increases, manufacturers' respective CO₂ targets will be adjusted to become more stringent for a given mass of vehicle or, if the average mass of the EU's the new fleet decreases, the targets will become less stringent.

The study had the following main elements:

- An analysis of datasets to identify trends;
- The development of scenarios to explore the implications of the two mechanisms noted above that link manufacturers' targets with 'mass';
- Literature reviews, e.g. of the potential and costs of mass reduction and the attitudes of consumers to lighter vehicles;
- An engagement with stakeholders through interviews and a dedicated workshop;

- An assessment of the impacts on manufacturers – in terms of the impact on the distance to their respective CO₂ emissions targets and the associated costs – of applying the findings of the literature review on the potential for, and the costs of, mass reduction technologies to the EU context; and
- A qualitative exploration of alternative options that would make mass reduction technologies as attractive to manufacturers as other CO₂ reduction technologies if a mass-based utility parameter remains in place beyond 2020.

Analysis of trends in vehicle mass

Analysis of recent data on vehicle mass was carried out to identify how vehicle mass has changed in recent years. This analysis showed that the sales-weighted average mass of both the new car and new LCV fleets in the EU has been increasing. For cars, the sales-weighted average mass of the new fleet increased between 2004 and 2013, rising by 3.2% from 1,347 kg to 1,390 kg (although there was a slight decrease in mass between 2012 and 2013). This trend of increasing vehicle mass was evident for all car segments and for the majority of brands. Additional drivers of the increase in mass in recent years appear to be growth in sales of cross-over vehicles and a loss in market share for the lighter B-segment and C-segment conventional cars. The take-up of crossover vehicles and multi-purpose vehicles (MPVs) is particularly relevant as these vehicles typically weigh about the same as a conventional passenger car from next segment up. An increase in the market share for diesel cars is a further factor, as these cars are on average heavier than cars that use petrol. Between 2010 and 2013, the sales-weighted average footprint of new cars rose by 6.7% from 3.15 m² to 3.36 m², which was a higher rate than the increase in the sales-weighted average mass over the same period (which was only 1.9%), even though longer-term trends suggests that pan area has been increasing at a slower rate than mass¹.

For LCVs, there are fewer data, but these show that between 2009 and 2013, the overall sales-weighted mass of the new EU van fleet increased by 10% from 1,600 kg to 1,761 kg. Within each class, the increase in sales-weighted mass was significantly smaller, demonstrating that the overall mass increase has been due to an increase in the sales of the larger LCV classes relative to the smaller ones. Indeed, it appears that many of the most popular LCV models have increased in mass, thus moving them up into the next mass class.

Implications of changes in vehicle mass on manufacturer-specific CO₂ targets

As mass – and footprint – have been increasing, it is important to understand fully the implications of the mechanisms within the Regulations that link mass to manufacturers' targets and to identify what the difference would be if footprint was the utility parameter. To this end, **scenarios were developed** to demonstrate mathematically the impact of the two mechanisms in the Regulations that link each manufacturer's CO₂ target to: i) the mass of its own new car fleet; and ii) the mass of the entire new EU car fleet (i.e. the M₀ adjustment). While this analysis was only undertaken for cars, similar mechanisms exist within the LCV CO₂ Regulation, so it is likely that similar conclusions could be drawn if the same analysis was undertaken for LCVs. For cars, the scenarios clearly show that if the average mass of a manufacturer's new fleet declines, the manufacturer would be closer to its CO₂ emissions target when 'footprint' was the utility parameter than when 'mass' is the utility parameter. This is because when 'mass' is the utility parameter, the manufacturer's position relative to the target line changes both horizontally to the left as well as vertically downwards, whereas if 'footprint' was the utility parameter the manufacturer's position would only change vertically downwards. Under the assumptions used in this report, if 'footprint' is used as the utility parameter, an average manufacturer would be 8.7 gCO₂/km closer to its target as a result of an average mass reduction of 10%. By contrast, if 'mass' is used as the utility parameter, the same 10% reduction in vehicle mass would mean that an average manufacturer would only be 4 gCO₂/km closer to its target.

This finding suggests that 'footprint' should be the utility parameter favoured by manufacturers, as they would benefit in full from the application of mass reduction technologies in terms of meeting their targets.

¹ Although 'footprint' and 'pan area' are not exactly the same, as 'footprint' is defined as 'vehicle wheelbase' multiplied by 'track width', whereas pan area is defined as 'vehicle length' multiplied by 'vehicle width', the two will generally increase and decrease together.

In turn, this suggests that the application of mass reduction technologies is disincentivised when ‘mass’ is the utility parameter, as the cost-effectiveness of mass reduction technologies from the perspective of the manufacturer is lower than if ‘footprint’ had been the utility parameter. As a result of this apparent disincentive, it would be in policy-makers’ interests to use ‘footprint’ as the utility parameter to ensure that the policy framework does not hinder the application of technologies that could yield benefits for consumers and for society.

As the sales-weighted average mass of the new car fleet has been increasing for a number of years, manufacturers’ targets will become more stringent from 2016 as a result of an adjustment of M_0 . In such a situation, the benefits for a manufacturer – in terms of being closer to its CO₂ emissions target – of introducing mass reduction technologies would effectively be negated, as a result of the more stringent target. This suggests that, when the mass of the new car fleet is increasing, the M_0 adjustment acts to further disincentivise the introduction of mass reduction technologies, at least in the short-term. For the same reason as above, it would therefore be in policy-makers’ interests to have ‘footprint’ as the utility parameter. It is worth noting that, in the longer-term, the existence of the M_0 adjustment could begin to increase the incentive to use mass reduction technologies, as the impact of any increase in the value of M_0 , as a result of a continuing increase in the average mass of the new car fleet, will be proportionately larger for manufacturers that are closer to their targets.

Even if ‘footprint’ is used as the utility parameter, the distance to target for any manufacturer would probably also depend to some extent on the changes in the characteristics of its competitors’ fleets, even though changes in mass would not have any effect. This is because it is highly likely that, if ‘footprint’ was the utility parameter, there would be a similar mechanism to the M_0 adjustment, e.g. an F_0 adjustment (where F_0 would equate to the average footprint of the whole EU new car market). This adjustment would reflect any changes in the footprint of the new vehicle fleet to ensure that the required overall reduction in average CO₂ emissions was still achieved. The difference in this respect is that mass reduction is a more important and direct influencing factor than footprint in terms of reducing a car’s CO₂ emissions. Hence, from a purely mathematical perspective, there are arguments in favour of using ‘footprint’ instead of ‘mass’ as the utility parameter in the passenger car CO₂ Regulation, at least.

Review of potential materials and techniques for reducing vehicle mass

The next stage of the research was to carry out a review of the literature to identify the potential for mass reduction in vehicles, and the materials that might be used to achieve such reductions. The literature review focused on options for reducing the mass of the bodyshell (i.e. the main frame of the car, also known as ‘body-in-white’, and closures, i.e. doors, bonnets, etc), the powertrain and chassis systems (i.e. suspension, braking systems, steering systems, wheels), as these three elements each account for more than 20% of the total mass of a typical vehicle. The literature suggests that there are a number of different materials that might be used to reduce the mass of a vehicle including various types of high strength steel (HSS), aluminium, plastics, carbon fibre reinforced plastic (CFRP) composites and magnesium. Three US-based studies were more comprehensive than the other publications that were reviewed as they investigated in detail the mass reduction potential for specific vehicle models, whereas the other studies were less comprehensive.

The literature suggests that there is no single, “best” approach for achieving mass reduction in vehicles, as a combination of the various materials already mentioned are likely to be used in different parts of the vehicle. Over the last couple of decades, the use of HSS has increased in the US to around 250kg (around 15% of a vehicle’s total mass) at the expense of regular steel, although the use of regular steel is still as twice as high as the high strength variety, which is consistent with some of the vehicles available on the EU market, e.g. the 2008 Ford Fiesta. More recent vehicles that have entered both the EU and US markets have even higher levels of HSS in their bodyshells (e.g. the 2012 Volkswagen Golf VII, which has 80% HSS content in its bodyshell). Research has suggested that it is possible to design a body structure for a vehicle comprising 97% HSS. The average amount of aluminium used in the new car fleet in the EU in 2011 was estimated to be 140 kg per vehicle, or just over 10% of the average mass of a car, while the same report suggested that the use of 300 kg of aluminium (around 17% of the total vehicle mass) in an E-segment car was close to the practical limit for that segment. There are

significant differences in the level of take-up of aluminium in different vehicle segments, primarily because the additional cost of this material means that it is generally too expensive to use in smaller vehicles where profit margins are typically smaller and consumers are very price-sensitive, but can be more readily used in larger, more luxurious vehicles where purchasers are much less price sensitive. Magnesium is more frequently used in components rather than in the body structure and its use is small, probably less than 1%, although in the US the major domestic manufacturers have a target of increasing the use of magnesium in new cars to 159 kg per vehicle by 2020. Plastics make up no more than 10% of the mass of vehicles in the US, while studies for the EU market have suggested that a wider use of plastics could deliver mass savings of up to 85 kg. More recently, some manufacturers, notably BMW in their i3 model, have used CFRP. While the wider potential for CFRP is not yet clear, the fact that BMW produced around 20,000 i3 models in 2014 (its first full year of production) suggests that it has potential for wider market application, although at this point in time it is not suitable for extensive use in vehicles produced in high volumes.

The choice of materials used by any manufacturer to reduce the mass of their vehicles will depend on many factors, including the ease of production and assembly, compatibility with high volume manufacturing, structural performance considerations, e.g. in crash tests, and the associated costs. The latter could be substantial as they include costs incurred by manufacturers in changing to alternative production methods and equipment that are required for manufacturing with different materials. There may be knock-on benefits associated with mass reduction, as reducing the mass of the main vehicle systems and components (i.e. primary mass reduction) allows additional consequential mass reductions (secondary mass reduction) to be achieved, as for example, lighter braking and suspension components can be used on lighter vehicles. It has been estimated that for every 1 kg in primary mass reduction, it is possible to achieve a further 0.7 to 1.5 kg in secondary mass reduction, although there is much uncertainty about the extent of secondary mass reduction that is possible in practice.

Another approach that leads to mass reduction that has been seen on the market in recent years is the downsizing of engines, e.g. downsized engines produced by Ford and Volkswagen are 30 kg and 22 kg lighter than the respective conventional engines that they replaced. Another approach used by Citroën for its C4 Cactus model that was introduced in 2014 was to simplify the functional specification of the car, thereby allowing lighter components and systems to be used. This demonstrates that alternative ways of thinking about the functional specifications of new vehicles can help to realise significant reductions in overall vehicle mass.

Detailed review of major US studies on the potential for vehicle mass reduction

While the wider literature review provided some evidence on existing and potential uses of materials for reducing the mass of vehicles, only **three US studies** provided a comprehensive assessment of the technical potential and associated costs for reducing the mass of a particular light duty vehicle. A study undertaken by Lotus Engineering from 2010 focused on the Toyota Venza in the US. It investigated a vehicle that had more advanced and radical solutions applied (a “high development vehicle”) and one that did not have such solutions applied (a “low development vehicle”). The results of the analysis for the high development vehicle indicated that it would be possible to reduce the mass of the Toyota Venza by up to 32% (38% mass reduction excluding the powertrain), i.e. from 1,700 kg for the baseline vehicle to 1,290 kg, with only a 3% increase in cost. For the low development vehicle, a mass saving of 20% was achieved (21% mass reduction excluding the powertrain), which reduced the mass of the vehicle to 1,422kg, with a cost saving of 2.1% against the baseline vehicle.

A 2012 study for the US EPA undertaken by FEV, which also focused on the Toyota Venza, provided a review of alternative, feasible options for reducing vehicle mass, resulting in an 18% mass reduction (of 312 kg on a baseline vehicle weighing 1,711 kg), for a potential cost saving of US\$148 compared to a base Toyota Venza vehicle. The study found that further overall cost savings could be made if some high-cost mass reduction options are not selected, while there is potential to achieve greater mass reductions with marginal cost increases. A 2012 study carried out by Electricore for the US National Highway Traffic Safety Administration (NHTSA) focused on the US-market Honda Accord and achieved a mass reduction of 327 kg compared to the base vehicle mass of 1,410 kg. This amounts to a 23% reduction in mass at a cost increase of \$319 or \$1.03 per kg, against a baseline cost of \$21,980.

These studies and the wider literature indicate that it is possible to achieve a 15-20% mass reduction for the selected current US-market conventional production passenger car while incurring little or no increase in costs. This is achievable primarily through focusing on designing a lighter body-in-white structure through the use of HSS, aluminium (particularly for closures), and possibly composites. This is likely to result in an increase in costs for the body-in-white structure itself due primarily to the higher material costs. It is possible to offset this increased body-in-white cost through mass reduction in other areas such as the suspension, braking and powertrain systems, which can be achieved due to the overall lower vehicle mass (i.e. as a result of secondary mass reduction). Mass reduction in these systems often involves smaller components with lower material costs. There remain a number of important caveats to these findings. In particular, there has only been a limited assessment of crashworthiness; a lack of consideration of the impacts of mass reduction on noise, ride and handling; difficulty in verifying cost estimates; insufficient account of platform strategies and parts commonality; and a need to account for existing uptake of mass reduction technologies.

There are a number of reasons why the direct applicability of the findings from the three main US studies to the European context might be questioned. First, the baseline vehicles used in the US studies were heavier than the average European passenger car, which weighed 1,390 kg in 2013. Second, some of the techniques that delivered mass reductions in the US studies already have a significant market penetration in Europe (for example, the use of HSS in the standard body structures of the two baseline US vehicles is lower than average for new cars in Europe, downsized engines are already commonly used in vehicles available in the EU market, etc). Third, the overall costs of mass reduction in the US studies include assumptions on labour and manufacturing costs as well as material costs, which will not necessarily apply to Europe. For example, average car manufacturing labour costs in Europe were 21% lower than those in the US in 2010, with those in Eastern Europe, where a growing amount of vehicle manufacturing takes place, 78% lower. However, in some EU countries (e.g. Germany) labour costs are higher than in the USA. Fourth, the main sources of cost savings in the US EPA study on the Toyota Venza study are from the suspension, brakes, wheels and tyres, but these component were particularly heavy compared to vehicle designs common in Europe. Finally, none of the studies take into account the fact that platform sharing and parts standardisation may have a negative impact on manufacturers' abilities to optimise for minimum vehicle mass.

Our conclusion on the basis of the literature review is that the mass reduction approaches used are generally relevant to the European context, but that the calculated costs for a given reduction may be somewhat optimistic to transfer directly to the EU. As a result we believe that the costs in Europe will be somewhat higher for a 20% mass reduction. Discussions with EU industry stakeholders, including vehicle manufacturers and component suppliers, also indicated that whilst the mass reductions outlined in the US reports are possible for EU market vehicles, such reductions are highly unlikely to be achieved without incurring additional costs. Based on all of the literature reviewed and the evidence obtained in the course of this study, we conclude that a 20% reduction in the overall mass of European vehicles could be achieved, which might incur an increase in direct costs of up between €200 and €300 per vehicle, depending on vehicle size. This assumes that the baseline vehicle is an average 2010 new car in Europe and only the application of those mass reduction technologies that will be available for mass production through to the 2020 time frame. All other factors remain unchanged, i.e. the costs refer only to mass reduction of the baseline 2010 car while ensuring it would continue to meet the legislation it was designed for at the time.

Stakeholder attitudes and consumers views on mass reduction

Stakeholder interviews with industry experts were conducted to understand the industry's views on mass reduction and to estimate the possible costs associated with reducing the mass of vehicles. Stakeholders indicated that mass reduction has become a key CO₂ reduction strategy for many OEMs in recent years and the focus is expected to become greater in the future, although its perceived importance varies between OEMs. Whilst there is some evidence to indicate some new models are lighter than their predecessors, in some cases the claims of mass reduction appear to be overstated. Many stakeholders agreed with the assessment that 'crossover' vehicle sales have seen strong growth at the expense of more conventional cars, and that this has acted against OEMs' ability to reduce vehicle mass. Other factors, such as more stringent crash legislation were cited as being responsible for mass increases. Meeting CO₂ targets is the main driver for mass reduction. Other drivers depend on an OEM's market segment, but include improved handling and lower costs. For electric vehicles, mass reduction provides a cost-effective way of increasing range. Stakeholders expect that a multi-

material approach to minimising vehicle mass will be the way forward for the future, perhaps combining advanced high-strength steel body structures with aluminium closures, fibre reinforced composites for selected components, and greater use of plastics to replace metal where possible.

A number of barriers to mass reduction were identified by stakeholders including, increased material costs, costs associated with changing manufacturing processes, platform strategies and parts standardisation and end-of-life recycling requirements.

Stakeholders believe that the new worldwide light-duty vehicle test procedure (WLTP) will make mass reduction more important than it currently is. This is primarily due to the changes which eliminate inertia classes and including the mass of optional extras in vehicle test configurations.

The majority of stakeholders did not feel that a mass based utility parameter discourages mass reduction. The analysis in this study clearly shows that this is incorrect. Manufacturers also indicated that a footprint-based system could result in them not offering smaller vehicles in the market, and hence the average footprint would increase. However, there is no evidence to support this assertion. The average mass and the average footprint of new vehicles have both been increasing during a period mass has been used as the utility parameter in the car and LCV CO₂ Regulations. There is no evidence that having mass as the utility parameter is the underlying reason for the observed increases in vehicle mass. Hence, it is not clear why using footprint as the utility parameter might lead to an increase in the average footprint of new vehicles.

Various manufacturers stated that changing the utility parameter from mass to footprint would require re-opening lengthy negotiations on all aspects of the vehicle CO₂ Regulations. Given that it is possible that the modalities for post-2020/21 Regulations on CO₂ emissions from light duty vehicles could be different to those in place under the existing car and van CO₂ Regulations, such negotiations will be required in any case, regardless of whether mass or footprint is used as the utility parameter.

Consumer attitudes to mass reduction were also investigated as part of the study. In general, consumers do not have a view on mass reduction *per se*, but are likely to have opinions on the consequential effects of measures to reduce the mass of vehicles, such as impacts on fuel economy, noise levels, and acoustic quality. A range of parameters that are of interest to consumers when making their car purchasing decisions were identified and a selection of these parameters were tested to identify whether any of them are related to kerb mass. In most cases, the relationships were weak, indicating that there is insufficient evidence to use mass as a proxy for any of the vehicle attributes that are important to consumers. Consequently, we conclude that vehicle mass is not a parameter that is important to consumers when making vehicle purchasing decisions.

Costs of vehicle mass reduction to manufacturers and financial benefits to society

Drawing on the findings of this study, new sets of cost estimates for vehicle mass reduction were developed for both passenger cars and light commercial vehicles. Previous research carried out by TNO *et al* identified costs for 10%, 25% and 40% reductions in the mass of the body-in-white (BIW). However, reductions in BIW mass do not translate into equivalent reductions in the overall mass of the vehicle. Whilst achieving a 40% reduction in the mass of the body-in-white is feasible in the 2020 time period, the literature review and discussions with stakeholders indicated that achieving a 40% reduction in overall vehicle mass would be technically very challenging and prohibitively expensive. We note that the US EPA approach is based on estimating costs for 10%, 20% and 30% reductions in total vehicle mass. Taking all of these factors into account, we have developed new cost estimates for achieving 10%, 20% and 30% reductions in overall vehicle mass for passenger cars. These estimates are presented in the tables below, and reflect our findings that the previous estimates developed by TNO *et al* are too high, whilst alternative cost estimates developed from US EPA data are too low.

Table i: New estimates for the costs of whole-vehicle mass reduction for passenger cars

	Absolute costs			Unit costs
	Small cars	Medium cars	Large cars	
10% reduction in total vehicle mass	€31	€39	€48	€0.3/kg
20% reduction in total vehicle mass	€200	€250	€300	€0.9/kg
30% reduction in total vehicle mass	€738	€923	€1,106	€2.2/kg

For LCVs, there is very limited previous research on the costs of mass reduction and new analysis has been carried out during this study. The scope for applying mass reduction to LCVs is much lower than for passenger cars, because the production volumes are much lower, the model life-cycles are generally much longer and there is limited potential to apply secondary mass reduction techniques. For all of these reasons, the mass reduction potential for LCVs is lower than for cars and the costs are significantly higher. The analysis carried out in this study indicates that in the medium term (out to 2030) it is possible to reduce LCV mass by up to 12%. In the longer term, mass reductions of up to 25% may be possible, but this would require extensive use of fibre-reinforced plastics, which are currently very expensive. New estimates for the costs of mass reduction in LCVs are presented in the table below.

Table ii: New estimates for the costs of whole-vehicle mass reduction for light commercial vehicles (absolute cost values)

	Absolute costs			Unit costs
	Small cars	Medium cars	Large cars	
3% reduction in total vehicle mass	€83	€115	€166	€2.2/kg
12% reduction in total vehicle mass	€719	€1,010	€1,439	€5.4/kg
25% reduction in total vehicle mass	€10,809	€15,053	€22,123	€37.4/kg

As mass reduction leads to improvements in vehicle fuel economy and CO₂ emissions, there will also be reductions in fuel costs for consumers and businesses that use vehicles. We have analysed the lifetime savings in fuel costs for average petrol and diesel cars and for an average diesel light commercial vehicle. This analysis shows that for an average current petrol car, there is a lifetime fuel cost saving to the vehicle user associated with mass reduction of €5.5 per kg. For an average diesel car, the figure is €5.9 per kg and for an average diesel LCV, it is €11.3 per kg. The absolute levels of cost savings are dependent on a number of factors including baseline vehicle mass, baseline vehicle fuel consumption, lifetime distance travelled and fuel prices. We have also estimated how these unit cost savings are likely to change between now and 2020, in line with anticipated improvements in fuel efficiency for cars and LCVs. The results of this analysis indicate that the unit cost savings are likely to decrease as vehicles become more fuel efficient, with likely declines in cost savings of 20% and 15% for passenger cars and LCVs respectively.

Comparison of the impacts on and costs for manufacturers of using footprint and mass as a utility parameter

The costs and CO₂ emissions reduction potential associated with the mass reduction technologies that have been identified within this report were combined with the costs and CO₂ reduction potentials for other technologies identified in previous work (i.e. TNO *et al*, 2011) to identify the impacts for manufacturers. As with the previous work, the impact of these costs and CO₂ reduction potential on car manufacturers was investigated using different utility parameters, specifically 'mass' and 'footprint'. The impacts were estimated in the context of a hypothetical post 2020/21 target that was defined under the WLTP, rather than the New European Drive Cycle (NEDC). As post-2020/21 targets have not yet been set, and the NEDC CO₂ values have not yet been fully translated to WLTP values, the results of the analysis should only be taken to be an indication of the relative effects on manufacturers of alternative post 2020 mass-based and footprint-based regulatory regimes.

As the analysis is set up to deliver the same level of CO₂ reductions for cars, it was only the distribution of the reductions between manufacturers that varied when a different utility parameter was used. In most cases, the impact, in terms of distance to target, was marginal. The total costs to reach the target for passenger cars were around 16% lower under a footprint-based system than under a mass-based system. For all manufacturers bar one, the costs would be lower if 'footprint' was used the utility parameter, the one exception being Tata/Jaguar Land Rover.

Alternative options for ensuring that mass is as attractive as other CO₂ reduction options

The rationale behind the exploration of **alternative options** that would make mass reduction technologies as attractive to manufacturers as other CO₂ reduction options if a mass-based utility parameter remains in place beyond 2020 was the need to counter the disincentives for applying such mass reduction technologies that result from the design of the existing Regulations (as noted above). A long-list of potential options, which was identified from the literature and by the engagement with stakeholders, was progressively reduced to a short-list of options that was assessed in detail. Every option on the short-list of options had potential issues. The option that was considered to have the most potential was to award manufacturers credits (and debits) for vehicles based on the 'density' of their vehicles relative to the overall average 'density' of the new vehicle fleet, where 'density' is defined as mass over footprint (and so measured in kg/m²). Even this option would need to be explored thoroughly to ensure that it provides the right incentives and avoids perverse incentives, as well as providing an equitable treatment for manufacturers. In this respect, it is worth noting that this option would introduce an additional layer of complexity to the Regulation, which increases the risk of unforeseen consequences, and was not supported by stakeholders at the workshop held as part of the project.

Summary and conclusions

The aim of this report was to explore the potential for mass reduction in passenger cars and LCVs. This included analysing the implications for cost-effectiveness, in the context of potential post-2020/21 CO₂ emissions reduction targets for such vehicles, including the implications for the choice of utility parameter. To achieve these aims it was necessary to explore ongoing market trends in vehicle characteristics such as mass and footprint, as well as trends in the uptake of lightweight materials. It was also necessary to understand the mechanisms within the existing Regulations that link manufacturers' targets to vehicle mass. The potential for mass reduction, including the implications for CO₂ emissions and costs, was identified by reviewing the relevant literature, including major US studies, while the attitudes of manufacturers and consumers were identified through a combination of literature review and stakeholder engagement. On the basis of this information, updated estimates of the costs of vehicle mass reduction in the EU were developed. These estimates were used to assess the implications for manufacturers, in relation to the respective distances to their CO₂ targets and the costs associated with meeting these targets. Finally, the potential to use an alternative option was explored that would make mass reduction technologies as attractive to manufacturers as other CO₂ reduction options if a mass-based utility parameter remains in place beyond 2020.

Based on the data analysed, the average mass of new cars and LCVs registered in the EU is increasing and that the average footprint of new cars is also increasing. The drivers for the mass increase in cars

include an increase in sales of crossover vehicles and MPVs (these vehicles are typically as heavy as a conventional passenger car from the next segment up) and an increase in the market share of diesel cars, which are typically heavier than similar cars that use petrol. For LCVs, it appears that many of the most popular models have increased in mass, thus moving them up into the next mass class.

The literature review and stakeholder engagement suggested that mass reduction is becoming an increasingly important element of manufacturers' CO₂ reduction strategies. According to industry stakeholders, the targets set in the car and LCV CO₂ Regulations were one of the main drivers of mass reduction, while the forthcoming change in the test procedure (to the WLTP) will make mass reduction more important. As is clear from the results mentioned above, such strategies are not yet leading to a reduction in the average mass of the new vehicle fleet. There was no evidence from the literature to suggest that consumers have strong opinions on lighter vehicles, as long as the overall performance of vehicles was not adversely affected. The literature review also suggested that while many mass reduction technologies are already beginning to be taken up for LDVs, there is still a significant potential, although at higher costs than have been suggested for the US. The literature and the engagement with stakeholders suggested that there will be a multi-material approach to reducing the mass of vehicles, with different strategies being adopted by different manufacturers.

On the basis of the literature reviewed and the stakeholder engagement undertaken in the course of this study, we conclude that a 20% reduction in the overall mass of European light duty vehicles could be achieved, which might incur an increase in direct costs of up to €250-€300 per vehicle (€0.9 per kg saved). This assumes that the baseline vehicle is an average 2010 new car in Europe and that only the mass reduction technologies that will be available for mass production before 2020 will be applied; all other factors remain unchanged. Whilst the majority of stakeholders, including Tier 1 suppliers, believed that achieving such a mass reduction for the stated level of costs was achievable, several manufacturers believed that the costs associated with achieving this level of mass reduction would be much higher.

Drawing on the research carried out for this study, new estimates for the costs of achieving 10%, 20% and 30% reductions in passenger car mass were developed. These new estimates are based on estimates developed by the US EPA, but they have been adjusted to take into account that some low-cost mass reduction techniques have already been applied in the EU market. New estimates for the costs of LCV mass reduction were also developed; the costs of reducing LCV mass are likely to be higher than for passenger cars.

For cars, the estimated costs of mass reduction were integrated into the cost curves used for the 2020 targets (which were also amended to include plug-in hybrid electric vehicles and to examine emissions reduction on the basis of the WLTP rather than the NEDC). The implications for manufacturers of achieving a hypothetical post-2020/21 CO₂ reduction target (measured on the WLTP) were estimated for cases where (i) mass and (ii) footprint are the utility parameters. This showed that, in terms of distance to their CO₂ targets, more manufacturers would benefit from a mass-based system than a footprint-based system (the overall CO₂ emissions reductions across the whole new car fleet to be achieved under the alternative systems were designed to be the same). However, from a manufacturer's perspective it is the costs of meeting the target rather than the emissions reductions needed that are more important. In this respect, all but one manufacturer would face significantly lower costs if 'footprint' was the utility parameter (16% lower on average).

Based on all of the above, the findings from this study indicate that the costs associated with mass reduction in cars and LCVs in the EU are lower than had been estimated in previous studies for the European Commission. Additionally, the analysis suggests that delivering the same overall level of CO₂ reduction would be cheaper if 'footprint' rather than 'mass' was used as the utility parameter for a hypothetical post 2020/21 target. This suggests that 'footprint' should be the preferred option for the utility parameter to be used for any post 2020 in the LDV CO₂ Regulations.

To counter penalties associated with mass reduction under the current car and LCV CO₂ Regulations, alternative options that would make mass reduction technologies as attractive to manufacturers as other CO₂ reduction options were explored to identify whether any of these might be used if a mass-based system remains in place beyond 2020. This exploration did not yield an obvious alternative option that might be implemented. Additionally, stakeholders did not support the inclusion of such an additional option.

In the course of the engagement with stakeholders, the majority accepted that having 'mass' as the utility parameter discouraged mass reduction *in theory*, but the majority of manufacturers thought that this was not the case in practice and so preferred to keep 'mass' as the utility parameter for any post 2020 targets. Most suppliers believed that changing the utility parameter to 'footprint' would put greater emphasis on mass reduction.

In terms of the future choice between 'mass' or 'footprint' as the utility parameter for any post 2020 CO₂ reduction target for cars, two of the three original reasons why the Impact Assessment accompanying the original proposal for the passenger car CO₂ Regulation chose 'mass' over 'footprint' are no longer valid. There are no longer issues over data availability and international compatibility, as data to calculate 'footprint' are now collated in the EU in a consistent manner, while legislation regulating the CO₂ emissions of light duty vehicles in North America now uses 'footprint'. The one remaining original argument in favour of 'mass' is that it is more understandable than footprint as a concept, which was mentioned as a reason for retaining 'mass' as the utility parameter in the course of the stakeholder engagement. This may still be the case amongst the general public, but those involved in reducing CO₂ emissions from cars, including policy-makers and manufacturers, will have become increasingly familiar with the concept of 'footprint' in recent years, not least as a result of the various reports that have been undertaken on the issue of the utility parameter.

Consequently, it is worth identifying whether there are now additional reasons in favour of keeping 'mass' as the utility parameter for any post 2020 CO₂ reduction targets for cars. The argument that having 'mass' as the utility parameter does not penalise mass reduction in practice might be supported by the various statements that manufacturers have made in support of mass reduction and its importance to meeting their respective CO₂ reduction targets. This commitment has not yet been translated into a lower average mass of new cars, at least not up to and including 2012. Regardless of the reasons why average mass has not decreased, it can be concluded that having mass as the utility parameter between 2009 and 2012 did not result in a reduction in the average mass of the new car fleet. For many of the other arguments put forward by stakeholders for retaining 'mass' as the utility parameter, it was often not clear why a similar argument could not be made for changing to 'footprint'.

A change from using mass as the utility parameter to footprint (e.g. for a 2025 CO₂ target), would require manufacturers to revise the parameters within which decisions are made about the most cost-effective means of reducing the CO₂ emissions of their new vehicle fleets. It is perhaps the uncertainty that such a change would entail that underlies the desire amongst most manufacturers to retain 'mass' as the utility parameter for any post-2020/21 CO₂ emissions reduction target. To put this in a wider context, the modalities for any post-2020/21 targets would need to be developed with the potential market for the respective year in mind, which is likely to include a much higher proportion of electric and hybrid vehicles for example. Hence, it is distinctly possible that the form of the respective Regulation for any post 2020/21 targets will be different from that used for the 2015 and 2021 targets. In this context, any change in the utility parameter used would just be one of many factors that manufacturers would need to take into account.

Table of contents

1	Introduction.....	14
2	Overview of the passenger car and light commercial vehicle CO₂ regulations and their implications for mass reduction.....	16
2.1	Overview.....	16
2.2	Mechanisms that link manufacturers' targets to mass reduction	17
3	Trends in vehicle mass and in the application of mass reduction measures.....	19
3.1	Overview.....	19
3.2	Analysis of trends in vehicle mass	20
3.3	Underlying reasons for mass change trends.....	32
3.4	Summary of findings on trends in vehicle mass.....	44
4	Implications of changes to the mass of vehicles on individual manufacturer CO₂ targets under the car and van CO₂ Regulations	45
4.1	Overview.....	45
4.2	How the mechanisms differ where 'mass' and 'footprint' are the utility parameters	46
4.3	Implications of the M ₀ adjustment on the market as a whole	48
4.4	Implications for manufacturers with lighter and heavier average masses	50
4.5	Relevance of concepts from 'game theory'	54
4.6	Conclusions	55
5	Availability of materials and potential for mass reduction	57
5.1	Overview.....	57
5.2	Body-in-white and closures	58
5.3	Powertrain	73
5.4	Chassis/suspension systems	76
5.5	Other approaches for reducing vehicle mass.....	79
5.6	Summary of findings from the literature	79
6	Detailed review of major US studies on the potential for vehicle mass reduction	81
6.1	Review of Lotus Engineering 2010 Phase 1 vehicle mass reduction study.....	81
6.2	Review of US EPA (FEV, 2012) Phase 2 vehicle mass reduction study	84
6.3	Review of the NHTSA (Electricore et al, 2012) mass reduction study.....	93
6.4	Comparison and discussion of findings from the Lotus (2010), FEV (2012) and Electricore (2012) studies	96
6.5	Comparison to findings from other literature	98
6.6	Summary of findings from literature review.....	103
6.7	Relevance of the findings from the US studies to the European vehicle market	105
7	Stakeholder attitudes and consumer views on vehicle mass reduction.....	107
7.1	Overview.....	107
7.2	Manufacturer attitudes to vehicle mass reduction.....	107
7.3	Consumer attitudes	123
8	Costs of vehicle mass reduction to manufacturers and financial benefits to society	128
8.1	Overview.....	128
8.2	Previous estimates for the costs of vehicle mass reduction	128
8.3	Development of new cost estimates based on the findings from this study.....	131
8.4	Financial benefits of vehicle mass reduction to vehicle users	137
9	Comparison of the impacts and costs of using mass and footprint as a utility parameter	141
9.1	Overview.....	141
9.2	Comparison of efforts needed by manufacturers to achieve possible post-2020 CO ₂ reduction targets	141

9.3	Comparison of costs that might be incurred by manufacturers in achieving possible post-2020 CO ₂ reduction targets	144
9.4	Summary	150
10	Alternative options for ensuring that vehicle mass reduction is as attractive as other CO₂ reduction options	151
10.1	Overview.....	151
10.2	Long-list of options identified as a result of the literature review and stakeholder consultation	151
10.3	Evaluation of the long-list of options against important conditions	155
10.4	Assessment of short-list of options.....	156
10.5	Conclusion.....	161
11	Summary and conclusions	162
Appendices		
Appendix 1	Data sources used for assessing trends in passenger car and LCV mass	
Appendix 2	Additional figures relating to Chapter 4	
Appendix 3	Additional detail with respect to the Lotus Engineering (2010) study on the Toyota Venza	
Appendix 4	Additional detail with respect to the FEV (2012) study on the Toyota Venza	
Appendix 5	Additional detail with respect to the Electricore et al (2012) study on the Honda Accord	
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	
Appendix 7	Assessment of long-list of options for incentivising mass reduction	
Appendix 8	Cost curve analysis	

1 Introduction

The European Commission's Directorate General for Climate Action (DG CLIMA) commissioned Ricardo-AEA and its partners TEPR, the Technical University of Graz (TU Graz) and the Centre for Automotive Industry Research (CAIR) at Cardiff Business School to undertake detailed analysis to improve the understanding of 'downweighting' – i.e. vehicle mass reduction – for passenger cars and light commercial vehicles (LCVs, commonly known as vans). This analysis was required to better understand how the potential for mass reduction and the associated costs might be taken into account in future CO₂ regulatory requirements.

A fundamental challenge in the design of a CO₂ regulation for new cars and vans is that of accommodating a wide diversity of powertrain packages, product designs and vehicle specifications without unduly penalising individual manufacturers or distorting the market. For the initial phase of the CO₂ regulations for cars and vans, the European Commission investigated and evaluated a range of options regarding how this diversity might be maintained using a meaningful and cost-effective measure of utility and for the purposes of the regulations in place up to 2020/21, vehicle mass has been defined as an appropriate measure of utility.

The overall objective of this study is to provide meaningful technical input into the ongoing development of the passenger car and van CO₂ regulations for the period beyond 2020/21. Whilst the current EU car and LCV CO₂ regulations use vehicle mass-based utility parameters for target setting purposes, there is a question over whether mass would be the most suitable parameter for achieving the most cost effective CO₂ reductions after 2020/21.

Questions have been raised over whether a mass-based utility parameter acts as a disincentive for manufacturers to reduce the mass of their vehicles, and whilst there are other technological options for reducing vehicle CO₂ options, reductions in mass can play a very important contributory role in improving energy efficiency and cutting emissions. A 10% reduction in vehicle mass gives approximately a 3% reduction in CO₂ emissions, assuming that no other changes are made to the vehicle (i.e. only mass is removed and hence the power to mass ratio of the vehicle increases). However, if in addition to reducing vehicle mass, the engine is also de-powered to maintain performance (i.e. the power-to-mass ratio remains the same as before), then a 10% reduction in vehicle mass gives a reduction in CO₂ emissions of around 6.5% (Cheah, 2010, Heywood, 2010). As this study is considering the most cost effective approaches for reducing vehicle CO₂ emissions, it is assumed that engine de-powering is employed in combination with mass reduction, and hence a 10% reduction in vehicle mass is assumed to give a 6.5% reduction in vehicle CO₂ emissions. It is possible that the relative attractiveness and cost effectiveness of vehicle mass reduction as an emissions abatement option may change in future years. Consequently, there is a need for comprehensive and detailed research to understand the potential of vehicle mass reduction in the EU market and to identify and assess measures that could be used to encourage manufacturers to adopt mass reduction strategies.

This report sets out the findings from our research using the following structure.

- Chapter 2 provides an overview of the EU's car and LCV CO₂ regulations with a particular focus on the mechanisms that are of relevance to this report, namely those that link a manufacturer's CO₂ reduction target to vehicle mass.
- Chapter 3 examines relevant trends with respect to cars and vans that are of relevance to the project, including changes in the mass and size of the new vehicle fleet, and identifies, as far as possible, the reasons for these trends.
- Chapter 4 explores the implications of changes to the mass of vehicles on manufacturers as a result of the mechanisms in the car and LCV CO₂ Regulations that link a manufacturer's target to mass. It uses a number of scenarios to explore the implications of different mass trends, and compares the results for alternative measures of vehicle utility, i.e. mass and footprint.
- Chapter 5 examines manufacturer and consumer attitudes to vehicle mass reduction.
- Chapter 6 provides a review of the potential for applying mass reduction techniques to light duty vehicles, based on recent research on this topic.
- Chapter 7 undertakes a detailed analysis of the available literature on vehicle mass reduction, focusing in particular on key US studies, as these were considered to be the most comprehensive. It concludes by identifying the extent to which the cost information from the literature can be applied to the European situation.

- Chapter 8 takes the findings on the costs from the previous chapters and uses these to estimate the impacts on manufacturers, in terms of the distance to target and additional costs per vehicle, of the use of mass reduction technologies, for the cases where 'mass' and 'footprint' are used as alternative utility parameters.
- Chapter 9 explores options that could make mass reduction technologies as attractive to manufacturers as other CO₂ reduction options if a 'mass' is retained as the utility parameter beyond 2020.
- Chapter 10 presents the summary and conclusions of the study.

2 Overview of the passenger car and light commercial vehicle CO₂ regulations and their implications for mass reduction

2.1 Overview

Regulation (EC) 443/2009 and Regulation (EU) 510/2011 set mandatory fleet-based CO₂ reduction targets for new light duty vehicle fleets. For cars, Regulation 443/2009 (the 'passenger car CO₂ Regulation') sets a fleet-wide target of 130 gCO₂/km to be met by 2015 (European Commission, 2009a). Regulation (EU) 510/2011 (the 'light commercial vehicle CO₂ Regulation'²) sets a similar target for LCVs of reducing the CO₂ emissions of the new fleet to 175 gCO₂/km by 2017 (European Commission, 2011a). The Regulations both set indicative targets for 2020, of 95 gCO₂/km for cars and 147 gCO₂/km for LCVs, which have now been confirmed, although the target for cars is to be met one year later than originally planned (i.e. in 2021) (European Commission, 2014).

The Regulations' 'expected results' include:

- Reducing CO₂ emissions of cars and LCVs;
- Creating incentives for the industry to invest in/develop new technologies;
- Lowering fuel and operating costs for consumers and businesses;
- Increasing employment and GDP (as a result of recycling of avoided spending on fuel); and
- Developing the long-term competitiveness/sustainability of the European automotive industry.

The Regulations are applicable to manufacturers, not Member States, and the targets are to be met by manufacturers through improvements in vehicle technology. The approach is more complex than EU legislation regulating air pollution from vehicles, for example, as this generally sets limit values for each regulated pollutant³. Such an approach was considered impractical for CO₂ emissions, as it would restrict the range of cars that could be put on the market. Hence, an approach was devised that sets each manufacturer a different target to reach in terms of the average CO₂ emissions of the new cars (or LCVs) that it sells each year. These targets reflect the existing profile of each manufacturer's new vehicle fleet. If a manufacturer does not meet the required target in any year, an excess emissions premium will be applied that directly relates to the scale of under-compliance.

In order for the targets to be able to reflect the characteristics of each manufacturer's vehicle fleet, it was necessary to relate the targets to a measure of a vehicle's 'utility'. Various possible 'utility parameters' were considered in the studies that were undertaken in support of the legislation, but the focus of the Impact Assessment supporting the original proposal for the passenger car CO₂ Regulation was on the choice between 'mass' (defined as the mass in running order) and 'footprint' (defined as wheelbase multiplied by track width). At the time, 'mass' scored better than footprint with respect to "data availability", "understandability" and "international compatibility", while 'footprint' was considered to be a better measure of the actual utility of a car, to be less likely to cause perverse effects and not to discriminate against some CO₂ reduction options (i.e. those that reduce mass) (European Commission, 2007). Largely as a result of the lack of data, mass was chosen to be the utility parameter relative to which manufacturers' CO₂ reduction targets would be met. For LCVs, the use of 'pan area' was considered along with 'mass', but again 'mass' was chosen as the utility parameter for vans for reasons of data availability and practicality (European Commission, 2009b). Some of the arguments in favour of 'mass' at the time of the original Regulations are no longer valid; the relevant data to calculate 'footprint' are now collated as part of the monitoring requirements of both Regulations, while 'footprint' is used in comparable legislation in the US, Canada and Mexico, so 'footprint' can no longer be viewed as "internationally incompatible".

² Commonly referred to as the van CO₂ Regulation

³ In other words, any vehicle being marketed within the EU has to have emissions that are no higher than these limit values.

2.2 Mechanisms that link manufacturers' targets to mass reduction

There are two mechanisms that link a manufacturer's CO₂ reduction target to mass reduction. First, as noted above, every year the respective targets for each manufacturer are directly linked to the sales-weighted average mass of its vehicles that were registered as new in the EU market. The respective targets are calculated according to a formula in Annex I of the respective car or van CO₂ Regulations, which determines a manufacturer's target as a function of the mass of its new vehicles that are registered that year. Any change in the average mass of a manufacturer's new car (or LCV) fleet will change the manufacturer's target that year. An added complication is that a manufacturer could potentially meet its targets by increasing the mass of its vehicles. In this respect, the slope of the line that represents the limit value curve (as represented in Figure 2-1) is important; this is set at a level that minimises the risk of such actions.

Second, the Regulations include a mechanism to account for changes in the average mass of the overall new car (or LCV) fleet. The average mass of the new vehicle fleet, referred to as M_0 , is part of the formula used to calculate each manufacturer's CO₂ reduction target. The mechanism in each Regulation periodically adjusts M_0 to reflect changes in the average mass of the new car or LCV fleet to ensure that the required overall CO₂ emissions target is achieved, while leaving the overall stringency of the Regulation the same. This has the following potential effects:

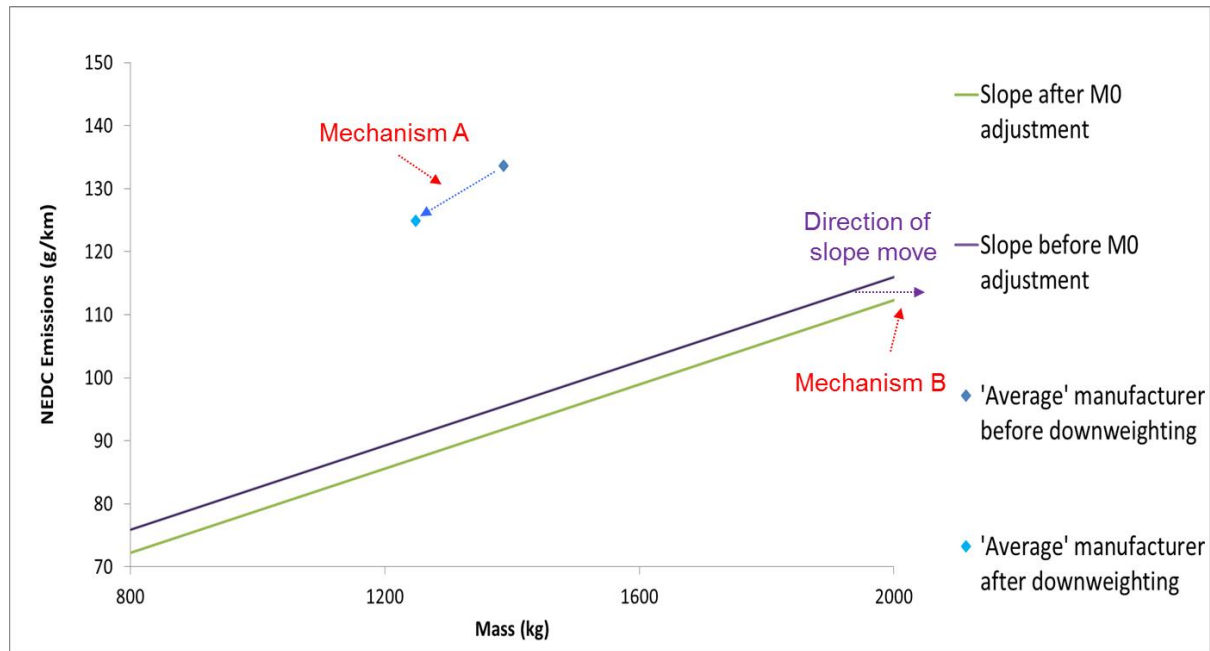
- If the average mass of the EU's new car (or LCV) fleet increases, manufacturers' respective targets will be adjusted to become more stringent for a given mass of vehicle.
- If the average mass of the EU's the new fleet decreases, the respective targets will be adjusted to become less stringent for a given mass of vehicle.

The adjustment to M_0 takes place every three years, with the first review for cars taking place in 2014 with any revised M_0 , which will be the average mass of new passenger cars in 2011, 2012 and 2013, being applied from 2016 onwards. The next adjusted M_0 for cars will be applied in 2019 and will be the average mass of new passenger cars in 2014, 2015 and 2016. For LCVs, the respective M_0 reviews and adjustments happen two years later than those for cars. The two mechanisms that link a manufacturer's target to changes in mass are shown in Figure 2-1 for the case where the average mass of the car fleet is increasing while the manufacturer considered decreases its fleet's average mass. In this figure, as the CO₂ emissions target for each manufacturer is a function of its mass, the target is represented in the form of a line that demonstrates that a manufacturer's target is dependent on the average mass of its new vehicle fleet. In Figure 2-1::

- **Mechanism A** represents the change in the position of the manufacturer relative to the limit value curve as a result of its reduction in mass and the associated reduction in CO₂ emissions. The position of an 'average' manufacturer is shown before and after the average mass (and average CO₂ emissions) of its new car fleet has declined.
- **Mechanism B** represents the movement of the target slope, in this case to make the targets more stringent, as a result of an M_0 adjustment.

Mechanism A shows that where the average mass of a manufacturer's car fleet decreases and its CO₂ emissions decrease as a result, its position relative to the target changes both vertically, as its average CO₂ emissions have declined, and horizontally (to the left), as its average mass is also lower. (The assumptions underlying the change of position are set out in Section 4). Mechanism B shows that the target line itself can move as a result of the M_0 adjustment, which will clearly have implications for the distance to its target for each manufacturer. The implications of these mechanisms, as well as those of similar mechanisms if 'footprint' had been the utility parameter, will be explored in more detail in Section 4.

Figure 2-1: Mechanisms relating to mass that influence a manufacturer’s target under the Regulations



By reducing the mass of a vehicle, the amount of fuel/energy required to complete the drive cycle used for quantifying CO₂ emissions performance would be lower, leading to corresponding reductions in CO₂ emissions. As set out in Chapter 1, a 10% reduction in mass gives a 3% reduction in CO₂ emissions, but if the engine is also de-powered at the same time as reducing mass in order to maintain the same power-to-mass ratio, a 10% reduction in mass gives approximately a 6.5% reduction in CO₂ emissions. Given that the study focuses on the most cost effective approaches to CO₂ reduction, it has been assumed that engine de-powering will also be employed and therefore a 6.5% CO₂ reduction for 10% mass reduction is assumed for the analysis carried out in this study.

3 Trends in vehicle mass and in the application of mass reduction measures

3.1 Overview

This chapter describes how the average mass values of new passenger cars and light commercial vehicles have evolved over the years, with particular attention to recent time periods. It also describes which elements have had an influence on the overall trends.

As the average mass of the new vehicle fleet is influenced by the types of vehicle sold, an examination of changes in the average mass for each vehicle segment and changes in the market shares of each segment is required.

The definitions of passenger cars (M1 vehicles) and light commercial vehicles (N1 vehicles) are set out in Directive 2007/46/EC. The Directive does not include definitions of individual vehicle segments and classes for either cars or LCVs.

For passenger cars, vehicle segment segments in Europe are not formally defined in legislation or by dimensional characteristics, but tend to be based on comparisons with particular vehicle models. The vehicle segment definitions commonly used in the European market are set out in the table below (European Commission, 1999).

Table 3-1: Vehicle segment definitions for passenger cars

Segment label	Description
A	Mini-cars
B	Small cars (superminis)
C	Medium cars (often referred to as “lower medium” cars)
D	Large cars (often referred to as “upper medium” cars)
E	Executive cars
F	Luxury cars
S	Sport coupés
M	Multi-purpose vehicles

Recent and ongoing changes in the European vehicle market mean that a number of new vehicle segments have been introduced in recent years. For the purposes of this analysis, these additional segments have been labelled as follows:

Table 3-2: Vehicle segment definitions for crossover and multi-purpose vehicle (MPV) passenger cars

Segment label	Description
BX	B-segment crossover vehicles
BM	B-segment multi-purpose vehicles
CX	C-segment crossover vehicles
CM	C-segment multi-purpose vehicles
DX	D-segment crossover vehicles
EM	E-segment multi-purpose vehicles
EX	E-segment crossover vehicles
LAV	Leisure activity vehicles

For LCVs, further classification is on the basis of mass classes. These N1 vehicle classes are defined in Directive 2004/3/EC, as set out in Table 3-3 below.

Table 3-3: Mass categories for light commercial vehicles

Class	Segment mass
Class I	Reference mass \leq 1305 kg
Class II	1305 kg < Reference mass \leq 1760 kg
Class III	1760 kg < Reference mass \leq 3560 kg

The impacts on average mass of changes in key vehicle characteristics have also been analysed; these characteristics include fuel type, footprint, engine size and power.

The remainder of this chapter is structured as follows:

- Section 3.2 assesses whether the sales-weighted average mass of new vehicles sold each year in the EU has been increasing.
- Section 3.3 investigates the reasons for changes in the sales-weighted average mass of new vehicles, comparing measured mass changes with variations in other factors that may influence mass.
- Section 3.4 summarises the results and clarifies whether the analyses provided are sufficient to allow the underlying factors which are driving trends in sales-weighted average mass to be quantified and ranked in order of importance.

3.2 Analysis of trends in vehicle mass

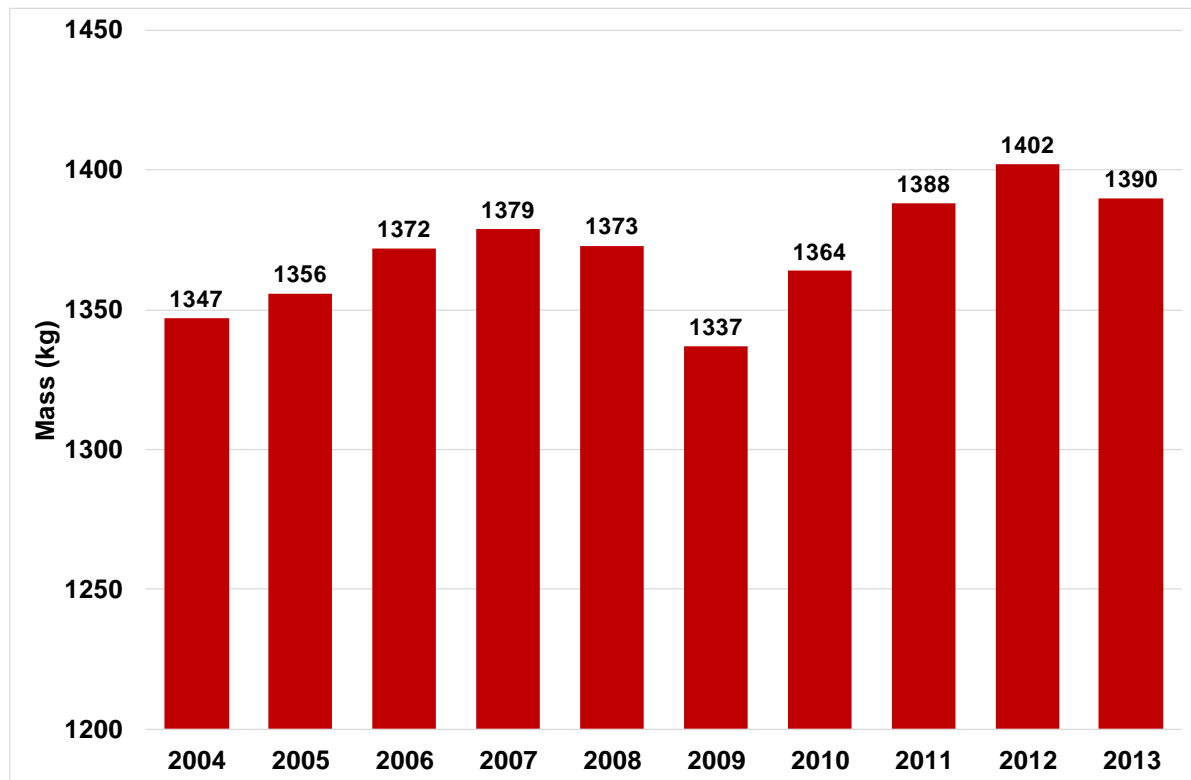
This section presents the results of data analysis carried out to identify and assess trends in how vehicle mass has changed over time. The data sources used as the basis for this analysis are described in Appendix 1.

3.2.1 Trends in passenger car mass

Monitoring data (European Environment Agency, 2014) indicates that the sales weighted average mass of new passenger cars in the EU27 increased by 3.2% between 2004 and 2013. Examining the data in more detail indicates that mass increased from 1347 kg to 1373 kg between 2004 and 2008, before falling significantly in 2009. However, from 2010 to 2012, average mass increased by 38 kg (2.8%) to

peak at 1402 kg. Data for 2013 indicates that average mass has decreased slightly from 1402 kg to 1390 kg (a 0.8% reduction); it remains to be seen whether this is the start of a mass reduction trend.

Figure 3-1: Sales-weighted average mass of new passenger cars: 2004-2013 (Source: EEA, 2014)

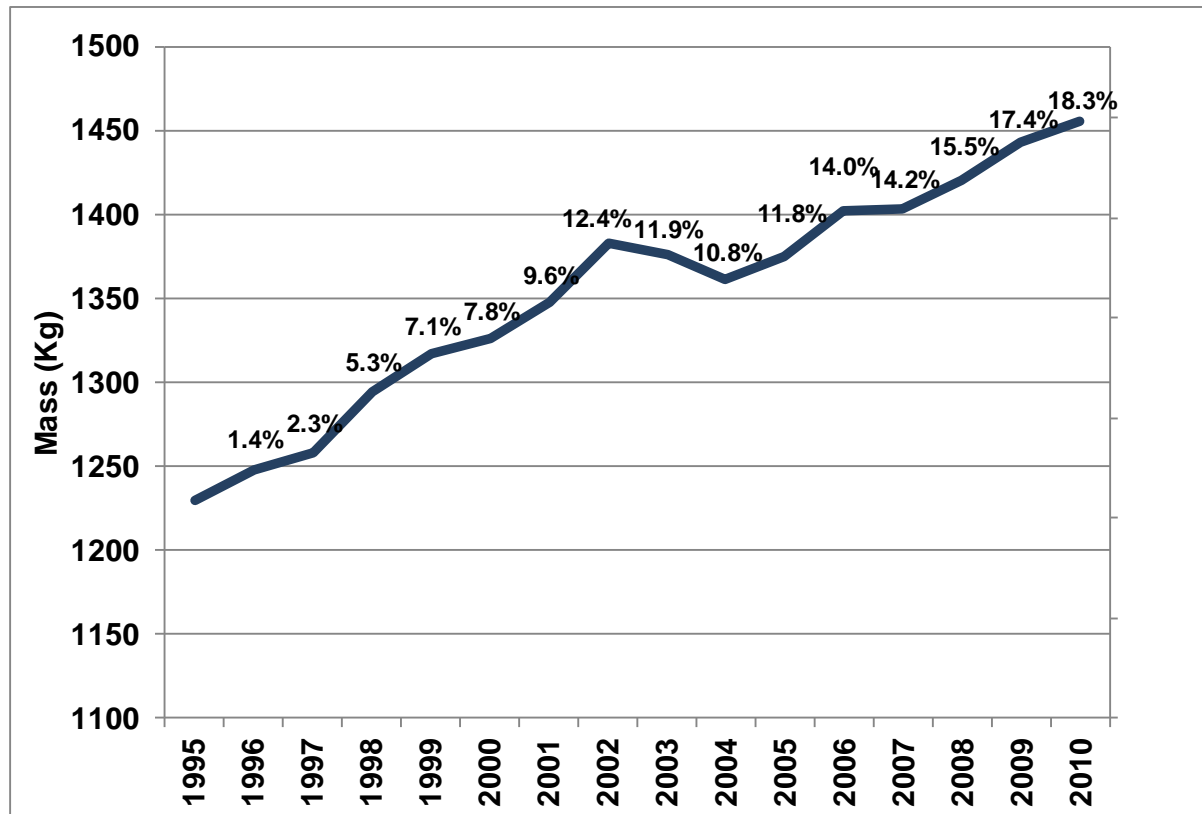


Note: Vehicle mass figures are mass in running order

Additional analysis examined trends in vehicle mass for the ten best-selling vehicles in seven EU countries covering the time period 1995 to 2010, drawing on data analysed as part of a previous study for the European Commission (AEA, 2011).

Figure 3-2 shows average mass and percentage increase calculated using 1995 as baseline year (1995=0). As illustrated by the figure, the long term trend shows a consistent mass increase for the period considered (18% overall increase, averaging at more than 1% per year), apart from the years 2002 to 2004, where average mass saw a small decline.

Figure 3-2: Evolution in the average mass of best-selling passenger car models between 1995 and 2010



Note: Vehicle mass figures are mass in running order; percentage increases are all referenced to the base value for 1995.

The values shown cover only seven countries and are not sales-weighted; the chart above is therefore somewhat biased towards larger segment vehicles, which are heavier but do not account for the majority of sales. The impact of this bias can be quantified by comparing the 2010 value from this dataset with the 2010 value from the EEA monitoring dataset (European Environment Agency, 2014). The 2010 overall average figure from AEA (2011) of 1456 kg is 92 kg higher (6.7%) higher than the 2010 sales-weighted average passenger car mass from the EEA monitoring dataset. For this reason, the data from AEA (2011) has been used to examine trends (i.e. percentage changes in vehicle mass over time) rather than focusing on the absolute mass values for the period between 1995 and 2010.

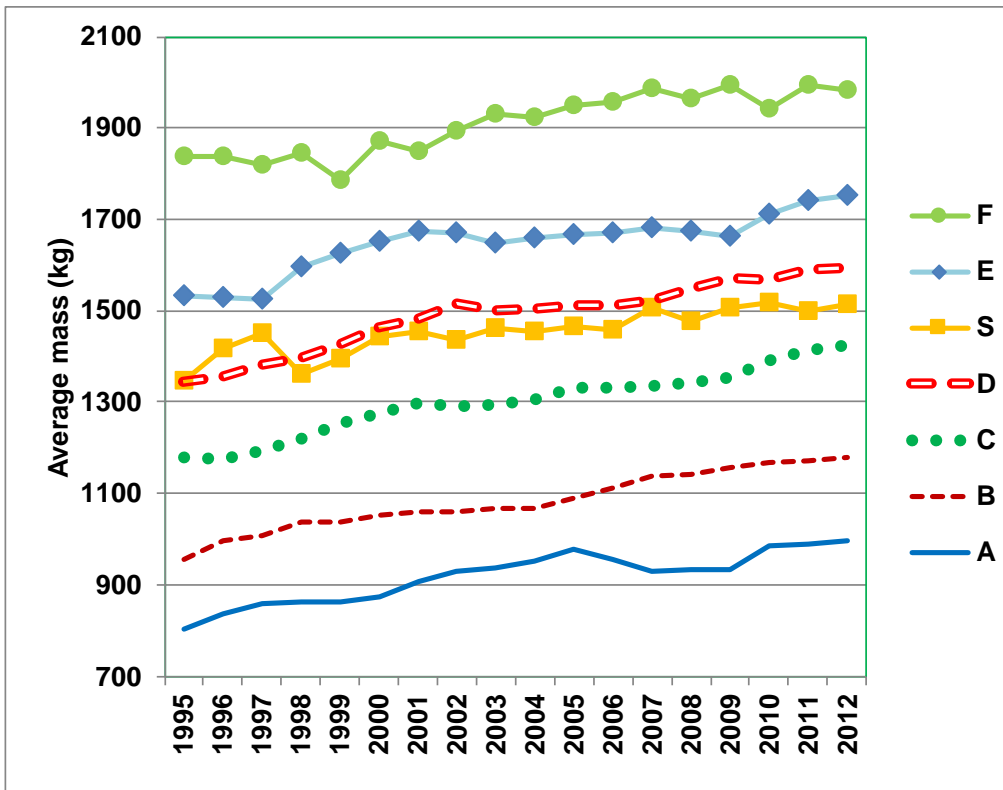
3.2.1.1 Mass trends by segment

Breaking down mass trends by segment over the period 1995 to 2012, the increase observed is consistent across all segments (see Figure 3-3). In that time, the average mass of any given segment has grown to be roughly equal to that of the next segment up; thus a B-segment car registered as new in 2012 weighs about the same as a C-segment car originally registered as new in 1995. For example, the average mass of a Peugeot 208 (B-segment) in 2012 is 1,251 kg, 393 kg heavier than the Peugeot 205 sold in 1995 (857 kg) and 77 kg heavier than the best-selling C-segment model in 1995 (Volkswagen Golf). The B-segment is the segment which has shown the greatest percentage increase in vehicle mass (20% from the 1995 baseline).

Figure 3-3 combines the two datasets analysed (AEA, 2011), (European Environment Agency, 2013), showing the long term evolution of average mass for the conventional segments.

Crossovers, multi-purpose vehicles (MPVs), sport-utility vehicles (SUVs), leisure activity vehicles (LAVs) and van-derived cars have been excluded from this chart because of the low number of entries before 2010.

Figure 3-3: Average mass by segment 1995-2012 (Principal data sources: (AEA, 2011), (European Environment Agency, 2013))

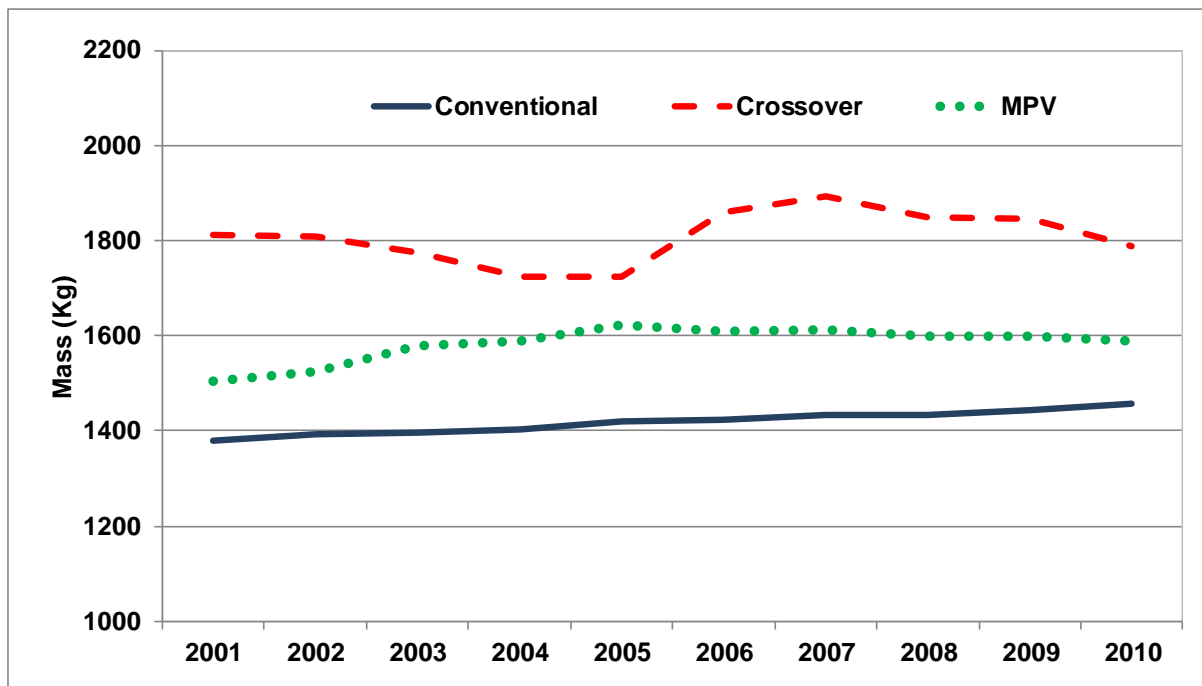


Note: Vehicle mass figures are mass in running order

It is interesting to note that, even though manufacturers often try to reduce the mass of high performance vehicles to improve performance, these types of vehicles also show a clear increase in average mass (11% increase in average mass between 1995 and 2012 for S-segment vehicles).

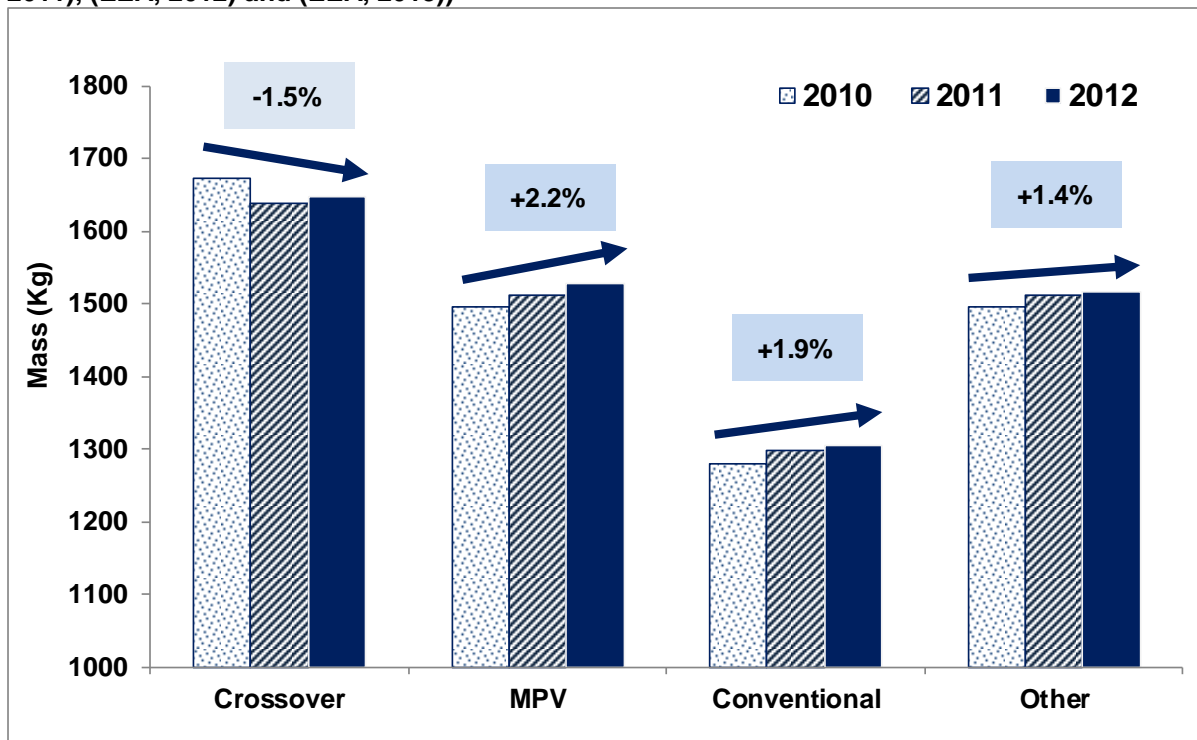
It is also possible to group models according to their type (e.g. conventional cars; MPVs; crossovers etc). Grouping models in this way indicates that the average mass of conventional cars and MPVs both increased between 2000 and 2010. Average mass trends for crossovers are more variable, although there was still a slight increase in average mass between 2000 and 2010. Figures for crossovers and MPVs are not very consistent due to the lower number of vehicles sold before 2010, and because the market for these types of vehicles is still rapidly evolving. In 2000, C-segment and B-segment crossovers were much less popular than in 2010, with many fewer models available on the market. For example, B-segment derived crossovers (BX-segment) did not feature in the bestselling models before 2010. One factor which has tended to reduce the upward trend shown by MPVs is that in recent years many smaller MPVs have appeared on the market. The remaining segments (Sport, Luxury, SUV and LAV) have been excluded from this analysis.

Figure 3-4: Mass trends by type 2000-2012 (Principal data source: AEA, 2011)



Note: Vehicle mass figures are kerb mass figures

Figure 3-5: Sales-weighted average mass by type 2010-2012 (Principal data sources, (EEA, 2011), (EEA, 2012) and (EEA, 2013))



Note: Vehicle mass figures are mass in running order

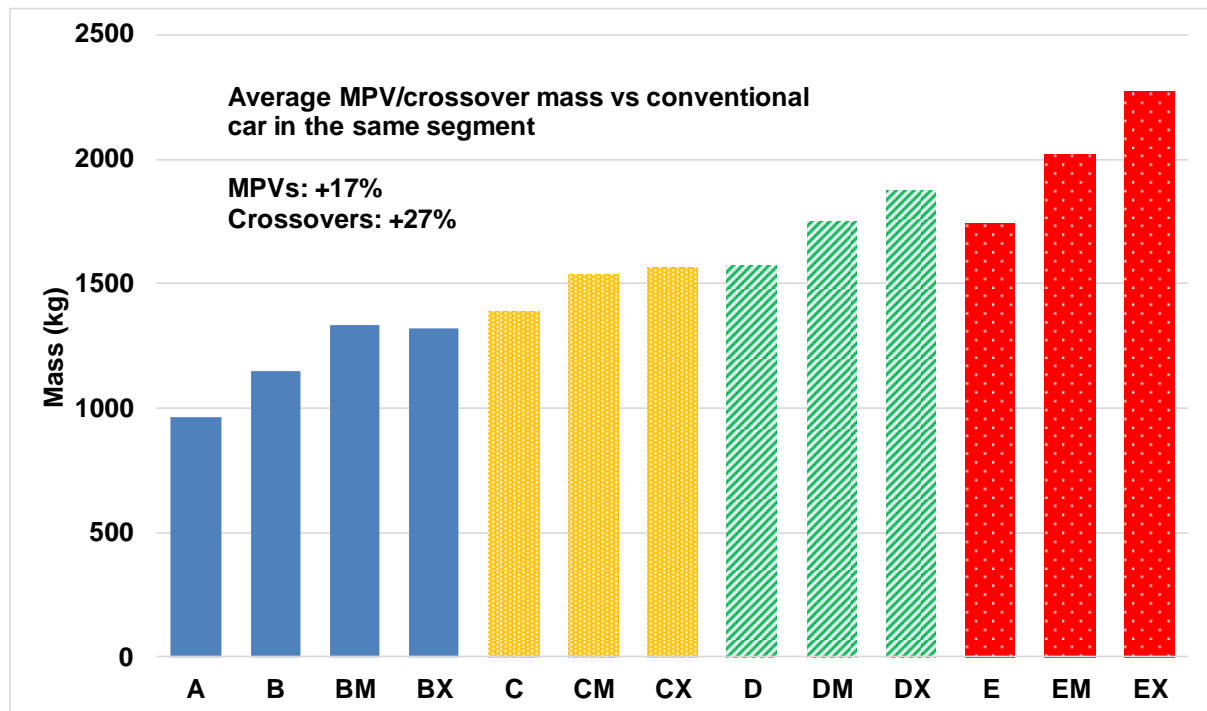
Sales-weighted average mass for 2010, 2011 and 2012 (taken from the EEA monitoring data), grouped by segment types, shows a slightly less marked increase in mass. Average vehicle mass values for the *conventional* passenger car and *MPV* segments have increased by approximately 2% between 2010 and 2012, whilst the average mass of passenger cars in the “other” category has increased by 1.4% (this category groups LAV, SUV van-derived cars, and S-segment cars together). By contrast, the sales-

weighted average mass of *crossovers* declined over this period (-1.5%); this decline is due to an increase in the availability and popularity of smaller crossover vehicles (i.e. B-segment and C-segment crossovers) in recent years. The values in Figure 3-5 show that the increase in the overall average sales weighted mass (2.8%) cannot be explained simply by an increase in mass within each segment.

Figure 3-4 and Figure 3-5 show that crossovers and MPVs have substantially higher average masses than the conventional cars they are derived from. Analysis of the combined sales-weighted average mass values for the three years covering 2010 to 2012 indicates that MPVs are 17% heavier and crossovers are 27% heavier than conventional passenger cars in the same segments.

Figure 3-6 examines whether this overall trend for MPVs and crossovers to be significantly heavier than conventional cars is true within each segment size.

Figure 3-6 Average mass by segment (Principal data sources: (EEA, 2011), (EEA, 2012) and (EEA, 2013))



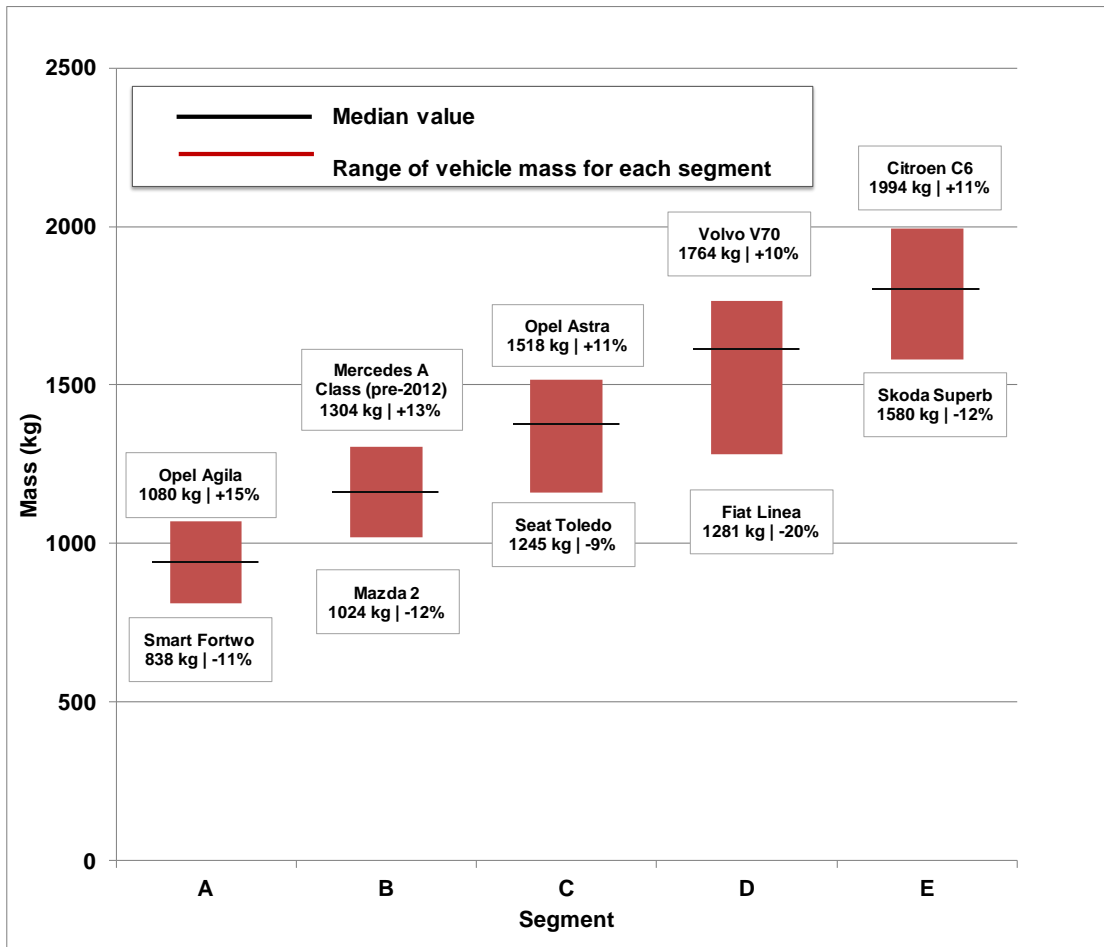
Note: Vehicle mass figures are mass in running order

For each one of the main segments analysed, the related MPV and crossover average mass is always comparable with the next larger conventional car segment. The trend for increased mass is particularly noticeable for larger crossover vehicles. Executive crossovers (EX segment) are over 30% heavier than conventional E-segment executive cars and are 13% heavier than MPVs of corresponding size (EM segment). It is also instructive to look at the range of mass values within each of the major segments.

Figure 3-7 shows the five main conventional passenger car segments, A to E. It is immediately apparent that for each segment there is typically a range of up to +/-15% either side of the median value with large overlaps between each segment size. To an extent this reflects the fact that there is a range of vehicle sizes within each segment (for instance a two-seat Smart Fortwo cannot be directly compared to four-seat Hyundai i10 despite them both being classified as A-segment vehicles).

In other cases, it is harder to justify the differences in mass. The C-segment Opel Astra hatchback launched in 2009 has kerb mass values listed between 1465 kg and 1684 kg, depending on the model variant, and the sales weighted average mass in the years 2010-2012 is 1518 kg. By comparison, the Seat Leon launched across Europe in 2012, and which is a direct competitor to the Astra, has kerb mass values listed between 1189 kg and 1415 kg.

Figure 3-7: Range of sales weighted mass within each main passenger car segment (Principal data sources: (EEA, 2011), (EEA, 2012) and (EEA, 2013))



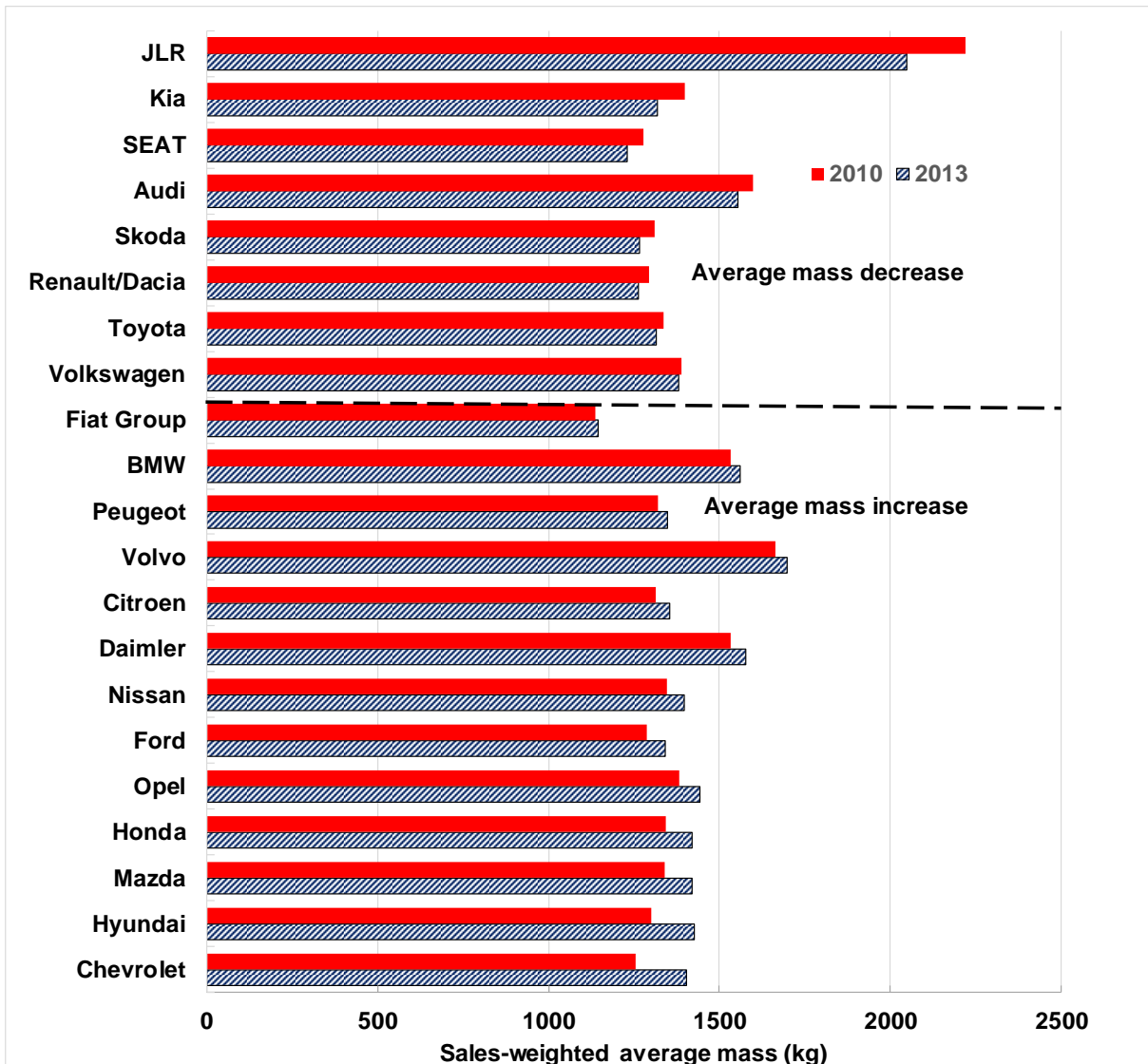
Note: Vehicle mass figures are mass in running order. The red columns shows the range of average recorded mass values for the vehicles allocated to that segment from the EU database (2010-2012)

3.2.1.2 Mass trends by manufacturer

Looking more widely at variations between the overall sales-weighted mass figures of different manufacturers, recent changes can be examined.

Figure 3-8 shows how average mass has changed from 2010 to 2014 for those manufacturers registering more than 100,000 cars per year. In the chart, manufacturers have been ranked according to reductions achieved. Of the brands included, 13 showed an increase in sales-weighted mass between 2010 and 2013, and eight exhibited a decrease. Jaguar Land Rover achieved the greatest average mass reduction at 7.8%. This reduction is primarily due to the introduction of smaller, lighter models such as the Range Rover Evoque (manufactured by Land Rover), and the intensive use of aluminium in the body structures of key new vehicles, including the latest generation of the full size Range Rover, introduced in 2012. By contrast, Chevrolet exhibited the largest increase in sales-weighted average mass, with a 12% increase between 2010 and 2013.

Figure 3-8 - Mass variation 2010-2013 by manufacturer. (Principal data sources: (EEA, 2011) and (EEA, 2014))

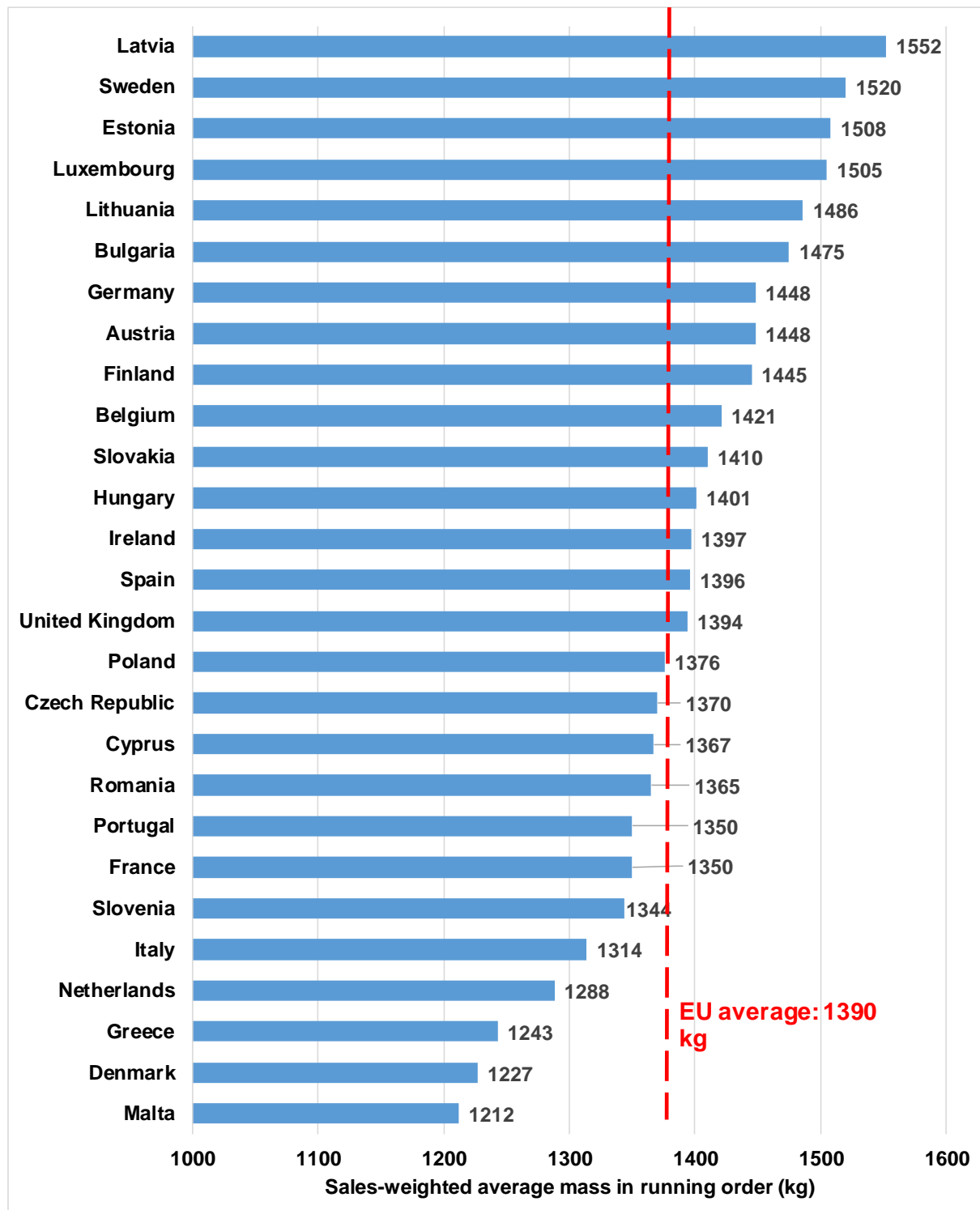


Note: JLR = Jaguar Land Rover; vehicle mass figures are mass in running order

3.2.1.3 Mass trends by country

It is also possible to observe country-specific trends. Average mass by country in 2013 (Figure 3-9) shows a difference of 340 kg between Latvia (highest) and Malta (lowest), with Latvia 11% above the EU average and Malta 13% below.

Figure 3-9 - Average sales weighted mass 2013 by country. (Principal data source: (EEA, 2014))



Note: Vehicle mass figures are mass in running order

It is instructive to examine trends in vehicle mass over time for each country as well. The following two charts (Figure 3-10 and Figure 3-11) present trends in vehicle mass for the period from 2004 to 2013 for (a) each EU15 Member State and (b) each EU12 Member State. As can be seen, for most EU12 countries, vehicle mass steadily increased between 2004 and 2013, and any reductions in average mass that occurred at the start of the economic crisis are relatively small.

By contrast, the trend lines for EU15 countries are very varied; for a number of EU15 countries, very significant reductions in average new car mass occurred between 2008 and 2009, before mass started increasing again from 2010. The sharp reductions in the average mass of new cars in Denmark and the Netherlands from 2007 are striking and are likely to be due to vehicle taxation regimes introduced in

these countries; in particular, the Netherlands has linked annual car tax to vehicle mass (T&E, 2013). Sweden levied its annual vehicle tax on the basis of mass up to 2005 (when it switched to CO₂), but this has not had any visible effect on their long term trends. Germany, France and Austria all experienced a noticeable reduction in the average mass of new passenger cars in 2009 which is likely to be due to consumers opting for smaller and more efficient vehicles during the economic crisis. In France, the introduction of the bonus-malus CO₂-based taxation scheme in 2008 is also likely to have contributed to reductions in mass after that year.

Figure 3-10: Sales-weighted average vehicle mass in running order by country for EU15 Member States (Source: (EEA, 2014))

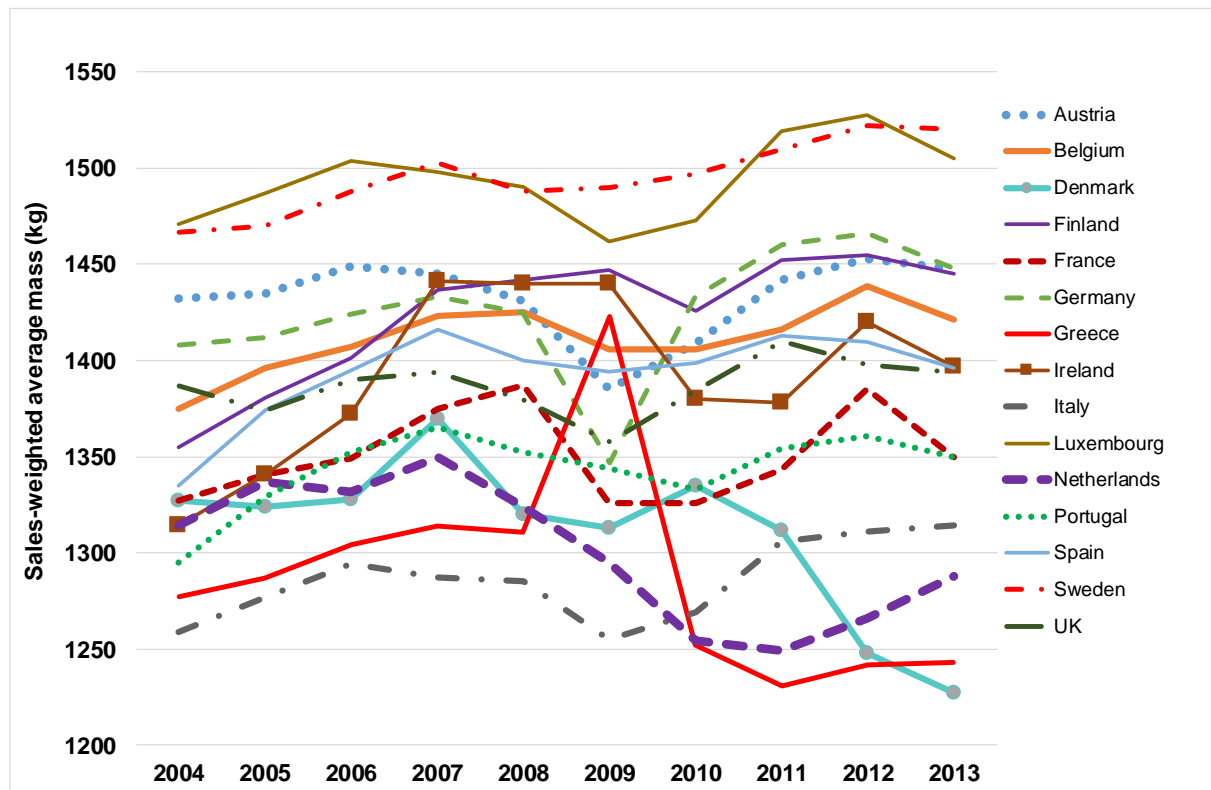
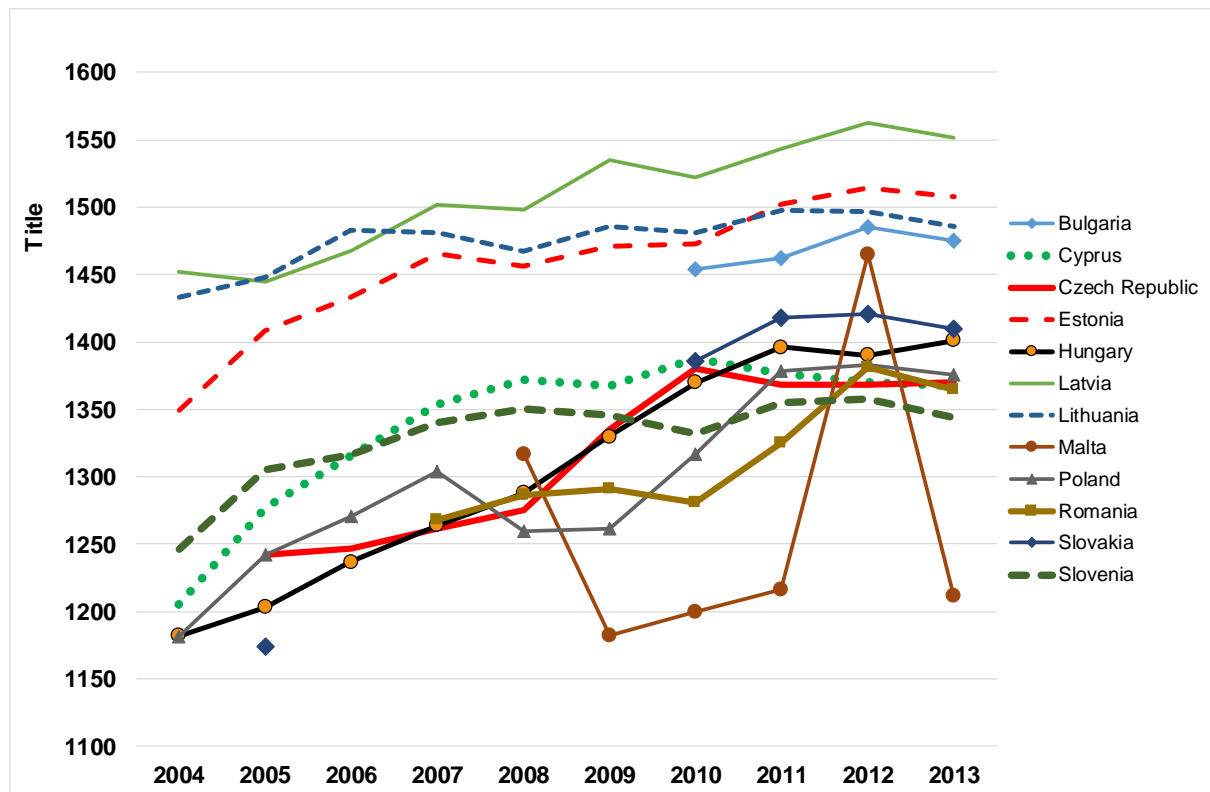


Figure 3-11: Sales-weighted average vehicle mass in running order by country for EU12 Member States (Source: (EEA, 2014))



3.2.2 Trends in light commercial vehicle mass

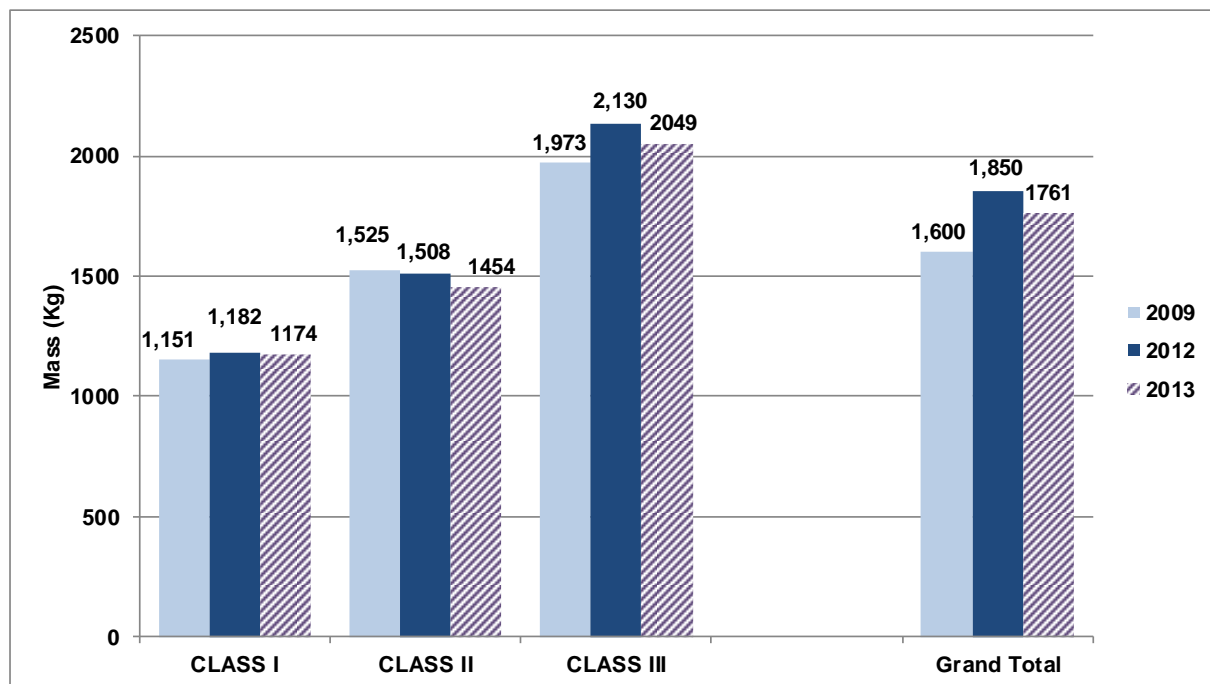
Data on light commercial vehicles are much less readily available than for passenger cars. CO₂ monitoring data were only available for 2012 and 2013 over the course of this study (European Environment Agency, 2013b, 2014), and this was supplemented with additional data from a previous study covering 2009 (TNO *et al*, 2012b). Full details on the data used for this study can be found in Appendix 1.

Figure 3-12 shows how the sales-weighted mass of LCVs changed between 2009 and 2013, with data presented on changes in overall average mass and changes in average mass by LCV class. These data show that between 2009 and 2012, the overall sales-weighted mass of the new EU LCV fleet increased by 16% from 1,600 kg to 1,850 kg, before declining to 1,761 kg in 2013. Overall, LCV mass increased by 10% between 2009 and 2013.

Since LCV classes are defined by mass, a different type of analysis (compared to that presented for passenger cars, above) is required to understand why these changes have happened.

Figure 3-12 suggests that the sales data could be the key, as mass change within categories is of a much smaller scale than for cars, with Class II vehicles even showing a decrease in average mass over the full time period covered. Furthermore, the EEA monitoring data for 2013 indicates that sales-weighted average mass for all classes of LCV declined between 2012 and 2013.

Figure 3-12: Sales-weighted average mass of light commercial vehicles – 2009, 2012 and 2013



Note: Vehicle mass figures are mass in running order

3.3 Underlying reasons for mass change trends

3.3.1 Reasons for changes in vehicle mass for passenger cars

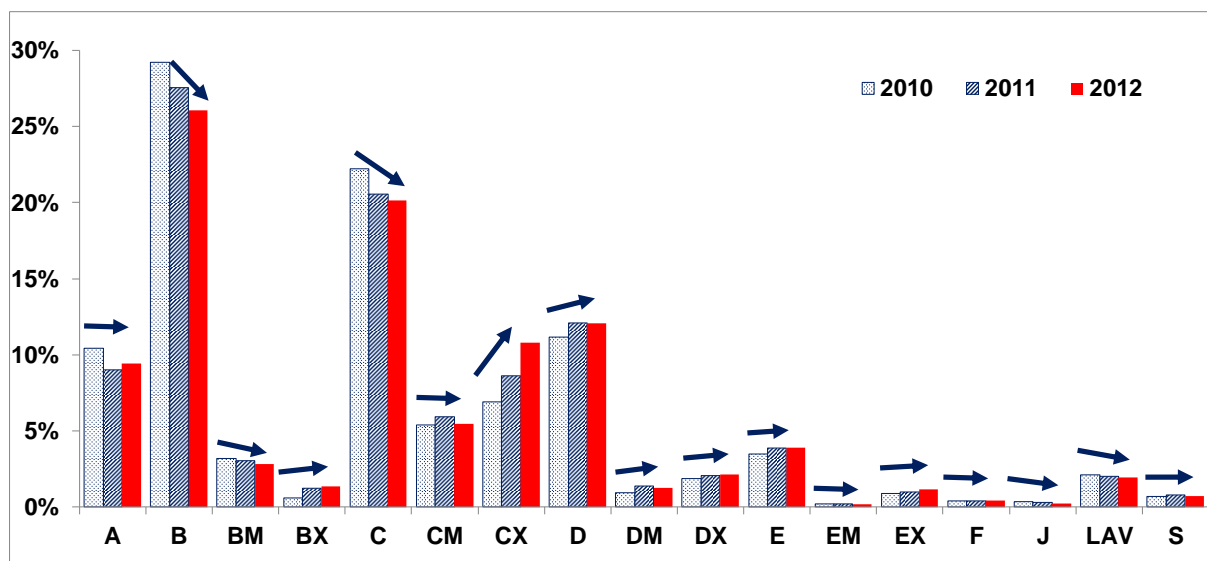
Increases in the average mass of new passenger cars are likely to be due to a combination of the following factors:

- Changes in the relative popularity of different market segments
- Increases in the popularity of cars fitted with diesel engines
- Increases in the physical size of passenger cars

3.3.1.1 Changes in the relative popularity of different market segments

The average mass of the best-selling passenger car models in selected EU Member States increased by 18% over the period 1995-2010 (AEA, 2011), whilst the average EU-27 new fleet mass increased by 3.2% between 2004 and 2013. Additionally, the average new fleet mass increased by 2.8% between 2010 and 2012 (1.9% between 2010 and 2013, due to the reduction in fleet average mass in 2013). Analysis of mass increases broken down by vehicle type (i.e. conventional cars, crossovers, MPVs and others) shows percentage increases lower than the overall percentage increase. This indicates that it is likely that market shares of sales have shifted between these different segments. The following chart shows how market shares evolved in the period 2010 to 2012.

Figure 3-13: Market share by segment (Source: (EEA, 2013))



Although the period under consideration is rather limited (i.e. 2010 to 2012), the data indicate that whilst the market share of conventional cars in the B and C-segments has declined, market share of crossover vehicles in these segments has increased markedly. Sales of D-segment crossovers have also seen strong growth, while MPVs and the remaining types of vehicles maintained a fairly stable market share, apart from an increase for the D-segment.

Comparing mass changes in each vehicle type with the overall mass increase across the whole market, the overall average sales-weighted increase in mass of 2.8% between 2010 and 2012 cannot be explained only by average increase in vehicle mass within each passenger car segment (Table 3-4). It must therefore be at least partially due to a shift in purchasing choices towards crossovers from conventional models.

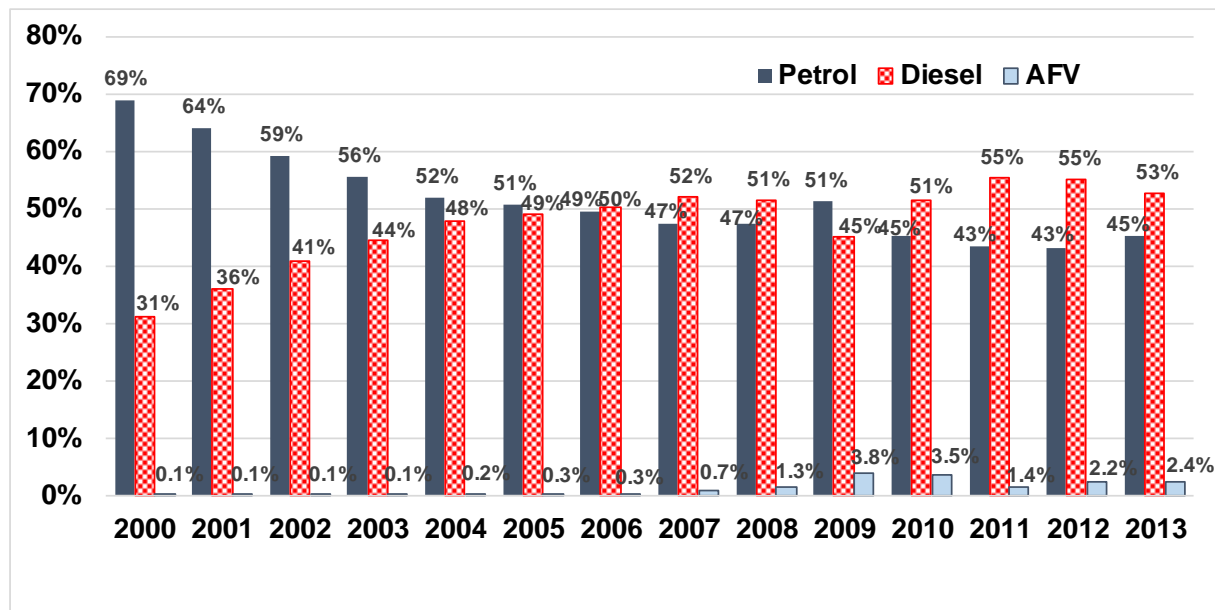
Table 3-4: Mass change versus market share change for the period 2010-2012

Vehicle type	% Mass change	Absolute market share change
Conventional	+1.9%	- 5.1%
Crossover	-1.5%	+5.2%
MPV	+2.3%	+0.1%
Other	+1.4%	-0.2%
Overall	+2.8%	

3.3.1.2 Increases in the popularity of cars fitted with diesel engines

Diesel-powered vehicles are generally heavier (typically 40-50 kg heavier) than equivalent vehicles equipped with petrol engines, and hence another factor that is likely to have contributed to increasing the overall average mass of the fleet is the increase in the popularity of diesel cars. As can be seen from Figure 3-14, since 2000, the proportion of diesel-fuelled cars sold across the EU has increased very dramatically. In 2000, only 31% of new cars sold in the EU were equipped with a diesel engine; from 2010 onwards, more than 50% of new cars sold in the EU have been fitted with diesel engines, although data for 2013 indicates a decline in the popularity of diesel compared to the previous year.

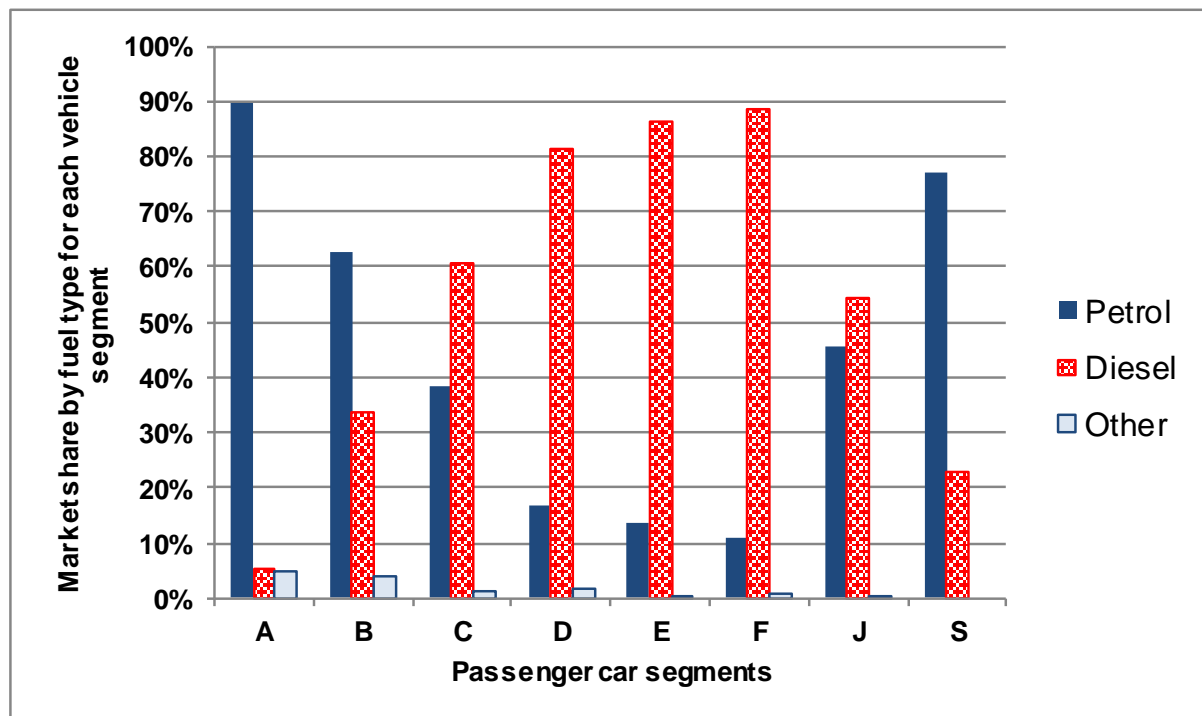
Figure 3-14: Market share of new car sales by fuel type 200-2013 (Source: EEA (2014))



Note: AFV = Alternatively fuelled vehicle

Furthermore, the average diesel car is between 24% and 26% heavier than the average petrol car, depending on the year of interest (24% difference in 2009; 26% in 2013). The reason for this is primarily because diesel engines are less popular in smaller vehicles (i.e. the A and B segments) and much more popular in larger vehicles (e.g. the C, D, E and F segments). Hence the sales-weighted average mass for diesel cars is dominated by larger, heavier cars, whilst most small cars are fitted with petrol engines. This can be seen from the chart below which presents the 2012 market share of new car sales by fuel type for key passenger car segments.

Figure 3-15: 2012 market shares of EU new car sales by segment and by fuel type (Source: EEA, 2013)



These trends are further exemplified by comparing changes in the sales-weighted average mass values for petrol cars and diesel cars over the period 2004 to 2013 (EEA, 2014). Whilst the sales-weighted average mass for diesel cars has increased by 5.2% over this time period (from 1463 kg to 1539 kg), the sales-weighted average mass for petrol cars has decreased by 1.5% (1237 kg to 1218 kg). This is primarily due to an increase in the percentage of diesel cars in larger (heavier) vehicle size categories and a decrease in the percentage of diesel cars in smaller size categories (see Figure 3-17 below). In 2010, C-segment cars accounted for 39.6% of new diesel cars sales, whilst B-segment, D-segment and E-segment cars accounted for 32.2%, 25.9% and 6.4% of new diesel car sales respectively. By 2012, C-segment cars accounted for 35.1% of new diesel car sales, whilst B-segment, D-segment and E-segment cars accounted for 26.5%, 26.8% and 8.2% of new diesel car sales respectively. The additional exhaust after treatment systems required for diesel engines to meet recent emissions regulations may also have contributed to the increases in the average mass for new diesel cars.

Figure 3-16: Average mass by fuel type - 2004-2013 (Source: EEA, 2014)

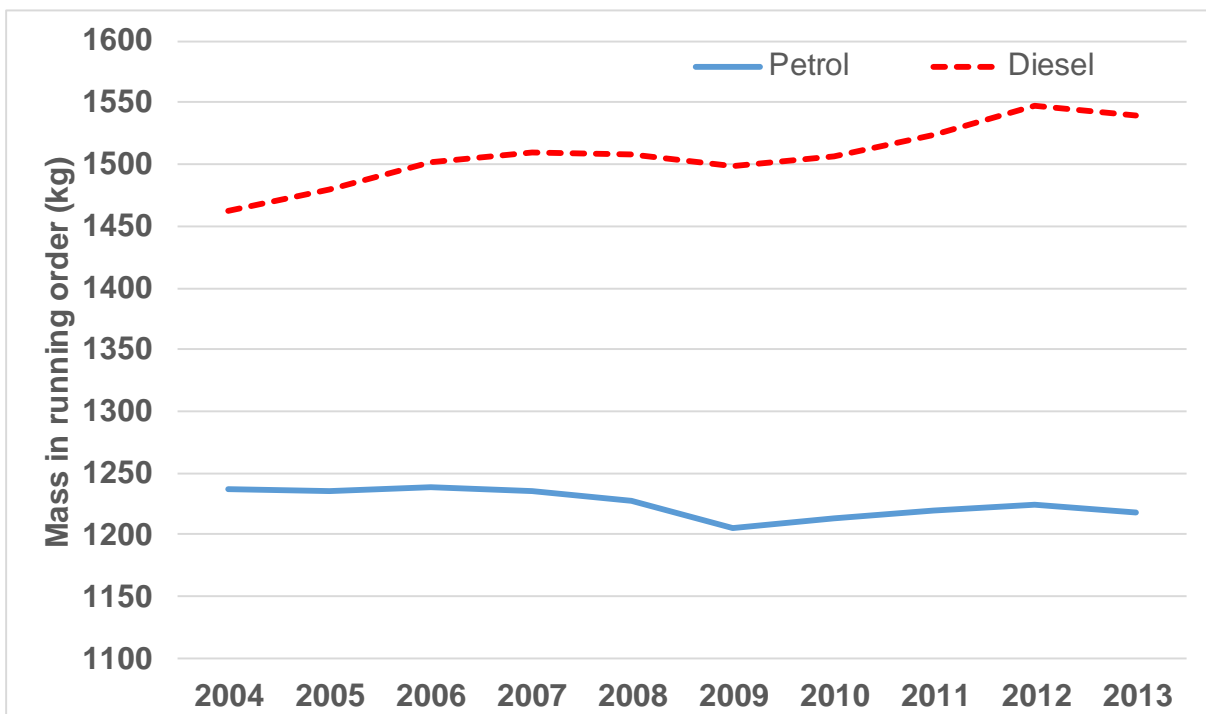
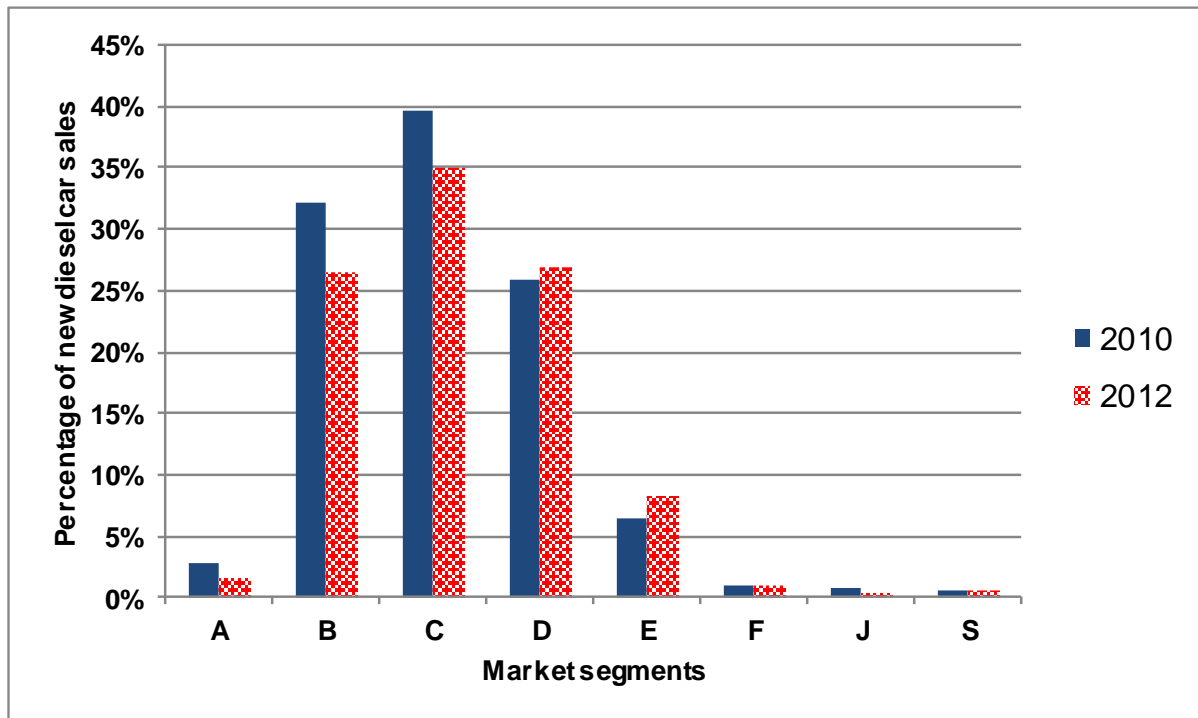


Figure 3-17: Comparison of new diesel car sales split by market segment for 2010 and 2012



3.3.1.3 Impacts of hybrid-electric and battery electric technology on vehicle mass

Future growth in sales of hybrid and fully electric vehicles is likely to lead to further increases in the sales-weighted average mass of passenger cars. Comparisons of battery electric and internal combustion engine versions of specific vehicle models demonstrate that mass can increase by between 17% and 31% (Table 3-5). For the electric version of the Volkswagen Up! (A-segment) the battery alone weighs 230 kg, almost 20% of the whole vehicle (Volkswagen, 2014a). Hybrid powertrain models incur smaller mass increases – for example the Toyota Yaris and Auris are available as both conventional petrol vehicles and as petrol-electric hybrids; the latter variants incur a 6-8% increase in kerb mass.

As discussed in Chapters 1 and 2 of this report, a 10% reduction in vehicle mass for internal combustion engine (ICE) vehicles gives approximately a 3% reduction in CO₂ emissions, assuming that no other changes are made to the vehicle, and a 6.5% reducing in CO₂ emissions if the powertrain is depowered in tandem with reducing mass. Reductions in CO₂ emissions (and hence fuel consumption) of this nature also mean that driving range increases. For pure electric vehicles, reductions in mass provide greater relative benefits in energy efficiency and driving range compared to mass reductions for equivalent conventional ICE vehicles. For example, Volkswagen has estimated the increases in driving range associated with a 100 kg reduction in mass for petrol and battery electric versions of the Golf as follows (Volkswagen, 2011):

- 2.4% increase in driving range for a conventional petrol-engined 1.4 litre TSI Golf Mk VI⁴
- 3.6% increase in driving range for a prototype battery electric version of the Golf Mk VI, known as the VW360e.

Given the high costs of lithium ion batteries and consumer desire for increased range for electric vehicles, this is likely to lead to a strong focus on mass reduction to (a) improve driving range and/or (b) reduce on-board battery storage capacity, thereby reducing production costs.

⁴ This assumes no engine down-powering. As set out in Chapter 1, greater improvements in efficiency are possible if the vehicle's engine is down-powered at the same time as reducing mass. In this example, down-powering the petrol engine would give larger improvements in driving range than 2.4%.

Table 3-5: Comparison of kerb mass for conventional vehicle models, battery electric and vehicle models and hybrid-electric vehicle models

Lightest conventional ICE model	Kerb mass (kg)	Lightest BEV / Hybrid model	Kerb mass (kg)	Percentage increase
Smart Fortwo	770	Smart ForTwo Electric Drive	900	17%
Mitsubishi i	900	Mitsubishi i-MIEV	1070	19%
VW UP!	929	VW e-UP!	1214	31%
Renault Fluence (1.6 auto petrol)	1339	Renault Fluence Z.E.	1605	20%
Nissan Tiida	1257	Nissan Leaf	1493	19%
Toyota Yaris (petrol)	1065	Toyota Yaris hybrid	1150	8%
Toyota Auris (petrol)	1355	Toyota Auris hybrid	1420	6%

3.3.1.4 Increases in the physical size of vehicles

In the context of trends in vehicle mass, examining how the physical size of vehicles has changed over time is useful, as vehicle mass tends to increase with increasing physical size. Footprint and pan area are metrics that can be used to quantify the physical size of a vehicle. Footprint is defined as vehicle wheelbase multiplied by its track width whilst pan area is vehicle length multiplied by vehicle width. An examination of both metrics is necessary as data on footprint has only been collected since 2010; by contrast, we were able to obtain pan area data for the period 1995 to 2010. Our analysis shows that both footprint and pan area have increased over time. Sales weighted average footprint increased from 3.15 m² to 3.36 m² between 2010 and 2012, equivalent to a 6.7% increase. Pan area increased by 12% between 1995 and 2010. Hence, a key contributor to the observed increases in average vehicle mass is the increase in the physical size of vehicles.

By using pan area as a proxy for the surface area of a vehicle, we can calculate approximate values for “vehicle density” (i.e. mass per unit surface area, in kg/m²). This has allowed us to investigate whether sales-weighted average vehicle mass is increasing more or less rapidly than average vehicle size. Long term trends indicate that vehicle density increased by 4% between 1995 and 2010, meaning that vehicle mass increased more rapidly than vehicle size. This means that only part of the mass increase can be attributed to increases in size.

Figure 3-18: Pan area and mass variation 1995-2010 (1995=0). (Principal data source: AEA, 2011)

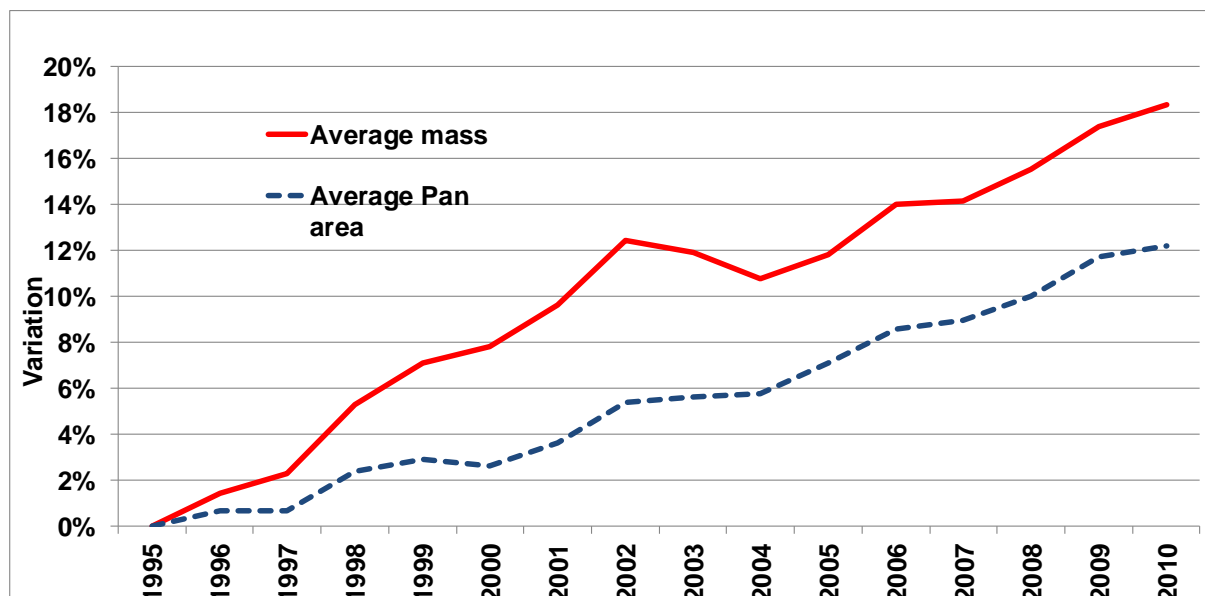
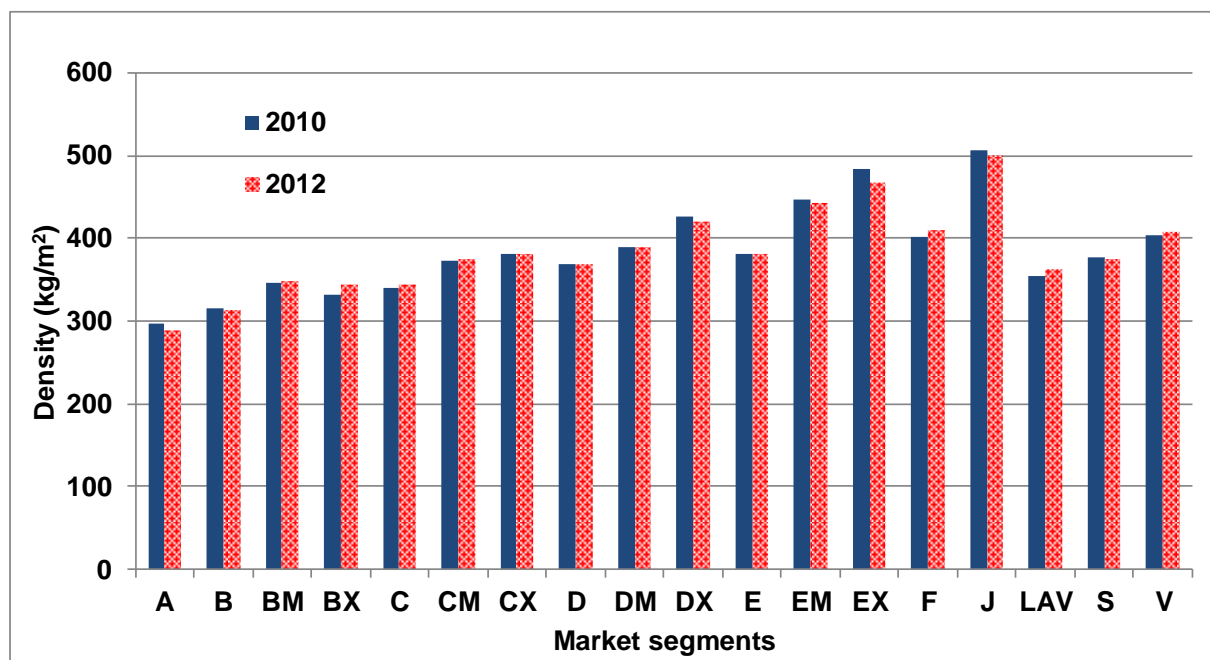


Figure 3-19 shows how 'vehicle density' (in this case calculated as kerb mass divided by footprint) varies across different vehicle segments. Perhaps counter-intuitively, it reveals that smaller vehicles are significantly less 'dense' than larger ones, with body-on-frame SUVs (J-segment) and executive crossover vehicles (EX) being the most 'dense'. The density of body-on-frame vehicles would be expected to be high due to the additional mass associated with using a ladder-frame structure. Similarly, the density of EX-segment crossover vehicles would also be expected to be high due to the fact that many of these vehicles are equipped with four-wheel drive systems.

Figure 3-13 showed how sales of crossover vehicles (CX, DX and EX segments), large cars (D segment) and executive cars (E segment) have increased as a proportion of total new car sales, whilst the market shares of B and C segment cars have declined. Comparing these changes in market shares with the data below on vehicle density for each segment, the shift in the market towards heavier, high-density vehicle segments is an additional contributor to the increases in sales-weighted average mass.

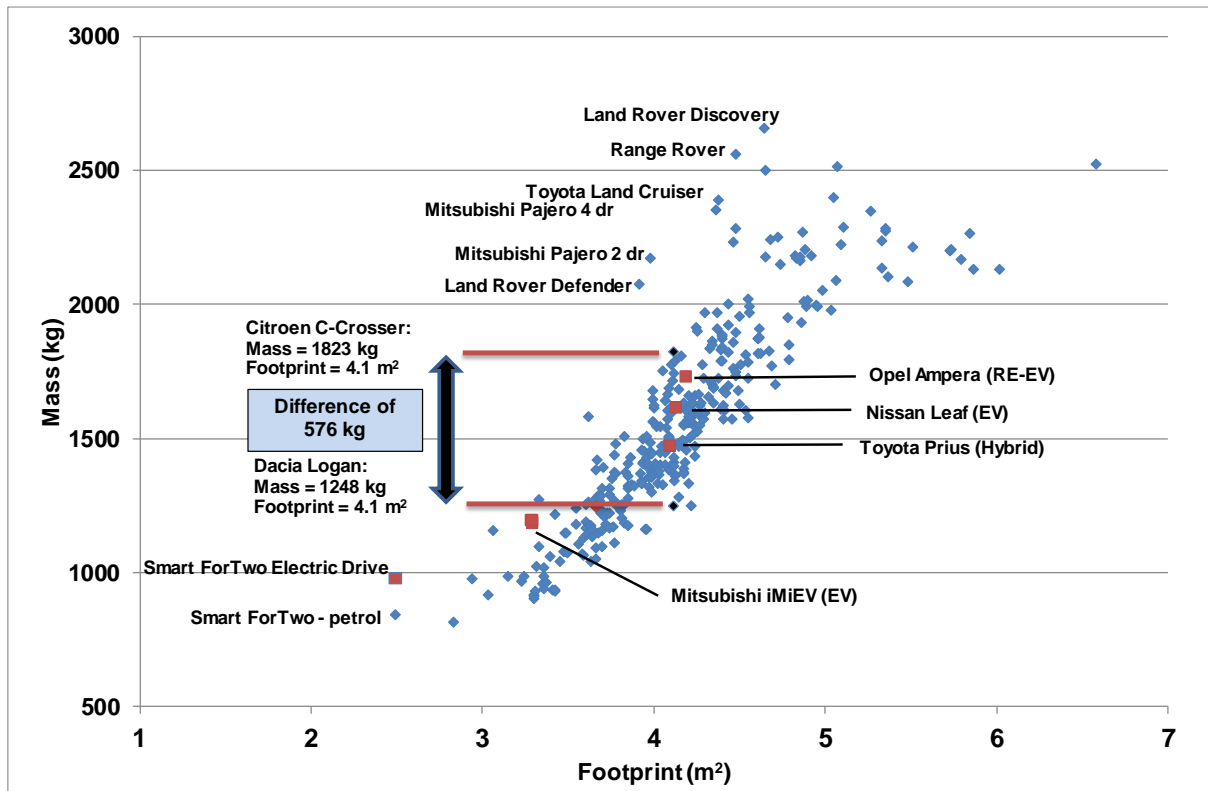
Figure 3-19: Variation of 'vehicle density' (mass/footprint) across vehicle segments. Principal data sources: (EEA, 2011) and (EEA, 2013))



For a given footprint, there can be a large variation in the sales weighted average mass of different models (Figure 3-20). For example the data includes two models both with a 4.1 m² footprint, the Dacia Logan and Citroen C-Crosser. The Dacia has a sales weighted average mass of 1248 kg and for the Citroen this value is 1823 kg (46% higher value). While this may be due to these being different vehicle types (that do not directly compete in the marketplace) that happen to share a common footprint, it does illustrate the wide range of vehicle masses that currently exist, suggesting that some reductions in mass may be possible amongst the heavier models.

Figure 3-20 also highlights a selection of other vehicles that have very high mass values in relation to their footprint (Land Rover Discovery, Range Rover, Toyota Land Cruiser and Mitsubishi Pajero). The design characteristics of these vehicles, including the fact that they are all equipped with four wheel drive systems, are responsible for the high mass values.

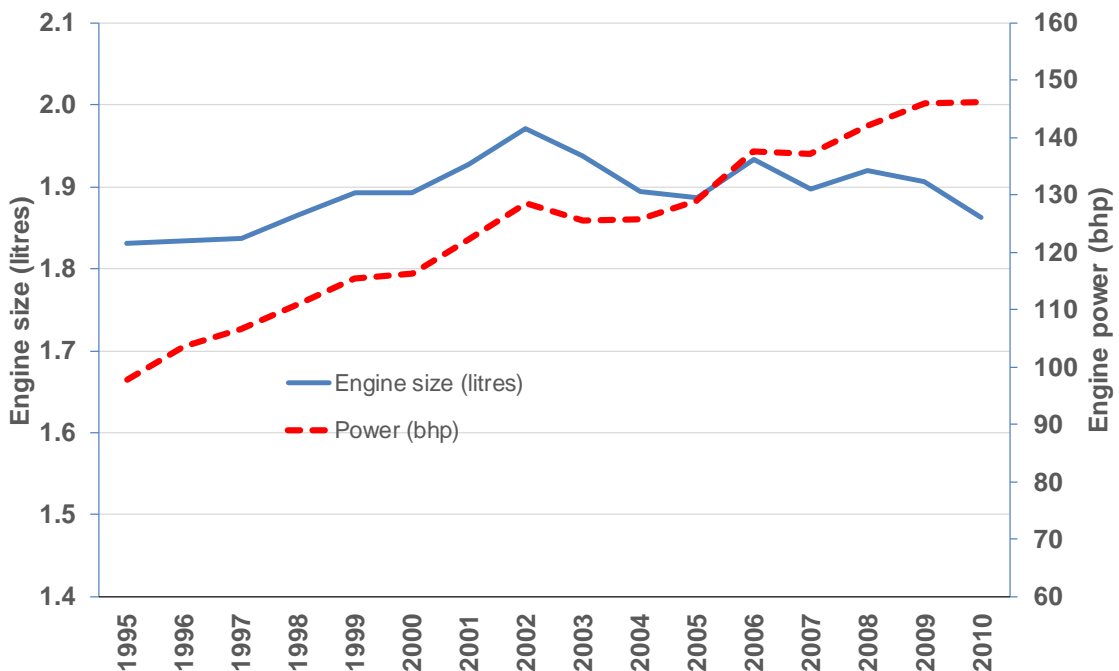
Figure 3-20: Sales weighted average mass versus footprint (cars and LCVs)



Note: Vehicle mass figures are mass in running order

For passenger cars, especially for the smaller segments, the engine constitutes a relatively large proportion of vehicle mass. A look at long and short term trends does not show any clear correlation between engine size and mass, as engine size peaked in 2002 and has declined since, while mass has continued to rise. The chart below has been restricted to conventional, MPVs and crossover vehicles, as SUVs and sport cars generally have larger engines and may have had too much influence on averages.

Figure 3-21: Average engine capacity and power (conventional, MPV and crossovers)



Note: bhp = Brake Horse Power

3.3.2 Reasons for changes in vehicle mass for light commercial vehicles

For light commercial vehicles, changes in vehicle mass over the last few years are likely to be due to the following reasons:

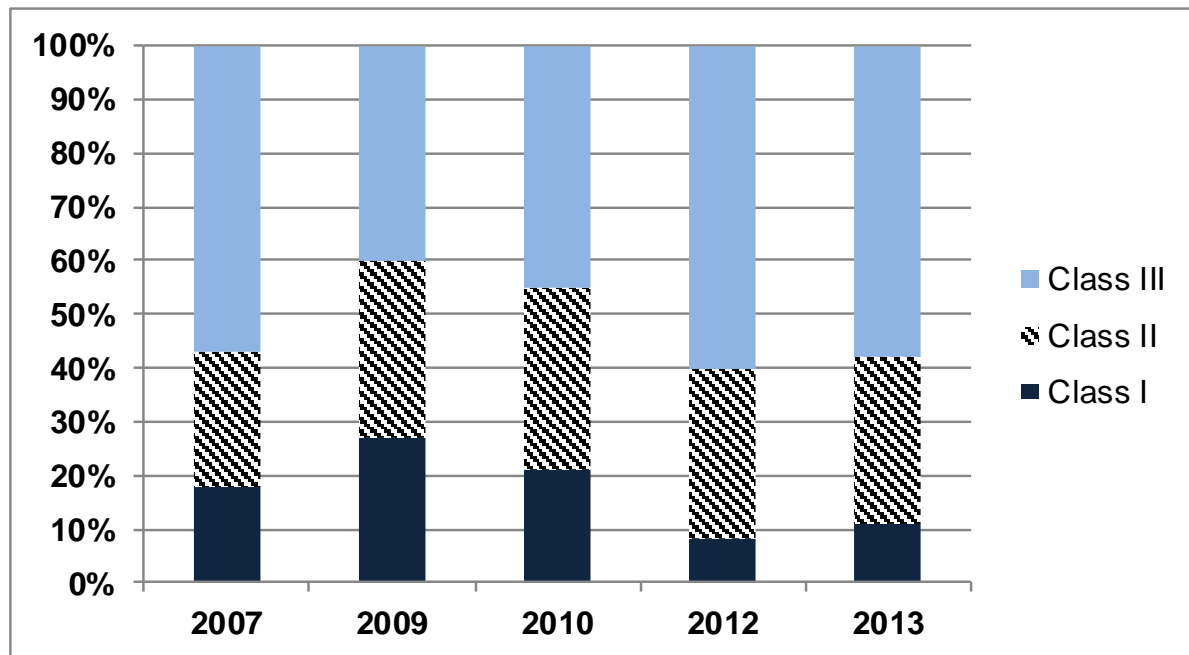
- Shifts in the relative popularity of new Class I, Class II and Class III LCVs
- Substitution of heavy goods vehicles (HGVs) by LCVs
- Increasing importance of safety performance in the LCV market
- Emergence of new LCV market segments
- Increase in LCV feature content to make the driving experience more similar to passenger cars

The following sections explore each of these factor in more detail.

3.3.2.1 Shift in the relative popularity of Class I, Class II and Class III LCVs

Figure 3-22 provides data on market share by LCV class from the EEA monitoring reports (EEA, 2013b, EEA, 2014) combined with data obtained from previous research carried out on behalf of the European Commission (TNO et al, 2012b). Between 2007 and 2009 there was an increase in market share for smaller vans, perhaps prompted by a combination of the recession and national scrappage schemes in a number of Member States. Since then it appears that the LCV market has shifted towards higher classes, and therefore heavier vehicles.

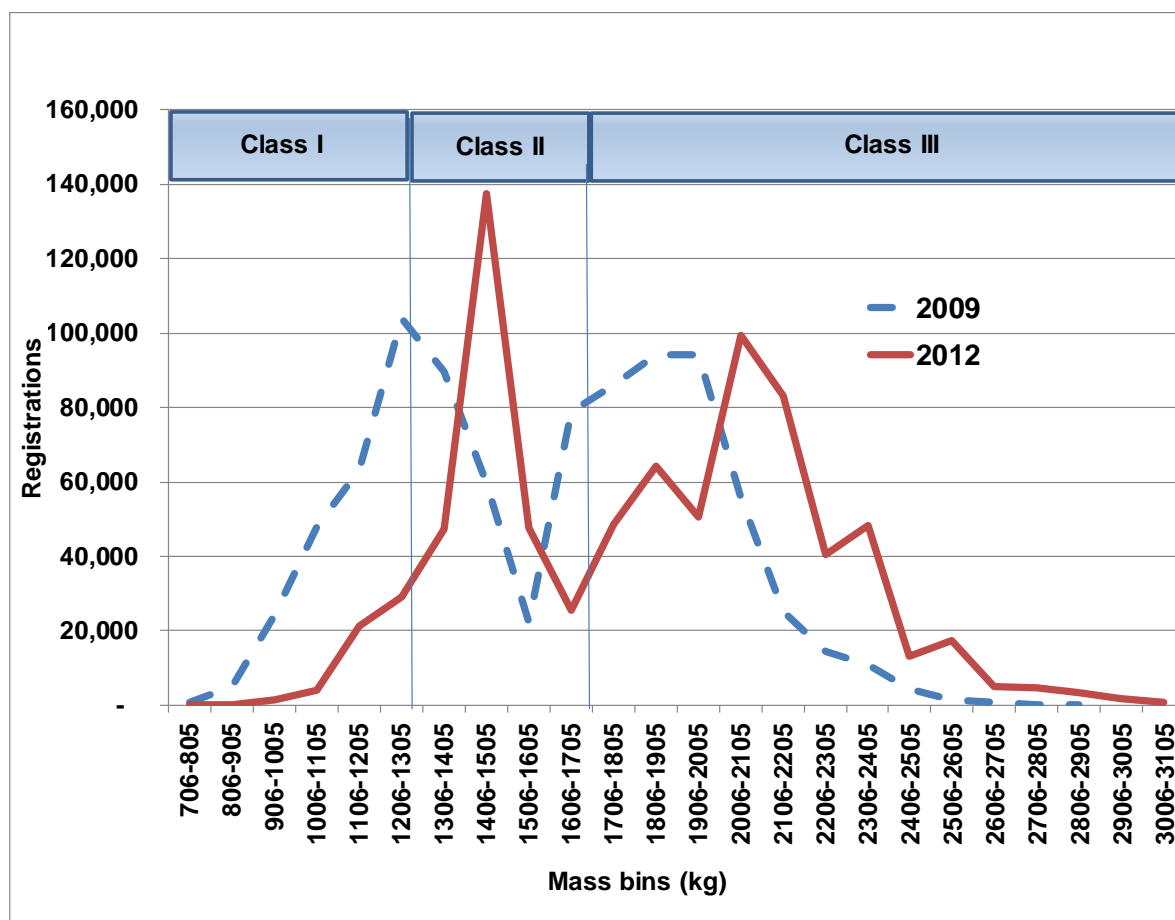
Figure 3-22: LCV sales by class in selected years between 2007 and 2012 (Principal data sources: (TNO et al, 2012b), (EEA, 2013b), (EEA, 2014))



Registrations of Class I vehicles (i.e. those below 1305 kg), have declined in market share from 27% in 2009 to 11% in 2013.

A comparison with Figure 3-12 in Section 3.2.2 suggests a different explanation; because of the way classes are defined, it is possible that a significant proportion of what would have previously been Class I vehicles have increased in mass enough to jump to the Class II category (i.e. vans with mass between 1305 kg and 1760 kg).

Figure 3-23: LCVs Class I, II and III sales (100 kg bins). (Principal data sources: (TNO et al, 2012b), (EEA, 2013b))



Note: Vehicle mass figures are mass in running order

Figure 3-23 seems to validate this hypothesis, as the peak of registrations moved from the 1206-1305 kg mass bin to the 1406-1505 kg bin in 2012. The average mass of these peaks was 1,254 kg (in 2009) and 1,456 kg (in 2012), a difference of 16% which matches the overall change for the LCV sector. The shift from Class II to Class III is less clear, but it is still possible to identify a peak in sales moving from the top end of Class II to the lower end of Class III (Figure 3-23).

This explanation is borne out if sales and mass data for a selection of the best-selling van models are examined for the years 2009 and 2012 (see Table 3-6).

Table 3-6: Comparison of sales-weighted average mass for selected best-selling vans in 2009 and 2012. (Principal data sources: (TNO et al, 2012b), (EEA, 2013b))

Model	Sales-weighted average mass for the years 2009 and 2012 (kg)		Percentage increase between 2009 and 2012
	2009	2012	
Citroen Berlingo	1330	1391	5%
Peugeot Partner	1338	1471	10%
Renault Kangoo	1338	1493	12%
Ford Transit Connect	1307	1384	6%
Ford Transit	1583	1771	12%

Note: Vehicle mass figures are mass in running order

As can be seen from the data in the table, there have been significant increases in sales-weighted average mass between 2009 and 2012 for these individual models. For the Citroen, Peugeot, Renault and Ford Transit Connect vans, the increases in the sales weighted average masses mean that a greater proportion of these vehicles now fall into Class II rather than Class I. For the full-size Ford Transit, the increase has been sufficient to shift the sales-weighted average for this vehicle from Class II to Class III. At least part of this increase can be attributed to changes in purchasing behaviours. For example, the Ford Transit is available in a huge number of variants, with different carrying capacities and different kerb mass values (typically, the variants with greater carrying capacity have higher kerb mass values). Analysis of the Ford Transit sales data for 2009 and 2012 shows that there was a significant shift in purchasing behaviour over this time period. Total Ford Transit sales in the EU in 2009 and 2012 were 67,611 and 77,040 respectively. In 2009, 43% of Transits sold were Class II vehicles, and the remaining 57% were Class III vehicles. By 2012, only 17% of Transits sold were Class II vehicles, whilst 83% were Class III vehicles. The latest generation Ford Transit, which was released to the market in 2013 only consists of Class III vehicles, which means that the available payload of Transit vans with a gross vehicle mass of 3.5 tonnes is, in some cases, smaller than for previous models.

For Class III LCVs, there has been a significant increase in the sales of vehicles in the 2306 kg to 2405 kg mass bin. Most of this increase can be accounted for by a dramatic increase in sales of specific Mercedes and Volkswagen LCVs with variants that fall into this mass banding. In 2009, only 4,617 Mercedes Sprinters in the 2306-2405 kg mass bin were sold; by 2012, this had increased to sales of 28,310. Similarly, in 2009 only 1,964 Volkswagen Crafter and Transporter vans in the same mass bin were sold; by 2012, this has increased to 15,239. There is also another smaller peak in 2012 sales in the 2506-2605 kg mass bin that did not exist in 2009. Again, this is due to very large increases in the sales of Mercedes and Volkswagen vans in this mass band. In 2009, just 232 Mercedes Sprinters were sold with mass in the range 2506-2605 kg; by 2012, sales of this model in this mass bin had increased to 12,102 vehicles. Sales of Volkswagen's Crafter and Transporter models in this mass bin also increased over this time period (from 1,041 vehicles in 2009 to 4,299 vehicles in 2012).

3.3.2.2 Substitution of HGVs by large LCVs

In some Member States, there is evidence that operators are choosing to replace HGVs with large LCVs because they are significantly cheaper to operate (RAC Foundation, 2014) and more suitable for current market conditions. For example, in the UK, LCV operators do not require a specialist driving licence, any specific training or an operator's licence. By contrast, HGV drivers require all of these things. Salaries for LCV drivers are around 40% lower than for HGV drivers, and businesses have found it more difficult to find and recruit suitably qualified HGV drivers. Furthermore, increasing levels of restrictions on the operation of HGVs in urban areas (based on size, mass, height, width, emissions, etc) mean that large LCVs are now often more practical for use in these locations.

3.3.2.3 Increasing importance of safety performance in the LCV market

Safety performance has become increasingly important in the LCV market, following trends that started in the passenger car market. In the last few years, increasing amounts of safety equipment have been fitted to popular LCV models as standard equipment, with corresponding increases in vehicle mass. For example, in 2009, Ford made a number of minor revisions to its first generation Transit Connect van. These changes included equipping the vehicle with the following safety features as standard (Ford Motor Company, 2009):

- Electronic stability control (including anti-lock braking, hydraulic brake assist, active yaw control, and roll-over mitigation systems)
- Driver's airbag fitted as standard, with passenger airbag available as an option
- Side airbags fitted as standard to some model variants and available as an option for all variants.

Many other LCVs models are now fitted with a wide range of safety equipment that was previously unavailable in the LCV market, including (amongst others):

- Understeering control systems
- Acceleration slip regulation (ASR)
- Brake disc drying technology
- Trailer stability assist
- Lane keeping alert systems

Until 2012, light commercial vehicles had not been included in the EuroNCAP crash testing programme, but since that year, a number of business and family LCVs have been tested. Given that the EuroNCAP

has had a significant impact on the number and range of safety features now fitted as standard to passenger cars, it is likely that the increased focus on LCV safety could have a similar effect on the LCV market in future years. For example, the latest Ford Transit Custom is the first LCV to receive a five star EuroNCAP rating.

3.3.2.4 Emergence of new LCV market segments

Another factor that has contributed to the increases in LCV average mass is the emergence of new market segments. Two clear examples of this are the emerging markets for crew vans and four-wheel drive vans.

Crew vans

Crew vans have two rows of seating (rather than just one row, as in most vans) to improve the functionality of the vehicle with respect to carrying passengers. Most of the major manufacturers have introduced crew vans to the market in the last few years. Adding a second row of seats tends to increase the mass of the vehicle compared to standard panel vans with one row of seats. Table 3-7 presents kerb mass data for a selection of panel vans with one row of seating and their equivalent crew van variants with two rows of seating. As can be seen from the table, crew vans are heavier than their conventional panel van equivalents by between 35 kg and more than 120 kg. Note that there are also now some LCV models available with three rows of seats where both the second and third row can be folded, tilted or removed completely to provide the user with even more flexibility (e.g. Ford Transit Custom Kombi). As can be seen from the table below, this additional flexibility increases the vehicle’s kerb mass significantly; the Transit Custom Kombi is more than 320 kg heavier than the equivalent standard Transit Custom panel van.

Table 3-7: Kerb mass values for selected standard panel vans and equivalent crew vans

Model	Kerb mass values	
	Standard panel van	Crew van / multi-row seating
Mercedes Vito	1870 kg	1905 kg
VW Transporter T30 SWB 2.0 TDi	1848 kg	1887 kg
Ford Transit Custom 310 L2 H1 2.2 TDCi (74 kW)	1858 kg	Double cab:1972 kg Kombi: 2181 kg
Fiat Scudo 130 Multijet SWB	1788 to 1800 kg	1846 kg

Four wheel drive vans

Over the last few years, all of the major manufacturers have started offering four wheel drive variants of their mass-market larger panel vans, which are heavier than the equivalent two-wheel drive variants. For example, the Ford Transit, Mercedes Sprinter, Volkswagen Crafter, Opel/Vauxhall Movano and Iveco Daily are all available with four wheel drive for specific model variants. According to Mercedes-Benz UK, four-wheel drive versions of the Sprinter have kerb mass values that are 130-165 kg greater than the two-wheel drive versions (Mercedes-Benz, 2014). Similarly, four-wheel drive versions of the Ford Transit are approximately 200 kg heavier than equivalent front-wheel drive versions (Ford Motor Company, 2014).

Availability of front-wheel drive and rear-wheel drive versions of the same LCV model

Some larger vans are now available with a choice of either front-wheel drive or rear-wheel drive, whereas previously they might have been front-drive only. Rear-wheel drive vans have a higher kerb mass, but offer better traction when heavily laden and are better for towing. Front wheel drive offers a larger volume load space and higher overall load capacity in kg. The following LCV models are all available with choice of both front-wheel drive and rear-wheel drive:

- Ford Transit
- Mercedes Vito
- Nissan NV400
- Opel/Vauxhall Movano

- Renault Master

The impacts of rear-wheel drive on kerb mass can be significant; for example, the Ford Transit 350 L2 H2 medium roof van is 114 kg heavier when specified with rear wheel drive than it is when specified with front wheel drive. Similarly, the Renault Master is around 140 kg heavier when specified with rear-wheel drive compared to front-wheel drive versions.

Increase in LCV feature content

Over the last few years, there has been significant effort expended on making the LCV driving experience more like driving a passenger car. This has led to more sophisticated suspension systems being fitted to LCVs, and a lot of emphasis has been placed on reducing noise, vibration and harshness (tackling NVH adds a lot of mass through the application of bitumen damping pads and sound insulation materials). Other comfort and safety features from cars are also being fitted to LCVs (usually as standard equipment), all of which increase the average kerb mass of the vehicle. Such equipment includes:

- Electrically powered windows/mirrors
- Rear parking sensors
- Built-in satellite navigation systems
- Torque Vectoring Control
- Traction Control
- Load Adaptive Control
- Smart Regenerative Charging
- Battery Management Systems
- Adaptive cruise control

The above equipment changes to make LCVs more car-like will affect both smaller and larger vans to some extent, and this additional equipment is likely to have contributed to the observed increases in average LCV kerb mass.

3.4 Summary of findings on trends in vehicle mass

Key findings from the analysis carried out are as follows:

- The average mass of new passenger cars and LCVs has been increasing steadily over the last few years.
- For passenger cars, vehicle mass data covering a large selection of best-selling models in Europe for the period 1995 to 2010 was analysed and this showed that average mass of new cars has increased by 18% over this time period, an average increase of more than 1% per year.
- Additionally, analysis of vehicle mass data for all new car sales in the EU27 covering the period 2004 to 2013 showed that sales-weighted average mass increased over this time period by 3.2%, although average mass declined by 0.8% between 2012 and 2013.
- Increases in the average mass of passenger cars were observed for all segments, but trends for each brand varied; 13 brands showed an increase in average mass and eight brands showed a decrease in average mass.
- The increase in the average mass of passenger cars is due to a combination of increases in the physical size of vehicles, a shift away from petrol cars to diesel cars, and the increasing popularity of crossover vehicles which are heavier than equivalent conventional hatchbacks, saloons and estate cars.
- For LCVs, sales weighted average mass increased by 16% to 1,850 kg between 2009 and 2012, an increase of over 250 kg, before declining in 2013 to 1,761 kg. Overall, average LCV mass increased by 10% between 2009 and 2013.
- Increases in the kerb mass of LCVs are likely to be due to a combination of factors including a shift in sales towards LCVs with larger load capacities, additional safety and comfort features being fitted as standard, and the emergence of new market segments.

4 Implications of changes to the mass of vehicles on individual manufacturer CO₂ targets under the car and van CO₂ Regulations

4.1 Overview

The two mechanisms that link each manufacturer's CO₂ reduction target to changes in both the average mass of its vehicle fleet and to changes in the average mass of the entire new EU vehicle fleet (as a result of the M₀ adjustment) were set out in Section 2.2. These mechanisms have a variety of implications, many of which have not been fully explored, although some reports have examined some of the implications of these mechanisms (e.g. ICCT, 2012b).

The focus of this chapter is on the implications of these mechanisms for manufacturers in the context of meeting the targets in the passenger car CO₂ Regulation. The mechanisms, but not the actual target numbers, will be similar in the context of the LCV CO₂ Regulation. Given that the 2015 target for cars has already been met, the implications for reducing the mass of cars in the context of the 2021 target were explored. Between 2012 and 2021, there will be two reviews of M₀, both of which could result in the value of the parameter being adjusted to reflect changes in the average mass of the new car fleet. For the sake of simplicity, the scenarios that were developed to explore the implications of the mechanisms contain only one M₀ adjustment prior to 2020 (although this could in practice be the net impact of two M₀ adjustments).

Five scenarios were developed to explore the most interesting cases in which the average mass of a manufacturer (termed "Manufacturer A" for the purposes of this analysis), and its competitors change (or not) compared to business-as-usual (BAU). These scenarios are summarised in Table 4-2.

In each of Scenarios 1 to 3, the average mass of Manufacturer A declines by 10%, so the difference between these three scenarios is what happens to the average mass of Manufacturer A's competitors: in Scenario 1, this stays the same; in Scenario 2 it increases by 10%; while in Scenario 3 it decreases by 10%. Scenario 4 is different in that it represents the case in which the average mass of the new cars sold by Manufacturer A stays the same as in the BAU case, whereas the average mass of its competitors' cars decreases by 10%. Only one scenario, Scenario 5, was undertaken for the case in which 'footprint' is the utility parameter, as in this case any changes to the average mass of the market has no impact on the target of Manufacturer A.

To facilitate the analysis, a simple market of ten manufacturers with equal market share was assumed. The figures that were used in the scenarios for average mass, footprint and CO₂ emissions were based on actual figures for manufacturers in 2012 to ensure that the analysis was representative of the real world market situation; hence, the starting point for the analysis is the situation in 2012.

For all scenarios, it is assumed that a 10% mass reduction delivers a CO₂ reduction of 6.5% (ICCT, 2011b) (i.e. the power-to-mass ratio of the vehicle remains constant through engine de-powering in addition to vehicle mass reduction, as discussed in Chapters 1 and 2). Furthermore, the assumption is that these reductions are delivered by the introduction of CO₂ abatement options that involve mass reduction, such as those that are the focus of this report. This is assumed to be the case to explore the implications of the mechanisms that link the manufacturers' targets under the Regulations to the mass of their vehicles. By doing this it is possible to understand further how these mechanisms might affect the introduction of CO₂ reduction options that involve mass reduction.

Table 4-1: Scenarios developed for testing the impacts of changes in the sales-weighted average mass of vehicles sold by one or more car manufacturers

Scenario	Utility parameter	Mass reduction of "Manufacturer A"	Average mass change by other manufacturers	Subsequent change in average mass of market
BAU	Mass	0%	None	0%
1	Mass	10%	None	Down by 1%
2	Mass	10%	Up by 10%	Up by 8%
3	Mass	10%	Down by 10%	Down by 10%
4	Mass	0%	Down by 10%	Down by 9%
5	Footprint	10%	Not relevant for target of Manufacturer A	Not relevant for target of Manufacturer A

Additionally, to explore the extent to which different types of manufacturer might be affected by the changes analysed, each of these five scenarios was developed for three different types of manufacturer, as follows, where:

- i) Manufacturer A was an 'average' manufacturer, i.e. both the average mass and the average CO₂ emissions of its new car fleet were equal to the market average.
- ii) Manufacturer A was a 'heavier' manufacturer, i.e. one that had a high average mass and a high average CO₂ emissions; and
- iii) Manufacturer A was a 'lighter' manufacturer having a low average mass and low average CO₂ emissions.

The numbers and percentages shown in the figures in this section, and those in Section 4.2, are specific to the starting conditions, including the original distances to the CO₂ targets, which are based on the actual numbers for 2012, as noted above. If the original distance to the target for any manufacturer is smaller, the implications will be different as demonstrated in Section 4.4.

The issues covered in this chapter are sometimes mentioned in the wider context of 'gaming' or game theory. The extent to which such concepts are relevant is discussed in Section 4.5, while Section 4.6 concludes the chapter.

4.2 How the mechanisms differ where 'mass' and 'footprint' are the utility parameters

Scenarios 2 and 5 are particularly pertinent in the context of understanding whether and how the choice of utility parameter affects the relative attractiveness of mass reduction as a CO₂ abatement option for vehicle manufacturers. Figure 4-1 and Figure 4-2 represent the results for Scenarios 2 and 5 respectively – in terms of changes in targets and distance to targets – for an 'average' manufacturer. The results for the other scenarios can be found in Part 1 of Appendix 2. The illustration representing Scenario 2 shows:

- The position of an 'average' manufacturer and the distance to its target (i.e. 38.1 gCO₂) **before** any mass reduction;
- The target slope **before** an adjustment in M₀;
- The position of an 'average' manufacturer and the distance to its target (i.e. 34.1 gCO₂) **after** mass reduction;
- The target slope **after** an adjustment in M₀;

- The distance of an ‘average’ manufacturer to its target **after** mass reduction and **after** an adjustment in M_0 (i.e. 37.7 gCO₂).

Figure 4-2 represents Scenario 5, where ‘footprint’ is the utility parameter, and so does not include the fourth or fifth of the above elements. Additionally in Scenario 5, the position of the ‘average’ manufacturer after mass reduction is vertically below its position before mass reduction, unlike in Scenario 2 (or in Scenarios 1 and 3 – see Part 1 of Appendix 2).

Figure 4-1: Results for an ‘average’ manufacturer under Scenario 2 (where ‘mass’ is the utility parameter and the average mass of Manufacturer A declines by 10%, while the average mass of its competitors increases by 10%)

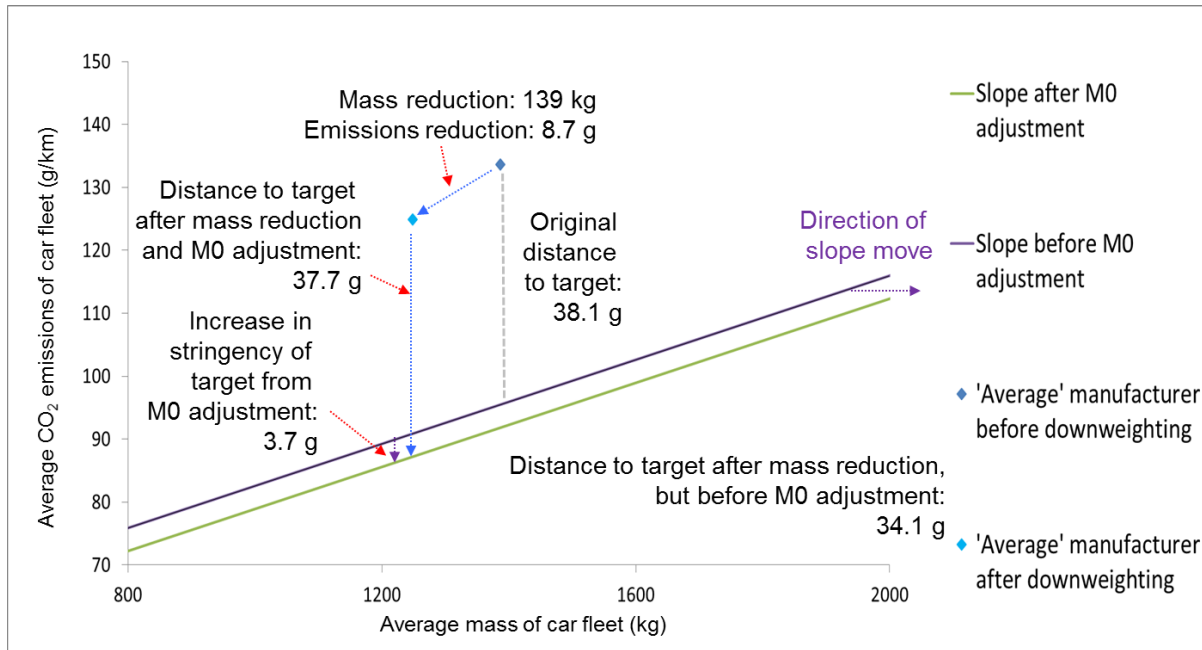
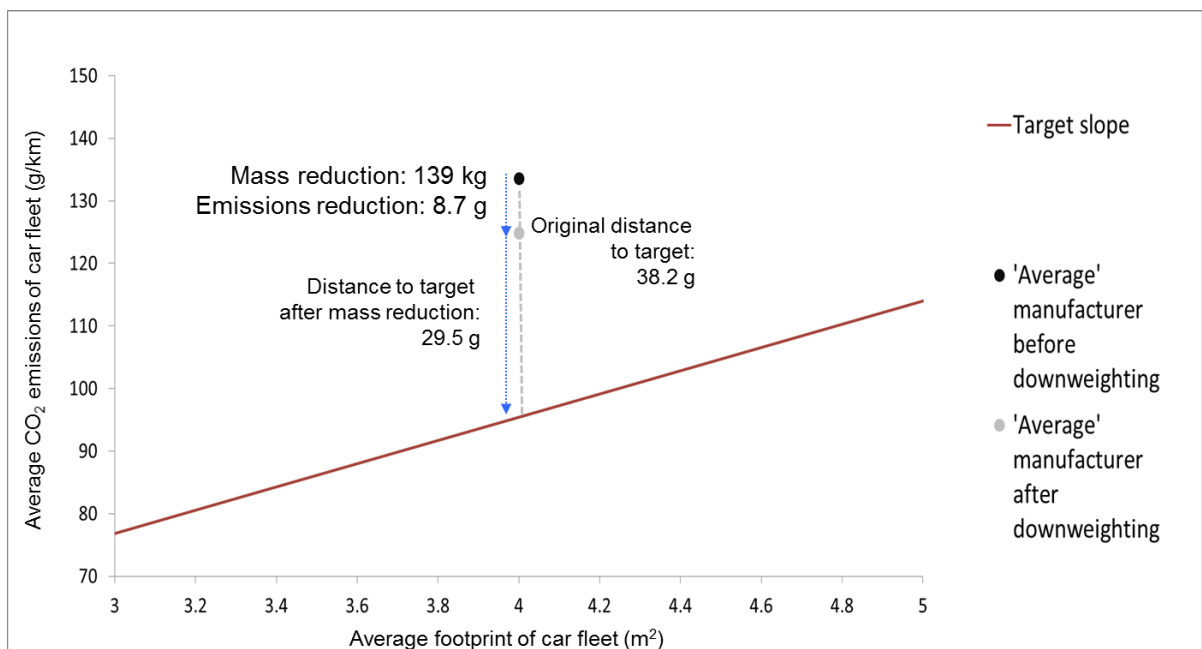


Figure 4-2: Results for an ‘average’ manufacturer under Scenario 5 (where ‘footprint’ is the utility parameter and the average mass of Manufacturer A declines by 10%)



These figures show that where 'mass' is the utility parameter (e.g. in Figure 4-1), the distance to target for any manufacturer will depend on two mechanisms, as noted in Section 2.2. The first mechanism is the change in the mass of Manufacturer A's own new car fleet, while the second is any change in the average mass of the entire new EU car fleet, as a result of the potential M_0 adjustment. As noted previously, the latter depends on the changes in the average mass of Manufacturer A's competitors. In Scenario 2, for the 'average' manufacturer, an original distance to target of 38.1 gCO₂/km becomes only 37.7 gCO₂/km, as the benefits resulting from a reduction in its average mass are virtually negated by the impact of the M_0 adjustment. This demonstrates the extent to which mass reduction options can have little impact on reducing a manufacturer's distance to its target where 'mass' is the utility parameter.

On the other hand, in Scenario 5 where 'footprint' is the utility parameter (see Figure 4-2) any change to the average mass of Manufacturer A's competitors does not affect the position of Manufacturer A relative to the target line. The only factor that affects the distance of the manufacturer to its target is the decline in the average CO₂ emissions of its new car fleet that results from a reduction in the average mass of its fleet. Hence, Manufacturer A benefits in full, in terms of being closer to its target, from the introduction of CO₂ reduction options that involve mass reduction. Under a footprint-based system, Manufacturer A also has greater certainty with respect to how far away from its target it will be following the introduction of mass reduction measures because its target is not affected by changes in the average mass of new vehicles produced by its competitors.

Additionally, it is worth quantifying the relative impact on Manufacturer A under the alternative utility parameters. In both Scenario 2 and Scenario 5, the manufacturer takes the same action that delivers an average mass reduction of 139 kg and a reduction in CO₂ emissions of 8.7 gCO₂/km on average. In Scenario 5 (where 'footprint' is the utility parameter), the manufacturer moves vertically towards its target, as noted above (see Figure 4-2) and so moves 8.7 gCO₂/km closer to its target. Under Scenario 2, where 'mass' is the utility parameter, the fact that the manufacturer also moves horizontally to the left as a result of the mass reduction means that the manufacturer is only 4 gCO₂/km closer to its target after having reduced its average mass by 10% (prior to the M_0 adjustment, i.e. 38.1 gCO₂/km minus 34.1 gCO₂/km; see Figure 4-1). This means that where 'mass' is the utility parameter, under the assumptions used for these scenarios, a manufacturer would be 4.7 gCO₂/km farther from its target by reducing its average mass by 10% than it would have been if 'footprint' had been the utility parameter (before any M_0 adjustment).

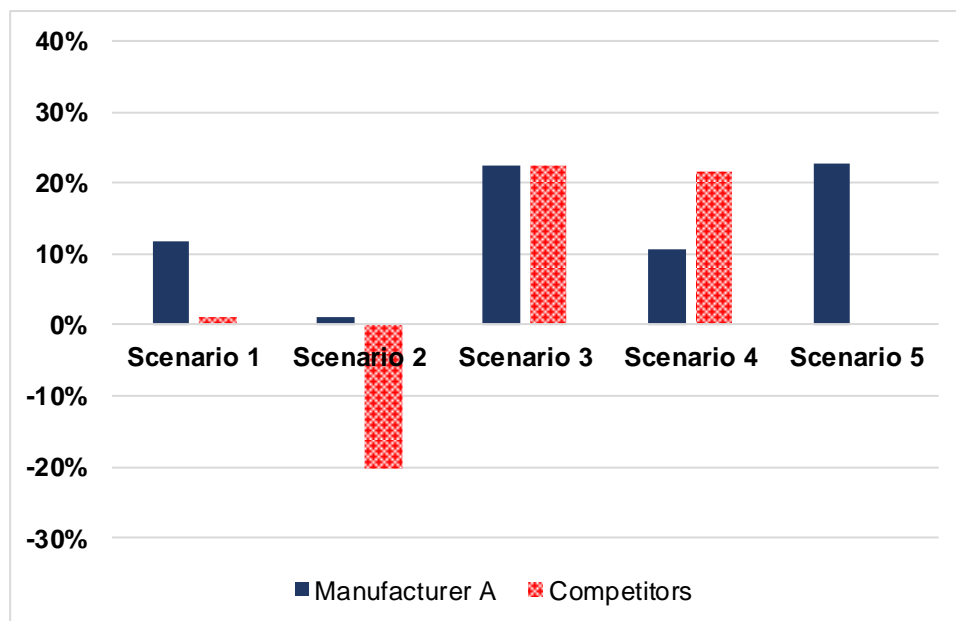
This analysis shows that where the average sales-weighted mass of the whole EU new car market is increasing, the use of mass as a utility parameter disincentivises manufacturers from pursuing mass reduction strategies to reduce CO₂ emissions. This is because a manufacturer will not be rewarded with the full benefits of such strategies, as increases in the sales-weighted average mass of the whole market will mean that the CO₂ reduction target for this manufacturer (and indeed all other manufacturers) will be adjusted to become more stringent, i.e. more difficult to meet. Essentially, this manufacturer would be penalised because of the actions of other manufacturers. If 'footprint' is used as the utility parameter, changes in the sales-weighted mass of the whole market would not affect the targets set for individual manufacturers, meaning that there would be no disincentive associated with adopting mass reduction measures to reduce vehicle CO₂ emissions.

Even if 'footprint' is used as the utility parameter, it is likely that the distance to target for any manufacturer would depend to some extent on the changes in other characteristics of its competitors' fleets, even though changes in mass would not have had any effect. This is because it is highly likely that, if 'footprint' was the utility parameter, there would be a similar mechanism to the M_0 adjustment, e.g. an F_0 adjustment (where F_0 would equate to the average footprint of the whole EU new car market). Such an adjustment would reflect any changes in the footprint of the new vehicle fleet to ensure that the required overall reduction in average CO₂ emissions was still achieved. As can be seen from Figure 3-18, this would be important as the average footprint of the new car fleet has also been increasing, although at a slower rate than the average mass. The difference in this respect is that mass reduction is a more important and direct influencing factor than footprint in terms of reducing a car's CO₂ emissions.

4.3 Implications of the M_0 adjustment on the market as a whole

Figure 4-3 represents the results for Manufacturer A and its competitors, where Manufacturer A is an 'average' manufacturer and the respective average masses change in accordance with the scenarios set out in Table 4-1. The results where, respectively, Manufacturer A is a 'heavier' and a 'lighter' manufacturer, as defined in Section 4.1, are given in Part 2 of Appendix 2.

Figure 4-3: Relative changes in terms of the distance to their respective targets for an ‘average’ manufacturer and its competitors after mass reduction and M₀ adjustment (where relevant)⁵



Notes: A positive change indicates that Manufacturer A and/or its competitors are closer to their respective targets after mass reduction and the M₀ adjustment. The numbers in this figure are related to those in the figures referred to in Section 4.2. As an example, the blue bar for Scenario 2 in this figure is calculated using the numbers from Figure 4-1, specifically it is the change in the distance to target as a result of the two mechanisms (i.e. 38.1g minus 37.7g) divided by the original distance to target, i.e. 38.1g. The other blue and red bars are calculated in a similar manner.

The results confirm that when the average mass of the car fleet of a particular manufacturer falls, e.g. by taking action to reduce the mass of its cars through the application of mass reduction technologies, the manufacturer will always be relatively closer to its CO₂ target than its competitors, as long as they do not take equivalent action, with everything else being equal. This is illustrated in Figure 4-3, as in Scenarios 1, 2 and 5 the blue bars are taller than the red bars. This applies whether ‘mass’ or ‘footprint’ is the utility parameter, although the benefit to the manufacturer is almost twice as much in the latter case as in the former. Under Scenario 3 (where the average mass for all manufacturers falls in the same proportion), all manufacturers will be equally closer to their target than they would have been before the M₀ adjustment.

Interestingly, the results for Manufacturer A under Scenarios 3 and 5 are similar. If all manufacturers took action to reduce the mass of their new cars by a similar amount, the results would be similar whether ‘mass’ or ‘footprint’ was the parameter, as a result of the impact of mass reduction and, in the case of the former, the M₀ adjustment.

As was noted in Section 4.2, under Scenario 2 the potential benefit of mass reduction to Manufacturer A in terms of being closer to its target is virtually completely negated by the impact of the M₀ adjustment, although it would be much better off than its competitors. Based on recent trends in the average mass of the new car fleet (as illustrated in Figure 3-18), M₀ will be adjusted upwards in 2016. Hence, Scenario 2 (as illustrated in Figure 4-1) is the most likely scenario that any manufacturer whose average mass has decreased will face at that point in time.

For Manufacturer A, it is also interesting to note that the results are similar (in terms of the proportional distance that Manufacturer A moves closer to its target) under Scenarios 1 and 4. This implies that a manufacturer can gain almost as much from taking no action to reduce the mass of its cars (as long as

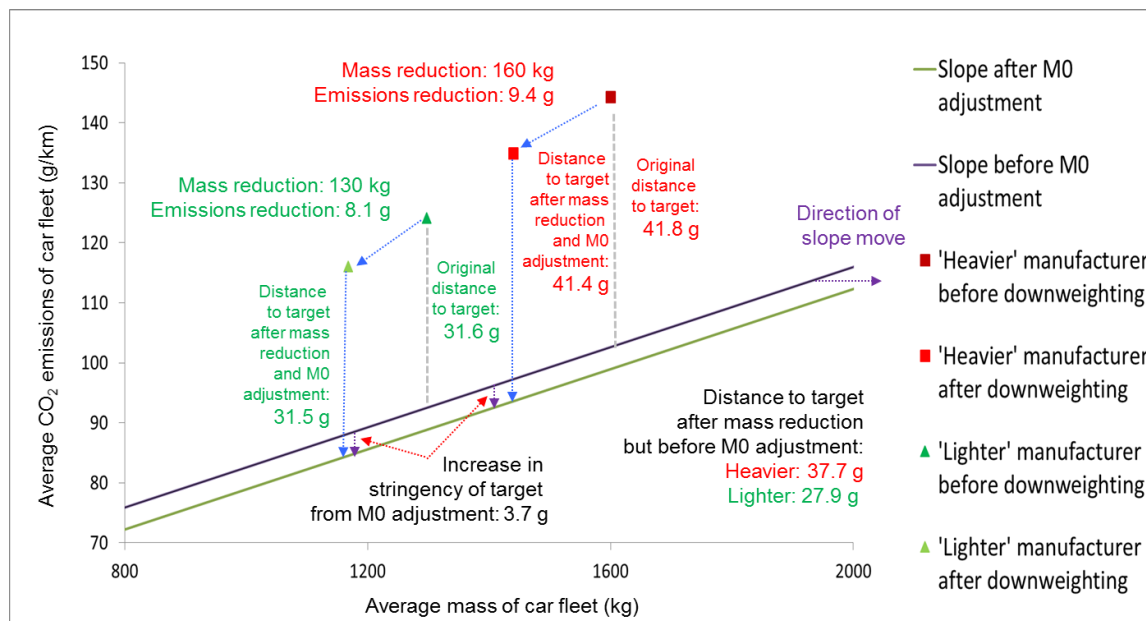
⁵ The reason for the ‘competitors’ to be 20% farther away from their targets in Scenario 2 is that we assumed that as the mass of the competitors increases, so must their CO₂ emissions. We recognise that, in practice, this has not been the case, as the average mass of the EU new car fleet is increasing, whereas its average CO₂ emissions are decreasing as manufacturers are adding other CO₂ reduction technologies to their cars. However, for the purpose of these scenarios we are assuming that all CO₂ reduction is delivered through the implementation of weight reduction technologies and that no other CO₂ reduction technologies are being applied. Hence, for the sake of consistency, we assume that no other CO₂ reduction technologies are applied when the mass of the competitors’ fleet increases. Hence, their CO₂ emissions will increase. To be consistent with the assumptions about the CO₂ emissions reductions that would accompany a mass reduction (see Section 4.1), and because there was no strong reason to assume otherwise, we assumed that a 10% mass increase would be accompanied by 6.5% reduction in CO₂ emissions.

its competitors do, i.e. Scenario 4), as from being the only manufacturer to reduce the mass of its cars (Scenario 1). Hence, in a situation where the average mass of the new car fleet is declining, it would be possible for a manufacturer to benefit from others' actions to reduce the mass of their cars, without needing to take any action itself.

4.4 Implications for manufacturers with lighter and heavier average masses

As noted above, scenarios were also developed for a manufacturer that had a high average mass and a high average CO₂ emissions (i.e. a 'heavier' manufacturer) and one that had a low average mass and CO₂ emissions (a 'lighter' manufacturer). Scenario 2 for both of these types of manufacturer is represented in Figure 4-4. This illustrates how the distance to target for different manufacturers is affected by the two mechanisms. In absolute terms, the impact of the M₀ adjustment is the same, i.e. 3.7 gCO₂/km, whereas the impact of the CO₂ emissions reduction associated with a 10% mass reduction is different. This demonstrates that for a 'lighter' manufacturer the negative impact of the M₀ adjustment will be more significant proportionally than for a 'heavier' manufacturer.

Figure 4-4: Results for a 'heavier' and a 'lighter' manufacturer under Scenario 2 (where 'mass' is the utility parameter and the average mass of Manufacturer A declines by 10%, while the average mass of its competitors increases by 10%)

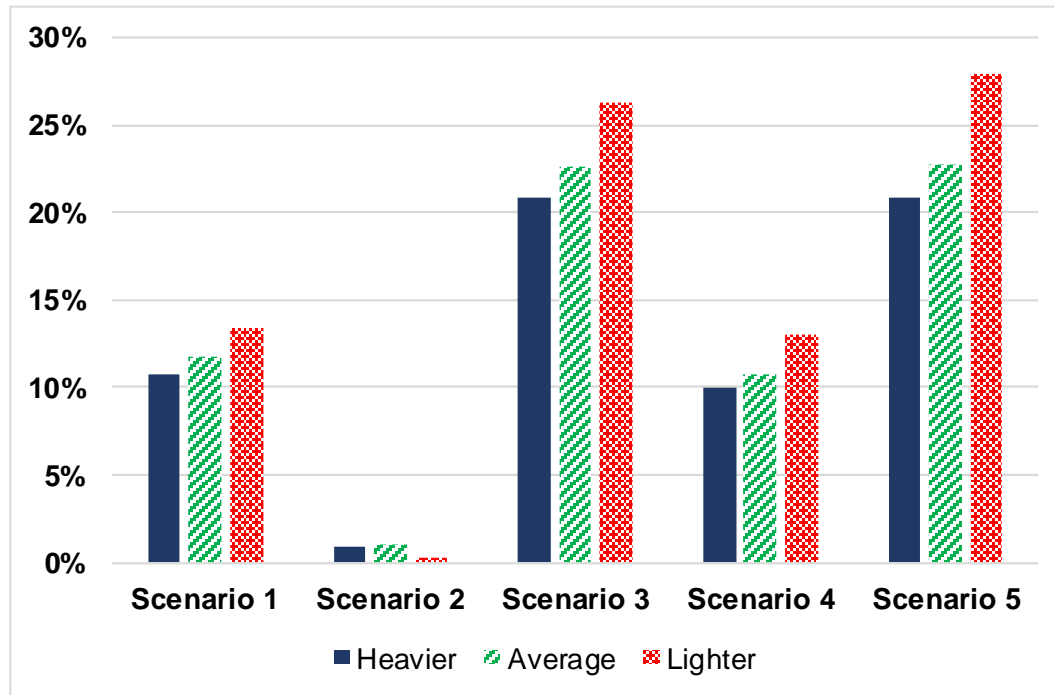


The figure above shows that under Scenario 2 (where the sales weighted average mass of the whole market has increased by 10%), if the mass of the fleet of a heavier manufacturer declines to achieve a fleet-weighted average reduction of 9.4 gCO₂/km, it will only be 0.4 gCO₂/km closer to target because of the impacts of the M₀ adjustment. In this case, the manufacturer only receives 4.3% of the benefit of taking action to reduce its CO₂ emissions through mass reduction. The situation is worse for a manufacturer of lighter vehicles; in the above example, a reduction in the fleet-weighted average CO₂ emissions for this manufacturer of 8.1 gCO₂/km through the adoption of mass reduction measures only results in the manufacturer being 0.1 gCO₂/km closer to its target. In this case, the manufacturer only receives 1.2% of the benefit of taking action to reduce CO₂ emissions through mass reduction.

Figure 4-5 compares the impacts on a 'heavier' and a 'lighter' manufacturer of the various scenarios, compared to the figures for an average manufacturer that were presented in the previous section. This shows that for all scenarios aside from Scenario 2, a lighter manufacturer will generally benefit more (in terms of distance to its target) from the same proportion of mass reduction than a heavier manufacturer, and that this is independent of the utility parameter used. The exception is for Scenario 2, which, as described above, represents the case where the average mass of the market is increasing, as lighter manufacturers suffer more from the effect of the M₀ adjustment than other types of manufacturer. Figure

4-5 also shows that for all types of manufacturer, the results are similar under Scenarios 3 and 5, and under Scenarios 1 and 4.

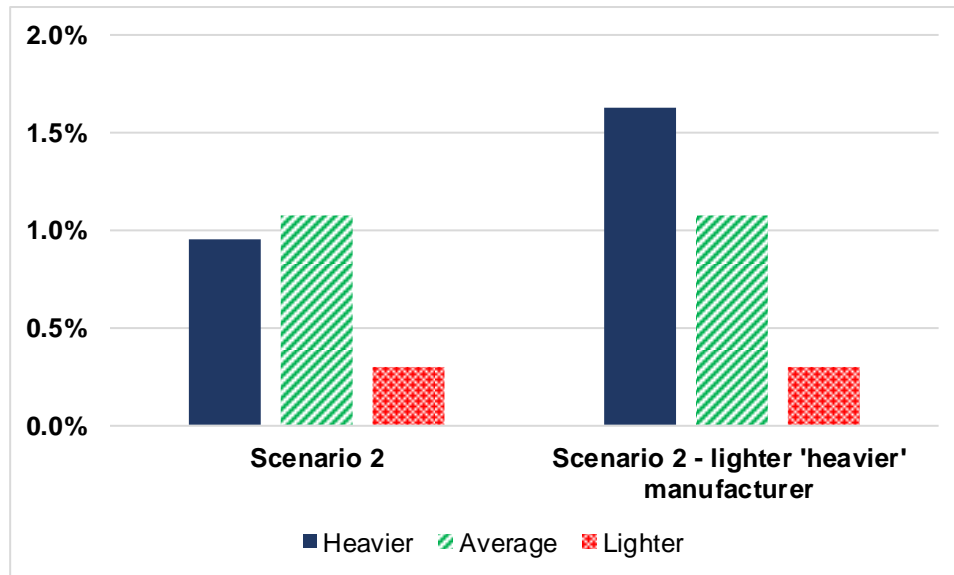
Figure 4-5: Relative changes in terms of the distance to their respective targets as a result of mass reduction (and M_0 adjustment, where relevant), by type of manufacturer, for all scenarios



Notes: A positive change indicates that Manufacturer A is closer to its target after mass reduction and the M_0 adjustment. The figures for an ‘average’ manufacturer are the same as those presented in Figure 4-3, i.e. the blue bars in this Figure correspond directly to the blue bars in Figure 4-3.

It is noticeable that the trend for Scenario 2 in Figure 4-5 is not clear, as the distance to target for the ‘heavier’ manufacturer is also less than that for the ‘average’ manufacturer. This is as a result of the particular ‘heavier’ manufacturer that was selected to represent this type of OEM, as the ratio of the average mass to average emissions for this ‘heavier’ manufacturer is higher than the equivalent ratio for the ‘average’ and ‘lighter’ manufacturers. If the average mass of the ‘heavier’ manufacturer is reduced to 1,500 kg (from nearly 1,600 kg) to bring the ratio of average mass to average emissions closer to those for the ‘average’ and ‘lighter’ manufacturers, the trend that is suggested by Figure 4-5 is clearer (see Figure 4-6), as this alternative ‘heavier’ manufacturer is further away from its target than an ‘average’ or a ‘lighter’ manufacturer under Scenario 2.

Figure 4-6: Relative changes in terms of the distance to CO₂ targets as a result of mass reduction (and M₀ adjustment, where relevant), by type of manufacturer



Notes:

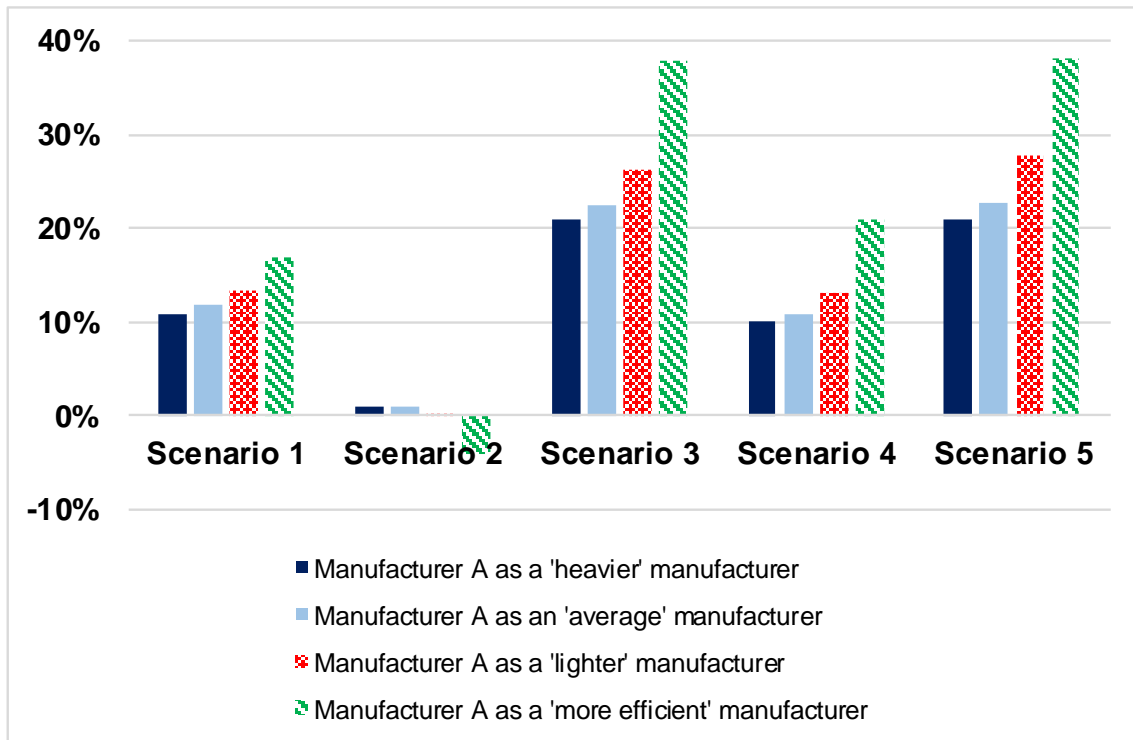
- a) The chart presents results for two versions of Scenario 2 (where ‘mass’ is the utility parameter and the average mass of Manufacturer A declines by 10%, while the average mass of its competitors increases by 10%): i) as in Figure 4-5.
- b) A positive change indicates that Manufacturer A is closer to its target after mass reduction and the M₀ adjustment. The numbers for ‘Scenario 2’ are the same as those presented in Figure 4-5. For ‘Scenario 2 – ‘lighter’ heavier manufacturer’, the figures for the ‘average’ and the ‘lighter’ manufacturer are the same as those in ‘Scenario 2’. The only difference is the figure for the ‘heavier’ manufacturer as this has a mass of 1,500kg compared to the ‘heavier’ manufacturer of ‘Scenario 2’, which has a mass of nearly 1,600kg.

As noted in Section 4.1, the numbers and percentages shown in all of the figures in the chapter are specific to the starting conditions, including the original distances to the target. This is illustrated, to some extent, by Figure 4-6.

Figure 4-7 illustrates this point further, as it gives the results for all five scenarios for a ‘more efficient’ Manufacturer A compared to the other types of manufacturers explored above. This ‘more efficient’ Manufacturer A has average CO₂ emissions of 115 gCO₂/km, which is around 10 gCO₂/km closer to its target than when Manufacturer A is a ‘lighter’ manufacturer⁶. This ‘more efficient’ manufacturer would be even closer to its target than any of the other manufacturers considered in Figure 4-5 for all of the scenarios other than Scenario 2. For the latter scenario, this manufacturer, which was originally closer to its target, is more adversely affected by the subsequent M₀ adjustment than manufacturers that were originally further away from their targets. This is because the absolute reduction in emissions from a 10% mass reduction is less for such a manufacturer than for other manufacturers, while the impact of the M₀ adjustment is constant in absolute terms.

⁶ This ‘more efficient’ manufacturer has the same average mass and average footprint as the ‘average’ manufacturer from Figure 4-3. All the figures for the ‘heavier’, ‘average’ and ‘lighter’ manufacturers remain the same as those presented in previous figures in this section.

Figure 4-7: Relative changes in terms of the distance to their respective targets for a manufacturer with original CO₂ emissions of 115g/km compared to that for a ‘heavier’, ‘average’ and ‘lighter’ manufacturer after mass reduction and M₀ adjustment (where relevant)

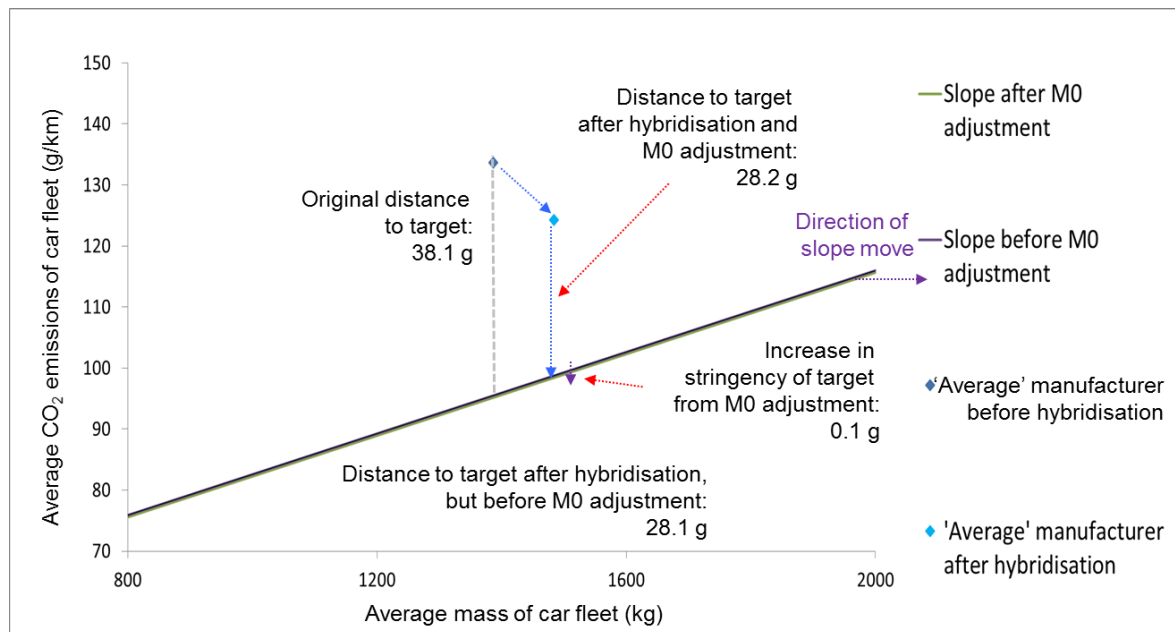


Notes: A positive change indicates that Manufacturer A is closer to its target after mass reduction and the M₀ adjustment. The numbers in this figure for the ‘heavier’, ‘average’ and ‘lighter’ manufacturers are the same as those in Figure 4-5. The only difference is the addition of the numbers for the ‘more efficient’ manufacturer – the emissions of this manufacturer are 10 g lower than those of the ‘lighter’ manufacturer, while its average mass and footprint are those of the ‘average’ manufacturer.

- The potential impact on hybrid-electric vehicles of the M₀ adjustment is interesting to consider, as these vehicles are typically heavier than comparable ICE vehicles (about 3% heavier on average) but have significantly lower CO₂ emissions (on average, 54% less compared to similar models)⁷.
- Figure 4-8 demonstrates how the two mechanisms that link a manufacturer’s sales-weighted average CO₂ target to its sales-weighted average mass affect a manufacturer that moves from 0 to a 20% share of hybrid vehicles in its new car fleet. Such a manufacturer would move closer to the target line, both vertically downwards, i.e. by having lower CO₂ emissions, and horizontally (to the right) as its sales-weighted average mass would increase. So while the M₀ adjustment has a negative impact on the manufacturer, the increase in its average mass is beneficial as it makes achieving the target easier in contrast to the situation for a manufacturer that introduces mass reduction technologies instead of hybrid-electric vehicle technology (see, for example, Figure 4-8)

⁷ <http://lowcvp.org.uk/assets/reports/Influences%20on%20the%20Low%20Carbon%20Car%20Market%20from%202020-2030%20-%20Final%20Report%2010811.pdf.pdf>

Figure 4-8: Results for a manufacturer having 20% of its new car fleet as hybrid-electric vehicles



Note: This figure assume that all of the other manufacturers take no action that leads to a change in the average mass of their new car fleets, so the only reason for the M_0 adjustment is the increased mass of the fleet of Manufacturer A. This manufacturer has focused on hybrids so that 20% of its new car fleet are hybrids.

4.5 Relevance of concepts from ‘game theory’

A number of concepts that are sometimes referred to in the context of ‘gaming’ or ‘game theory’ have been discussed in relation to the mechanisms demonstrated above. Scenario 4 in particular has been referred to as exhibiting traits of the **prisoners’ dilemma** (e.g. ICCT, 2012b). Whether Scenario 4 is in fact an example of such a dilemma is questionable. The prisoners’ dilemma describes a situation in which the rational response of an individual/organisation is not to cooperate, whereas cooperation would actually deliver greater benefits to all those concerned. If the prisoner’s dilemma applied in the context of mass reduction under the passenger car/LCV CO₂ Regulations, it would have to be formulated in the following way: it is in the industry’s interest to take action to reduce the mass of their vehicles (as their respective targets will decline), but that individual manufacturers will not take action unless their competitors do.

As was demonstrated above in Scenario 3 (see Figure 4-3), if all of the industry took “similar” levels of action to reduce the mass of their vehicles (i.e. they ‘cooperate’ in the language of the prisoners’ dilemma), their overall target would become less stringent and they would all incur “similar” proportional levels of costs (assuming they all took action to reduce the mass of their cars to a “similar” extent). Hence, there is no doubt that all manufacturers would benefit from all taking action to reduce the mass of their cars, as their respective targets would decline, as would the overall costs of meeting their targets. It is debatable whether it would be a rational response for a manufacturer not to take action to reduce the mass of their vehicles. As was discussed above, the fact that ‘mass’ is the utility parameter means that a manufacturer would not benefit in full (in terms of being closer to its target) from the implementation of mass reduction technologies. A manufacturer taking action to reduce vehicle mass would always benefit as it would be closer to its target and would subsequently be closer to its target compared to its competitors all other things being equal. Hence, it is not clear that the prisoners’ dilemma applies completely in the case of the application of mass reduction for cars in the context of the targets set out in the passenger car CO₂ Regulation. Whilst it is in industry’s interest to take action to reduce the mass of its cars (as their respective targets will become less stringent), the messages to individual manufacturers are more complex.

On the other hand, another problem – the **first mover’s dilemma** – is relevant in the context of taking action to reduce the mass of vehicles (as it is more generally in the context of action by manufacturers to improve the efficiency of their vehicles). A manufacturer choosing to be the first mover – i.e. the first

to take innovative action such as the introduction of mass reduction options to reduce its CO₂ emissions – faces increased risks and costs compared to its competitors. Its rivals will be able to learn from the experience of the first mover and implement the same actions at less risk and for less financial outlay. Where the Regulation does not give full credit for the use of mass reduction technologies, as is currently the case with ‘mass’ as the utility parameter, this dilemma is arguably more of an issue for mass reduction technologies than for other CO₂ reduction technologies. This is because a manufacturer taking action to reduce the mass of its cars would not only face the problems of being the first mover, it would also not benefit as much from taking such action (in terms of being closer to its target) under a mass-based system, as it would under a footprint-based system (see Section 4.2).

Rather than being an example of the prisoners’ dilemma, Scenario 4 is a demonstration of a **‘free rider’ problem**, as a manufacturer benefits under this scenario (by having a less stringent target) from the action of others without incurring costs or facing risks itself. In the case where either ‘mass’ or ‘footprint’ was the utility parameter, a free rider problem could occur if the respective adjustment (either M_0 or F_0) led to a less stringent target as a result of other manufacturers reducing the utility of their cars, i.e. by making these smaller or applying fewer accessories. In other words, Manufacturer A could keep its utility the same, but benefit as the average utility of the new car fleet declined. Unlike for footprint, there is the potential to reduce the mass of a vehicle using lighter materials, but without reducing its overall utility. In such a case, Manufacturer A would gain from the actions of others without having to incur any of the additional costs associated with the introduction of mass reduction technologies.

Finally, it is worth considering the extent to which the issues discussed in this section are relevant to manufacturers. The first mover’s dilemma and the free rider problem (demonstrated by Scenario 4) will be relevant in the context of a manufacturer taking action to reduce the mass of its cars. Such considerations are likely to contribute to a manufacturer’s decision about whether to take action to reduce vehicle mass. In any such decision, there are many wider factors at play, not least the associated direct and indirect costs and the potential reaction of their customers.

As far as the M_0 adjustment is concerned, it seems inconceivable that manufacturers have not taken account of the potential implications of an adjusted M_0 on their respective targets, as the adjustment has been in the Regulation since it came into force in 2009. Furthermore, the annual EEA monitoring reports have also made it clear that the average mass of the new car fleet has been increasing (although there was a small reduction in average mass in 2013). To some extent, the next M_0 adjustment could work in favour of mass reduction technologies. Based on recent trends in the sales-weighted average mass of new passenger cars, M_0 will be increased in 2016, and so manufacturers’ targets will become more stringent. This would require the application of more CO₂ reduction technologies, which could include more of those that reduce the mass of vehicles. In turn, this could have implications for the second M_0 adjustment in 2019 if it were to halt the trend in average mass increases. Continued increases in average mass should already lead manufacturers to conclude that mass reduction will have a higher benefit for them in the future (once M_0 is adjusted) than it has until now.

4.6 Conclusions

This section has demonstrated mathematically the impact of the two mechanisms in the Regulations that link each manufacturers’ CO₂ target to: (i) the mass of its own new car fleet; and (ii) the mass of the entire new EU car fleet. It clearly shows that if the average mass of a manufacturer’s new car fleet declines, the manufacturer would be closer to its target with ‘footprint’ as the utility parameter than with ‘mass’ as the utility parameter. Under the assumptions used in the scenarios developed for this report, if ‘footprint’ was the utility parameter, an average manufacturer would be 8.7 gCO₂/km closer to its target as a result of an average mass reduction of 10%, whereas if ‘mass’ was the utility parameter, the same 10% reduction would only move the same manufacturer 4 gCO₂/km closer to its target. This is the result of the fact that when ‘mass’ is the utility parameter, the manufacturer’s position relative to the target line changes both horizontally as well as vertically, as is demonstrated in Figure 4-1; if ‘footprint’ was the utility parameter the manufacturer’s position would only change vertically (see Figure 4-2).

This result suggests that ‘footprint’ should be the utility parameter favoured by manufacturers. With ‘footprint’ as the utility parameter they would benefit in full from the application of mass reduction technologies in terms of meeting their targets. In turn, this suggests that the application of mass

reduction technologies is disincentivised if ‘mass’ is the utility parameter, as the cost-effectiveness of mass reduction technologies from the perspective of the manufacturer would be less than if ‘footprint’ had been the utility parameter. For example, in the scenario described above, the cost of the respective technologies that deliver the 10% mass reduction would only take the manufacturer 4 gCO₂/km closer to its target if ‘mass’ was the utility parameter, compared to 8.7 gCO₂/km achieved for the same cost if ‘footprint’ had been the utility parameter. As a result of this apparent disincentive, it would be in policy-makers’ interests to use ‘footprint’ as the utility parameter to ensure that the policy framework does not disincentivise the application of technologies that could yield benefits for consumers and for society.

As can be seen by Figure 3-18, the average mass of the new car fleet has been increasing, although the data for 2013 shows a small decrease in average mass for that year compared to 2012. Based on these trends, from 2016 the average mass of the new car fleet, M_0 , which is used to calculate each manufacturer’s target, will be increase. This, in turn, will make the targets for all manufacturers more stringent. As was demonstrated in Figure 4-3, in such a situation, the increase in stringency resulting from the M_0 adjustment could effectively negate any benefits – in terms of being closer to its target – for a manufacturer that would otherwise be closer to its target as a result of mass reduction. This is where the first mover dilemma, discussed in Section 4.5 comes into play: a manufacturer would have to be particularly bold to incur the risks and costs associated with being the first mover to introduce mass reduction technologies, if there would be little benefit (in terms of being closer to their target) from doing so. Hence, when the mass of the new car fleet is increasing, the M_0 adjustment acts to further disincentivise the introduction of mass reduction technologies. For the same reason as above, it would therefore be in policy-makers’ interests to have ‘footprint’ as the utility parameter.

If the average mass of the car fleet was decreasing, and therefore the M_0 adjustment from 2016 would lead to a less stringent target for all manufacturers, there would be less of a case for replacing ‘mass’ with ‘footprint’. This is because the effect of the mass reduction and the subsequent M_0 adjustment with ‘mass’ as the utility parameter would be similar (in terms of the resulting distances to target) to the case where ‘footprint’ was the utility parameter (see Figure 4-5). Also, if the mass of the new car fleet was decreasing, it would be difficult to argue that having ‘mass’ as the utility parameter had been a disincentive to mass reduction technologies in practice. In such a case the free rider issue might arise, as one or more manufacturers could benefit from less stringent targets, in spite of the average mass of their new vehicle fleets not declining, as a result of the mass reduction efforts of other manufacturers. While some might consider this situation not to be fair, it is not necessarily an issue for policy-makers if the overall targets are still being met. If it becomes an issue that is a concern to the industry more generally, it might be appropriate for policy-makers to look into alternative mechanisms for ensuring that all manufacturers take similar actions to deliver the industry-wide emissions reductions.

Hence, for the reasons outlined above, there is a case, at least in the short-term, for a change in the utility parameter from ‘mass’ to ‘footprint’, as result of looking at the mathematics of the alternative utility parameters. To determine whether there is a stronger case for a change of utility parameter, it will be necessary to look at the CO₂ reduction potential of mass reduction technologies, and their associated costs, as well as the wider issues of concern to manufacturers. This is explored in the following chapters.

In the longer-term, the existence of the M_0 adjustment itself might have an increasingly significant impact on the attractiveness of mass reduction technologies to manufacturers. This is because, as manufacturers move closer to achieving their targets, the impact of any upward M_0 adjustment as a result of a continuing increase in the average mass of the new car fleet, will be proportionately larger, as shown in Figure 4-7. Hence, in the longer term, the M_0 adjustment mechanism could begin to increase the incentive to use mass reduction technologies, and thus counter the disincentives noted above.

Finally, even if ‘footprint’ is used as the utility parameter, the distance to target for any manufacturer would probably also depend to some extent on the changes in the characteristics of its competitors’ fleets, even though changes in mass would not have any effect. This is because it is highly likely that, if ‘footprint’ was the utility parameter, there would be a similar mechanism to the M_0 adjustment, e.g. an F_0 adjustment (where F_0 would equate to the average footprint of the whole EU new car market). This adjustment would reflect any changes in the footprint of the new vehicle fleet to ensure that the required overall reduction in average CO₂ emissions was still achieved. The difference in this respect is that mass reduction is a more important and direct influencing factor than footprint in terms of reducing a car’s CO₂ emissions.

5 Availability of materials and potential for mass reduction

5.1 Overview

This chapter provides a review of the potential for applying mass reduction techniques to the main systems and components of light duty vehicles, based on recent research and development activities in this area. It includes a review of different material technologies and other approaches that can be used to reduce the mass of vehicles, and highlights advanced lightweight technologies that have been demonstrated recently and that could potentially be applied more widely to production vehicles. In reviewing the literature on the topic of vehicle mass reduction, three major US studies were identified. Detailed re-engineering studies on existing production models (the US-market Toyota Venza and Honda Accord) were carried out in each of these studies with the aim of demonstrating that significant reductions in vehicle mass can be achieved. Due to the very comprehensive nature of these studies, we have dedicated a separate chapter (Chapter 6) to carry out a detailed assessment of the findings from these studies. With this in mind, this chapter focuses on other research and development activities, and has a particular focus on development activities that are supporting mass reduction in EU-market vehicles (although developments in other parts of the world are also covered).

In a typical light duty passenger car, the body-in-white accounts for around 20% to 28% of the total mass, the powertrain components also account for around 25% of total mass and chassis components (suspension components, braking systems, wheels, etc) account for around 25% of total vehicle mass. For LCVs, these three systems also dominate total vehicle mass, with both the body-in-white and powertrain systems each accounting for approximately 20% of total mass and chassis systems for around 30% (Ricardo-AEA, 2015 (forthcoming)).

Any increase in vehicle mass tends to incur further incremental increases in vehicle mass. For example, as the mass of the body-in-white increases, a larger, heavier and more powerful engine is usually required to provide sufficient performance and larger, heavier braking systems are required to ensure appropriate braking performance. By the same token, if the mass of a major system such as the bodyshell is reduced (i.e. primary mass reduction), then a lighter, less powerful engine is required and lighter braking systems can be fitted. These consequential mass savings are known as secondary mass reduction. The potential for applying secondary mass reduction is much greater for passenger cars than for LCVs; this is because even if the kerb mass of an LCV is reduced, it still needs to be able to carry a significant payload.

As outlined in Chapters 1 and 2, a 10% reduction in mass can reduce CO₂ emissions by around 3% if all other vehicle parameters remain the same, but CO₂ reductions of around 6.5% are possible if the engine is down-powered at the same time as reducing overall vehicle mass. Hence, an increased focus on mass reduction could provide significant benefits to vehicle owners/operators and society as a whole in terms of improvements in vehicle fuel economy and reduction in emissions of CO₂.

Taking all of the above into account, this chapter focuses on the potential for mass reduction in the following vehicle systems:

- Body-in-white and closures
- Powertrain
- Chassis systems

These systems alone account for approximately 75%-80% of the total mass of passenger cars and LCVs. Hence, in order to achieve significant reductions in overall vehicle mass, it is necessary to focus mass reduction efforts on these systems.

Strategies for reducing vehicle mass include:

- Use of lightweight materials
- Optimising or improving existing designs
- Combining or eliminating parts, assemblies, and/or their function
- Re-sizing parts and systems
- Removing content or features from the vehicle
- Revising manufacturing or assembly operations

For each of the key vehicle systems, the latest developments in mass reduction using some or all of the above methods have been investigated along with the potential for wider application of these technologies and approaches.

5.2 Body-in-white and closures

The bodyshell of a light duty vehicle comprises the body-in-white (BIW) and the body closures. The body-in-white is an unpainted, assembled bodyshell, minus its doors, bonnet, and bootlid/tailgate. Essentially, the BIW is the main body structure, made from a series of body panels that have been joined together using one or more joining techniques. A conventional body-in-white is typically constructed from steel panels, spot-welded together. The body closures are the movable openings on a vehicle bodyshells and typically comprise the doors, bonnet and bootlid/tailgate.

In recent years, significant R&D activity has been focused on methods for reducing the mass of the vehicle bodyshell. These efforts have included the use of advanced computer-aided engineering (CAE) techniques to optimise bodyshell design, and the application of novel lightweight materials. Reducing the mass of the body-in-white and closures can have direct impacts on vehicle energy consumption, given the high importance of the bodyshell in overall vehicle mass. Furthermore, reducing the mass of the bodyshell can have further incremental benefits, in terms of enabling secondary mass reduction (i.e. reducing the mass of the vehicle means that other systems can be downsized).

A general finding from the literature review is that there is no single, “best fit” approach to the future use of lightweight materials for automotive bodyshells. Whilst there are examples of vehicles produced almost wholly from high strength steels, aluminium or composite materials, future best practice is likely to rely on a multi-material approach that is based on increased use of all of these materials (and others), whilst the proportion of conventional mild steel used in body structures will continue to decline (Ducker Worldwide, 2011). Each of the different materials has both advantages and disadvantages, and the challenge will be for automotive manufacturers to select a suitable material mix that provides the appropriate performance and cost characteristics for the specific types of vehicles that they plan to produce in future years.

The following sections provide details of the different lightweight materials currently or soon to be available for use in automotive applications.

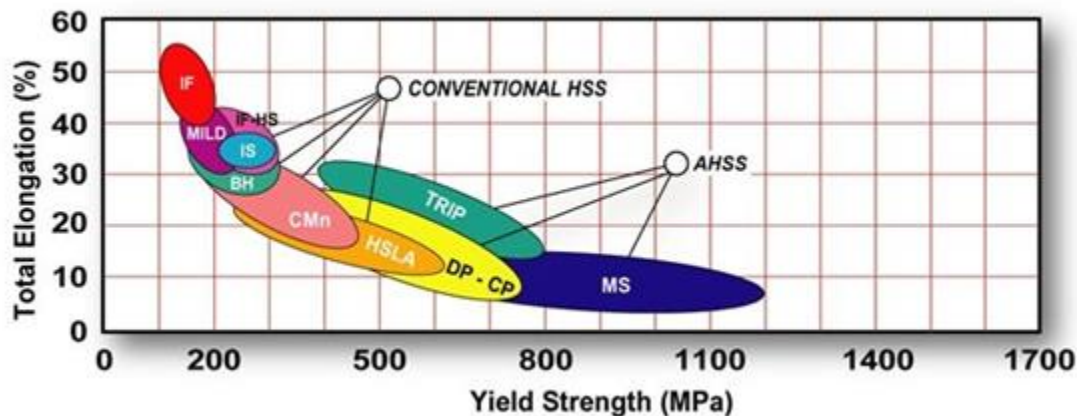
5.2.1 Steel

The vast majority of vehicle body structures and closures are made from press-formed sheet steel panels that are joined together using spot welding. Steel has many benefits, including the fact that it is relatively inexpensive and easy to work with (in terms of press forming and joining techniques). Whilst conventional automotive mild-grade steels are cost effective from the point of view of production costs, given the general increase in vehicle mass, selectively replacing conventional mild steel with various types of high-strength steel can give significant reductions in overall vehicle mass.

High strength steels (HSS) have been used in the automotive sector for more than 30 years. These materials offer increased yield strength and tensile strength compared to mild steel, thereby allowing significant reductions in the overall mass of body components (thinner, lighter HSS body panels can be used to achieve the same level of strength and stiffness as a bodyshell constructed from conventional mild steel).

There are many different ways of classifying automotive steels (World Auto Steel, 2014) including (i) strength, (ii) metallurgical characteristics and (iii) combinations of mechanical properties. The terms High Strength Steel (HSS), Ultra-High Strength Steel (UHSS) and Advanced High Strength Steel (AHSS) are commonly used to reflect the yield strengths and tensile strengths of different types of steels. HSS is a generic term that is often used for any steel with yield strengths in the range 210 MPa to 550 MPa and tensile strengths in the range 270 MPa to 700 MPa. The terms UHSS and AHSS are typically used for steels with a yield strength above 550 MPa and tensile strength greater than 700 MPa.

Figure 5-1: Categorisation of steel grades by yield strength (Source: World Auto Steel)



Metallurgical designation can be useful for determining the material composition of particular types and grades of high strength steels; examples include carbon manganese, bake hardenable, high-strength interstitial-free, and high-strength, low-alloy steels. For AHSS, typical metallurgical designations include dual-phase (DP), complex phase (CP), transformation induced plasticity and martensitic steels (MS).

The key difference between conventional HSS and more recently introduced AHSS grades concerns the microstructures of these materials. Conventional HSS typically have single phase ferrite microstructures, whilst AHSS have multi-phase microstructures. It is the multi-phase microstructure of these materials that gives them their much higher yield strengths and tensile strengths that allow smaller amounts of the material to be used to achieve the same mechanical performance as conventional HSS.

When designing body structures using HSS or AHSS, the overarching aim is to maximise the benefits associated with the higher strengths of these materials compared to conventional mild steels. Essentially, the main aim is to “down-gauge” the design of individual body components so that the wall thickness of the component is reduced, thereby saving mass whilst maintaining structural performance and strength. There are limitations to this approach as it is less effective for components where stiffness performance is important; this is because the elastic modulus and density (and consequently, the specific stiffness) values of different types of steel are very similar (KVA Incorporated, 2008). Hence, care needs to be taken when designing with HSS and AHSS as it is possible to introduce new failure modes that would not exist if the component had been fabricated in thicker gauge conventional mild steel. Additionally, using HSS and AHSS can introduce additional noise, vibration and harshness issues as the increased strength and reduced gauge thickness can make these materials more effective in transmitting vibrations through the vehicle’s body structure (potentially requiring the application of additional heavy vibration damping materials).

5.2.1.1 Use of high strength steels by the automotive industry

A report into lightweight materials and safety (German, 2010) found that HSS and aluminium have better crash characteristics than conventional steel, noting that the safety benefits of HSS are the prime reason for its increased usage in the auto market. More than 55% of the body structure of the 2008 Ford Fiesta is made from HSS, which was the first car in the subcompact segment (B-segment) to earn top-crash ratings in Europe, China and the US. The conclusion of the report states:

“advanced materials can decouple size from mass (weight), creating important new possibilities for simultaneously improving both fuel economy and safety without compromising functionality”.

Since safety and cost are some of the main determinants in body structure material selection and given the cost effectiveness of high strength steels found across the three full vehicle studies reviewed in Chapter 6, this report further supports the assertion that HSSs will be the main materials seen used in reducing vehicle mass for mass production vehicles in the near future.

High strength steels are already being deployed across all class segments and by all manufacturers. Ford’s plans for reducing vehicle mass include *“increasing use of ... lighter-weight components and lighter-weight materials.”* (Ford Motor Company, 2014). As part of their mass reduction plans for the body structure they note “new types of steel that are up to three times stronger than current steels and

improve manufacturing feasibility because they can be formed into parts more easily” (Ford Motor Company, 2014).

According to the “2013 Vehicle Technologies Market Report” (Oak Ridge National Laboratory, 2014), over the last couple of decades, the use of high strength and medium strength steels has increased in the US to around 270 kg per vehicle (around 15% of a vehicle’s total mass) at the expense of conventional mild steel. The report indicates that between 1995 and 2011, the use of conventional mild steel in cars declined by an average of 91 kg per vehicle, while the use of high and medium strength steels increased by an average of 129 kg per vehicle.

5.2.1.2 Research activities on the future role of steel in reducing the mass of vehicle bodysHELLS

Over the years, the steel industry has conducted a number of R&D projects to investigate the feasibility and potential for advanced, lightweight steel body structures. Key projects include:

- ULSAB (Ultra-Light Steel Auto Body)
- ULSAB-AVC (ULSAB Advanced Vehicle Concepts)
- ULSAC (Ultra-Light Steel Auto Closures)
- Future Steel Vehicle

The ULSAB, ULSAB-AVC and ULSAC studies were all conducted more than ten years ago and were highly influential in encouraging the adoption of high strength steels. Many of the lightweight steel technologies developed and trialled during these projects have now been implemented in production vehicles in Europe and in the United States. The most recently completed major R&D project carried out by the steel industry, in collaboration with the vehicle engineering consultancy EDAG, is the Future Steel Vehicle project (World Auto Steel, 2011). The aim of the project was to design and develop an advanced vehicle body structure from novel types of steel for a hypothetical B-segment plug-in electric vehicle. The target mass for the body structure of this vehicle was 190 kg which was compared to a current, advanced steel body structure (2010 Volkswagen Polo) which weighs 231 kg. The final body structure designed over the course of this project had a mass of 188 kg (i.e. lower than the target value), which was achieved through using HSS and AHSS materials for 97% of the body structure. Additionally, a wide range of advanced steel forming and other technologies were used to produce the various components that together comprise the vehicle’s body structure. These technologies included the use of (amongst others):

- Tailor rolled blanks
- Various types of hydroformed tubes (induction welded, laser welded, multi-walled)
- Multi-walled tubes
- Laser welded finalised tubes
- Laser welded tube profiled sections

According to the final study report, based on CAE crash performance analysis carried out during study, the final FSV bodysHELL could be used to produce a complete vehicle that achieves maximum five-star safety ratings under both the Euro NCAP and US NCAP test procedures. Furthermore, the study authors claim that the FSV body structure can be manufactured for a total cost of US\$1,115, with “no cost penalty” compared to conventional body structures.

5.2.2 Aluminium

For a given volume of material, aluminium is much lighter than steel (it is around one third the density of steel), and consequently it offers significant potential for mass reduction in vehicle body structures and closures. Whilst aluminium is less dense than steel, it is also not as strong as steel. Hence, for structural applications in vehicles, the thickness of aluminium panels needs to be 50% greater than an equivalent steel panel to maintain the same structural performance characteristics (e.g. stiffness, strength). Even after taking into account the need to increase the thickness of aluminium body panels, it can offer up to 50% reductions in mass for individual components (European Aluminium Association, 2007).

The following sections describe the current use of aluminium in vehicles and body components, and set out the mass saving opportunities that are possible through the application of this material in vehicle bodysHELLS and closures.

5.2.2.1 Current use of aluminium in vehicle body structures and closures

Aluminium has been used for many years in vehicle manufacturing as a way to reduce mass, but to date, its use has primarily been in areas other than for body structures and closures (although there

have been a small number of European light duty vehicles with all-aluminium body structures, including models produced by Audi and Jaguar Land Rover, as well as vehicles with body structures partially constructed from aluminium). In particular, aluminium has predominantly been used for wheels, engine blocks, cylinder heads and gearboxes. However, Ford's 2015 F-150 pick-up uses a rivet-bonded all aluminium body structure - the highest volume aluminium body structure in production to date (Edmunds, 2012).

Research carried out in 2012 (Ducker Worldwide, 2012) catalogued the amount of aluminium used in new cars sold in Europe in 2011. A total of 57 individual vehicle model ranges were included in this analysis, which together account for 44% of total EU new car sales in 2012. For each of the selected models, information on aluminium content was gathered from European Aluminium Association (EAA) members and through interviews with the individual OEMs. The research showed that the aluminium content of the selected models is 160 kg on average, ranging from 74.5 kg in a Fiat 500 to 561 kg in a Range Rover. Ducker carried out further research to assess the overall average aluminium content for all new cars sold on the EU market in 2011; their research indicated that those vehicles excluded from their sample were generally less aluminium-intensive designs, and once the full new car fleet was taken into account, **average** aluminium content in 2011 for EU passenger cars was 140 kg per vehicle (equating to just over 10% of the mass of an average passenger car). Again, it should be reiterated that these average figures relate to total aluminium content for the full range of components, and not just body components and systems.

Ducker's research included a detailed breakdown of where aluminium was used in vehicle construction for each of the key vehicle size segments (European A, B, C, D and E segments).

Figure 5-2: Average aluminium content and use of aluminium for BIW and closures for selected EU vehicle segments in 2011

Vehicle segment	Average total aluminium content per vehicle (kg)	Aluminium content as a percentage of total vehicle mass	Percentage of total aluminium content used for the body-in-white	Percentage of total aluminium content used for closures
A / B	103 kg	9%	1%	<1%
C	135.3 kg	10%	<1%	2%
D	184.2 kg	12%	3%	4%
E	301.3 kg	17%	11%	13%

Ducker's research clearly shows that the percentage total aluminium content in vehicles increases as the size of the vehicle increases, rising from 9% in A-segment cars to 17% in E-segment cars. Furthermore, the research shows that small cars (A/B segment vehicles) barely use any aluminium in their bodysHELLS (1% of total vehicle aluminium content is for the body-in-white, whilst much less than 1% is used for the closures). The findings for C-segment cars indicated that 2% of total vehicle aluminium content is used for the closures, whilst less than 1% is for the body-in-white. By contrast, the findings for D and E segment cars indicate that aluminium is used much more intensively for the BIW and closures. In D-segment cars, 3% of the total aluminium content of the vehicle is used in the body-in-white and 4% for the closures. Ducker indicates that 50% of the D-segment vehicles included in the sample have aluminium bonnets and bumpers and a proportion also have partial aluminium body structures (typically, aluminium is used intensively for the front end body structures of many popular D-segment vehicles). In Europe, E-segment cars have far and away the highest proportion of aluminium use in body structures and closures; the Ducker research indicated that for these types of vehicles 24% of the total aluminium content is used for the body-in-white and closures. The E-segment figures are skewed by the presence of certain vehicles that have all-aluminium bodysHELLS, including the Audi A8, Range Rover and Jaguar XJ models. The presence of these vehicles on the market does indicate that all-aluminium bodysHELLS can be cost effective for larger, more luxurious vehicles where customers are less price-sensitive and the profit margins are typically greater.

A report (European Aluminium Association, 2013) into the application of aluminium in the transport sector states that 21% of cars produced in Europe have an aluminium bonnet. Increasing magnesium content in aluminium based alloys increases strength and formability, as well as improving mechanical and corrosion properties, and is well suited for applications in the structure, closures and body panels (Hirsch, 2011).

The research carried out by Ducker for EAA also included indications on the future market potential for further penetration of aluminium in the EU passenger car market. In particular, their research identified that there is further potential for the aluminium content of EU passenger cars to increase in future years to reduce vehicle mass to help meet the 2020/21 CO₂ reduction targets for light duty vehicles. Ducker predicts that based on current trends, the aluminium content of new passenger cars in the EU will reach an average of 150 kg per vehicle by 2015 and the requirements to reduce CO₂ emissions support a possible average level of take-up of 180 kg per vehicle by 2020 (compared to 140 kg in 2011). Interestingly, Ducker believes that the 2011 level of penetration of aluminium in the E-segment (average of 300 kg of aluminium per vehicle) was already reaching the practical limit within this segment, and that in the future, increased aluminium penetration in the A/B and C-segments will be much more important in terms of achieving the EU's 95 gCO₂/km emissions target.

5.2.2.2 Fully-aluminium body structures

Intensive use of aluminium in vehicle body structures is not necessarily straightforward. The average yield stress values of aluminium alloys are typically lower than steels and similar to magnesium alloys. This means that aluminium is not as strong as steel, which has important implications for vehicle body construction. Alloying aluminium with other materials is an effective method of increasing its strength so that it can be used as a replacement for steel in body structural applications. The strongest aluminium alloys are typically the 7xxx series and 2xxx series, which are aluminium-zinc-magnesium alloys and aluminium copper alloys respectively. 5xxx series and 6xxx series are the next strongest aluminium alloys (aluminium-magnesium and aluminium-magnesium-silicon respectively), both of which are very suitable for use in body structures and closures.

Production of whole body structures from aluminium requires the use of heavily modified production processes compared to the manufacture of bodyshells in steel. There are two main methods which can be used:

- **Space-frame construction.** This approach is based on the use of a structural frame made from aluminium extrusions that is then fitted with non-structural aluminium body panels. The extrusions are joined together via thin-wall ductile castings which allow the different frame components to be welded together. Pressed aluminium panels are then used for the exterior body panels, the floor and the bulkhead components. Space-frame construction has been adopted by Audi for vehicles such as its A8 luxury saloon and the A2 hatchback (the latter was produced until 2005).
- **Monocoque body construction.** Using this process, the major body panels are either (a) welded and bonded together or (b) riveted and bonded together (with the bonding being achieved through the use of structural adhesives). Monocoque body construction in aluminium has been adopted by Jaguar Land Rover for various models including the Jaguar XJ series and the Range Rover.

One of the biggest barriers to the more widespread use of aluminium in vehicle body structures has been the need to adopt alternative technologies and processes for joining body panels and other body components together. The production of steel bodyshells is based around the almost universal use of resistance spot welding. Body-in-white manufacturing facilities all over the world are equipped with automated resistance spot welding robots for assembling vehicle bodyshells, and hence the need for alternative joining processes requires significant financial investment. The issue here is that unlike steel, aluminium alloys demonstrate high levels of electrical and thermal conductivity and hence have low levels of electrical resistance. This means that if resistance spot welding is used for aluminium panels, the welding current (and consequent energy requirements) are much higher than for steel panels, and there is a need for specialised equipment and significant additional preparatory activities. Experience has shown that whilst resistance spot welding of aluminium panels is possible, it is relatively unreliable and requires a lot of additional effort.

To exploit aluminium body construction technology, vehicle manufacturers and suppliers have developed alternatives to spot welding based on the use of mechanical joining techniques and alternative types of welding technologies. The use of clinching processes and self-piercing rivets have been particularly successful, as have the use of specialised aluminium adhesives. Alternative welding techniques for aluminium include MIG welding and laser welding. Although it is technically feasible for these techniques to be used, as a number of all-aluminium production vehicles have been released to the market over the past 20 years, these techniques may not currently be economically viable for volume mass production of mainstream vehicles. Until 2014, all of the vehicles that had been put into production with all-aluminium body construction have been niche vehicles or luxury vehicles that can be sold at a price premium in the market place. Since late 2014, Ford's F-150 pick-up truck (the best-selling light

duty vehicle in the USA) has been equipped with an all-aluminium bodyshell, although this vehicle is not at all representative of vehicles sold in the European market. In particular, it uses all-aluminium non-structural body panels that are fitted to a full-boxed, high-strength steel frame. Body-on-frame vehicle construction is a type of production process that has virtually disappeared from the European market, but is relevant in the US context where most pick-up trucks use this type of construction.

5.2.2.3 All-aluminium production vehicles

The first production vehicle with an all-aluminium bodyshell was the 1989 Honda NSX high performance sports car, which utilised a monocoque construction. The mass of the bodyshell of this vehicle was 163 kg, which on its own was 200 kg lighter than the steel equivalent (European Aluminium Association, 2013a).

Following the Honda NSX, the next major manufacturer to develop volume production all-aluminium vehicle was Audi, with the 1994 Audi A8 luxury saloon car. Audi's approach is based on space-frame construction, and following the original A8, the company has released a number of other vehicles with fully-aluminium bodyshells, each of which has been based on further development of the space-frame concept. These vehicles include two further generations of the A8 (second generation from 2002 and third generation from 2009), the 1999 Audi A2 B-segment hatchback and the 2007 Audi R8 high performance sports car. Each new model has included significant refinements to the space-frame construction approach to reduce mass, simplify the production process and reduce manufacturing costs. The latest 2009 A8 model includes some significant mass reduction innovations, including the application of a multi-material approach for some elements of the bodyshell. Examples of these innovations include the following items:

- The spare wheel well is made from glass-fibre reinforced plastic
- A plastic/aluminium single-piece hybrid material solution has been used for the front end body structure
- Partially form-hardened steel components were integrated into the B-pillar area of the aluminium body structure
- A new design of door structure allowed a reduction in vehicle mass of 11 kg.

Audi estimates that the aluminium space-frame design employed on the A8 results in the vehicle being 140 kg lighter than if it was produced using a conventional steel monocoque design (Lehold, 2011).

Over the three generations of the Audi A8, there has also been a consistent trend to reduce the number of body-in-white components. The first generation (1994) model comprised 334 separate parts; for the second generation (2002) model, this was reduced to 267 parts; the latest third generation (2009) model has only 243 parts in its body-in-white. The reduction in parts count reduces the amount of joining required in the bodyshell and can help to reduce the overall cost of manufacturing the vehicle. Parts count reduction was achieved through the increased use of large, multi-functional structural aluminium castings.

Whilst Audi has moved to reduce the numbers of the parts count in all-aluminium BIW structures, at the same time, the company has increased the number of different types of aluminium alloy used in body construction. Again, looking at the three generations of the A8 is instructive; the first generation model used seven different types of aluminium alloy, with yield strengths ranging from 100 MPa to 200 MPa; the second generation model used ten different alloys with yield strengths from 100 MPa to 240 MPa; the latest third generation model uses a total of thirteen different alloys with yield strengths from 100 MPa to 280 MPa.

Audi has also demonstrated the potential mass reduction benefits of the aluminium space-frame approach by producing a prototype all-aluminium version of a conventional steel production vehicle. In 2009, Audi demonstrated a lightweight prototype version of its A5 two-door coupe model (Audi AG, 2009). By replacing the conventional steel monocoque bodyshell with an aluminium space-frame design, Audi was able to reduce the total mass of the vehicle from 1420 kg to 1310 kg, a saving of 110 kg (7.7%).

As an alternative to Audi's space-frame approach to aluminium body construction, Jaguar Land Rover has invested heavily in developing all-aluminium monocoque (unitary) body construction. Jaguar's first all-aluminium production vehicle was the 2003 Jaguar XJ series which was around 200 kg lighter than the previous XJ model it replaced, even though the new model was longer, wider and taller (European Aluminium Association, 2013a). A range of novel joining technologies were applied to the bodyshell of this vehicle, including the first industrial use of rivet-bonded joining technology with self-piercing rivets

and structural adhesive used to join aluminium body pressings, castings and structural extrusions together.

The 2009 Jaguar XJ series (which replaced the 2003 model) added further technical refinements to the aluminium monocoque concept. Whilst this vehicle is based on the 2003 model's platform and floorpan, the upper body structure and exterior design was all new. Key changes included the use of more high-strength 6xxx series aluminium alloys (19% of the body structure is made of this material as opposed to 11% in the 2003 model), reduced parts count for the body-in-white, and the use of a high-strength hydroformed aluminium extrusion for the vehicle's A-post (front screen pillar). In terms of joining technology, the numbers of self-piercing rivets was reduced by 11% to 2,840, whilst the amount of structural adhesive used was increased by 50%. Additionally, MIG welding has been completely eliminated from the production process.

More recently, Jaguar Land Rover's latest generation of Range Rover (introduced in 2012) has moved from steel construction used in the previous model to an all-aluminium monocoque body construction. The body-in-white of the new model is 180 kg lighter than that of its predecessor, and the full vehicle is up to 420 kg lighter than the previous model. In the same way that the 2009 Jaguar XJ series increased the amount of 6xxx series aluminium alloys compared to the 2003 model, the 2012 Range Rover uses this material even more intensively; 37% of the body structure is made of 6xxx series alloys. With respect to the use of 6xxx series materials, innovations include the use of high-strength aluminium alloys for various exterior body panels, including the roof. The particular materials chosen have a high quality exterior finish, whilst still being easy to press-form into body panels. Another innovation is the use of specially developed high-strength EN AW-6014 aluminium alloy for use in crash-sensitive parts of the body structure. This material's properties allow it to be formed into 20% thinner panels compared to the previous EN AW-5754 grade alloy, whilst still providing a high level of structural performance. By reducing the gauge of the material in this way, both mass and component cost have been reduced.

5.2.2.4 Hybrid steel-aluminium body structures and partial aluminium body structures

As an alternative to all-aluminium body structures, which require extensive changes to production processes, a number of manufacturers have released production vehicles with aluminium-intensive body structures that allow the mass reduction benefits of aluminium to be realised whilst using steel to maximise rigidity where it is needed. The underlying principle behind these multi-material approaches is to use the "right material in the right place".

The most straightforward approach to this multi-material concept was adopted by BMW for its 2003 5-series and 6-series models. The entire front-end structure of these vehicles was constructed from aluminium, whilst from the front bulkhead backwards, the body structure was made from steel. BMW claimed that this approach not only yielded significant mass reductions, but also allowed the vehicle to have a 50:50 front/rear mass distribution. 18% of the bodyshell of the 2003 5-series was made from aluminium; for the 6-series, this increased to 26%, as the doors for this vehicle were also made from aluminium. It is interesting to note that when BMW replaced the 2003 5-series in 2010, the replacement model returned to an all-steel body construction.

Hybrid steel-aluminium body structures make use of both materials throughout the body structure and to date, this approach has been used in high-performance sports cars to reduce mass and to achieve the optimal distribution of loads to maximise handling performance. The 2006 Audi TT and the 2012 Porsche 911 both employ different types of hybrid steel-aluminium construction.

In the case of the Audi TT, a space-frame approach, similar to that used in Audi's all-aluminium cars, has been employed. For the first time, steel components have been introduced to the space-frame. The use of aluminium allowed the mass of the 2006 TT to decrease by between 20 kg and 90 kg compared to its predecessor (specific reduction depends on the particular model variant), even though the vehicle is physically larger than the previous model. Compared to a conventional equivalent all-steel vehicle, the body structure of the 2006 TT has been estimated by Audi to be 100 kg lighter. The bulk of the vehicle's bodyshell is made from aluminium (69% of the mass of the bodyshell for the coupe variant, and 58% for the open-top roadster variant).

The multi-material approach to body construction means that special techniques have to be applied to join the body panels together and to ensure corrosion protection between aluminium/steel joints. In particular, it is not possible to weld aluminium and steel components together whilst ensuring that the resultant joint is sufficiently strong and that it will remain free from corrosion. For this reason, no welding is used at all between steel and aluminium body parts. Instead, self-piercing rivets and screws, combined with the use of structural adhesives have been used to create bonds between steel and aluminium components. Clinching techniques have also been used to join steel and aluminium components in this vehicle. When joining aluminium components to other aluminium components, self-

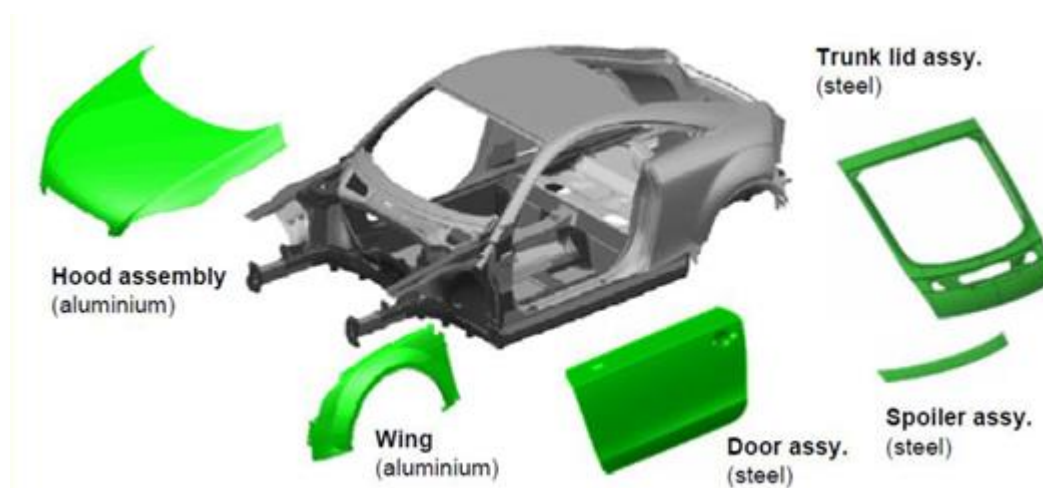
piercing rivets, structural adhesives, MIG welding, laser welding and clinching techniques have all been used. As in a conventional steel bodyshell, resistance spot welding is used for joining steel components together. A wide variety of joining techniques have been applied to construct the TT's bodyshell, many of which are variations on techniques that Audi and its suppliers have developed for their all-aluminium bodyshells. It is highly likely that Audi's long-term investment in aluminium body construction technology has allowed them to apply various joining technologies developed for those vehicles more widely, and more efficiently than other manufacturers would currently be able to do.

Figure 5-3: Hybrid steel-aluminium body construction of the 2006 Audi TT. (Source: European Aluminium Association, 2013a)



Note: red areas are aluminium; grey areas are steel.

Figure 5-4: Material composition of closures and other non-structural body components on the 2006 Audi TT. (Source: European Aluminium Association, 2013a)



Following the 2006 TT, Audi has also developed a steel-aluminium hybrid bodyshell for the 2011 Audi A6 and Audi A7. In this case, the aluminium content is much lower, at around 20% of the total bodyshell. The bodyshell of the 2011 A6 is approximately 30 kg lighter than that of the previous A6 model. The aluminium components are largely located in the front end of the structure.

Daimler has also started producing vehicles with steel-aluminium hybrid bodyshells; the 2013 Mercedes-Benz S-Class has a bodyshell that is 50% aluminium combined with high-strength and ultra-high strength steels. All of the exterior body panels on this latest S-Class (including all of the closures) are made from aluminium.

5.2.3 Magnesium

Magnesium has been used in the automotive industry for many decades as a way of reducing mass, but to date, its use has not predominantly been in the vehicle's bodyshell. Magnesium is much lighter than both steel and aluminium, and hence the potential for further mass reductions to be achieved could be significant. For a given mass of material, magnesium is three to four times as expensive as aluminium, which is currently a significant barrier to greater adoption.

Previous and current automotive bodyshell applications include the use of magnesium die-cast roof frames for the US-market Chevrolet Corvette sports cars, and a partial magnesium frame for the retractable hard-top convertible roof of the US-market Cadillac XLR sports car. In the European market, both Volkswagen and Mercedes-Benz have introduced thin-wall magnesium die castings for body panels. For example, the 2000-2006 Mercedes CL-class coupe included a one-piece magnesium die-cast door inner panel that weighed only 4.56 kg (Riopelle, 2004).

Ford has also started to use magnesium for selected body panels. In particular, its US-market Lincoln MKT large crossover vehicle includes the use of a one-piece die-cast tailgate inner panel. This panel is the first ever die-cast magnesium closure that has satisfied the United States 55 mph rear crash impact requirements. The panel is possibly the world's largest magnesium casting (its dimensions are 1379 mm by 1316 mm) but it has a total mass of only 8 kg; this approach reduced the mass of the tailgate inner by 10 kg compared to a conventional steel assembly. Whilst there is usually a cost penalty associated with the use of magnesium compared to steel, the additional material costs can be counteracted by the reductions in costs due to part-count reduction (Luo, 2013).

Figure 5-5: 2009 Lincoln MKT die cast magnesium tailgate inner panel. (Source: Gibbs, 2010)



Photo: Meridian Lightweight Technologies

Thin-wall die-casting processes are currently used to produce the majority of magnesium body panels used in automotive applications. The die-casting process means that only body components with a significant section thickness can currently be produced from magnesium. In 2013 General Motors (GM) announced that it has been testing a new process for producing sheet magnesium body panels that will enable thinner and lighter panels to be produced in the future. GM's approach for producing these thinner panels is to heat up sheet magnesium stock to very high temperatures (450 degrees Celsius) and then mould it into the required shape. GM has recently produced prototype bootlid inner panels using this process and claims that this approach can reduce panel mass by 1 kg compared to a conventional steel panel (General Motors, 2012). A key challenge for widespread use of this production technique is that heating up magnesium sheet stock to 450 degrees Celsius is not compatible with mass production of body panels. Sheet steel panels can be pressed in a matter of second at room temperatures. For this reason, GM will continue developing this new magnesium panel production process with the ultimate aim of being able to manufacture thin body panels at room temperatures.

Another reason that magnesium is currently used very sparingly in vehicle production is because both the price of the raw material is high, and the production costs for turning stock magnesium into automotive body components are also high. The prices for magnesium are more than 75% higher than for steel and 33% higher than aluminium. Furthermore, body components are currently around seven

times more expensive to manufacture than steel components. China has the world's largest reserves of magnesium and dominates the global supply of this material because the production process used in China to produce pure magnesium from magnesium oxide (the Pidgeon process) has very low capital costs and does not require a skilled workforce. However, the yield from the Pidgeon process is low and the energy consumption and GHG emissions associated with this process are very high (Wulandari et al, 2010). Consequently, researchers have been investigating low-energy extraction methods for obtaining magnesium from sea water; in the longer term, this may be a cost-effective alternative source for obtaining magnesium.

In the US market, vehicle manufacturers only used 4.5 kg of magnesium per vehicle in 2005 (less than 1% of total vehicle mass), and whilst there have been small increases in the amount used per vehicle since then, the high costs associated with using this material means that take-up by the industry has been very limited. The US Automotive Materials Partnership (an industry partnership between Ford, Chrysler and General Motors) has a target for using an average of 350 lb (159 kg) of magnesium components in new vehicles by 2020 (US Automotive Materials Partnership, 2010) as a key method for reducing the mass of vehicles and improving fuel consumption performance. Given the increasing use of global vehicle platforms that are shared between US-market and European market passenger cars, it is likely that the amount of magnesium deployed in EU-market vehicles should also increase if the industry is able to meet its own goals.

Given that there are some key differences between the US and EU markets, the level of magnesium take-up in Europe could be smaller. In particular, the US market is dominated by sales of large pick-up trucks and SUVs (in 2014, light duty trucks (which comprise SUVs, pick-up trucks and minivans) accounted for 8.6 million new vehicle sales in the USA, compared to 7.9 million new passenger cars sold over the same period. The profit margins associated with vehicles in the US light duty truck segment are high and hence manufacturers of these vehicles can afford to pay the additional costs associated with expensive lightweight technologies for these types of vehicles because these vehicles are manufactured in very high volumes (Friedrich and Mordike, 2006). By contrast, in the EU market, SUVs account for a much smaller proportion of total vehicle sales, and furthermore the average percentage profit margins are not as high compared to US market SUVs and pick-up trucks as vehicles for the EU market tend to be more sophisticated and costly to produce. Hence the scope for applying magnesium to EU market vehicles in an economically viable manner is likely to be lower. In both markets, profit margins on smaller vehicles are generally very small, and hence in the short-term, the take-up of magnesium is likely to be low for these types of vehicles, regardless of which market they are produced for.

5.2.4 Plastics and fibre-reinforced composite materials

There is a long history of using plastic materials for vehicle body panels, with both fibre-reinforced materials and non-fibre-reinforced materials being used. Conventional, non-reinforced plastics have been used for outer body panels and various non-structural body components in a wide variety of vehicles, whilst fibre-reinforced plastics have a wider range of uses as they can be used for structural applications in the bodyshell.

Non-reinforced plastic polymers have been used by many manufacturers all over the world for panels such as front wings, door skins, bootlids and tailgates. The use of such materials is not a recent innovation, but improvements in polymer technology may mean that the potential for using such materials in the future is greater.

Examples of previous use of plastics for non-structural exterior body panels include:

- 1982 Citroën BX (bonnet, tailgate)
- 1988 Fiat Tipo (tailgate)
- 1996 Renault Megane Scenic (front wings)
- 1992 Chrysler Concorde / Dodge Intrepid (front wings)
- 2004 BMW 6-series (front wings)

Although there are many examples of plastic body panels having been introduced on production cars over the past twenty years, to date there has not been a move to using such materials more widely. The low level of take-up to date is probably due to cost impacts and the limited focus on mass reduction in recent years. In the last couple of years, there has been a notable increase in the use of plastic polymer materials for exterior body panels and closures. In particular, a number of recent new model releases have featured all-plastic tailgates, which combine both reinforced and non-reinforced plastic polymers (discussed further below).

In addition to non-reinforced plastic polymers, there is also many years' experience of using fibre-reinforced plastic polymer composite materials for vehicle body panels for applications that require a combination of low mass, structural strength and stiffness that is not possible to achieve with non-reinforced plastics. In particular, fibre-reinforced composite materials have been used for many years for body panels for low-volume vehicles. Composite materials are made from a plastic polymer matrix that is reinforced with high-strength fibres (e.g. glass, carbon, etc). Fibre-reinforced composites were originally developed in the 1940s for applications in the defence sector. The first high-profile application of composite materials in the automotive sector dates back to the 1950s, with the launch of the first generation US-market Chevrolet Corvette. This car was equipped with body panels made from glass-fibre reinforced plastic. All subsequent generations of the Corvette (right up to the present day) have been equipped with composite body panels. By the 1970s, the automotive sector had become the largest market for composite materials, with many applications beyond just body panels.

A number of European vehicles have been equipped with glass-fibre composite body panels attached to a steel space-frame structure, including (amongst others) various Lotus cars from the 1970s onwards, the first three generations of the Renault Espace (1984 to 2003) and the 1989 BMW Z1.

For a number of years, various vehicle manufacturers have used composite materials to replace selected exterior body panels that were previously made from steel. For example, in 1996 Renault introduced the Megane Scenic model which was fitted with front wing panels made from a non-reinforced plastic polymer material called Noryl GTX.

As mentioned earlier, a very recent trend has seen a number of new vehicles released on the European market that are equipped with all-plastic tailgate structures. In particular, the 2013 Peugeot 308 and the 2014 Nissan Qashqai are both equipped with all-plastic tailgate structures, replacing the steel tailgates fitted to their predecessor models. For the Peugeot 308, the tailgate structure is made from two plastic materials: long glass fibre reinforced polypropylene (PP-LGF) for the load-bearing elements and unreinforced polypropylene for the outer skin panels. By switching to an all-plastic tailgate, Peugeot and its supplier, Plastic Omnium, claim to have saved 3 kg in mass compared to producing the same tailgate in steel.

Other plastic component suppliers have also shown concept all-plastic tailgates in the last couple of years, indicating that there is likely to be significant potential to deploy this technology further on future vehicles. For example, in 2013 the major petro-chemical company, SABIC, presented an all-thermoplastic tailgate concept; as with the Peugeot 308 tailgate, the inner structural elements are made from glass-reinforced polypropylene polymer composite, whilst for the outer skin panels there are a number of different unreinforced plastic compounds that can be used, depending on whether the tailgate will be painted on-line in the vehicle manufacturer's paint shop with the rest of the bodyshell, or whether off-line painting will be carried out (online and offline painting are carried out under different temperature conditions). According to SABIC, their thermoplastic tailgate concept can reduce the mass of the tailgate by up to 30% (up to 12.5 kg saving) compared to tailgates of a similar size built from conventional materials such as steel.

5.2.4.1 Future potential

Plastics Europe (the trade association for the European plastics industry) has quantified the potential for using additional plastic materials in high volume production cars with the aim of reducing mass at similar system cost to incumbent technologies and materials. Their analysis indicates that in total, around 100 kg could be taken out of the whole vehicle through the strategic application of different types of plastics. This estimate includes the use of plastics across the full range of vehicle systems, and not just for body-in-white and closures. Based on the analysis carried out by Plastics Europe, a total of 25.5 kg could be removed from the BIW and closures through the strategic use of plastic materials; this equates to between 8% and 10% of the typical mass of a vehicle bodyshell. Additionally, Plastics Europe has indicated that a further 60 kg could be saved in the future through the use of composites and structural foams, but that these technologies are under validation at the moment. The mass savings that could be achieved for body components are presented in the table below.

Table 5-1: Mass reduction potential associated with strategic use of plastics for body components

Component or system	Potential mass reductions through the use of plastics
Front wings (fenders)	3 kg
Tailgate structure and tailgate panels	8.5 kg
Energy absorbers (crash management)	1.5 kg
BIW reinforcements	5 kg
Rail extensions	1.5 kg
Door modules	4 kg
Front end module	2 kg
Composites, foaming technologies (under validation)	Up to 60 kg

Source: Plastics Europe

5.2.4.2 Carbon-fibre reinforced plastics

Most recently, interest in composite materials for the automotive sector has been focused on the use of carbon-fibre reinforced plastics (CFRP). A number of manufacturers have carried out R&D in this area, with the most high profile including BMW, Daimler, Chrysler and Ford.

The 2003 Dodge Viper marked the first use of carbon fibre sheet moulded composite in a production vehicle, and it was used for fender supports and brackets, with carbon fibre also used in the windshield surround and inner door structures. Analysis of the application of carbon fibre in this vehicle notes the process employed is capable of 100,000+ cars a years (Quantum Composites, 2012). All carbon fibre based components achieved increases in stiffness alongside mass reductions, as well as reducing the number of parts required. The fender system alone resulted in a mass saving of 18 kg for the vehicle, despite using only 6.14 kg of carbon fibre sheet moulded composite (SMC). Carbon fibre has also been applied in premium models, where it is used in bonnets and fenders on vehicles such as the Chevrolet Corvette ZR1 and the Lexus LF-A. A small number of niche, low volume vehicles also incorporate a CFRP body structure. Examples include high-performance vehicles from Lamborghini and McLaren, as well an ultra-high efficiency vehicle produced by Volkswagen (the XL1). The XL1 is a plug-in hybrid electric vehicle that weighs 795 kg, of which 230 kg is due to the CFRP body structure. According to Volkswagen, only 23% of the vehicle (by mass) is made from steel or iron. At this point in time, CFRP remains very expensive; according to the consultancy Frost and Sullivan, the material costs approximately US\$20 per kg compared to around US\$1 per kg for conventional steel (costs are for raw materials and not finished components). Reductions in the cost of carbon fibre composites due to large scale industrialisation of the processes involved may result in a cost decrease of up to 70% by 2030, with development in the auto industry being supported by the desire for increasing carbon fibre usage in the aviation and other engineering industries (McKinsey & Co, 2012).

BMW has invested heavily in CFRP technology for its new range of "i" plug-in electric cars. The 2013 BMW i3 features a fully CFRP upper body structure that is fitted to an aluminium floor structure and underbody.

Figure 5-6: CFRP upper body structure of the 2013 BMW i3

The combination of lightweight materials was specifically chosen as a means of improving the overall electric driving range of the i3 without having to fit bigger, heavier lithium-ion batteries. As a consequence, the i3 weighs around 20% less than the Nissan Leaf electric car but has a similar driving range to the Nissan vehicle, even though its usable battery capacity is smaller at 18.8 kWh, compared to 24 kWh for the Nissan Leaf.

To produce the CFRP material for the i3 and i8 models, in 2009 BMW formed a joint venture with the SGL Group, a leading manufacturer of carbon fibre composites. This step was necessary because at the time, BMW's plans for its "i" models would have required 10% of the global market for CFRP. To ensure that it has sufficient supplies in future years, BMW has bought a 16% stake in SGL, and a member of the Quandt family, which controls BMW, has purchased a further 27% stake in SGL. BMW and SGL have set up a US\$100 million manufacturing site in the USA to manufacture the carbon fibres necessary for the CFRP bodyshells. These fibres are then transported from the USA to Germany where they are then used to manufacture the i3 and i8 bodyshells. BMW plans to introduce CFRP technology to other models in the future, starting with the next 7-series luxury saloon, although it is highly unlikely that this vehicle will feature a full CFRP bodyshell.

Whilst BMW and Volkswagen have invested a lot of time, effort and money into producing vehicles with CFRP bodyshells, few other mainstream vehicle manufacturers are following a similar path at the moment, although many have established joint ventures with other carbon fibre manufacturers to produce selected body panels for future vehicles. In 2011, Daimler announced a joint venture with the world's largest manufacturer of carbon fibres, Toray. Daimler plans to introduce carbon fibre body panels to selected Mercedes-Benz vehicles in the near future. Toray already manufactures a number of CFRP body panels for major vehicle manufacturers, although these are currently limited to high performance sports cars such as the Lexus LF-A, Mercedes SLR and Lamborghini models.

General Motors has also announced a joint venture with the second largest carbon fibre manufacturer in the world, Teijin, and other manufacturers, such as Ford have demonstrated prototype CFRP panels, such as the experimental CFRP bonnet for the Ford Focus announced in 2012, which at less than 5 kg is more than 50% lighter than the equivalent steel bonnet (Ford Motor Company, 2012b and Plastic Today, 2013a).

Barriers to take-up

One of the key determinants of whether composite plastic materials are suitable for vehicle bodyshells is the planned levels of production. For high-volume vehicles, composite solutions are usually not cost effective because moulding composite bodyshells is usually much more time-consuming than pressing body panels in steel. For low-volume models, composite materials can often be cost effective because the costs associated with producing the moulds necessary for manufacturing parts are usually much lower than the costs of the tooling required for steel body panels. The marginal cost of manufacturing an additional composite body panel is usually higher than its steel equivalent, which can mean that if a vehicle equipped with composite panels becomes more successful than anticipated in the marketplace, conventional steel body panels may become more cost effective than using composites.

Potential future market

In 2012, the global market for carbon fibre components was limited to around 5,000 vehicles (predominantly ultra-high performance sports cars), by 2020, the market may expand to 5 million

vehicles per year (Bloomberg.com, 2012). Given that BMW alone plans to build around 20,000 of its i3 model in 2014, the market has already expanded significantly since 2012 and it is likely that there will be further rapid growth in the near future. This is backed up by the fact that the major automotive supplier, Magna, announced in March 2014 that it had won two contracts to supply painted body panels made from CFRP for two 2016 model year vehicles.

5.2.5 Comparison of the relative costs of materials suitable for vehicle body components

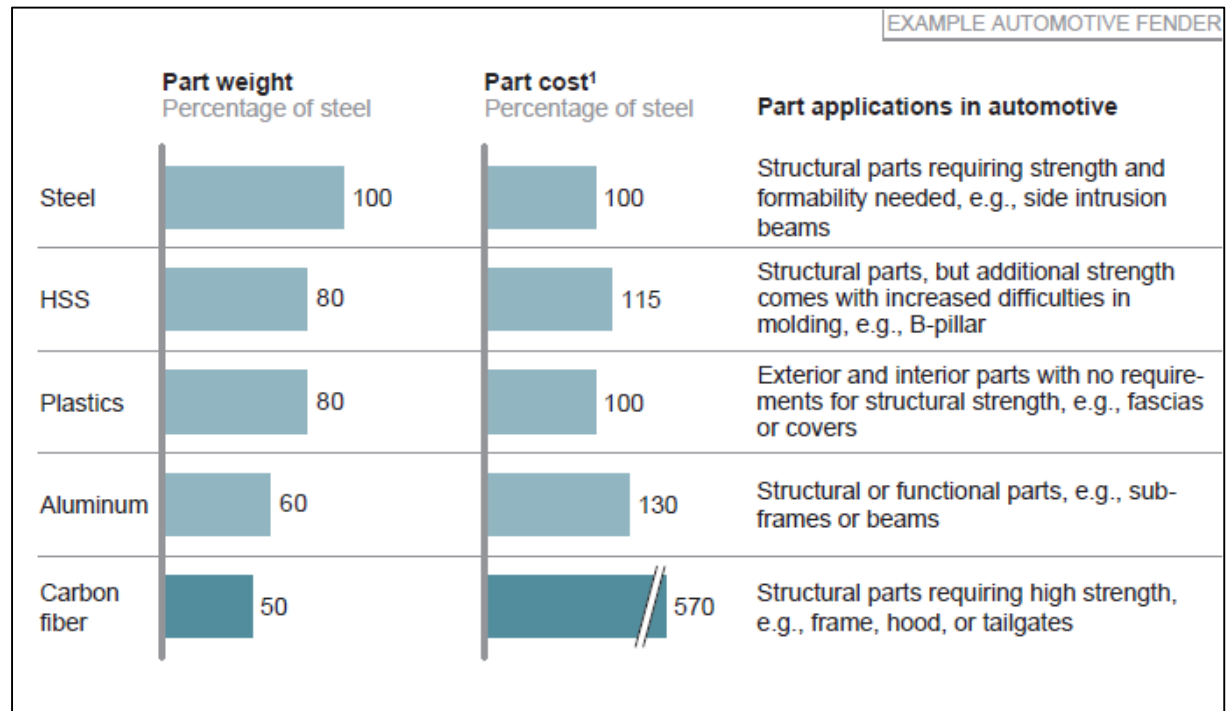
An important consideration when considering alternative materials for vehicle body components is the impact on production costs. The table below presents a high level summary of relative costs for the key materials discussed in the previous sections (Powers, 2010).

Table 5-2: Relative costs of key materials used for vehicle body components

Material	Relative cost per part
Mild steel	1.0
High strength steels	1.0 to 1.5
Aluminium	1.3 to 2.0
Magnesium	1.5 to 2.5
Composites	2.0 to 20.0

Carbon fibre’s cost makes mass production usage prohibitive at this point in time (i.e. in 2015), with only premium vehicles currently being able to utilise the material. One report states that the current cost of carbon fibre parts is 570% of that of steel (McKinsey & Co, 2012), with Figure 5-7 showing why, despite it having the greatest reduction in mass per component, other materials are currently preferred.

Figure 5-7: Comparison of lightweight material cost and mass reductions. Source: (McKinsey & Co, 2012)



5.2.6 Multi-material approaches to mass reduction in vehicle body structures

The previous sections have highlighted that there are many different approaches for reducing mass from vehicle body structures and closures. There is no single optimal material or approach that is best for reducing the mass of the body shell, as many different factors will come into play when deciding on an optimal approach, including (amongst others):

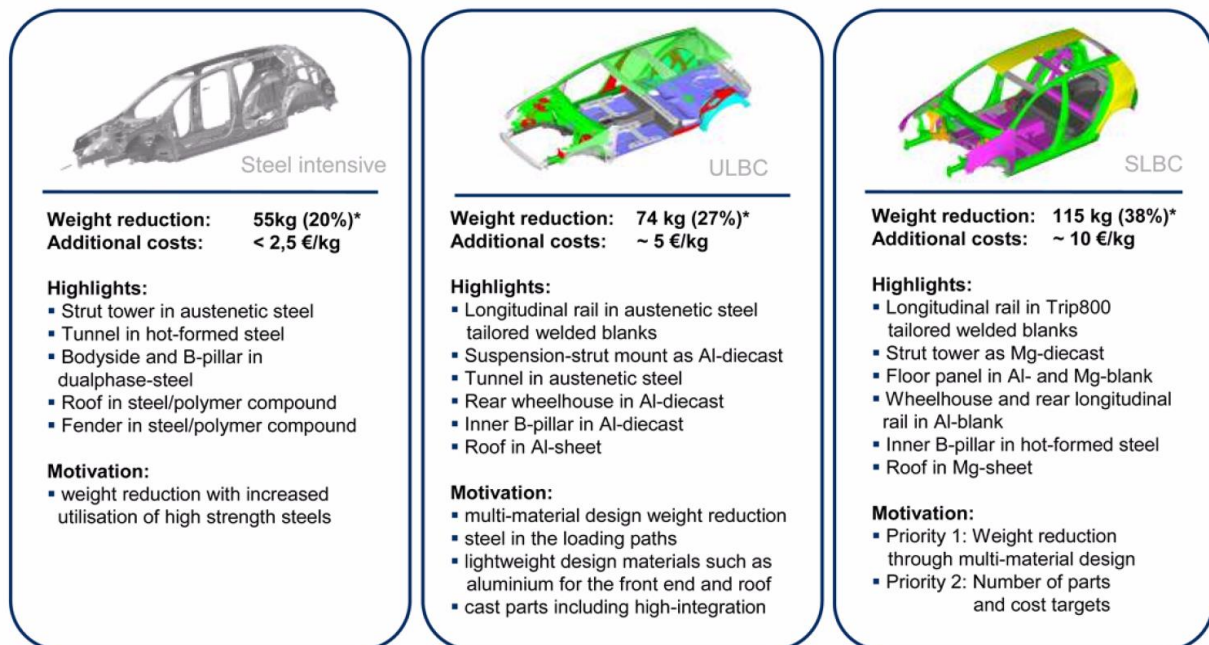
- Cost implications
- Potential for mass reduction
- Ease of production and assembly
- Compatibility with high volume manufacturing processes
- Structural performance

The optimal solution is likely to be a multi-material approach that draws on different materials to achieve the best balance of cost and performance. This can be seen from recent research projects and real-world product developments. For example, the SuperLIGHT-CAR study (SuperLIGHT-CAR, 2014) was a collaborative research and development project, with 38 partners, including large OEMs; Volkswagen (coordinator), Fiat, Opel, Volvo, Daimler, Porsche and Renault. The majority of other contributors were research organisations and trade associations (e.g. aluminium and steel), thereby helping to ensure that the study’s findings were unbiased.

The SuperLIGHT-CAR study focused on reducing the mass of the body-in-white of the VW Golf Mark V. In the first two years, the study produced three preliminary mass-reduced body-in-white concepts in parallel (Figure 5-7):

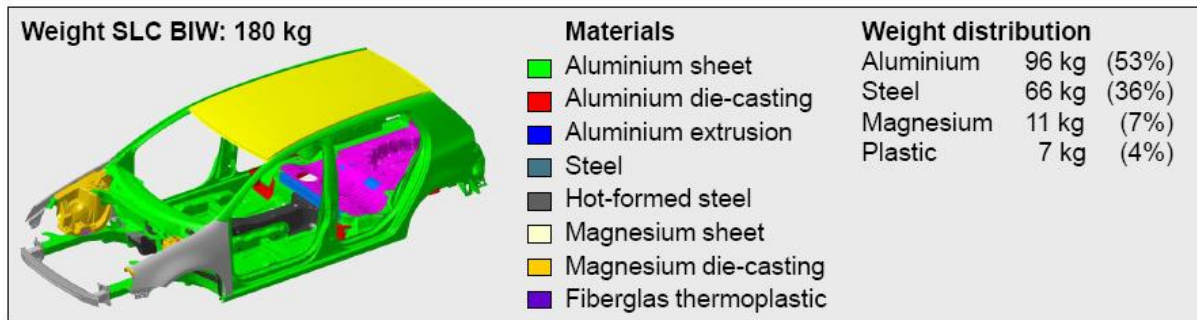
- **A steel intensive design** estimated to achieve a 55 kg mass reduction for <€2.5/kg saved
- **A ‘universal light body concept’ (ULBC)** estimated to achieve 74 kg mass reduction at ~€5/kg saved
- **A ‘superlight body concept’ (SLBC)** estimated to achieve 115 kg mass reduction at ~€10/kg saved

Figure 5-8: Three preliminary body-in-white concepts



The three concepts were then merged into the final SuperLIGHT-Car, which achieved mass reductions of 101 kg in the body-in-white (from 225 kg), for significant additional costs – an increase of 112% over original costs or €7/kg saved. The materials used in the final vehicle are as listed in Figure 5-9.

Figure 5-9: SuperLIGHT-Car Material use



The approaches used in the SuperLIGHT-Car project are now being applied to various production vehicles, some of which have been described in the foregoing sections (e.g. aluminium/steel and aluminium/CFRP hybrid body structures, increased use of magnesium and aluminium in predominantly steel bodyshells, selective use of reinforced and non-reinforced polymer composites throughout the bodyshell).

5.2.7 Summary

There is significant potential for reducing the mass of body components through the use of alternative materials such as high strengths steels, aluminium and composites. A summary of the percentage mass reductions to the bodyshell and closures that could be achieved through intensive use of key alternative materials is presented in the table below.

Table 5-3: BIW and closures mass reduction potentials for different materials

Material	Percentage mass reduction compared to conventional steel
Conventional steel	N/A
Advanced high-strength steels	10-20%
Aluminium	~40%
Carbon fibre	More than 60%

5.3 Powertrain

The mass of powertrain components can be reduced through the use of alternative materials and through engine downsizing. The following sections describe and analyse some options available.

5.3.1 Use of alternative materials

5.3.1.1 Magnesium

There is a long history of using alternative materials in engine construction. Traditionally, engine blocks were manufactured from iron or steel, but over the last several decades, there have been many production engines with blocks manufactured from aluminium. Given that there is already significant use of aluminium, for engine blocks the key potential future development in mass reduction is the possibility for using other materials such as magnesium. The US Automotive Materials Partnership (comprising Ford, Chrysler and GM) have invested in a research project using an Australian-developed magnesium alloy as the basis for a low pressure, sand-cast engine design. The magnesium alloy (known as AM-SC1) was developed by the Co-operative Research Centre for Cast Metals Manufacturing (CAST). In the research project, a V6 engine will be built and tested using this material.

Previously, a three-cylinder engine block made from AM-SC1 was built that weighs only 14 kg; this is 70% lighter than an equivalent engine block made from cast iron and 25% lighter than one made from aluminium (ABC Science, 2002). This engine was installed in a VW Lupo and driven for a total of 65,000 km over a period of three years to test its robustness and to assess the performance of the alloy material's microstructure with age. Analysis conducted by researchers at CAST indicated that whilst there was some ovalisation of the cylinders, the level of distortion was within acceptable limits and further developments in the alloy could overcome this problem (The Engineer, 2005).

Figure 5-10: 14 kg engine block made from AM-SC1 magnesium alloy. (Source: The Engineer, 2005)



A key problem associated with magnesium is that it has poor resistance to corrosion, but a recent development in stainless magnesium technology may help to overcome this problem (Gizmag.com, 2013), thereby allowing magnesium alloys to be used more widely in engines in the future.

5.3.1.2 Plastics

Plastics have not traditionally been used for major engine components because of the need to ensure high levels of heat resistance combined with high levels of durability. In recent years, new materials have been developed by suppliers that are being taken up by the automotive industry as a means for saving mass and reducing parts count (thereby reducing costs). A good example of this can be found on Ford's 3.5 litre and 3.7 litre V6 engines fitted to various US-market models. For these engines, the crossover coolant assembly, which was previously made from brazed metal components, has been replaced by an integrated component made from HTN PPA resin (produced by DuPont on Ford's behalf). According to Ford, the replacement component saves 1 lb (approximately 0.5 kg) in mass and reduces costs US\$1 per engine (PRWeb.com, 2013).

Figure 5-11: Polypropylamide resin manifold fitted to Ford's 3.5 litre and 3.7 litre V6 engines



Other engine components that can now be manufactured from plastics include engine mounts, oil sumps and oil circuits. In 2013, the Renault-Nissan Alliance and the component supplier ZF, announced the development of polymer composite engine mounts, which will be fitted to selected future production vehicles (Moteurnature.com, 2013). In this case, the composite design, which is made from glass-fibre reinforced polyamide, replaces the traditional steel and rubber engine mounts, and according to Renault-Nissan and ZF, the new design is 25% lighter than the traditional alternative. ZF has indicated that the

new design is only appropriate for smaller vehicles; larger vehicles will still need conventional rubber/metal engine mounts.

Figure 5-12: Plastic engine mount developed by ZF for the Renault-Nissan Alliance

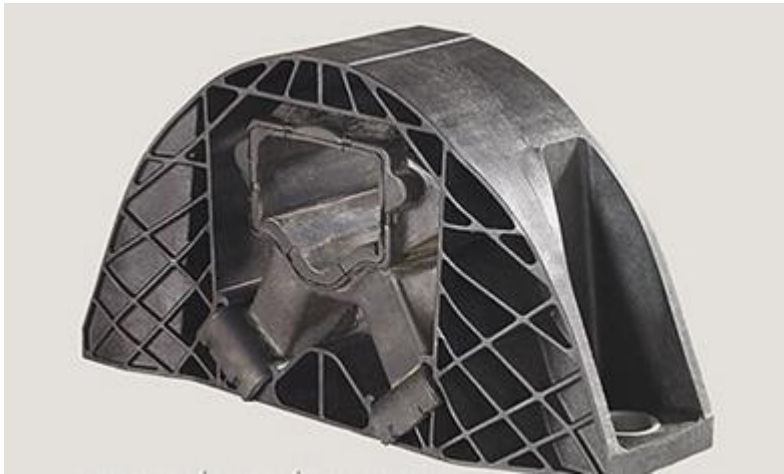
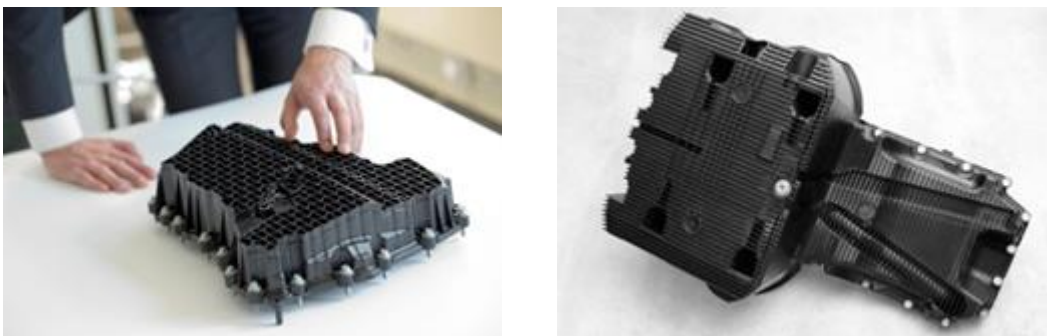


Photo: www.moteurnature.com

A form of glass-reinforced polyamide has also been used by Peugeot for the oil sump on its 508 D-segment model. The composite sump is 60% lighter than a traditional steel oil sump, offering significant mass reductions that could be applied to a wider range of vehicles. To develop a composite sump suitable for real-world applications, it was necessary for the component to be engineered to meet high levels of impact resistance – necessary, given that oil sumps are typically located in an exposed position underneath the vehicle's body structure.

Other engine components that can be produced in plastic include oil circuits, gearbox oil sumps, oil filter regulating pistons and oil sensors. For many of these components, the use of plastic polymers offers the double advantage of reduced mass and reduced cost (the latter through parts integration). The potential for reductions in cost is often the main driver for switching to plastic engine components such as these.

Figure 5-13: Polyamide oil sump from the 2010 Peugeot 508. (Source: PlasticsToday.com, 2013b)



Composite engine blocks

A more radical use of polymer materials in vehicle powertrains would be the use of composites to fabricate the engine block. A US-based company, Composite Castings LLC, has developed a complete four-cylinder engine block made from carbon-fibre-reinforced plastic. The design of the engine is based on Ford's 2.0 litre Duratec petrol engine, and by producing the block in CFRP it has been possible to reduce the mass by 9.1 kg compared to the standard aluminium block (around 45-50% lighter). At this point in time, the technology has not been adopted by any of the major vehicle manufacturers as the total unit costs of production are higher than for conventional cast aluminium and steel blocks. For high-performance track racing applications, there are customers who have started to purchase these CFRP engines. According to Composite Castings, the tooling costs for their CFRP blocks are 50% lower than

for die casting. It remains to be seen whether this technology will be taken up by the major OEMs for mainstream applications as it is likely that the increased production costs and slower production processes are not currently compatible with high-volume production. In future years it is possible that improvements in the production process and reductions in cost could make the technology viable for mainstream road vehicles.

Figure 5-14: Mould tool for CFRP engine block produced by Composite Castings

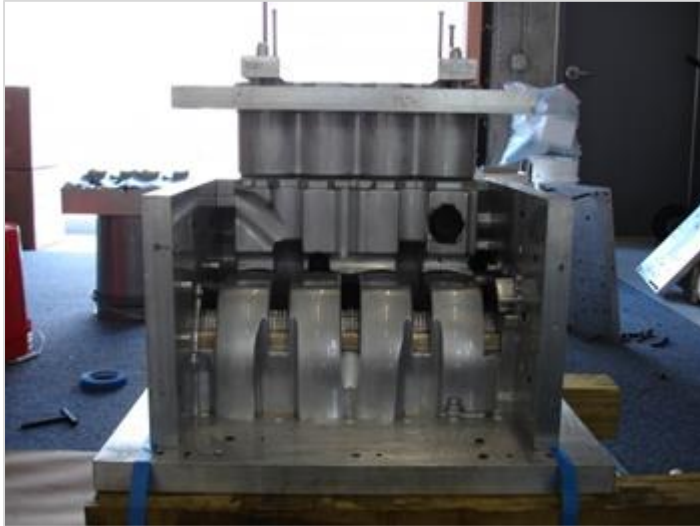


Photo: Car and Driver, May 2011

5.3.2 Downsized engines

A key trend in the automotive sector over the last few years has been the introduction of downsized gasoline engines which have been introduced as a means for achieving significant improvements in vehicle fuel economy and reduction in CO₂ emissions. The improvements in fuel economy arise primarily because of the reductions in engine cylinder capacity as relatively little power is required for keeping a vehicle at constant speed, even on high speed roads. By coupling a downsized engine with a turbocharger, energy from the exhaust gases that would otherwise be lost can be used to drive a compressor, thereby providing the additional power required for acceleration.

Whilst downsized engines have been designed to reduce fuel consumption primarily through improvements in efficiency (e.g. reductions in pumping losses), such downsized engines are often much lighter than the engines that they replace. This is because in many cases downsized engines are not only smaller in capacity than the engines they replace, but they also have fewer cylinders. For example, Ford, VW and General Motors have all introduced downsized three cylinder petrol engines that are replacement for conventional four cylinder engines. In Ford's case, its 1.0 litre three-cylinder Ecoboost engine weighs 30 kg less than the 1.6 litre four cylinder engine it replaces. Volkswagen's EA211 1.4 litre engine weighs 22kg less than the EA111 engine it replaces (Automotive Manufacturing Solutions, 2012). Fiat has taken a further step in engine downsizing by producing a two cylinder petrol engine (known as the Twin Air) to replace previous four cylinder engines. The engine is currently fitted to various small Fiat, Lancia and Alfa Romeo models. The Twin Air two cylinder engine is 20% lighter and has a cylinder capacity that is 25% smaller than an equivalent four cylinder engine with the same power output. Many other manufacturers have also started fitting downsized engines to vehicles across the full range of vehicle size categories.

5.4 Chassis/suspension systems

The vehicle chassis system is terminology commonly used in the automotive industry to refer to the collection of assemblies and components responsible for vehicle path control. The vehicle chassis system comprises:

- Suspension system and components
- Braking system and components
- Steering system and components

- Wheels and tyres

The overall mass of the chassis system is not dominated by a single component or assembly, but wheels and tyres are usually the heaviest items from this group.

As with other vehicle systems, there are significant opportunities for mass reduction of chassis components through the use of alternative materials and through system redesign. Many of the chassis components form part of the “unsprung mass” of the vehicle; this is the combination of components that is not supported by the suspension of the car. Vehicle manufacturers usually look to reduce the unsprung mass of the vehicle to improve the handling and ride characteristics of the vehicle – hence, there are many benefits associated with reducing the mass of chassis components aside from the potential benefits in reduced fuel consumption.

5.4.1 Suspension components

Key suspension components include springs, dampers, anti-roll bars, knuckles and suspension control arms. For each of these components, manufacturers have a significant amount of choice in the materials that can be used for fabricating these parts. Steel has traditionally been used for many of these components, but vehicles are increasingly fitted with suspension components made from a wider range of materials. Aluminium is particularly suitable for structural suspension components such as control arms and knuckles. There is also potential for polymer composite materials to be used for suspension components, with examples of transverse composite leaf springs fitted to a small number of production vehicles including the Chevrolet Corvette (the Corvette has used composite leaf springs for all models since 1981), the Mercedes-Benz Sprinter van and the Volkswagen Crafter van. There are very significant mass savings associated with using transverse composite leaf springs in these applications - around 60% to 80% reduction in mass compared to equivalent steel leaf springs. For example, the composite leaf spring that is used for the front suspension of the Mercedes Sprinter weighs 5.5 kg compared to the 25 kg steel front leaf spring it replaced (a 78% saving in mass) (Composites World, 2014). Whilst composite leaf springs can be suitable for light commercial vehicles (and potentially could be applied more widely), they are not suitable for all types of light duty vehicles. In particular, using composite leaf springs in many passenger cars may not be feasible because of cost, durability and packaging issues. However, some vehicle manufacturers have announced that they are developing this technology for use in passenger cars. In 2011, BMW announced that it was developing glass-fibre reinforced composite suspension springs to replace traditional steel coil suspension springs in certain future models. According to BMW, the use of composite springs will save a total of 6 kg per vehicle (Motor Trend, 2011).

5.4.2 Braking system and components

Careful redesign of various braking components can be used to reduce the overall mass of the braking system. In 2011, BMW demonstrated its prototype “Slim Rim” brake rotor design which, whilst physically larger than a conventional brake rotor, is actually significantly lighter through design optimisation. In particular, the frictional surface of the rotor is shorter than on a conventional brake rotor and additional mass reduction measures have been applied to the component by removing material from where it is not needed. The Slim Rim brake rotor weighs 13 kg, compared to a conventional brake rotor which weighs 17.8 kg (Motor Trend, 2011).

Other options for reducing mass from the braking system include the use of electronic parking brakes. Electronic parking brakes were first introduced at the turn of the millennium, and can reduce mass by up to 7 kg compared to conventional parking brakes. The component supplier TRW has previously forecast that 20% of new vehicles built in Europe will be fitted with this technology by 2015 (up to 50% for larger vehicles) (TRW Automotive, 2010). There are already many EU market vehicles fitted with this technology including popular models from Audi, BMW, Ford, Renault, Volkswagen and Volvo.

5.4.3 Steering system and components

Over the last few years, new vehicles are increasingly being fitted with electric power assisted steering (EPAS) systems in place of traditional hydraulic power steering systems as a way to cut fuel consumption. EPAS systems use up to 90% less energy than hydraulic systems, and can give a 4% reduction in fuel consumption and CO₂ emissions (CNET.com, 2014). Primarily, EPAS reduces fuel consumption because it eliminates the need for an engine-driven hydraulic pump. These systems are also lighter than traditional hydraulic power steering systems, and potentially offer additional fuel consumption benefits because of their reduced mass.

According to research carried out by Strategy Analytics in 2011, EPAS systems accounted for more than 50% of the total global market for power steering systems in 2010, with significant projected future growth in future years (Infineon Technologies, 2011). To date, the bulk of the demand for EPAS has been in the European and Japanese markets, but rapid growth in other markets is expected over the next few years. According to recent research, nearly all newly launched passenger cars and SUVs sold in the Western hemisphere and Japan are equipped with EPAS (Kuebler, E., M. Eickhoff and M. Budaker, 2013). This means that the potential for further uptake (and mass reduction) may be rather limited in the EU market; essentially only models that have not been replaced for a number of years are likely not to be currently fitted with EPAS.

5.4.4 Wheels

For many years, aluminium and magnesium alloys have been used to produce lightweight wheels for passenger cars. The majority of alloy wheels produced today are made from aluminium alloys, and in 2011, around 50% of new cars were fitted with alloy wheels as standard (European Aluminium Association, 2011). Market penetration is likely to increase in future years as manufacturers move away from using traditional steel wheels. Aluminium alloy wheels were not originally introduced for mass reduction, but for styling purposes. Aluminium alloy wheels can be manufactured by either casting or forging aluminium, with the vast majority (around 90%) of alloy wheels produced using casting processes. Cast aluminium alloy wheels can offer mass reduction advantages compared to steel, but in most cases, this is not the reason for using this material; Casting allows a very wide variety of styles to be produced, and it is the styling potential that accounts for the popularity of cast alloy wheels in the marketplace today. Many cast aluminium alloy wheels are not lighter than steel equivalents, and with the trend towards larger diameter wheels, the average mass of vehicle wheels has been increasing. For mass reduction, forged aluminium wheels offer significant benefits compared to cast aluminium wheels, as they are typically 25% lighter, with the potential for even greater mass savings. Forged aluminium wheels also demonstrate better mechanical properties than cast wheels – in particular, their impact and fatigue performance is significantly better, although they are more expensive to manufacture.

A relatively recent development in cast aluminium wheel technology is the “Air Inside” production technology developed by BBS Wheels. The technology allows hollow areas to be cast inside the spokes of a wheel, reducing total mass by around 5 kg for a typical wheel and increasing stiffness by around 60%.

Other options for reducing the mass of vehicle wheels include the use of high strength steels and composite materials. HSS and AHSS steel grades offer the potential for significant mass reduction and new production techniques allow these steels to be produced in visually attractive designs that are similar to cast aluminium alloy wheels.

Component suppliers and vehicle manufacturers have recently started developing composite materials that are suitable for fabricating lightweight wheels. In particular, both Audi and BMW have been working in this area with their suppliers. Audi’s latest A8 model, which went on sale at the beginning of 2014, is equipped with hybrid polymer composite / aluminium wheels made by the Lacks Wheel Trim Systems. According to the wheel manufacturer, the hybrid composite material, which is known by the brand name Chromtec, consists of a lightweight structural backbone made from forged aluminium combined with a polycarbonate ABS co-polymer for the wheel covers (Automotive Engineer, 2013). Polyurethane cellular foam is injected into the gap between the aluminium backbone and the polycarbonate cover to give the wheel its structural stiffness (Motor Authority, 2013). The polycarbonate ABS surface is also plated with a nickel-chrome surface so that the finished wheel looks very similar to conventional aluminium alloy wheels. Each wheel is 4.4 kg lighter than a conventional aluminium alloy wheel, thereby reducing the total mass of the vehicle by 17.6 kg. The Audi A8 is the first production vehicle available on the market with composite wheels.

At the beginning of 2014, BMW announced that it has been developing lightweight carbon fibre reinforced plastic (CFRP) composite wheels (BMW group, 2014a); news reports indicate that BMW could fit CFRP wheels to selected vehicles in the near future (Electric Vehicle News, 2014). According to BMW, they have been developing two different types of CFRP wheels – a full-CFRP design and a hybrid CFRP / forged aluminium design. The full CFRP wheel is 35% lighter than a forged aluminium wheel, whilst the hybrid design (which comprises a CFRP wheel rim and forged aluminium spokes) is 25% lighter.

5.5 Other approaches for reducing vehicle mass

5.5.1 Applying mass reduction technologies to other areas of the vehicle

Beyond the bodyshell, powertrain and chassis systems, it is also possible to apply a wide range of mass reduction technologies to other parts of the vehicle. Examples of innovations that may have wider applicability in future years include:

- Lightweight interior trim materials and fascia (dashboard) components
- Polycarbonate glazing (already used on the high-efficiency Volkswagen XL1 vehicle)
- Downsized / design-optimised auxiliary equipment such as heating/ventilation equipment
- Lightweight insulation materials and structural foams.

These areas have not been examined in detail, as the focus on this chapter has been on the vehicle systems that account for the bulk of a vehicle's mass. Research and development activities are also ongoing in these areas, and application of technologies for reducing mass to these areas could also play a role in cutting vehicle weight.

5.5.2 Removing content or features from the vehicle

Another option for eliminating mass from vehicles is to simplify the content and features included in the vehicle. The Citroen C4 Cactus production vehicle has demonstrated that such an approach can contribute significantly to reducing overall vehicle mass. The C4 Cactus is a C-segment crossover vehicle with a total kerb mass of 965 kg. This compares very favourably to rival C-segment models fitted with downsized engines. For comparison, the Ford Focus 1.0 litre weighs 1165 kg and the Volkswagen Golf with 1.2 litre engine weighs 1100 kg.

The mass reductions achieved in the C4 Cactus are the result of using a combination of different approaches. High-strength steels are widely used throughout the body structure and aluminium is used for the bonnet and crash beams. The feature content of the vehicle has also been simplified with the twin aims of reducing mass and cost. Examples include the following (Autocar, 2014):

- The vehicle is fitted with a one-piece rear seat (i.e. no split-folding facility) which saves 6 kg
- The rear windows do not wind down (they are hinged), saving 11 kg
- Whilst the vehicle is fitted with a glass panoramic roof, no interior blind is available – instead, the glass has been treated with ultra-violet and heat-resistant materials
- The C4 Cactus platform (which is actually derived from that used on the B-segment Citroen C3 and DS3 models) has been engineered on the basis that any vehicles produced on this platform will have a maximum speed of 190 km/h (118 mph), much lower than the maximum speeds assumed when engineering most other C-segment vehicles. By engineering the platform in this way, the suspension, braking and cooling systems have all been downsized, allowing significant reductions in mass.

There is clear potential for the approaches employed on the C4 Cactus to be applied more widely, particularly as for many mainstream vehicles and markets, there is little (if any) real-world need to engineer a vehicle to be capable of achieving speeds above 190 km/h.

5.6 Summary of findings from the literature

This chapter demonstrates that there is significant ongoing R&D activity on vehicle mass reduction across the automotive industry, and that many new technologies, processes and approaches are being applied to new production vehicles with the aim of reducing vehicle mass.

There are many benefits associated with focusing mass reduction efforts on the systems and components that contribute the most to overall vehicle mass. In a typical light duty passenger car, the body-in-white powertrain and chassis systems are responsible for the majority of total vehicle mass. Hence, any focus on mass reduction should therefore be targeted at these sets of components and systems first, whilst also recognising that mass can be reduced from almost any area of the vehicle.

Related to this is the fact that any increase in vehicle mass tends to incur further incremental increases in vehicle mass. For example, as the mass of the body-in-white increases, a larger, heavier and more powerful engine is usually required to provide sufficient performance and larger, heavier braking systems are required to ensure appropriate braking performance. By contrast, reducing the mass of the main vehicle systems and components (primary mass reduction) allows additional consequential mass reductions (secondary mass reduction) to be achieved. A lighter body structure will require a smaller, less powerful engine to achieve the same overall performance as a larger, more powerful engine fitted to a heavier vehicle. The lighter vehicle will also need smaller, lighter braking and suspension components, and secondary mass reductions may also be possible elsewhere. Various pieces of literature have indicated that for every 1 kg in primary mass reduction, it is possible to achieve a further 0.7 to 1.5 kg in secondary mass reduction. There is a great deal of uncertainty in the levels of additional secondary mass reductions that are possible, with a study by MIT highlighting that if just four of 13 key sub-systems are unavailable for re-design then the figure for secondary mass reduction drops to a mean of 0.12 kg per kg. However, the scope for applying secondary mass reduction to LCVs is likely to be more limited, due to the need for these types of vehicles to maintain the ability to carry heavy payloads.

The literature also indicates that there is no single, "best" approach for achieving mass reductions. For example, in the body-in-white and closures, the optimal approach is likely to consist of a multi-material approach, with high-strength steels, aluminium, magnesium and composite materials all being used to greater or lesser amounts. In many cases, all of these materials will be used to reduce mass from an individual vehicle model, and indeed, this is already happening in practice, as there are vehicles already on the market that apply such an approach. Increased use of composite materials is likely in future years, and there is the potential for more widespread use of CFRP for structural applications, although at present, the costs of CFRP body structures are prohibitive for mass-produced vehicles.

The application of advanced mass reduction technologies requires manufacturers and their suppliers to invest in alternative manufacturing processes and technologies. Even shifting from steel to aluminium in bodysell production means that mass production techniques such as spot-welding cannot be used. There are very significant cost implications for manufacturers associated with such changes, and for many mainstream manufacturers, a widespread shift to alternative materials may not be economically viable in the immediate short term, but as costs come down and more experience is gained, it is likely that more widespread adoption will be both technically and commercially viable in the near future.

6 Detailed review of major US studies on the potential for vehicle mass reduction

This chapter reviews three major US studies that have examined in detail the technical potential and costs associated with technologies for reducing the mass of light duty vehicles. These studies are as follows:

- A study undertaken by Lotus Engineering published in 2010 commissioned by ICCT which focused on the Toyota Venza (Lotus Engineering, 2010).
- A study undertaken by FEV published in 2012, commissioned by the US EPA to build on the 2010 Lotus study. It also focused on the Toyota Venza (FEV, 2012).
- A 2012 study undertaken by Electricore, EDAG and George Washington University for the US National Highway Traffic Safety Administration (NHTSA) that focused on US-market Honda Accord (Electricore et al, 2012).

In view of their importance, each of these studies is reviewed in a separate section. As each of the latter two build on the Lotus Engineering (2010) study, there is some reference to the earlier studies in the context of the review of the later studies; a more comprehensive comparison of the three studies is presented in Section 6.4.

6.1 Review of Lotus Engineering 2010 Phase 1 vehicle mass reduction study

6.1.1 Introduction

The Lotus Engineering (2010) study was funded by the International Council on Clean Transportation (ICCT) with the aim of reviewing the future potential for reducing the mass of a volume-produced vehicle. The Toyota Venza (2009) was selected as the baseline vehicle due to the high sales of the vehicle in the USA, and its five star results on frontal and side crash tests.

The overall aims of the study were to:

- benchmark component systems of the vehicle against others in the market
- investigate emerging and current mass reduction technologies
- establish the costs of reducing the mass of the Toyota Venza

The study involved the creation of two alternative vehicle designs with specified target mass reductions (less powertrain):

- 'low development' - 20% mass reduction using 2017 manufacturing techniques
- 'high development' - 40% mass reduction using 2020 manufacturing techniques

The boundary conditions specified that the functional performance of the vehicle must be maintained; reducing vehicle size, footprint or occupant space was not permitted. Furthermore, crash test performance had to be maintained (although the study did not include any detailed crash test analysis to confirm this). Cost limitations were placed on the 'low development' and 'high development' vehicle at 92-104% and 97-109% of baseline vehicle manufacturing costs respectively.

6.1.2 Approach used

Lotus Engineering subcontracted A2Mac1 to complete the teardown of the baseline vehicle. Subsystems and systems used in the Venza were compared against A2Mac1's library of vehicles.

Research into lightweight technologies that may be applied to the Venza included examining techniques used in other markets including electronic goods, the food container industry, aerospace, watercraft, motorsports, motorcycles, furniture and bicycles. In the report, analysis of each system contains the review of these technologies in relation to the application to the system, with the mass reduction potential. The 'low development' vehicle adopted existing passenger car technologies whilst the 'high development' vehicle considered a broader scope; for example ablation cast aluminium wheels (used in trucks and motorcycles) and callipers used in motorcycles were used in the 'high development' vehicle.

The cost analysis was delivered by a Detroit based company called Intellicosting, which specialises in cost analysis work for the automotive industry. Each component from the Venza was assigned a cost, whilst alternative lightweight components were either costed by suppliers or were assigned a cost by Intellicosting. No separate costs for labour, burden (or overhead) and materials costs were considered in the study, with percentage change in costs (compared to the baseline) being provided by Intellicosting. Some components require OEM investment and tooling amortisation, which was not considered in the costing. Cost constraints were applied as part of the selection process for reduced mass components; Table 6-1 provides a breakdown of these constraints.

Table 6-1: Cost constraints applied to selection of reduced-mass parts

	Low development		High development	
	Mass reduction target	Relative cost to baseline Venza	Mass reduction target	Relative cost to baseline Venza
Vehicle	20%	+20%	40%	+50%
System level	20%	+20%	40%	+50%
Sub-system	20%	No constraints	40%	No constraints
Component level	20%	No constraints	40%	No constraints

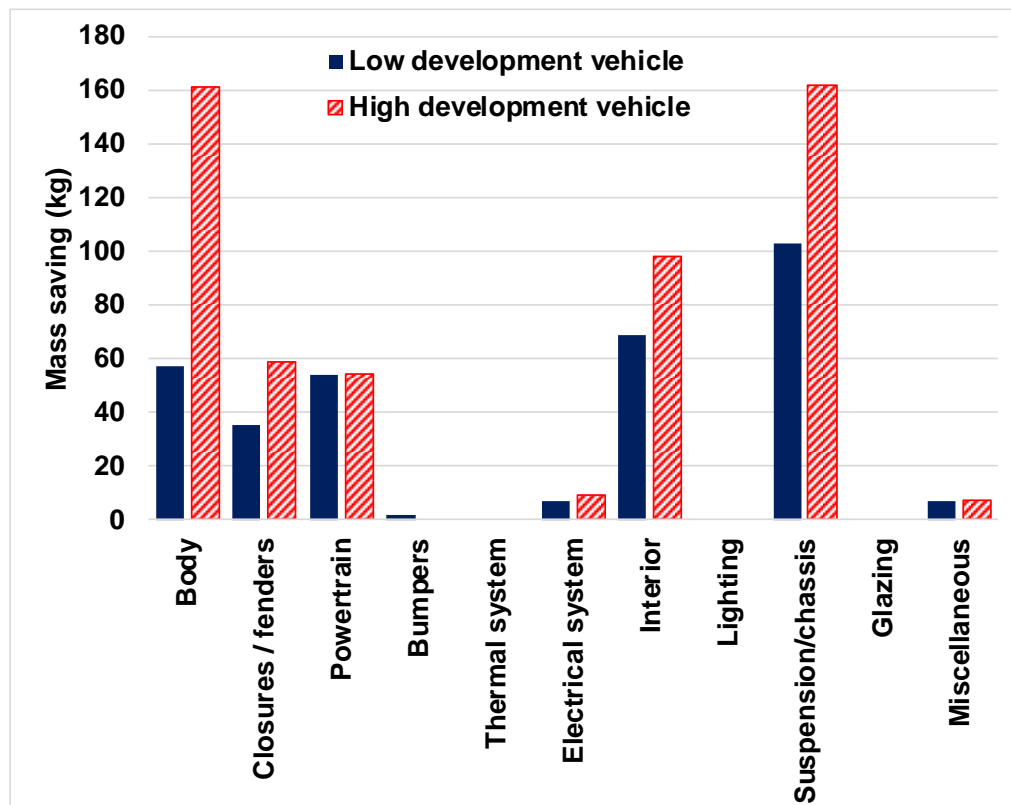
6.1.3 Results

Table 6-2 provides a summary of the Lotus (2010) study results; the high development vehicle achieved a 32% mass reduction (the study quotes a 38% reduction in mass if the powertrain is not included) with a 3% increase in cost to the baseline vehicle. The low development vehicle achieved a 20% mass reduction (the study quotes a 22% reduction in mass if the powertrain is not included), with a cost saving of 2% against the baseline vehicle. Significant cost savings were achieved in areas where large mass reductions were made; notably the interior and suspension/chassis, although mass reductions in the suspension/chassis were secondary mass reductions (meaning the savings could only be achieved as a result of mass reductions achieved elsewhere).

Table 6-2: Summary of mass reductions and associated costs

	Base	Low Development			High Development		
	Mass (kg)	Mass (kg)	% saving	Cost Factor	Mass (kg)	% saving	Cost Factor
Body	382	325	15%	0.98	221	42%	1.35
Closures/ fenders	143	108	25%	1.02	84	41%	0.76
Powertrain	410	356	13%	N/A	356	13%	N/A
Bumpers	18	16	11%	1.03	18	0%	1.03
Thermal	9	9	0%	1.00	9	0%	1.00
Electrical	24	17	29.3%	0.95	15	36%	0.96
Interior	251	182	27.4%	0.97	153	39%	0.96
Lighting	10	10	0.0%	1.00	10	0.0%	1.00
Suspension/Chassis	379	276	27%	0.96	217	43%	0.95
Glazing	44	44	0%	1.00	44	0%	1.00
Misc.	30	23	24%	0.99	23	24%	0.99
Totals	1700	1366	20%		1150	32%	
% against baseline	100%	78%		98%	62%		103%

Figure 6-1: Mass savings for each sub-system – Lotus 2010 study



6.1.4 Summary of findings

The majority of mass reductions have been achieved through changes to the body structure, powertrain, fenders, closures and interior. The reductions achieved have in turn allowed alternative, lightweight suspension and chassis components to be used (secondary mass reduction). For both the closure/fender systems and suspension/chassis systems, mass reductions are achieved through the use of alternative parts from production vehicles, especially for the low development vehicle. Although this shows reductions in mass are realistic for the Toyota Venza, it is questionable that the percentage mass savings achieved could be assumed to be achievable across the passenger car fleet as a whole since there appear to be a range of other production vehicles which already feature these lighter designs.

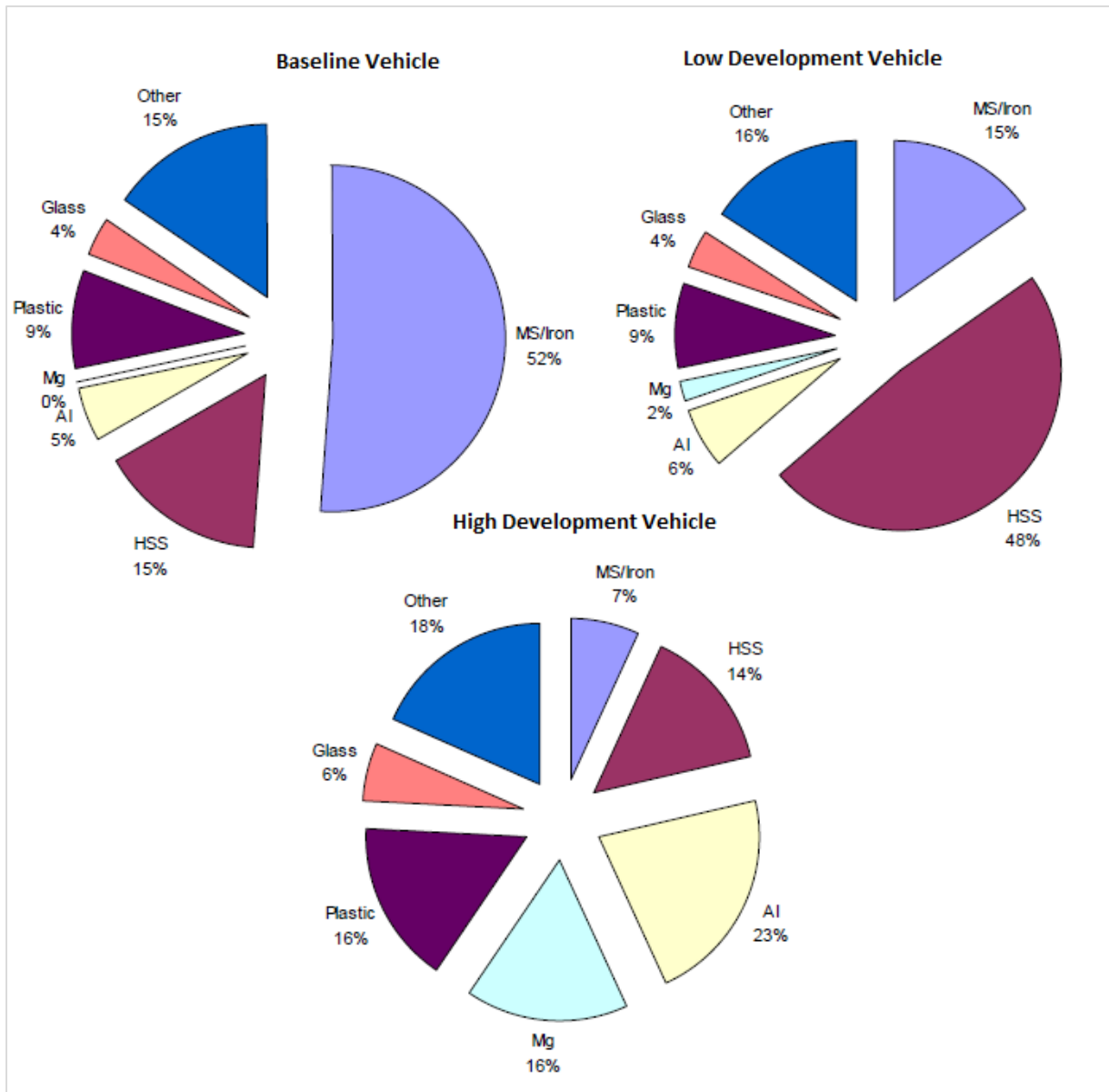
Considerable reductions in mass have been made through design improvements and material substitution. The redesigned body features extensive use of HSS and advanced high strength steel (AHSS). In the interior, the use of LCD/LED touch screen systems for a large number of controls is a feature which has now become increasingly common in the market place, as is the use of MuCell plastics for interior trim items.

The high development vehicle uses magnesium and aluminium extensively as alternatives in the body system.

The analysis of materials used in the baseline, low and high development vehicles (shown in Figure 6-2) show that mass reduction has been achieved through a reduction in the use of iron and mild steel, whilst there is an increase in the use of high strength steels, aluminium, plastic and magnesium. The increased cost of the high development vehicle reflects the different materials used (especially in the body system). The low development vehicle uses a larger proportion of HSS (mainly in the body system) which, in combination with mass reductions elsewhere results in reduced costs.

The powertrain was selected by the EPA for the vehicle. A downsized 2007 Toyota Camry 1.7 litre hybrid-electric petrol engine was selected for both the low and high development vehicles. The engine was optimised through the Lotus SABRE study to provide the same power output as the baseline vehicle, but using a three cylinder engine instead. A previous study conducted on the mass reduction potential of the engine was conducted by Oak Ridge National Laboratory. The engine and battery were downsized due to the findings of these studies by 13% (a 54 kg reduction), to 356 kg.

Figure 6-2: Materials use in baseline, low and high development Toyota Venza vehicles



6.2 Review of US EPA (FEV, 2012) Phase 2 vehicle mass reduction study

6.2.1 Introduction

The EPA contracted a team led by FEV to perform a further, more detailed study (FEV, 2012), building on the findings of the Lotus study reviewed in the previous section. The focus of this study (referred to as the Phase 2 study) was firstly to perform relevant tests not conducted in Phase 1 by using computer aided engineering analysis (CAE) to review torsion and bending stiffness and crash tests of the body-in-white structure as well as noise, vibration and harshness (NVH) tests.

A further objective of the study was to establish actual costs for mass reduction by including direct manufacturing costs in the cost estimates for benchmarked and reduced-mass components. The study also investigated additional mass reduction opportunities available beyond those achieved by Lotus, including powertrain mass reduction opportunities. Overall, the aim for this study was to establish a 20%

reduction in mass at a 1% manufacturing cost saving, whilst not decreasing function, performance or safety compared to the baseline vehicle.

6.2.2 Approach used

The findings from the Lotus study were reviewed by FEV prior to starting any new analysis. The FEV study team then carried out a further tear-down analysis on another Toyota Venza (a 2010 model, as opposed to the 2009 model analysed by Lotus). Alongside the teardown of the vehicle, a brainstorming exercise was used to consider options for reducing the mass of vehicle systems. Each idea considered was intuitively scored according to:

- manufacturing readiness risk
- functionality risk
- estimated percentage change to mass
- estimated change to piece cost and
- estimated cost as a result of tooling

The ideas were then ranked and selected according to score, mass and cost (lowest cost per kg mass saving).

Further research was carried out on the shortlisted ideas to increase the portfolio of information available; this included sourcing manufacturing examples and speaking with suppliers⁸ to gain quantitative and qualitative information. Cost analysis was then conducted for ideas shortlisted using the manufacturing assumption and quote summary spread sheet (MAQs), which used assumptions about labour, materials and manufacturing costs. Reductions in mass and costs allocated to each shortlisted idea allowed a cost curve (mass reduction versus cost) to be produced showing the numerous possible combinations for a complete vehicle. The ideas selected achieved an 18% mass reduction at a cost of US\$0.47/kg.

The study team also carried out analysis to investigate how the Lotus low development vehicle performed in virtual body stiffness and crash test scenarios using computer-aided engineering (CAE) techniques. Comparison of the baseline CAE model to the modified CAE model predicted that the Lotus low development body would not meet target performance values for static bending and torsional stiffness. For the Lotus low development body:

- Torsional stiffness was predicted to be 20.4% less than baseline
- Bending stiffness was predicted to be 20.0% less than baseline

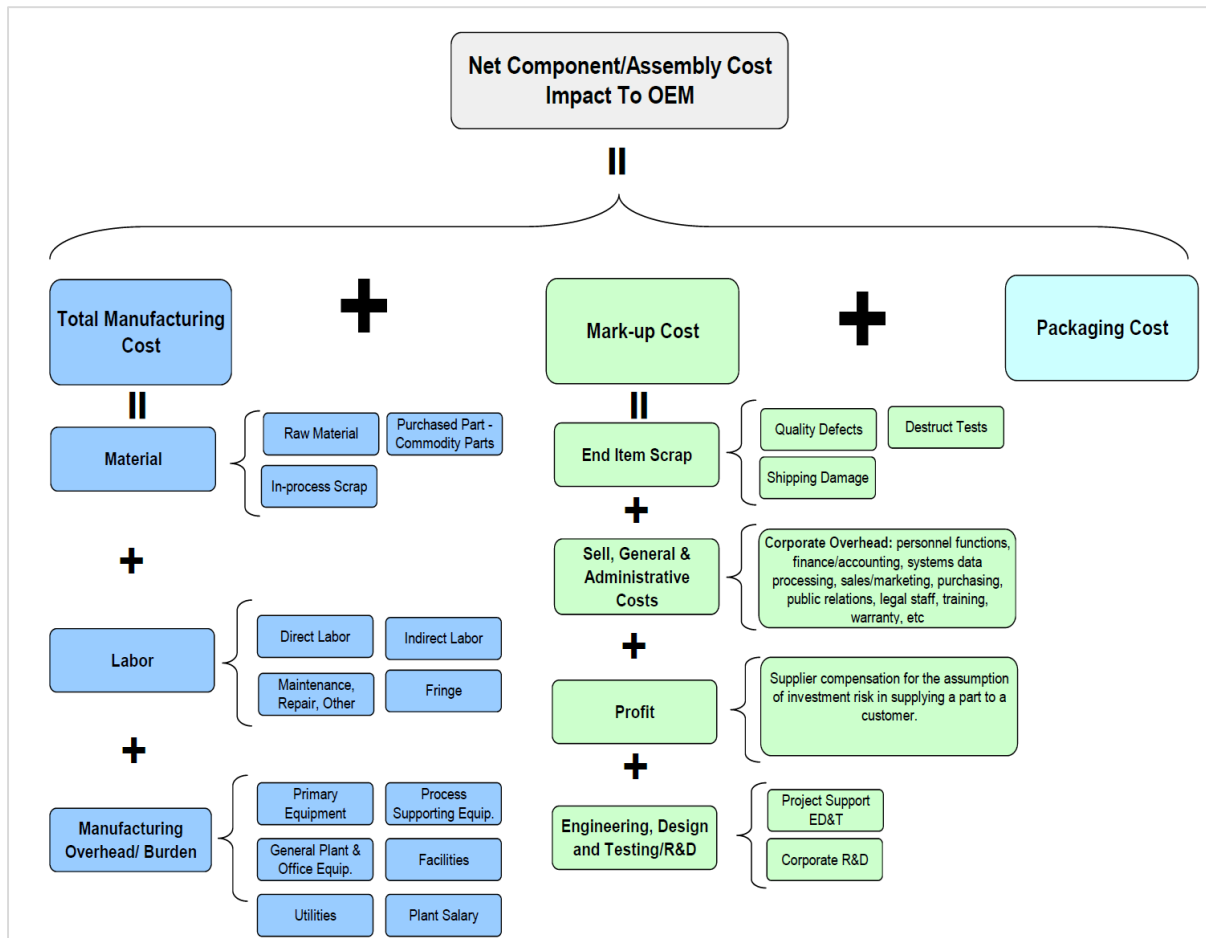
As a result, crash simulations were not conducted on the Lotus low development body. Instead the study team developed their own body-in-white structure together with closures and bumpers, achieving a 13% reduction in mass (compared to Lotus' claim of 16% for the low development body). CAE analysis of this design showed a reduction in bending stiffness of 5% and no reduction in torsional stiffness compared to the baseline vehicle.

6.2.2.1 Assessing 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 (US EPA, 2009). Figure 6-3 details all factors used to determine the system part manufacturing costs for both the baseline and mass-optimised vehicle. More details on the approach used for assessing costs can be found in Appendix 3.

⁸ Details of suppliers researched may be found in Appendix H.2 of the report, with little detail of questions posed to manufacturers.

Figure 6-3: Detail of costs included in cost analysis. Source: (FEV, 2012)



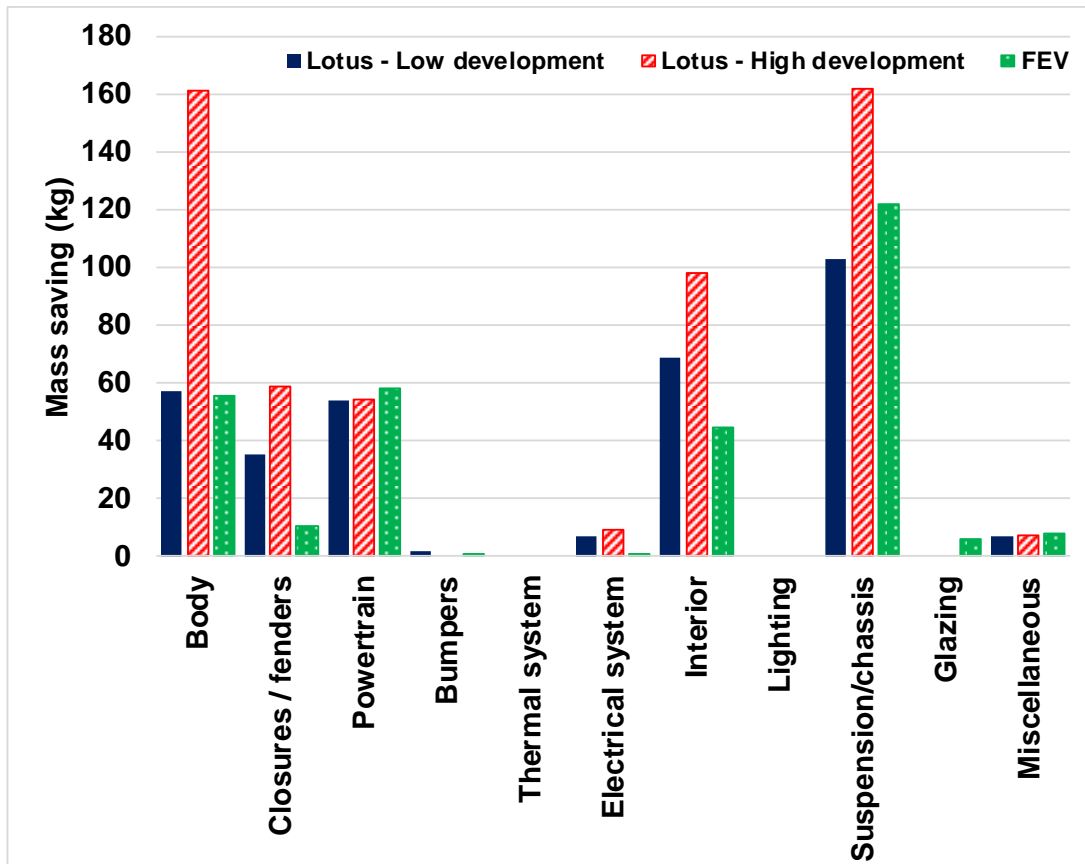
6.2.3 Summary of findings on vehicle mass reduction and associated costs

The FEV study achieved an 18% (312 kg) reduction in vehicle mass for a US\$148 saving in costs. These cost savings were achieved through reductions in labour and burden costs which more than compensated for an increase in materials costs.

The main systems used to reduce the mass of the Venza are reviewed: engine, transmission, body system (which includes the interior), suspension, braking, exhaust, fuel, steering and climate control.⁹ Overall the FEV study made similar changes to the Toyota Venza as Lotus made, providing further evidence that these systems are cost effective as well as realistic mass reduction options for the Venza. As in the Lotus study, different materials were used for the body-in-white, electronic gears and electronic braking systems. The closures incorporated the use of aluminium, the chassis and brakes were downsized and wheels were selected from the Toyota Prius.

⁹ Each weight reduction method has been assigned a primary or secondary weight reduction, with a category generalising the approach used, with notes providing further detail.

Figure 6-4: Comparison of mass reduction (compared to baseline vehicle) in equivalent systems for the Lotus and FEV studies



A review of the mass of major mass-optimised systems (in Figure 6-4) helps provide further understanding of how similar the approaches used for reducing mass were between the Lotus study and the FEV study. Table 6-3 provides more detail on the approach taken by FEV compared to Lotus.

Table 6-3: Comparison of US EPA and Lotus 2010 studies by vehicle system

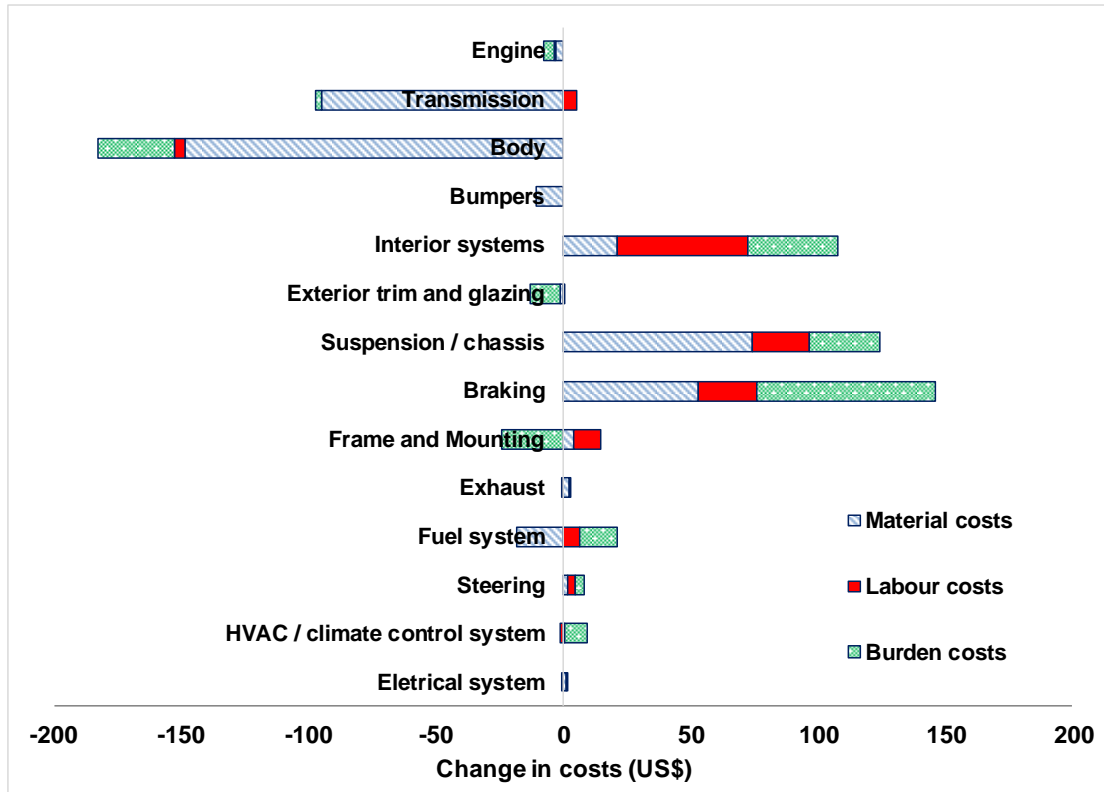
Engine	Where Lotus used an expensive hybrid system, FEV opted for a downsized 2.4 litre engine to replace the base Venza’s 2.7 litre engine. FEV analysed 70 component parts of the engine to identify mass reduction potential. Thirty options for reducing mass were selected, all but seven of which being parts that could be mass-optimised due to reduced functional requirements of the engine. These parts amounted to a 14 kg mass reduction for a \$31.96 cost reduction. Small material and design changes in the air system, dip stick tube, water pump and air conditioning compressors, allowed for further mass reductions.
Body and closures	FEV did not select as much high strength steel for the chassis, instead using thinner gauge steel as an alternative, but still adopting the use of aluminium for the bonnet. FEV adopted the same approach as Lotus by using aluminium for the bumper and rear hatch but did not use alternative front and rear doors as in the Lotus low development vehicle.
Interior	FEV opted for extensive use of MuCell and PolyOne ¹⁰ in the interior and an extensive change of seating as the Lotus study did. Handles, locks, latches and mechanisms were not changed as extensively, resulting in lower mass savings.
Suspension	The FEV study went further in exploring suspension options considered as primary mass reduction, by opting for different grade and gauge materials.
Glazing	FEV opted for thinner glazing. Lotus considered the standard Venza glazing a reasonable trade-off between the various required characteristics and retained it for both low and high development models.

The analysis of cost savings shows that the biggest savings were achieved in the suspension/chassis, braking and the interior systems (Figure 6-5). For the suspension/ chassis, labour and burden costs together amounted to 40% of the total costs saved. For the interior systems, over 80% of the cost savings are in labour and burden costs.

Changes made to the closures/fenders, body, engine and to a lesser extent, glazing and bumpers all resulted in cost increases. These increases were dominated by material costs. For example the use of a mass-optimised gear train, costing an additional US\$97 in materials for a 3.2 kg mass saving. The additional costs associated with the closure/fenders are primarily due to the use of aluminium.

¹⁰ An alternative to MuCell, used to increase air in moulded plastic components.

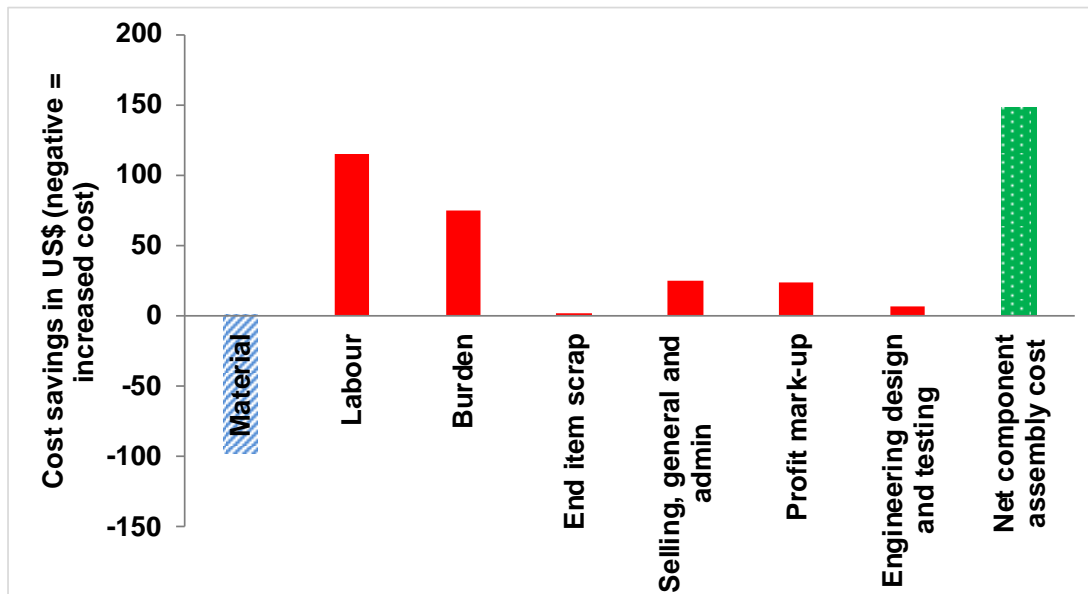
Figure 6-5: Cost reductions (\$) by system for reduced-mass vehicle (source: FEV, 2012)



Note: negative cost reduction = cost increase; body includes body structure, closures and fenders.

The overall cost implications can also be summarised in terms of the different types of cost. Figure 6-6 shows how there is an overall increase in materials costs of almost US\$100 (blue bar with diagonal stripes), but that this is offset by cost reductions in labour, burden and mark-up costs with the result that the net company/assembly cost to the OEM is a saving of almost US\$150 (green bar).

Figure 6-6: Breakdown of total vehicle cost reductions (U\$) by cost type (Source: FEV, 2012)



Note: negative cost reduction = cost increase

The use of different materials for constructing a component was usually combined with the adoption of a new manufacturing technique, which often resulted in reduced labour and burden costs. Examples of this include the use of hollow aluminium stabiliser bars in the suspension as opposed to solid steel bars, the use of a plastic fuel tank, or the use of a single cast aluminium suspension arm as opposed to multi

piece steel. The properties of the alternative materials allow for different moulding or stamping techniques which may not be used by other materials. They can also result in limitations in manufacture (e.g. welding of aluminium to create a strong bond requires laser welding or adhesive bonding). Table 6-4 summarises the use of design changes in association with use of lightweight materials, but also shows how the only material change that results in material cost reductions (over the study) is plastic.

Table 6-4: Mass changes of materials and associated cost reductions

Material changed to	Net mass of component after mass optimisation (kg)	Material	Cost reductions (US\$)		
			Labour	Burden	TOTAL
Aluminium	211	-18.5	29.21	27.05	37.76
Magnesium	80	-13.61	36.58	9.9	32.87
Magnesium Alloy	31	-10.08	-	-	-10.08
Plastic	208	27.11	17.29	36.17	80.57

Note: negative cost reduction = cost increase

6.2.4 Relevance of the findings on mass reduction to the European market

The Toyota Venza is manufactured in North America, and until recently was only marketed there. In 2013, Toyota announced that it would start selling the Venza in Eastern Europe (Russia and Ukraine) (Automotive Logistics, 2013). While the Venza is described as being a “crossover” vehicle, it is somewhat unusual since its styling is closer to a conventional passenger car than an SUV. It is therefore difficult to make direct comparisons between the Venza and common European models. Table 6-5 compares the Venza to a selection of similarly sized European market crossover / SUV vehicles. All are dimensionally taller, have a more ‘off road’ SUV type styling than the Venza and generally offer diesel rather than petrol engines. Perhaps as a result, all are significantly heavier.

Table 6-5: Comparison of equivalent popular SUVs used in Europe¹¹

Make	Vehicle	Length (mm)	Height (mm)	Width (mm)	Engine Size (litres)	Transmission	Fuel	Kerb mass (kg)
Toyota	Venza	4801	1610	1905	2.7, Inline 4 cylinder	6 speed auto	Petrol	1711
Hyundai	Santa Fe	4690	1685	1880	2.2, Inline 4 cylinder	6 speed auto	Diesel	1968
BMW	X3 xDrive 30d SE	4648	1675	2098	3.0, Inline 6 cylinder	8 speed auto	Diesel	1895
BMW	X5 M50d	4886	1762	2184	3.0 turbo, Inline 6 cylinder	8 speed auto	Diesel	2265
Volvo	XC90	4807	1784	2112	2.4 turbo, Inline 5 cylinder	6 speed auto	Diesel	2196 (min)

Note: Principal data sources include: Hyundai Motor UK, 2014; BMW Group, 2014c; Volvo Car Corporation, 2014

The mass reductions and many of the cost reductions identified appear to be applicable to many of the vehicles currently available on the European market. Material costs were obtained from international sources, resulting in the likely correct estimation of these costs for application in Europe. Data for burden costs has not been made available, but assumptions made for machinery purchase, hire, insurance and maintenance are likely to be comparable with European costs. Equivalent rates for rent of premises are likely to be very variable in Europe, with some equivalence to the US market. There is no inclusion of end of life vehicle costs, which would be a consideration of the European market. The US Bureau of Labor Statistics (BLS) provides comparative country labour rates for car manufacture (Bureau of Labor Statistics, 2014). Comparing these with Europe shows that for 'car manufacture for motor vehicle' and 'other transport equipment manufacture' hourly compensation costs in the US for 2010 were US\$45.33 compared with US\$35.63 (21% lower) in Europe. Perhaps more importantly given the growing move to locate manufacturing in Eastern Europe, average labour costs in Hungary, Poland and Slovakia were \$10.07 (78% lower). The lower labour costs in some parts of Europe compared with the US may be significant since they will reduce the ability of labour cost savings to compensate for increases in material costs. In Germany and France, labour costs in the vehicle manufacturing sector are higher than in the USA, meaning that mass reduction could be more attractive for companies with manufacturing facilities based in those countries.

It should be noted that although costs include purchase costs of new manufacturing equipment, there is no cost assigned to losses from old manufacturing equipment (loss of lifetime payback and waste costs). For example, the costs of press tooling for body panels are usually one of the most expensive manufacturing costs associated with vehicle production; typically these costs are amortised over the full life-time of the vehicle (on average, seven to ten years). A shift to alternative materials for body panels could render the press tools obsolete, and it may not be possible to sell the existing tooling as it is tailor-made for specific vehicle designs.

A further consideration is that some of the mass reduction approaches used for the Toyota Venza already appear to be more commonly applied in the European market – for example plastic fuel tanks which appear to be the industry norm, and high strength steels are already deployed more intensively than is the case for the baseline Venza. Widespread existing use of these approaches and technologies on European vehicles means that some of the key cost effective methods for reducing vehicle mass

¹¹ Data obtained from manufacturer websites.

have already been adopted; this may mean that reductions in mass for European vehicles may be more expensive than for the Toyota Venza as other materials and technologies will be required.

The use of different technology and materials can result in primary mass reduction of vehicles for no additional cost. A summary of the parts that may significantly contribute to reducing the mass of the European fleet is as follows:

- **Body-in-white:** Increased use of HSS¹² appears to be a cost effective approach to achieving further mass reductions. Steel tailor rolled blanks can also reduce mass through use of thinner gauge steel where possible and may result in material cost reductions. Aluminium may be used for the roof (and roof opening systems) and body structure applications. There is a significant cost impact in doing this and as a result this is typically limited to higher-end applications. While structural body applications of aluminium are estimated to have achieved 12-14% market penetration rates in Europe, roof and roof opening systems are only at 1-2% (European Aluminium association, 2013b). Magnesium roofs are already in production, offering an alternative to aluminium for additional cost.
- **Closures/Fenders:** The mass of the closures was higher than best practice in the base Venza. Adopting aluminium or magnesium alternatives results in considerable mass reductions at additional cost. Market penetration of aluminium for fenders, doors, bootlids and tailgates is substantially higher in Europe (10-13%) than in the North American market (3-6%). Market penetration of aluminium bonnets is already at 21-25% in Europe, but is even higher (29-33%) in North America (European Aluminium association, 2013b).
- **New technology:** Electronic gear shift modules, electronic parking brake systems, dual clutch transmissions and touch-screen control systems allow for significant mass and cost savings.¹³ There is potential in the EU market for these technologies to be deployed more widely, although some of these systems are already being rapidly adopted on new vehicle models (e.g. touch-screen control systems).
- **Interior:** The use of MuCell and PolyOne provides considerable material cost savings. The Trexel website¹⁴ lists a large number of automotive manufacturers who have already adopted MuCell, including; Mercedes, VW, BMW, Ford, Mazda and General Motors. The use of magnesium in seat frames offers considerable mass savings with a limited number of production examples available. Overall, mass reductions achieved from seating in the Venza may have limited application to a wider fleet, due to the benchmarked masses of the Venza seats being so high.
- **Electronics:** The use of aluminium and thinner plastics for coating as opposed to copper in wiring provides a considerable reduction in mass with little increase in cost.

Overall it is judged that the large majority of the mass reduction potential identified would be relevant for Europe. The FEV study did not take into account the costs associated with a transition to new manufacturing techniques. These costs can be a significant barrier to the introduction of new lightweight designs and materials. Once these new manufacturing techniques have been adopted, the FEV study indicates that significant mass reductions can be achieved for little or no additional cost. In the European context, we stress that the transferability of the findings from the FEV study are dependent on (a) the amount of mass reduction technologies already applied to existing vehicles and (b) vehicle manufacturing labour rates, which are largely dependent on manufacturing location.

6.2.5 Summary of peer reviewer comments

The FEV (2012) report was reviewed by William Joost (U.S. Department of Energy), Glenn Daehn, Kristina Kennedy, and Tony Luscher (The Ohio State University (OSU)), Douglas Richman (Kaiser Aluminum), and Srdjan Simunovic (Oak Ridge National Laboratory). Srdjan Simunovic and members of the OSU team reviewed various elements of the associated modelling.

Cost reduction assumptions were generally viewed as being clearly laid out and reasonable. William Joost stated:

¹² 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>

¹³ Lotus Engineering (2010) states that electronic parking brake systems have been adopted in Volkswagen Passat, CC, Tiguan, Audi A4, A5, A6, A8, Q5, Mercedes S-Class, and BMW 7-Series

¹⁴ Please see Trexel website; <http://www.trexel.com>

“Overall, the costing methods used in this study seem to be very thorough. The details of the approach provide considerable credibility to the cost estimates, however there will always be concerns regarding the accuracy of cost models for systems where a complete, detailed engineering design has not been established. I believe that this report does a good job of representing the cost penalties/benefits of the technologies but I would still anticipate negative response from industry.”

While Douglas Richman (of Kaiser Aluminum) concurred that most cost estimates appeared realistic and consistent with current production cost, he highlighted that:

“Cost estimates for reduced mass sheet products seem to include assumptions that drive unusually high material and equipment cost. This issue leads to a technology cost effectiveness that is not representative of actual production experience for sheet products.”

If this comment is accurate it may imply that either costs to achieve mass reduction have been overestimated, or that additional mass reduction options may have been unnecessarily disregarded.

6.2.6 Conclusions

The FEV (2012) study provides a review of alternative, feasible options for reducing vehicle mass, resulting in an 18% mass reduction, for a potential cost saving of US\$148 compared to a base Toyota Venza vehicle. The parts selected for mass reduction were very similar to those used in the Lotus (2010) study. Further cost savings could be made if some lower mass options had not been selected, while there is potential to achieve greater mass reductions with marginal cost increases.

Translating the cost estimates to accurately reflect the situation in Europe was not possible within the scope of this study, as labour and potentially burden costs could be quite different. Significant mass reductions that may be applied to a European fleet, at little additional cost, may be made through changes to the body-in-white, body systems, closures, electronic systems and the interior. Further research into the market penetration of materials and technologies such as HSS, aluminium, electronics and the use of novel processes such as MuCell, will help provide a further understanding of the potential mass reductions achievable in future European fleets.

6.3 Review of the NHTSA (Electricore et al, 2012) mass reduction study

6.3.1 Introduction and approach

The National Highway Traffic Safety Administration (NHTSA) commissioned Electricore, EDAG and George Washington University (Electricore *et al*, 2012) to examine the potential to reduce the mass of the 2011 US-market Honda Accord. NHTSA initiated this study to gain information about the maximum amount of mass reduction that was feasible and the costs attached to such mass reduction, so as to support the rulemaking of the Corporate Average Fuel Economy (CAFE) standards in the USA.

The aims of the study were to maximise mass reduction while maintaining the functionality and cost of the vehicle in various aspects compared to the base vehicle:

- Maintain or increase vehicle size
- Maintain retail price parity to within 10%
- Maintain or improve functionality of the vehicle's crashworthiness assessed using NHTSA's New Car Assessment Program (NCAP)
- Capable of high volume production (200,000 vehicles per year)

To avoid unlikely or overly aggressive manufacturing, design or material selections the team utilised only those selections which are currently in-use or planned to be introduced in the near future on low-production vehicles.

All costs are in 2010 US dollars, including material costs. Two cost assessment methods were used:

- **Technical Cost Modelling** was used for the body structure, closures, bumpers, fenders, front suspension, rear suspension, wheels and their corresponding assembly process.
- **Supplier assessments** were used to estimate the cost of various systems and components such as seats, brakes and the instrument panel.

Together these methods allowed the team to calculate the OEM manufacturing cost, including all supplier parts for the baseline vehicle and lightweight version.

6.3.2 Results

The NHTSA study (Electricore *et al*, 2012) achieved a mass reduction of 327 kg compared to the base vehicle mass of 1,410 kg¹⁵. This amounts to a 23% reduction in mass at a cost increase of US\$319 or \$1.03 per kg, against a baseline cost of \$21,980. The main cost savings were in the secondary mass-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 Table 6-6.

Table 6-6: Summary of mass reductions and associated costs

System	Base	Reduced mass vehicle			
	Mass (kg)	Mass reduction (kg)	Costs (US\$)	Percentage cost saving on baseline vehicle	Costs (US\$/kg)
Engine / Powertrain	331	69	-118.29	4.9%	-1.72
Body	328	73	147.00	5.2%	2.02
Closures / fenders	92	44	153.70	3.1%	3.50
Bumpers	16	7	1.22	0.5%	0.17
Thermal	0	0	0.00	0.0%	-
Electrical	34	5	0.00	0.4%	0.00
Interior	151	39	112.27	2.8%	2.86
Lighting	9	2	0.00	0.2%	0.00
Suspension / Chassis	280	86	27.59	6.1%	0.32
Glazing	34	0	0.00	0.0%	-
Miscellaneous	135	2	-3.97	0.1%	2.27
Totals	1410	327	\$319.5	23%	
% against baseline	100%	23%	1.45%		

6.3.3 Summary

Material and design changes resulted in an overall 23% mass saving compared to the baseline vehicle. Heavier metals were replaced where possible; use of steel in the vehicle reduced by 40% (from 698 kg to 415 kg) and cast/forged iron by nearly 70% (from 76 kg to 23 kg). Cast aluminium usage increased by 14 kg. Aluminium and magnesium, neither of which were present in the baseline vehicle were introduced to achieve large reductions in mass. 78 kg of aluminium (mainly used in the closures and fenders) and 15 kg of magnesium were used in the weight-optimised vehicle. The mass of plastics used was reduced by 24% (from 191 kg in the baseline vehicle to 145 kg in the mass-optimised variant). The changes in material usage between the baseline vehicle and the lightweight vehicle (LWV) are summarised in Table 6-7.

¹⁵ These numbers differ slightly as the Electricore (2012) study for NHTSA 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 Electricore study

Table 6-7: Summary of changes in material usage between baseline and LWV

Material	Baseline mass (kg)	Percentage of baseline (%)	LWV mass (kg)	Percentage of LWV (%)
Steel	698	49	415	38
Cast/forged iron	76	5	23	2
Cast/forged aluminium	187	13	201	19
Aluminium sheet	0	0	78	7
Glass	34	2	34	3
Copper	20	2	10	1
Plastics	191	14	145	13
Magnesium	0	0	15	1
Misc.	208	15	171	16
Totals	1414		1092	

These changes in material usage can also be seen by examining the material distribution in the two vehicles. Figure 6-7 shows the percentage of each material in both the baseline and LWV vehicle. The percentage of steel has fallen from 49% in the baseline vehicle to 38% of the LWV, with more of that steel consisting of higher strength grades. The overall material grade strength of the materials used in the body in white structure is shown in Figure 6-8. Cast iron is down from 5% to 2% of the LWV, with the percentage of aluminium (both sheeting and forged/cast) doubling from 13% to 26%, making up most of the increases in distribution.

Figure 6-7 Summary of changes in material usage between (i) baseline (left) and (ii) LWV (right)

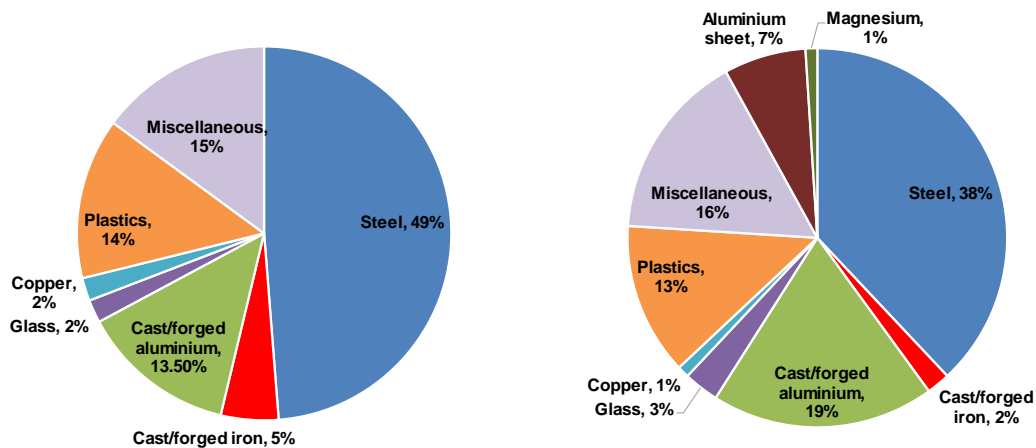
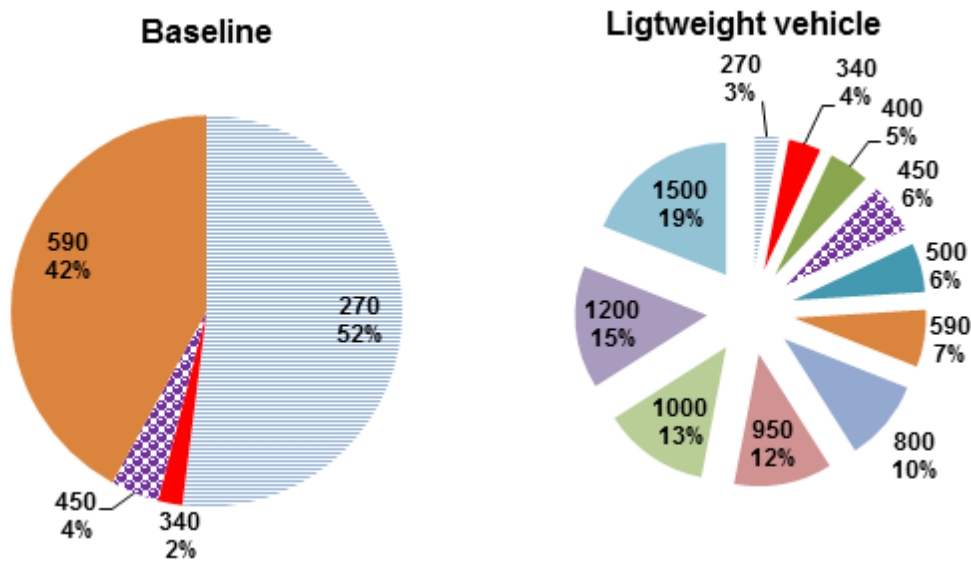


Figure 6-8: Material grade strength (MPa) comparison for body-in-white structures



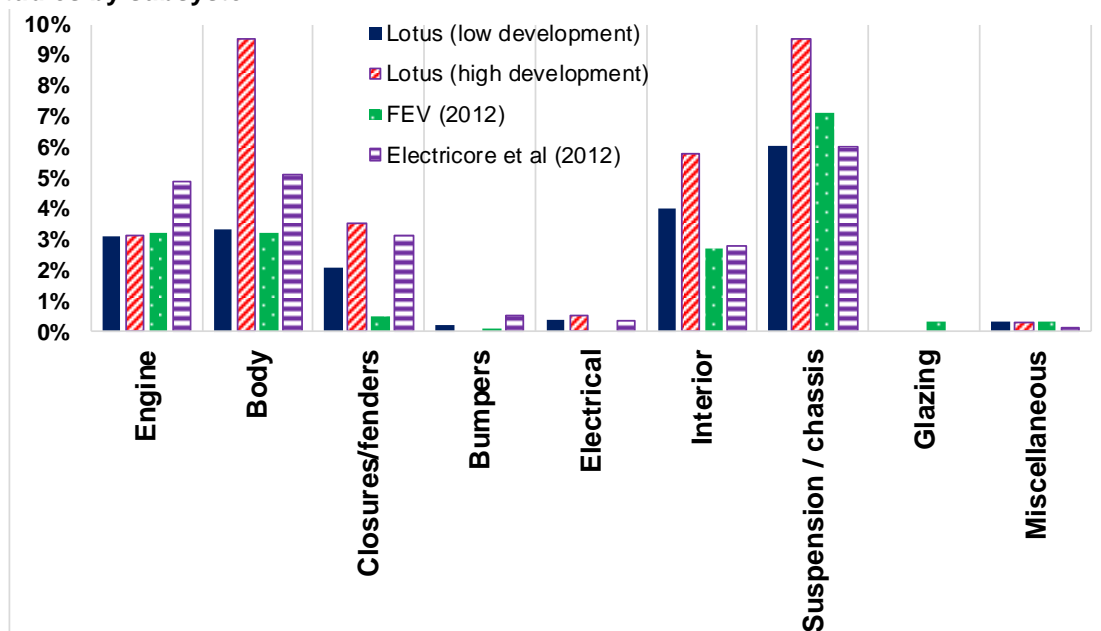
Due to reduced component sizes and the use of Honda Civic components already in production, the overall cost increase for the LWV was only \$319. The largest saving was in the powertrain where \$118 was saved due to lower material usage. These are secondary savings which can only be achieved due to changes in materials elsewhere, which result in a cost increase. Overall a mass saving of 23% was achieved against a cost increase of less than 1.5%. The LWV model presented in this study would therefore represent an economically desirable vehicle, with the small increase in price being more than offset by fuel savings over the vehicle’s life.

6.4 Comparison and discussion of findings from the Lotus (2010), FEV (2012) and Electricore (2012) studies

Comparing the three major US studies on vehicle mass reduction it is possible to see some common trends in some subsystems, as well as differing approaches in other areas. A summary across the studies showing percentage saving against vehicle baseline mass for the various subsystems is presented in Figure 6-9.

For all three, the greatest area of saving was in the suspension/chassis (including the wheels) with savings of 6-7% of baseline mass (excluding the high development Lotus vehicle). The replacement of steel parts with magnesium and aluminium components, as well as some use of higher strength steels, was supplemented by the redesign and downsizing of parts.

Figure 6-9: Comparisons of percentage mass savings against baseline vehicle for each of the studies by subsystem



Changes to the body saved between roughly 3% and 5% of vehicle mass and again there is a common approach across the studies. The use of higher grade steels allowing for thinner, and therefore lighter, components is universal, with redesign required in some components to maintain safety, strength and crash worthiness. The studies found that high strength steels could be used to meet manufacturing and supply requirements. There is increasing use of HSS in the automotive sector, and this appears to be the most cost effective route for vehicle manufacturers to reduce the mass of vehicle bodies. Figures given in the studies for the cost of an aluminium-intensive body-in-white (an extra \$720 over the AHSS for the Electricore study for NHTSA) would suggest that over the short-to-medium term, such body structures will only be seen towards the luxury end of the market.

The exception here is the high development Lotus vehicle, which achieved a 9% mass saving using glass fibre reinforced polypropylene, magnesium and structural plastics. The use of such materials is likely to be cost prohibitive for large scale manufacture in the near future and any penetration into the market for these materials will only be at the high end.

A third area where similar approaches were taken is for the closures and fenders. Here stamped steel is the common baseline material, with all studies choosing stamped aluminium as a replacement for the fenders and bonnet. One area of difference here is the approach to the doors. The Electricore study continued its use of stamped aluminium here, while the low development Lotus design mainly made use of redesign. The lack of any large changes to the door design or material in the FEV study results in much lower mass savings here than in the other two studies.

Stamped aluminium was used for the bumpers on both Lotus vehicles as well as in the FEV study. However the Electricore study used AHSS because it was cheaper than aluminium and achieved a greater mass saving, meaning it may be preferable to the selection of aluminium used by the Lotus Engineering and FEV studies.

Approaches to powertrain mass reduction differed greatly over all three studies. The Lotus study focused on a downsized hybrid system, while the FEV study involved a detailed redesign of the engine on a component by component basis, involving the use of magnesium, aluminium and plastic, as well as a general redesign. The Electricore study took an entirely different attitude and simply replaced the engine, as well as other components, with the current production downsized components from a smaller vehicle, in this case the Honda Civic. It is possible that such a current production engine could also benefit from changes in material specification and design leading to further mass savings. All three approaches to engine mass reduction were found to be economical and acceptable indicating the potential for secondary mass reductions in this area.

MuCell features in all studies as a mass saving replacement for many of the plastics in the vehicle, and is not expected to incur any cost increase. With this material already being used in production vehicles with no significant downsides, it is probable that increased market penetration will occur.

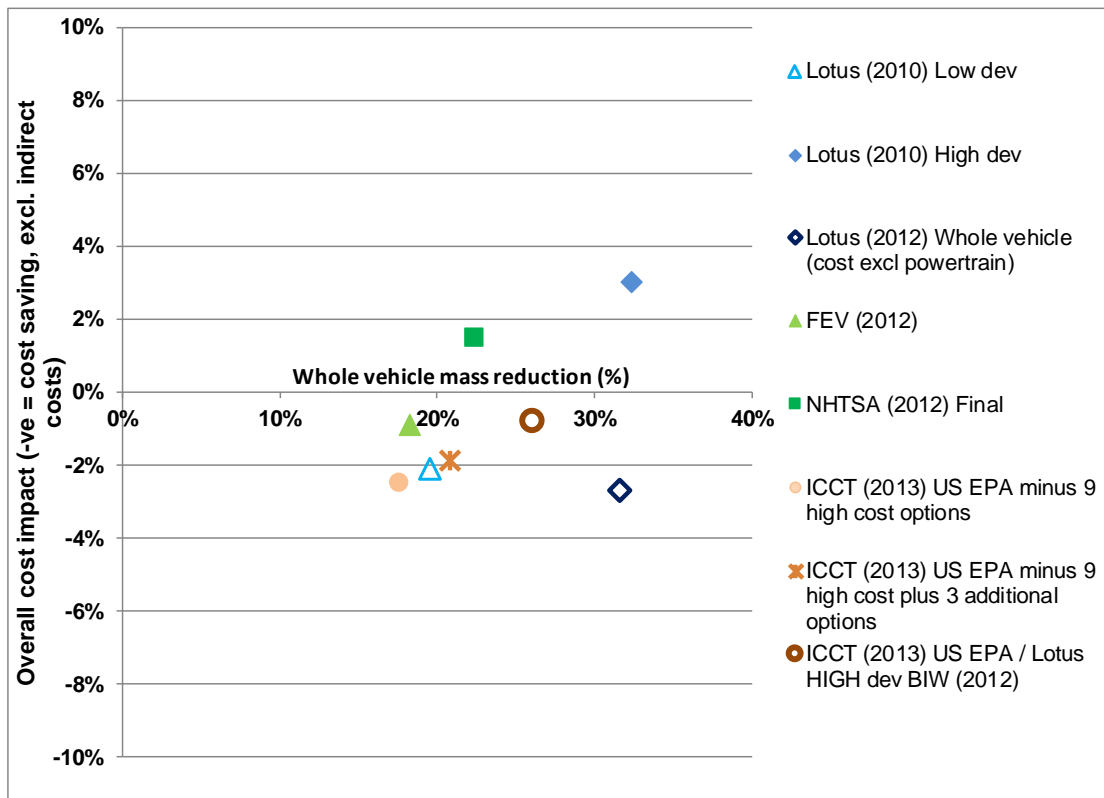
Magnesium was used in both the FEV study and the Electricore study for the instrument panel crossbeam bar, achieving significant reductions in mass.

For wiring harnesses, different approaches were used. The Lotus Engineering (2010) study assumed copper clad aluminium with an estimated mass saving of 35% (based on its use in the production Toyota Yaris). The FEV (2012) study used aluminium for the battery ground cables, and polyphenylene oxide (PPO) sheathing for the rest of the wiring loom to achieve a 20-30% mass reduction. Finally the Electricore (2012) study specifies aluminium to replace the standard copper wiring.

Only the FEV study opted for changes to the glazing, using thinner glass, though the other studies chose not to examine this area, as opposed to not finding any applicable technologies available.

Overall, a combination of common and different approaches to mass reduction have been applied in the three studies. The use of advanced high strength steels and aluminium for bodyshell components is common across all three studies, and reflects our findings on the availability and application of mass reduction technologies for body-in-white and closures presented in Chapter 5. It is also clear that different approaches can also be successfully applied to reduce vehicle mass. A key example is the very different approaches taken to powertrain mass reduction in the three studies. These examples reinforce the findings from Chapter 5 that for vehicle mass reduction there is unlikely to be a single, optimal pathway that is suitable for all vehicles. Instead, manufacturers will need to optimise their individual model ranges on the basis of costs, performance requirements, technical know-how and manufacturing capabilities. Figure 6-10 demonstrates that based on the findings of the three studies, mass reduction of around 20% of baseline mass is estimated to result in a cost change of up to ±2.5%. In the context of the European market, differences in the structure and composition of the new vehicle market compared to the US market must be taken into account, as well as existing levels of penetration for key mass reduction technologies. Furthermore, differences in labour costs in Europe compared to the US may also affect cost effectiveness.

Figure 6-10: Estimated cost of vehicle change against baseline mass reduction



6.5 Comparison to findings from other literature

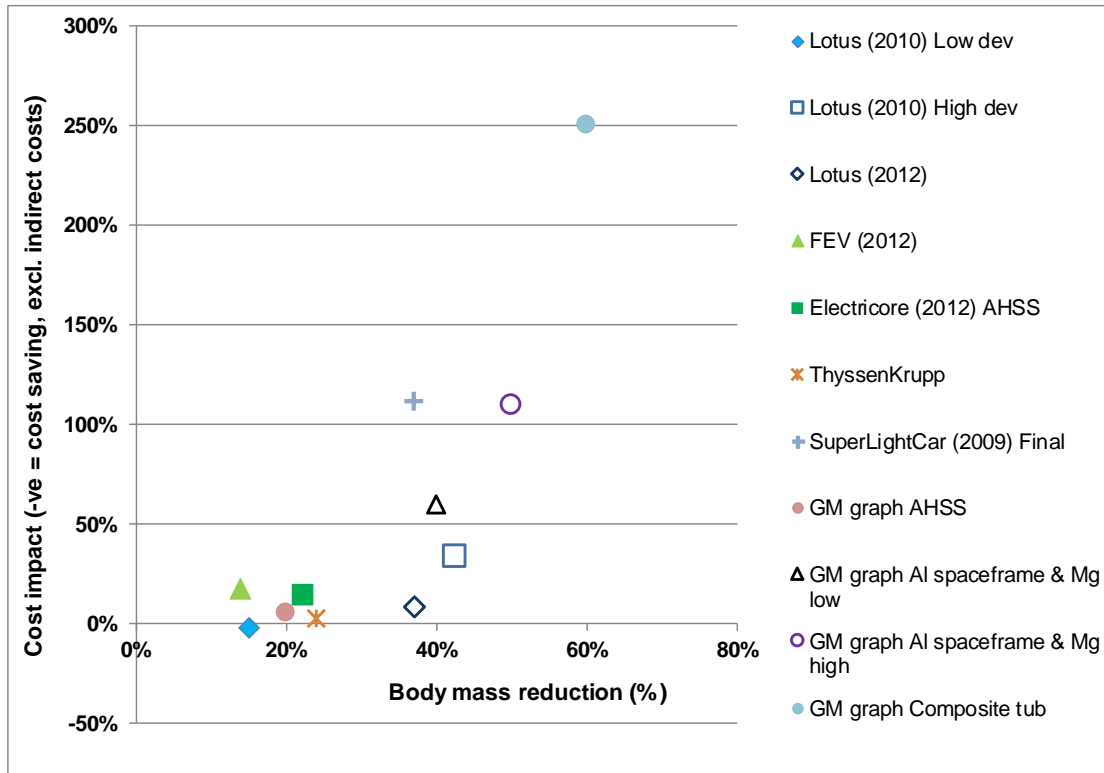
In this section the findings from the Lotus (2010), FEV (2012) and NHTSA (2012) are compared and contrasted with those from our wider review of literature regarding vehicle mass reduction.

6.5.1 Comparison to other material and body structure studies

The findings of the above studies are in general supported by the literature in the area of vehicle mass optimisation, as well as by the introduction of such materials and design choices being seen in production vehicles.

A comparison of the overall percentage costs for a given level of body mass reduction from various studies is presented in Figure 6-11. This shows figures from both the Lotus 2010 and 2012 studies, the results of the US EPA, NHTSA and SuperLIGHT-CAR studies as well as estimates obtained from General Motors.¹⁶

Figure 6-11: Comparison of estimated costs for body mass reduction



6.5.2 Comparison of NVH and crash testing approaches in vehicle mass reduction studies

As our analysis of different mass reduction studies has shown, the area with the greatest potential for 'primary' mass reduction is the vehicle body structure. It is critical that this is not achieved at the expense of safety, or noise, vibration and harshness (NVH) considerations.

Meeting minimum crash standards is a legislative requirement for all vehicles. The introduction of New Car Assessment Programmes (NCAP) in all major vehicle markets has resulted in manufacturers often needing to exceed minimum standards to remain competitive in the market place. NCAP programmes use a five star rating system and manufacturers will generally aim to achieve a minimum of four or five star ratings.

A good example of how NCAP has resulted in standards needing to significantly exceed the minimum is the Euro-NCAP frontal crash test. This is based on the standard European legislative test, but the impact speed has been increased from 56 km/h to 64 km/h.

Both legislative and NCAP crash test procedures require destructive testing of actual vehicles. For the purposes of the mass reduction studies reviewed here, this was not a practical approach. Instead the studies reviewed have used industry-standard CAE techniques to model the expected results. Use of such techniques is standard practice within the automotive industry for vehicle design and development.

¹⁶ Presentation at Integrated Fuel Economy Congress, 28 November 2012.

A summary of the approaches used in the different studies reviewed is given in Table 6-8.

Table 6-8: Summary of approaches used for crashworthiness and NVH

Study	Approach used and results found
Lotus (2010)	No assessment is made of the crashworthiness of the “low” and “high” development mass-optimised body designs. Proposed changes to the body structure did require that bending and torsional stiffness were considerations.
Lotus Engineering (2012)	<p>In this separate study, a CAE body structure was developed based on the Lotus Engineering (2010) study’s proposed “high” development body-in-white and was assessed to achieve a 37% mass reduction.</p> <p>A CAE model of the whole mass-optimised vehicle was used to simulate a wide range of FMVSS and IIHS tests. Since no CAE model of a current production vehicle was used, there was no correlation of the model to actual crash test results.</p> <p>Pass / fail criteria for higher speed crash tests are based on occupant injury assessment which was beyond the scope of the study. The study concluded that the results demonstrated the “potential for this design to meet FMVSS regulations and IIHS requirements”.</p>
FEV (2012)	<p>A CAE model was created of the baseline Toyota Venza and correlated to real vehicle results for bending, torsional stiffness and crash testing. This was then modified to create a mass-optimised CAE body structure. This predicted less than 5% worse bending stiffness and no reduction in torsional stiffness.</p> <p>A full CAE reduced-mass vehicle model was used to assess crashworthiness against four FMVSS/IHSS crash tests and a European offset frontal crash test at 35 mph (incorrectly described as “Euro-NCAP” which would imply a 40 mph impact speed).</p> <p>In all tests except one aspect of the rear impact test, the reduced mass vehicle design was assessed to outperform the standard Toyota Venza</p>
Electricore et al (2012)	<p>The base Honda Accord 2011 vehicle was scanned to identify the overall vehicle package. “Topology optimisation” was then used to identify optimised structural load paths for stiffness bending and torsion and a selection of US crash tests. This technique was used to create an optimised structural design while maintaining features such as the sunroof and folding rear seats. Three computer programs were set up to work in a continuous optimisation loop to converge on the most optimal stable mass efficient solution.</p> <p>A finite element analysis model of this lightweight vehicle (LWV) structure was then analysed for durability, stiffness, and seven US crash tests. In all cases the LWV was judged to have comparable performance to the baseline Honda vehicle. For rear crash, the baseline vehicle has not been tested, but the LWV was judged acceptable with no fuel leakage.</p>
VW et al, <i>Superlight car study (2009)</i>	As in the Electricore study, “Topology optimisation” was used initially to find the optimal load paths for stiffness and crash loads. The overall package was fixed at the start. A multi-material approach was selected. A finite element model consisting of about one million elements was created and LS-DYNA was used to analyse modal frequencies, static torsion and six crash test scenarios. These were

Study	Approach used and results found
	Euro NCAP offset front, side and pole crash tests as well as FMVSS rear crash and roof crush tests and an AZT insurance classification test. Results were assessed as comparable, or better, than the reference VW Golf vehicle with a significant improvement in the offset front crash test. Roof crush test results were three times better than required.

A full comparison of which NVH and crash tests were conducted in each of these four studies is given in Appendix 4.

In all these studies NVH, bending and stiffness results were judged to be acceptable and in several cases were assessed to be improved.

In general, US crash test requirements are more comprehensive and also include requirements to protect occupants not wearing seatbelts. As a result of this latter point, the vehicle engineering design and specification to ensure compliance with the crash test legislation – in particular the air bag systems – can be substantially different between US and European models.

The focus of all the studies other than the SuperLIGHT-CAR study has been on US crash test requirements. In some cases, US NCAP and IIHS standards, which are higher than the legislative minimum requirements, have been targeted.

6.5.2.1 Frontal impact crash tests

Both the FEV study and the Electricore study conduct the US NCAP flat frontal crash with a rigid wall barrier at 56 km/h. This is a test which is not currently utilised in Europe, but will be introduced to Euro NCAP testing in 2015 (albeit at the lower speed of 50 km/h).

Of more relevance to European considerations is the frontal crash with 40% offset deformable barrier (ODB). Passing this test is a legislative requirement in Europe at 56 km/h, and the same test is used in Euro-NCAP testing but at the higher speed of 64 km/h. The Electricore study includes this test at 64 km/h as it is also used by the IIHS (although only one crash test dummy is required compared to the four used in the Euro-NCAP test).

While the FEV study refers to this test as “Euro-NCAP”, the report states that it was conducted at 35 mph (equivalent to 56 km/h). Although this conforms to the European legislative requirement (ECE-R94), it is lower than Euro-NCAP’s specified 64 km/h.

The Lotus 2012 study also includes this 40% ODB test, referring to it as FMVSS 208, which specifies 40 km/h. The report states that the test was carried out at 35 mph (56 km/h), again lower than the Euro-NCAP specification of 64 km/h.

6.5.2.2 Side impact tests

The standard legislative side impact test requirements for the US market (FMVSS 214) require both a 54 km/h impact with a 1368 kg moving deformable barrier (moving crabwise at 27°) and a 32 km/h impact with a pole at a 75° angle. US NCAP testing increases the speed of the moving deformable barrier test to 61 km/h.

Both the Electricore and the Lotus (2012) studies cover both these tests. The US EPA study does not include a pole side impact test. None of the studies investigate the effect of the higher speed required to for US NCAP testing.

Only the SuperLIGHT-CAR study conducts any European side impact tests – examining both the standard Euro NCAP 50 km/h moving deformable barrier at 90° and a pole side impact test at 29 km/h. The NHTSA study did include an IIHS side impact test which is very similar to the Euro NCAP 50 km/h test, but uses a significantly heavier (1500 kg versus 950 kg) barrier. It could thus be argued that the mass-optimised Honda Accord structure having passed this test would be likely to pass the Euro NCAP one, although barrier dimensions and pass/fail criteria are different.

6.5.2.3 Rear impact tests

All four studies conducted the same rear crash test – the US FMVSS 301. In this test a moveable deformable barrier (MDB) impacts at 80 km/h (50 mph) into the rear of a stationary vehicle with an

overlap of 70%. The mass-optimised vehicles in all four studies are judged to meet the pass criteria for this test.

6.5.2.4 Roof crush tests

Again all four studies conducted the same roof crush test using US FMVSS 216 procedures. While all four judged that the body structures would pass the test, only the FEV and Electricore studies report that the structures met the higher standards required by IIHS in this test.

6.5.2.5 Study limitations

There is a range of different crash test requirements which manufacturers are expected to meet in the US and European markets. None of the studies examines all the requirements even for one of those two markets. For example, none of the studies make specific mention of more detailed regulations governing areas such as:

- Head restraints
- Steering mechanism
- Seat belt assemblies

Only the Lotus (2012) study specifically assessed factors such as anchorages for seat belt assemblies and child restraints systems.

It would be reasonable to assume that these more detailed regulatory requirements could be met with little or no modification to the proposed mass-optimised vehicle structures.

Another problem is that where a US crash test would initially appear to be identical to a European test, it often has detailed procedural differences, such as the dimensions of the moveable crash barrier or the number and position of test dummies to simulate vehicle occupants. It can also have different pass / fail assessment criteria.

Indeed a key limitation of all the studies is that none of them attempt to assess the likely impacts on vehicle occupants – they only examine the deformation of the vehicle body structure and intrusion into the passenger compartment. While minimising the latter is obviously important to the safety of the occupants, it is only one factor.

A crucial consideration is the deceleration forces experienced by vehicle occupants in a crash situation. Several of the studies conclude that the lightweight structure achieved reduced deformation compared to the baseline vehicle and equate this to “better performance”. The peer review of the FEV study points out that less deformation of the vehicle structure generally equates to higher decelerations and resulting forces on the occupant. It is generally desirable to efficiently use as much of the allowable free crush space as possible, not less.

A further significant concern is that only the Electricore study has assessed perhaps the most important crash test for the European market – the offset frontal test at 64 km/h used by Euro-NCAP. While the FEV study includes this test at 56 km/h as required to meet legislative requirements, achieving good results at the higher Euro-NCAP speed is fundamentally important to ensure competitiveness in the market. It is not therefore clear whether the mass-optimised vehicles assessed in the FEV study would achieve this.

An additional concern is the difficulty in being able to assess the accuracy of both the crash test simulations and the interpretation of their results. This is highlighted by a response from Honda to the LWV crash test results in the Electricore study (which was based on a Honda Accord) (Honda, 2013a).

Honda engineers examined in detail the Electricore study and highlighted a number of short-comings. Despite the study reporting that the lightweight vehicle achieved “good” ratings for intrusions on the offset frontal test, the Honda response states:

“On the whole, dashboard, lower (firewall), pedal area intrusion and deformation – impacting lower extremities is larger on LWV than ACCORD, resulting in more injury risk to the driver”

On the side impact test, Honda engineers highlight that the integrity of the safety cage on the LWV may be compromised due to “many predicted fractures”.

Again on the rear impact test, Honda noticed that the fuel filler pipe had not been included in the simulation and that when this was included, unacceptable deformation occurred.

In total, the corrective actions Honda identified would be needed to address these concerns added 50 kg to the body in white structure.

Further concerns regarding the potential accuracy of the CAE modelling are highlighted in the peer review of the Electricore study (NHTSA, 2012). These relate to the difficulty in modelling the failure and fracture characteristics of the high strength steels utilised in the body structure:

“Despite a long and extensive research effort on the subject, the methods for modeling localization and failure are still relatively scarce. There is no firm consensus on how to model failure in materials, especially in the high strength materials such as AHSS. The options available to the designers are specific to the FEM simulation programs they use.”

Modelling of fractures is not normally necessary with conventional lower strength steel vehicle designs since they will typically bend without fracture. With advanced high strength steels, material fracture becomes a real possibility and accurately modelling the potential formation of cracks in the structure to understand likely performance in real world crash test conditions becomes important.

The peer review also raises concerns regarding the potential impact of the joining processes used for advanced high strength steels. It comments:

“The AHSSs primarily derive their superior mechanical properties from their tailored microstructures, which can get strongly affected during thermo-mechanical processes such as welding. Active research in the welding of the AHSS shows possibilities of significant variations of the joint strengths due to the softening processes in Heat Affected Zone (HAZ).”

Again this issue requires very detailed consideration when modelling crash test characteristics to ensure accurate results.

6.5.2.6 Crash test summary of findings

In summary none of these studies demonstrate that the proposed lightweight body structures described would meet all the legislated crash test requirements for the European market. Only the SuperLIGHT-CAR study attempts to assess the Euro NCAP offset frontal impact test at 64 km/h – a test which is generally accepted to be critical for market competitiveness. It is extremely difficult to assess whether the crash test results of these studies and their interpretation are sufficiently accurate.

Nevertheless, these results do indicate that body structures which are significantly lighter than today's conventional designs do have the potential to achieve good performance in a range of standard crash tests.

6.6 Summary of findings from literature review

The overall conclusion of our detailed examination of the FEV study together with a range of other literature is that it would appear to be a realistic possibility to achieve about a 15-20% mass reduction of a selected current US-market conventional production passenger car while incurring little or no increase in costs. This is achievable primarily through focusing on designing a lighter body-in-white structure through use of high and ultra-high strength steels, aluminium (particularly for closures), and possibly composites. This is likely to result in an increase in costs for the body-in-white structure itself due primarily to the higher material costs. It is possible to offset this increased body-in-white cost through mass reduction in other areas such as the suspension, braking and powertrain systems, which can be achieved due to the overall lower vehicle mass (secondary mass reduction). Mass reduction in these systems often involves smaller components with lower material costs. There also appear to be significant opportunities to reduce mass in the interior trim and seats with little or no overall cost increase (or potentially a reduction in costs). In the longer term, applications of composite materials will allow further mass reduction but current costs are prohibitive for all but niche applications.

These high level findings are consistent across all the studies reviewed, although the FEV study is generally considered to be the most thorough example available.

There remain a number of important caveats to these findings:

1. **Limited assessment of crashworthiness:** The most important area for primary mass reduction is the body structure. This is also crucially important for the crashworthiness of the vehicle and hence the safety of vehicle occupants. While the four studies reviewed assessed crashworthiness by means of computer simulations and found the proposed lightweight structures to meet a selection of the requirements, it is challenging to assess the accuracy of these claims. This is particularly true given the problems associated with accurately modelling the crash characteristics of higher strength steels, fibre-reinforced composites and novel material joining techniques. The literature review indicates a general consensus that greater

use of advanced high strength steels is the most likely near future route to further body mass reduction. It is therefore crucially important that crash test modelling accurately reflects their potential for fracture and the impact of welding on their mechanical properties. A much more detailed assessment and critique of the modelling undertaken in the studies reviewed would be needed to allow greater confidence in the results. A further concern is that none of the studies assessed effects on vehicle occupants, instead focusing primarily on deformation of structures. In general, reduced deformation was considered an improvement; this may lead to higher decelerations and resulting forces on occupants. Ultimately only a physical full vehicle crash test using fully instrumented crash test dummies would provide positive proof of the accuracy of these simulations and the safety of occupants.

The FEV study appears to have conducted the offset frontal crash test at the legislated speed of 56 km/h rather than the higher 64 km/h speed used in Euro-NCAP assessments. The results of Euro-NCAP are perceived as crucially important by vehicle manufacturers in the marketing of mainstream vehicles, and the offset frontal crash test is perhaps the most important of all. Honda's critique of the Electricore study highlighted a number of short-comings in the crash test simulations. Addressing these reduced the potential mass reduction by 50 kg (3.4% of total standard vehicle mass) although these were essentially "retrofit" solutions and it may have been possible to reduce this in a more integrated design.

- Lack of consideration for noise, ride and handling:** While meeting crash test requirements is a legislative necessity, reducing the mass of the body structure and closures could also result in a worsening of other vehicle characteristics. These include pass-by noise, cabin noise and handling and ride characteristics.

Pass-by noise is an important issue since there are legislative requirements governing permitted noise levels. While the studies reviewed assessed static bending, static torsion, and modal frequency of body structures, in an assessment of general NVH, they do not appear to have considered external noise legislation. This could be particularly important for Europe as there are forthcoming reductions in permitted noise levels required for the European market which will be introduced progressively between 2014 and 2020.

The analysis in the studies is also insufficient to judge potential customer acceptability of engine, tyre and wind noise. Intrusion of noise into the cabin area can be a particular problem with lighter vehicle structures. While the US EPA study specifically avoided reducing under bonnet noise shielding, this is a consideration which does not appear to have been explored to any great extent in the studies and there may be a need to increase noise shielding and/or sound insulation materials to compensate.

Ride and handling characteristics are another area of importance for customer acceptability. Any changes made to suspension and steering systems will need to be checked to ensure that these aspects have not compromised. This is not something which any of the studies have been able to assess; as a basic indication, it is reasonable to assume that if static bending and torsion are maintained or improved, then it should be possible to achieve satisfactory ride and handling characteristics. Indeed Honda's recommended measures to address crash test shortcomings in the NHTSA study were also judged to have addressed ride and handling issues identified with the lightweight vehicle proposal.

- Difficulty in verifying cost estimates:** The engineering judgements regarding the potential to reduce mass of individual components are clearly elaborated in the reports reviewed, and would generally appear sound with the assessed potential mass reductions being judged accurate. The assessment of the likely cost impacts arising from the proposed changes is more opaque. While the stated methodology and approach appears comprehensive and reasonable it is very difficult to assess the accuracy. Assessing material cost impacts is comparatively straightforward; assessing the labour and 'burden' costs of the manufacturing processes involved in producing both the standard vehicle part and the proposed mass-reduced part is likely to be much more subjective. There is also no account taken of the indirect costs associated with switching to new materials and manufacturing processes. This could be a significant barrier to manufacturers taking up these new approaches. Overall, this does not suggest that the cost conclusions of the studies reviewed are inaccurate, merely that they are difficult to verify.
- Insufficient account of platform strategies and parts commonality:** All of these studies have examined potential mass reduction by examining one specific vehicle model. The results have not generally taken into account the wider design strategies employed by major OEMs, in particular the concepts of platform strategies and maximising commonality of parts between

different models. Achieving commonality of parts across different vehicle applications requires that the parts in question are designed for the “worst case” application in terms of stress analysis and durability. This is very likely to mean that they are not optimised for minimum mass when utilised in less demanding applications. It is difficult to quantify the impact of this on the findings; in responding to the Electricore study, Honda suggested ‘business considerations’ such as commonality and platform strategies would reduce potential mass reduction by 40 kg (2.7% of total standard vehicle mass). This was despite this study using a downsized powertrain taken entirely from a smaller Honda model. This suggests the likely limitation on mass reduction potential imposed by platform strategies and the need for parts commonality may be higher in other situations. The difficulty of parts commonality resulting in sub-optimal component masses for many applications is a particular problem for vans where there is often a much greater variety of product options available to customers.

5. **Need to account for existing uptake of mass reduction technologies:** Many of the suggested measures to achieve mass reduction in the studies reviewed are already employed on production vehicles, with examples being cited in the literature. While this demonstrates that they are both technically and commercially feasible, it also implies that a proportion of the existing vehicle fleet will not achieve further mass reduction from these approaches as they are already being deployed. If these approaches both reduce mass and cost, then it may be assumed that they will be attractive to other manufacturers, and due to the highly competitive nature of the market place, many may quickly be incorporated into new model designs across the vehicle fleet. While this is obviously desirable from a mass optimisation perspective, it means that estimates of mass reduction potential and costs resulting from a teardown of an existing production vehicle will inevitably quickly become outdated.

Finally, there are already examples of many of the mass reduction approaches utilised in these studies in production. Given that there appears to be an increasing focus on mass reduction in the industry, it can be expected that there will be further innovation in the future which will help reduce the costs of existing more expensive lightweighting technologies and lead to new opportunities for mass reduction.

6.7 Relevance of the findings from the US studies to the European vehicle market

There are a number of reasons why the applicability of the findings from the main studies reviewed might be questioned in a European context:

1. The base vehicles used in the US studies were larger and heavier than the average European passenger car in 2010 (1354 kg); the base vehicles used in the US studies were a 1711 kg Toyota Venza and a 1480 kg Honda Accord. Nevertheless evidence contained in these studies and other literature suggests that mass reduction potential expressed as a percentage is relevant across a range of vehicle sizes.
2. Some mass reduction techniques used are already achieving significant market penetration in Europe. Examples include plastic fuel tanks (95% market penetration¹⁷); aluminium bonnets (25%); and aluminium doors/bootlids/tailgates (10-13%) (European Aluminium Association, 2013b).
3. The use of high strength steels (HSS) in the standard body structures of these two vehicles is lower than average for a 2010 new car in Europe (Reuters, 2013).¹⁸ The body structure of the US-market Honda Accord comprises 48% HSS and the Toyota Venza contains 45% HSS¹⁹; neither vehicle uses any advanced high strength steel (AHSS) or ultra-high strength steel (UHSS). Some best-selling 2010 European models use 50-60% HSS and of this, 10-30% may be AHSS / UHSS.²⁰
4. The overall costs of mass reduction in the US studies include assumptions on labour and manufacturing costs as well as material costs. In the FEV study, material costs for the mass-reduced vehicle were higher, but this is compensated by lower labour and manufacturing costs. Any significant differences in the relationship between these costs in Europe would affect results. For

¹⁷ “Some industry reports indicate more than 95% of the fuel tanks produced in Europe are made from plastics.” See FEV (2012), page 682.

Toyota Venza has a steel fuel tank which was switched to plastic for the lightweight vehicle. Honda Accord has a plastic tank as standard.

¹⁸ For example Reuters (2013) suggests Europe uses more of the new advanced steels than North America.

¹⁹ Data received from FEV (18/11/2013) and Honda (21/11/2013). The figure for Toyota Venza includes closures, fenders and bumpers.

²⁰ The 2004 Ford Focus used 39% HSS, of which 9% AHSS/UHSS. 2008 Ford Fiesta used 59% HSS of which 31% AHSS/UHSS. The 2011 Ford Focus used 60% HSS, of 30% AHSS/UHSS (data provided by Ford Motor Company).

example, average car manufacture labour costs in Europe were 21% lower than in the US in 2010, with those in Eastern Europe, where a growing amount of vehicle manufacturing takes place, 78% lower.²¹ It is recognised that labour costs in some countries (e.g. Germany) are higher than in the USA, and hence mass reduction could be more attractive to manufacturers based in this country.

5. The main sources of cost savings in the FEV Toyota Venza study are from the suspension, brakes, wheels and tyres. Benchmarking conducted in the Lotus study suggests that these areas were particularly heavy compared to other vehicle designs common in Europe (even when normalised to the Venza's mass).
6. None of the studies take into account the fact that platform sharing and parts standardisation may have a negative impact on manufacturers' abilities to optimise for minimum mass. In response to the Electricore study, Honda estimated this might add about 40 kg (Honda, 2013a).

Our conclusion from the literature is that the mass reduction approaches used are generally relevant but that calculated costs for a given reduction may be somewhat optimistic. As a result we believe costs in Europe will be somewhat higher for a 20% mass reduction.

Discussions with EU industry stakeholders, including vehicle manufacturers and component suppliers, also indicated that whilst the mass reductions outlined in the US reports are possible for EU market vehicles, such reductions are highly unlikely to be achieved without incurring any additional costs.

Based on all of the literature reviewed and the evidence obtained over the course of this study, a 20% reduction in overall vehicle mass could be achieved for European vehicles. Such a reduction in mass might incur direct costs of between €200 and €300 per vehicle, depending on vehicle size. This assumes:

- The baseline vehicle is an average 2010 new car in Europe
- Application of mass reduction technologies which will be available for mass production through to 2020 time frame

All other factors remain unchanged (i.e. the costs refer only to mass reduction of the baseline 2010 car while ensuring it would continue to meet the legislation it was designed for at the time).

²¹ See 2010 figures for available here: <http://www.bls.gov/fls/ichccindustry.htm#29-30>

7 Stakeholder attitudes and consumer views on vehicle mass reduction

7.1 Overview

Attitudes to vehicle mass reduction are important in being able to fully understand current and likely future manufacturer strategies with respect to the types and characteristics of the vehicles that are currently on the market and that will enter the market in future years. This is not a straightforward topic as it entails a complex mix of market developments, legislative requirements, OEM strategies and attitudes, as well as consumer attitudes and preferences. Furthermore, such attitudes can include interest-driven judgments where it can be difficult (or indeed, impossible) to test the veracity of such judgments. This section focuses on identifying manufacturer and consumer attitudes as they relate to vehicle mass reduction.

7.2 Manufacturer attitudes to vehicle mass reduction

7.2.1 Approach for identifying manufacturer attitudes to vehicle mass reduction

To assess vehicle manufacturer attitudes to reducing vehicle mass, two key approaches were employed:

- Documentary research
- Stakeholder engagement

7.2.1.1 Documentary research

A search of published information was carried out to identify and review the publicly stated opinions of vehicle manufacturers with respect to vehicle mass reduction. Publicly-stated opinions on the adoption of new technologies often provide some high-level insights into a manufacturer's strategy for the coming years. Such opinions can be found in:

- press releases
- news articles
- conference papers
- interviews with OEM executives

A document search was carried out to identify public statements on the topic of mass reduction; these are presented in Section 7.2.2.

7.2.1.2 Stakeholder engagement programme

To complement this approach, a comprehensive stakeholder engagement programme was carried out. This consisted of structured interviews with experts from the vehicle manufacturers and from component suppliers to understand their views on vehicle mass reduction and to obtain revised estimates for the costs associated with applying mass reduction technologies. A total of 19 stakeholder interviews were conducted; interviewees included representatives from:

- seven vehicle manufacturers;
- four Tier 1 component suppliers;
- four materials suppliers (or their representative organisations); and
- four organisations from other sectors such as consumer groups, NGOs, academics etc.

In each case, interviewees were provided with a set of structured questions in advance of the interview, and their responses were captured as part of the interview process.

7.2.2 Findings from the documentary research on manufacturer's stated views

Table 7-1 presents the findings from the documentary research that we carried out to identify the publicly stated views of manufacturers. In each case, we have presented direct quotations made by manufacturer representatives from publications identified during the document search.

Table 7-1 Stated views of manufacturers relating to mass reduction

Importance of weight reduction to reduce CO ₂ /fuel consumption		
Manufacturer	Source & Date	Description
Ford	Paul Mascarenas, Chief Technical Officer, 2012	<p>This article provides a view of Ford’s use of carbon fibre technology on a new prototype vehicle. Paul Mascarenas, Chief Technical Officer, states:</p> <p><i>“There are two ways to reduce energy use in vehicles: improving the conversion efficiency of fuels to motion and reducing the amount of work that powertrains need to do. Ford is tackling the conversion problem primarily through downsizing engines with EcoBoost and electrification while mass reduction and improved aerodynamics are keys to reducing the workload”.</i></p> <p>The accompanying press release states:</p> <p><i>“Advanced materials such as carbon fibre are key to Ford’s plans to reduce the mass of its cars by up to 340 kg by the end of the decade” (Autoblog.com, 2013)</i></p>
Volkswagen	Board member -2012	Volkswagen reveals their new production ultra-lightweight vehicle, the XL1. A board member states that mass reduction through the use of carbon fibre technology is ‘One of the many distinguishing features on the XL1 that help us lighten the vehicle to reduce energy consumption’ (SABIC, 2013)
	Manufacturer Website article	<p>Discussing the Golf VII - reversing the spiralling trend of increased mass; 100 kg lighter than its predecessor:</p> <p><i>“Thanks to the pioneering design, the body shell alone comes in at 23 kilograms lighter. As a result, the new Golf uses fewer raw materials and consumes less fuel, ensuring it makes a positive contribution to protecting the environment.”</i></p>
	SuperLIGHT-CAR Presentation	<p><i>“...research into new lightweight designs can play a key role in reducing fuel bills” (Volkswagen AG, 2014b)</i></p> <p><i>“Automotive light weight solutions are necessary more than ever to reduce CO₂ emissions ” (Volkswagen AG, 2008b)</i></p>
	‘The Passat – Environmental Commendation’ – Press Release, 2009	<i>“Apart from developing especially efficient powertrain systems, Volkswagen aims to reduce fuel consumption and emissions by improving the energy efficiency of electrical components, optimizing rolling resistance and aerodynamic drag and pursuing lightweight design.” (Volkswagen AG, 2008a)</i>
BMW	Global Sales Head – 2010	In relation to BMW’s i3 plug-in electric car, Ian Robertson from BMW explained that <i>‘By using carbon fibre, which is a little more expensive but 30% lighter, you don’t need as many batteries for the same range. We will be the first manufacturer to take carbon fibre to effectively high volume. We are developing a lot of volume technology here’ (Autoblog Green, 2010)</i>

Importance of weight reduction to reduce CO₂/fuel consumption

Manufacturer	Source & Date	Description
	Friedrich Eichiner, Member of the Board of Management 2010	<i>“Lightweight construction is a core aspect for sustainable mobility improving both fuel consumption and CO₂ emissions”</i> (BMW Group, 2010)
Renault	G. Maeder – Renault	<i>“To meet commitments on CO₂ emission levels, it is important that we stabilize vehicle weight as from now, and then start bringing it down.”</i> (Renault, 2011)
Peugeot-Citroen	Press article - 2013	Advances in powertrain technology, combined with work to reduce vehicle mass and improve aerodynamic performance, have made it possible for the Group to lower its corporate average CO ₂ emissions (PSA Peugeot-Citroen, 2013)

How safety requirements can be met while reducing vehicle mass

Manufacturer	Source & Date	Description
Ford	Greg Frenette, Ford Motor Company, 2008	<i>“The use of advanced materials such as magnesium, aluminum and ultra high-strength boron steel offers automakers structural strength at a reduced mass to help improve fuel economy and meet safety and durability requirements”</i> (Ford Motor Company, 2008)

Impacts on cost

Manufacturer	Source & Date	Description
Volkswagen	Manufacturer Website article	With regards to the usage of higher grades of steel in their vehicles: <i>“Volkswagen plans to continue pursuing its lightweight steel construction strategy. Volkswagen recognises that it has a responsibility as a high-volume manufacturer, particularly when it comes to pricing.”</i> (Volkswagen AG, 2014b).
	SuperLightCar presentation, 2008	As part of the SuperLIGHT project it was stated that <i>“Multi-Material Concepts promise cost effective light weight solutions”</i> (Volkswagen AG, 2008b)
Nissan	Carla Bailo, Senior Vice President for R&D, 2013	<i>“next-next-generation vehicle designs must shed as much as 30% of their current mass without adding major costs”</i> (SAE International, 2013b)

Changes in OEM market positioning, with respect to releasing lighter or heavier types of vehicles in recent years (or in the near future)

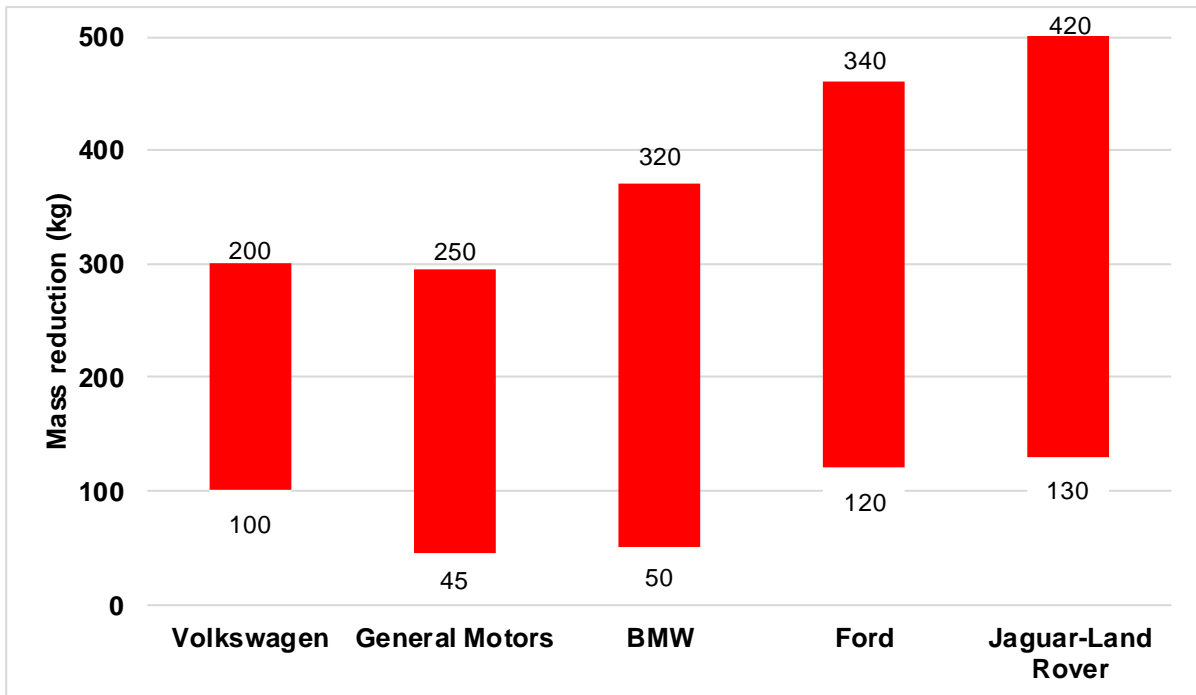
Manufacturer	Source & Date	Description
Ford	Manufacturer website article	Use of advanced materials will form part of Ford’s strategy to improve fuel consumption. <i>“To achieve our fuel-efficiency goals, we need to reduce the weight of our vehicles by 250 to 750 pounds (114-340 kg), without compromising vehicle size, safety, performance or customer-desired features”</i> (Ford Motor Company, 2012c).

Changes in OEM market positioning, with respect to releasing lighter or heavier types of vehicles in recent years (or in the near future)

Manufacturer	Source & Date	Description
Peugeot-Citroen	Christian Chapelle, Head of Drivetrains and Chassis	<i>“The Group has consistently improved engine architecture through... weight reduction: PSA Peugeot Citroën was the first carmaker to develop a full-aluminium diesel”</i> (PSA Peugeot Citroen, 2013b)
Nissan	‘Environmental and Social Report’ Press release, 2002	<i>“Nissan is involved in research and development to streamline parts structures, using nonferrous lightweight metals, such as aluminum, and resin material.”</i> (Nissan Motor Company, 2002).
	Press release 2013	<i>“aims to reduce the weight of Nissan’s vehicles by 15% with corresponding body structure rationalisation. Average 15% weight reduction by 2015”</i> (Green Car Congress, 2013)
Fiat	Stefano Maggi Fiat’s metallic materials manager, 2012	<i>“Fiat is developing magnesium and composite materials for use in future vehicles to reduce weight and improve efficiency, the OEM is also looking to increase its use of aluminium”</i> (Automotive Engineer, 2012)
Audi	Audi Technology Magazine, 2012	<i>“The ultra-lightweight design principle is not an obligation for engineers, but rather a state of mind. Audi engineers always consider the vehicle as a whole, making every gram count in every area... ultra-lightweight design has been a core competence at Audi for many years. The brand wants to continue expanding the global leadership that it already possesses in this field. In future, every new Audi model will be lighter than its predecessor”</i> (Audi AG, 2012)
Honda	Response to NHTSA study of Honda Venza	In a response to the Electricore study for NHTSA (Electricore et al, 2012) entitled “Mass Reduction for Light-Duty Vehicles for Model Years 2017-2025” Honda noted that due to OEMs using common platforms, the heaviest vehicle is likely to affect potential mass savings on lighter vehicles on the same platform (Honda, 2013a)

At the Lightweight Vehicles Conference held in October 2013, a summary quantifying the planned mass reductions of a selection of manufacturers was presented, potentially illustrating the increasing focus which is being placed on mass reduction for future models.

Figure 7-1: Mass reduction plans of selected global OEMs 2013-2020. Source: (Ernst & Young, 2013)



7.2.2.1 Vehicle manufacturer statements on mass reduction in Europe’s best-selling cars (2010-2012)

As well as the above public statements, detailed publicly available information on the application of mass reduction techniques and technologies was identified for a selection of vehicle models from three key passenger car segments (i.e. B, C and D segments).

Vehicle model	Manufacturer claims with respect to mass reduction	Analysis of evidence
Ford Fiesta (2008 onwards)	<p>The Fiesta “<i>makes extensive use of UHSS, including boron steel – one of the strongest weldable materials</i>”.(Ford Motor Company, 2011)</p> <p>The Fiesta “<i>weighs approximately 40 kilograms less, depending on engine choice, even though it stands on virtually the same footprint as the previous model and has 10 kilograms of new safety features and sound insulation.</i>” (Ford Motor Company, 2012c)</p>	<p>Analysis of kerb mass data for the previous and current models of Fiesta (2007 and 2010 models respectively) indicates that there has been a significant reduction in mass, in line with Ford’s statements. The full model range for the 2007 Fiesta had kerb mass values that ranged from 1095 kg to 1182 kg. For the 2010 Fiesta, the kerb mass values ranged from 1011 kg to 1163 kg. On average, these changes amount to a 50 kg reduction in the average mass of the Fiesta model range.</p>
Peugeot 208	<p>Peugeot states that it was “<i>determined to make the Peugeot 208 as light as possible. And thanks to laser welding and high-tensile sheet metal, the overall weight of the car can be as low as 975 kg. That’s up to 173 kg less than an equivalent 207 with an engine of similar power.</i>” (PSA Peugeot Citroën, 2014a)</p>	<p>Analysis of mass in running order data from the EEA car CO₂ monitoring database (European Environment Agency, 2013) yields the following information for the Peugeot 207 and 208:</p> <p>Peugeot 207: 1089 kg to 1494 kg Peugeot 208: 1035 kg to 1283 kg</p> <p>These data show that a significant amount of mass has been taken out of the Peugeot 208, in line with Peugeot’s claims.</p>

Vehicle model	Manufacturer claims with respect to mass reduction	Analysis of evidence
Volkswagen Golf	<p>The Golf VII is claimed by Volkswagen to be “up to 100 kg lighter and 23 per cent more fuel efficient than [the] previous model” (Volkswagen AG, 2012). According to Volkswagen, savings have been made in the following areas:</p> <ul style="list-style-type: none"> • up to 37 kg on the superstructure; • up to 26 kg on the running gear; • up to 22 kg on the engine; • up to 12 kg on special equipment; • and up to 3 kg on electrical components. 	<p>Volkswagen claims that the Golf VII is up to 100 kg lighter than its predecessor. Analysis of vehicle mass data (from the EEA car CO₂ databases for 2012 and 2013) for sales of the Golf VII and its predecessor, the Golf VI, was carried out to identify how accurate this statement is. The results of this analysis are as follows:</p> <ul style="list-style-type: none"> • 2012 Golf VI sales-weighted average mass: 1345 kg (1308 kg for petrol and 1369 kg for diesel variants) • • 2013 Golf VII sales-weighted average mass: 1308 kg (1268 kg for petrol and 1347 for diesel variants) <p>Whilst the data show that the Golf VII is lighter than its predecessor, this analysis indicates that for many model variants, the reduction in mass is much smaller than 100 kg. The overall reduction in sales-weighted mass is 37 kg, and a greater proportion of this reduction is due to the larger reductions in mass achieved for petrol variants of the Golf VII compared to diesel variants.</p>

Vehicle model	Manufacturer claims with respect to mass reduction	Analysis of evidence
Volkswagen Passat	<p>Hot stamping of body parts makes them lighter and stronger than conventionally formed parts and the Passat is VW's first model on which this process was used, resulting in a 20 kg reduction of mass (Volkswagen AG, 2010). About 7% of the BlueMotion model is constructed from light alloys such as magnesium and aluminium (Volkswagen AG, 2008). The engine uses a thin-wall crankcase together with fewer counterweights for reduced mass (Car and Driver, 2013).</p>	<p>It is not clear that the use of hot stamping has led to absolute reductions in the mass of the VW Passat. Prior to the introduction of the 2015 Passat, the last major model change for this model occurred in 2005 and significant revisions to the 2005 model were made in 2010. Hence, the impact of hot stamped body components should be evident from examining mass data for pre-2005, 2005-2010, and 2010-2014 variants. Our analysis of kerb mass data for three different model years gives the following values:</p> <ul style="list-style-type: none"> • 2004 model (B5 Passat): Kerb mass ranges from 1303 kg to 1912 kg • 2009 model (B6 Passat): Kerb mass ranges from 1343 kg to 1880 kg • 2014 model (B7 Passat): Kerb mass ranges from 1440 kg to 1726 kg <p>As can be seen from the data, the kerb mass of the lightest model in the Passat range has increased over time whilst the kerb mass of the heaviest model in the range has decreased over time. More detailed analysis shows that the latter observation is due to the fact that a number of heavy, high performance variants of the Passat are no longer offered by Volkswagen (i.e. 4.0 litre W8 engine variant, which was available in the 2004 model; 3.2 litre and 3.6 litre V6 engine variants which were available from 2005 to 2009).</p>

Vehicle model	Manufacturer claims with respect to mass reduction	Analysis of evidence
BMW 3-series	<p>The vehicle makes use of <i>“lightweight materials such as aluminium in the front of the car and chassis and high-strength steel in the body together with ultra-modern plastics. Engines and drive train components employ highly advanced magnesium alloys.”</i> This is claimed to have the effect of <i>“[lowering] the weight of components by up to 25% and results in outstanding body stiffness and passive safety for drivers and passengers. It also improves the dynamic driving characteristics thanks to a balanced weight distribution between front and rear axles (BMW Group, 2014b)”</i>.</p>	<p>Analysis of data on mass in running order from the EEA car CO₂ database indicates mass ranges as follows for the 2011 and 2013 BMW 3-Series models (previous and current generations respectively):</p> <ul style="list-style-type: none"> • 2011 model: 1415 kg to 1905 kg • 2013 model: 1182 kg to 1955 kg

7.2.2.2 Mass reduction in LCVs

Mass reduction in LCVs poses additional requirements, where durability requirements must be balanced against improvements in fuel efficiency and payload that can be achieved by reducing vehicle mass.

Compared to the passenger car sector, there are fewer production examples of mass reduction in the LCV market. However, there are some examples of implementation of lightweight designs at both the production and design stage.

A 2012 report for the UK Department for Transport (Element Energy, 2011) which examined low emission vans notes that manufacturers must maintain vehicle performance when fully laden (up to the gross vehicle mass). As a result, reductions in van kerb mass do not then allow powertrain downsizing if that results in reduced maximum engine power.

Based on discussions with OEMs, the report predicts an annual rate of mass reduction of 1% per year. It notes that “some OEMs felt that even a 1% reduction was optimistic, since vehicle masses have tended to increase over time, due to additional safety or emissions control equipment.” The report assumes that increased use of light materials in the body panels and chassis will offset future mass increases.

ArcelorMittal has developed an LCV underbody design that makes extensive use of UHSS and AHSS grade steels, allowing their engineers to reduce the mass of the underbody of a recent-model baseline LCV by 19.8%, from 193 kg down to 155 kg. They found that their study “has proven that UHSS and AHSS have the potential to lighten LCVs and reduce costs. By utilising them in other parts of LCVs, such as the upper structure, even greater savings should be possible while improving safety” (Arcelor Mittal SA, 2012).

A hybrid design was the focus of Bright Automotive, an American start-up company that failed to secure the funding it needed for further development. Their hybrid IDEA van made use of composite body panels and high aluminium usage to decrease mass and increase range, vital for a hybrid vehicle that wants to maximise usage of its battery capacity (Wired.com, 2009).

Advanced Composites Group (ACG) is also engaged in the design of a range-extended electric-hybrid commercial fleet demonstrator vehicle, in a project part-funded by the UK Technology Strategy Board. Using the company BPS240 body panels system which makes use of two-ply, partially impregnated epoxy, ACG states:

“this is possibly the first application of a lightweight composite intensive body in the light commercial vehicle sector and reducing the weight of the vehicle is fundamental to optimising the performance and range capability of the electric drive train whilst maintaining a competitive payload”
(InnovationInTextiles.com, 2011).

Moving on from hybrid design, VW has produced a concept all electric van named the “eT!” and states “we must make plans today for what the world of lightweight commercial vehicles might look like starting in the second half of this decade, including with regard to electrical drives” (Green Car Congress, 2011).

7.2.2.3 Applications of mass reduction techniques in the best-selling LCVs in the EU market

The ten best-selling LCVs in the EU market for 2012 are listed in Table 7-2 below. There are relatively few unique different models available on the market as a number of manufacturers have collaborated to produce identical models that are “badge-engineered” with the appropriate brand. For example, each of the following groups of vehicles models are mechanically identical and only have minor cosmetic differences in each case:

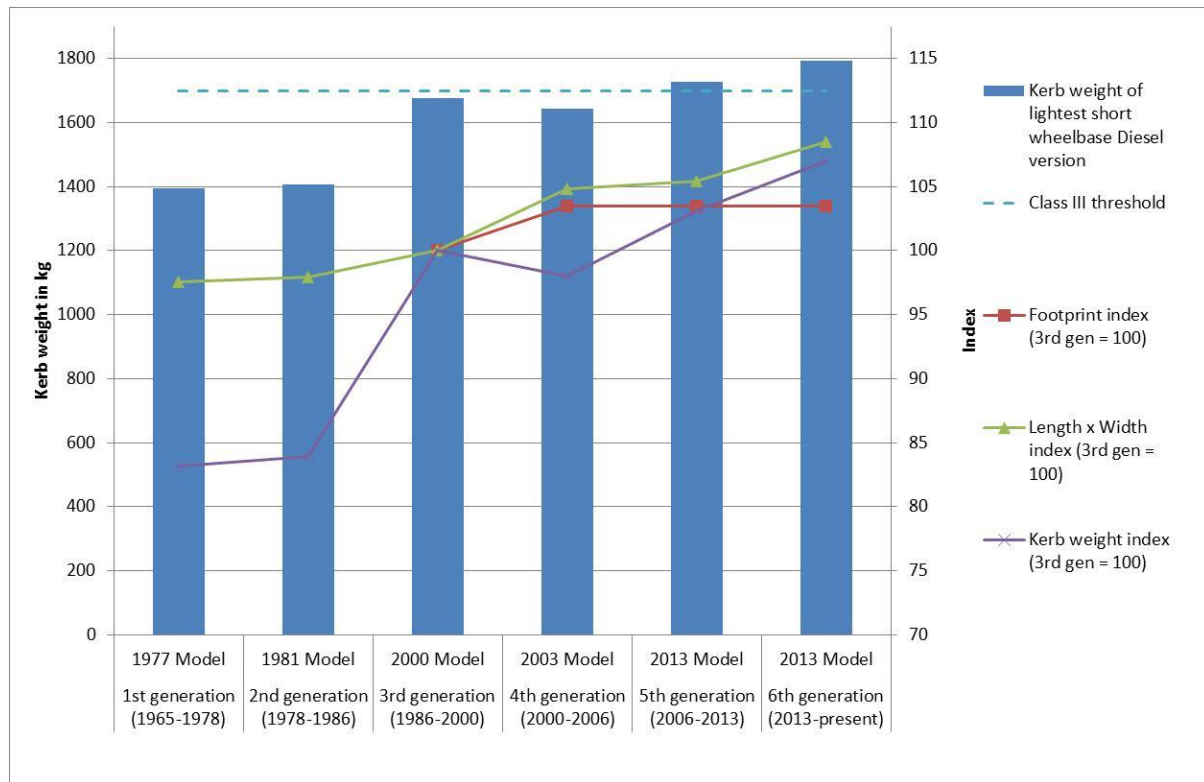
- Citroen Berlingo, Peugeot Partner
- Fiat Ducato, Citroen Jumper, Peugeot Boxer
- Renault Trafic, Opel/Vauxhall Vivaro, Nissan Primastar
- Fiat Fiorino, Citroen Nemo, Peugeot Bipper
- Renault Kangoo, Mercedes Citan
- Renault Master, Nissan NV400, Opel/Vauxhall Movano

Table 7-2: Best-selling light commercial vehicles in the EU27 in 2012

Model	Number of registrations (EU27)	Market share (EU27)
Ford Transit	129,214	9.4%
Mercedes Sprinter	79,946	5.8%
Renault Kangoo	69,644	5.1%
Volkswagen Transporter	69,539	5.1%
Volkswagen Caddy	61,839	4.5%
Fiat Ducato	60,096	4.4%
Renault Master	59,674	4.4%
Citroen Berlingo	59,191	4.3%
Peugeot Partner	58,284	4.3%
Renault Trafic	46,712	3.4%

The best-selling light commercial vehicle (LCV) in 2012 in Europe was the Ford Transit which achieved a 9.4% market share of the LCV market. This was the fifth generation of the Transit, with the new sixth generation coming on to the market during 2013. The Transit uses ultra-high-strength-steel in selected structural areas, as well as boron steel in the front cross member. These higher strength steels result in lower mass vehicles that still perform well in crash testing (Ford Motor Company, 2011). The smaller Transit Connect van features a cast aluminium engine block and cylinder head which reduces overall vehicle mass also helping fuel efficiency as well as a shorter exhaust design on vehicles with a bulkhead to reduce mass and improve payload (Netcarshow, 2014). Figure 7-2 illustrates how the Ford Transit's kerb mass has developed since the first generation model (data from 1977) through to the current sixth generation (2013). Although a small mass reduction was achieved in moving from the third to the fourth generation in 2003, overall there has been a 29% increase in kerb mass, with a progressively increasing "shadow" (length x width). It should also be noted that while early generations of the Transit were rear-wheel drive only, from the fourth generation onwards, front wheel drive versions were available. This may account for the reduction in mass of the lightest variant between the third and fourth generations.

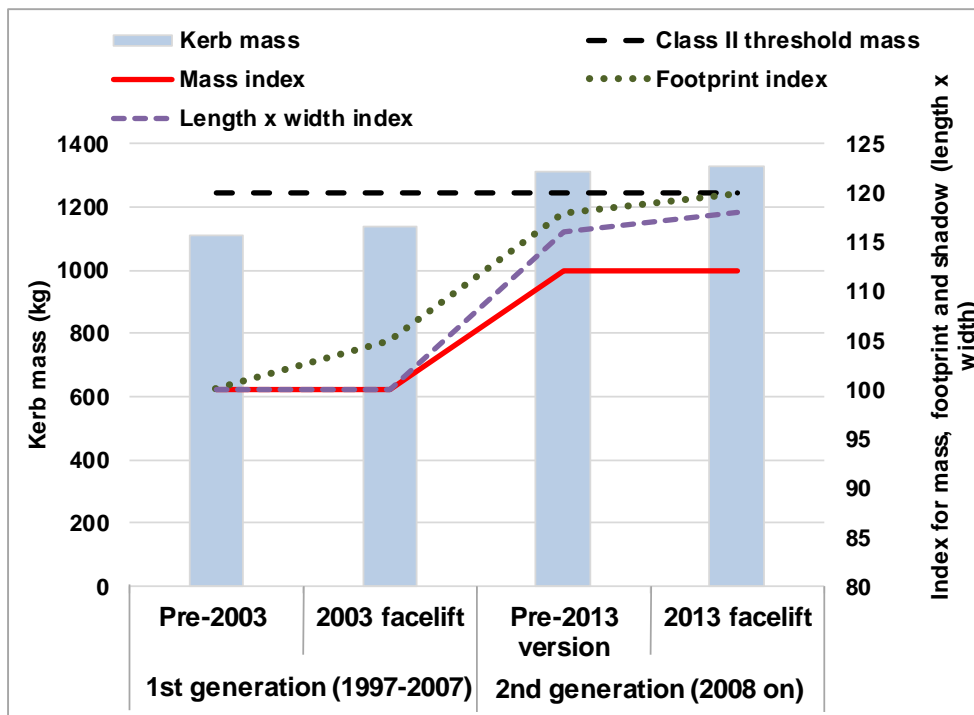
Figure 7-2: Comparison of Ford Transit models over time



Note: Data for footprint unavailable prior to third generation model.

The third highest selling LCV during 2012 was the **Renault Kangoo** with a 5.1% market share in Europe (ICCT, 2013). Engine options include a 1.6 16 V 106 hp engine that makes extensive use of lightweight materials to keep fuel consumption down (Renault, 2007). The Kangoo is one of many Renault vehicles to feature “lightweight, durable and strong Noryl GTX resin for the fenders as an alternative to steel”. This has contributed a 1.7 kg reduction in mass for the Kangoo (Jenike & Johanson, 2009). Figure 7-3 compares the kerb mass characteristics of the first and second generation Kangoo vans. These figures demonstrate how the increase in mass over time has led to this model moving from Class I (first generation) to Class II (second generation).

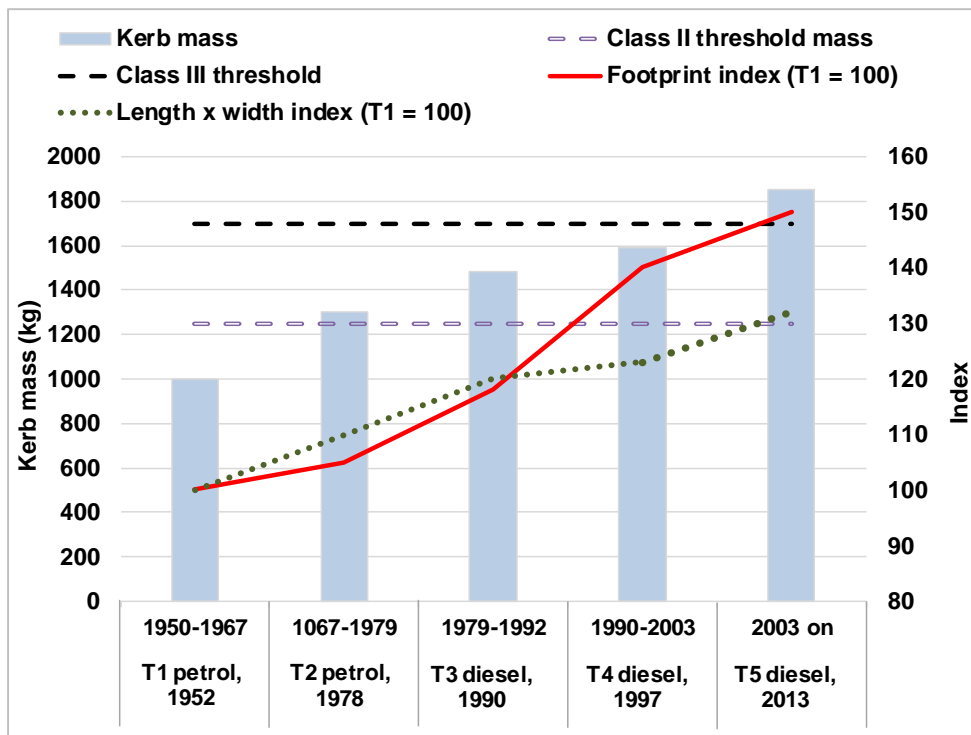
Figure 7-3: Comparison of Renault Kangoo models over time



The Volkswagen Transporter T5 is the fifth generation of the vehicle and has a market share of 5.1% within Europe. This latest version contains about 5% per cent light alloys, such as aluminium and magnesium which is actually less than one version of the previous model which contained 8% light alloys (Volkswagen AG, 2010). Instead the focus has been on reducing engine size to improve efficiency.

Again, comparing the various generations of the Transporter from the T1 of 1952 through to the latest T5 introduced in 2003, there is a clear progression in size and weight. Indeed the T5 is 86% heavier than the original T1. Figure 7-4 illustrates how the various versions have progressed from the Class I category of van through to the current version which falls into Class III.

Figure 7-4: Comparison of Volkswagen Transporter models over time



7.2.3 Stakeholder interviews

As part of this study, a comprehensive stakeholder engagement programme was carried out. This included interviews with experts from the vehicle manufacturers and from component suppliers to understand their views on vehicle mass reduction and to obtain revised estimates for the costs associated with applying mass reduction technologies.

A total of 19 stakeholder interviews were conducted; interviewees included representatives from seven vehicle manufacturers, four Tier 1 suppliers, four materials suppliers (or their representative organisations), and four from other sectors such as consumers, NGOs, academics etc. The main findings from these interviews were:

1. **Mass reduction has become a key CO₂ reduction strategy for many OEMs** in recent years and the focus is expected to become greater in the future, although the perceived importance varies between OEMs. Many stakeholders agreed with the assessment that sales of ‘crossover’ vehicle sales have grown significantly at the expense of more conventional cars, and that this has acted against OEMs’ ability to reduce vehicle mass. Other factors, such as more stringent crash legislation were cited as driving mass increase.
2. **Meeting CO₂ targets is the main driver for mass reduction.** Other drivers depend on an OEM’s market segment, but include improved handling and lower costs. For e-mobility, mass reduction provides a cost-effective way of increasing range.
3. **A multi-material approach to minimising mass is expected to be the way forward** for the future, perhaps combining AHSS / UHSS body structures with aluminium closures, fibre reinforced composites for selected components, greater use of plastics to replace metal where possible etc.
4. **The main barriers to mass reduction were identified as:**
 - a. Increased material costs
 - b. Costs of switching to new manufacturing processes
 - c. Cost and time to developing expertise in new materials
 - d. Platform strategies and parts standardisation
 - e. Challenge of coordinating lightweight vehicle design
 - f. Suitability of lightweight materials – e.g. manufacturing cycle times of fibre reinforced composites

- g. Demand for increased vehicle performance
 - h. End of life recycling requirements
5. **Moving to the new worldwide light-duty vehicle test procedure will make mass reduction more important.** This is primarily due to the changes which eliminate inertia classes and include the mass of optional extras. Some felt the new test cycle will favour larger cars due to the increased amount of high speed running and therefore the importance of aerodynamics. The faster acceleration rates required may also disadvantage vehicles with lower power to mass ratios.
 6. **The majority of stakeholders agreed that a 20% reduction in overall vehicle mass could be achieved for up to EUR 300.** However, there was a difference in opinion between vehicle manufacturers and suppliers. Several vehicle manufacturers strongly disagreed, feeling that much higher costs would be involved. Tier 1 and material suppliers were much more optimistic about the potential for mass reduction at this level of cost.
 7. **The majority of stakeholders did not want to move to a footprint based utility parameter.** Again there was a difference of opinion between vehicle manufacturers and suppliers. Only one vehicle manufacturer wished to move to a footprint based system.
 8. **The majority of stakeholders did not feel that a mass based utility parameter discourages vehicle mass reduction.** All stakeholders accepted that, in theory, it makes mass reduction a somewhat less attractive means of reducing CO₂ emissions, although most felt this did not discourage it in practice. Again there was a difference of opinion between vehicle manufacturers and suppliers, with most suppliers believing that a move to a footprint parameter would encourage greater emphasis on mass reduction.
 9. **Reasons given for retaining a mass-based utility parameter.** Stakeholders gave a number of reasons for wishing to retain mass as the utility parameter. These were as follows:
 - a. It is the fairest way of allocating CO₂ targets to different market segments
 - b. It does not discourage mass reduction in practice
 - c. A footprint system might result in OEMs not offering smaller vehicles
 - d. Changing would require re-opening lengthy negotiations on all aspects of the vehicle CO₂ legislation
 - e. Switching to a footprint based utility parameter might be damaging to Europe's competitiveness
 - f. Changing utility parameter would result in the loss of historical data on CO₂ reduction technologies
 - g. The industry should be allowed to retain this system if it desires
 - h. A mass based utility parameter is more readily understood
 10. **Reasons given for switching to a footprint based utility parameter.** Other stakeholders provided reasoning for a switch from mass to footprint for the utility parameter. These were as follows:
 - a. It would encourage earlier and greater application of vehicle mass reduction
 - b. It would reduce road collisions, deaths and serious injuries as it would encourage lower mass vehicles with larger, more stable footprints.
 - c. Footprint can be more clearly defined and recorded than mass
 - d. It may help low-cost 'value' manufacturers of larger, relatively low mass vehicles to cost-effectively meet their CO₂ targets.

7.2.3.1 Discussion of manufacturer statements and attitudes to vehicle mass reduction

As might be expected, the majority of manufacturers publicly indicate that they are, and have been, actively pursuing mass reduction strategies. However, as presented in Chapter 3, the evidence based on recent trends shows that sales-weighted average vehicle mass has been increasing for several years. Whilst selected individual models have recently been introduced to the market place that are lighter than their predecessors, changes in the relative popularity of different vehicle segments (i.e. the ongoing increasing popularity of crossover vehicles) means that average mass has continued to increase.

Whilst it is not possible to assess comprehensively the veracity of all of the manufacturer comments presented in the foregoing sections (in many cases, the statements relate to future models that have

not yet been released in the market), it is possible to assess some of the claims and statements made against recent market developments and product releases.

Many manufacturers claim that mass reduction has become a major strategy for reducing vehicle CO₂ emissions, and that their latest models are significantly lighter than their predecessors. Whilst there is some evidence to indicate some new models are lighter than their predecessors, in some cases the claims of mass reduction are overstated. For example, whilst Volkswagen claims that the Golf VII is up to 100 kg lighter than the Golf VI, our analysis of sales-weighted mass indicates an average reduction in mass of only 37 kg. Similarly, in 2013 Nissan claimed that it is aiming to reduce the mass of mass of its vehicles by 15% by 2015. Analysis of vehicle mass data undertaken during this study for recently introduced Nissan models such as the 2013 Nissan Note and the 2014 Nissan Qashqai indicates that vehicle mass for these models has reduced by only 7.5% and between 2% and 3% respectively. Furthermore, as discussed earlier in this report, sales of heavier crossover vehicles are increasing and this trend is offsetting any reductions in mass achieved for individual models.

Technologies to reduce the mass of specific components and systems are being applied more widely. For example, the increased use of high strength steels, aluminium, composites and other materials and technologies (see Chapter 5). It is less clear that the application of such technologies is sufficient to reduce the overall mass of each manufacturer's fleet, as recent trends in vehicle mass indicate continuing increases across the fleet (with the proviso that there was a small reduction in the sales-weighted average mass of new cars registered in 2013). Furthermore, it is possible that application of these materials is not always leading to reductions in the absolute mass of vehicles. Our analysis of mass data for selected vehicles where manufacturers have indicated that they have applied novel materials for reducing mass shows that overall vehicle mass is not always lower. Rather, the use of such materials avoids the vehicle being heavier than it otherwise would have been if conventional materials had been used.

The majority of manufacturers indicated that they do not want to move from a mass-based utility parameter to a footprint-based approach. They have argued that a mass-based utility parameter does not penalise mass reduction as a means for reducing vehicle CO₂ emissions. Analysis in Chapter 4 of this report clearly shows that this is not the case. Manufacturers also indicated that a footprint-based system could result in them not offering smaller vehicles in the market, although there is no evidence to support this assertion. The average mass and the average footprint of new vehicles have both been increasing during a period when mass has been used as the utility parameter in the car and LCV CO₂ Regulations. There is no evidence – i.e. it has not been suggested to us - that having mass as the utility parameter is the underlying reason for the observed increases in vehicle mass. By contrast, manufacturers have argued that mass reduction is not penalised by having mass as the utility parameter. Hence, it is not clear why using footprint as the utility parameter might lead to an increase in the average footprint of new vehicles (which would result from there being fewer smaller vehicles available on the market). In our view, there is no consistency in the arguments that having mass as the utility parameter does not penalise mass reduction, while having footprint as the utility parameter would discriminate against smaller vehicles.

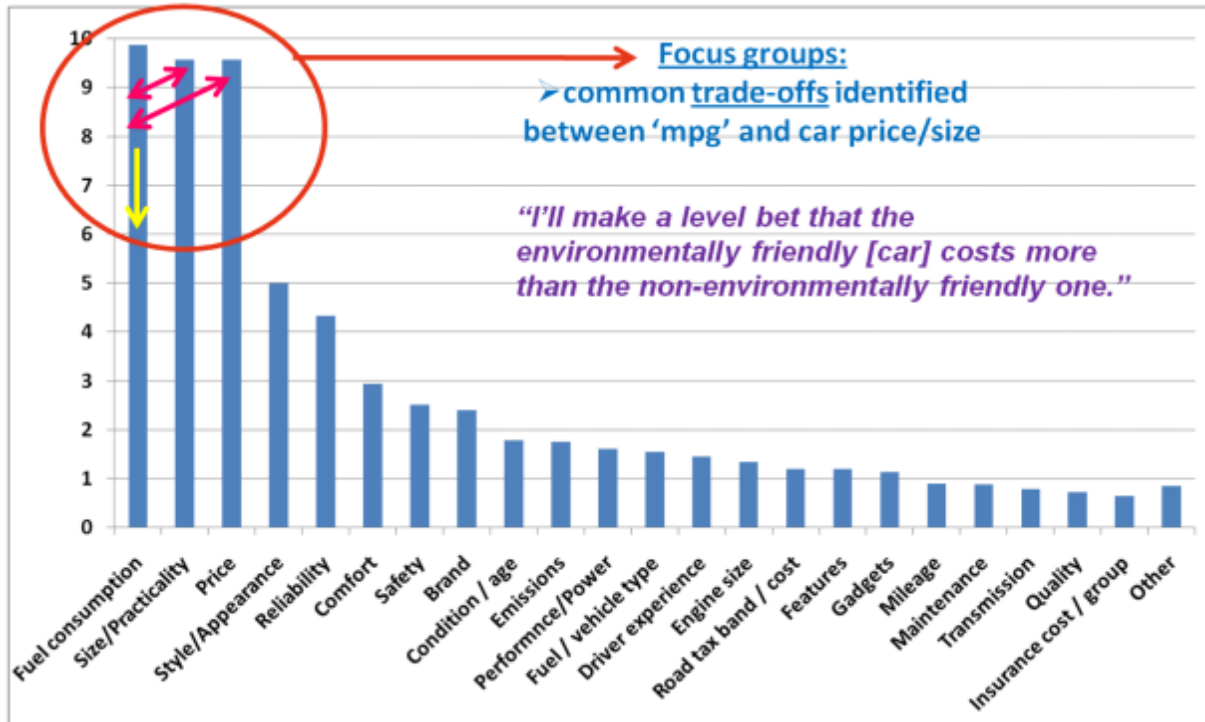
Various manufacturers stated that changing the utility parameter from mass to footprint would require re-opening lengthy negotiations on all aspects of the vehicle CO₂ Regulations. Given that it is possible that the modalities for post-2020/21 Regulations on CO₂ emissions from light duty vehicles could be different to those in place under the existing car and LCV CO₂ Regulations, such negotiations will be required in any case, regardless of whether mass or footprint is used as the utility parameter.

Through the stakeholder interview process, manufacturers and component/material suppliers indicated that a multi-material approach to mass reduction will be applied in future. Our analysis indicates that this view is correct, as different manufacturers are investing in different types of materials, with many using combinations of advanced high strength steels, aluminium and composite materials for body structures, closures and chassis components. Novel materials are also being applied to other components such as powertrains and interior components, including magnesium, plastics and fibre-reinforced composites. The wide range of strategies being applied means that there is not a single, optimal approach to mass reduction; rather, manufacturers and component suppliers are utilising materials and techniques that are compatible with their wider business strategies, their market position and their knowledge and expertise in alternative production technologies.

7.3 Consumer attitudes

There is no literature on consumer attitudes towards weight reduction *per se* and it is unlikely that consumers without expert knowledge on the implications of mass on different vehicle attributes would have any particular attitude to mass reduction. Surveys of car buyers indicate that there is a range of attributes that are of interest to consumers when purchasing a new vehicle, and mass is not an attribute that is identified in such surveys. For example the UK Low Carbon Vehicle Partnership conducted a survey on consumer attitudes (Lane, B. and N. Banks, 2010). The high level results of this survey are presented below.

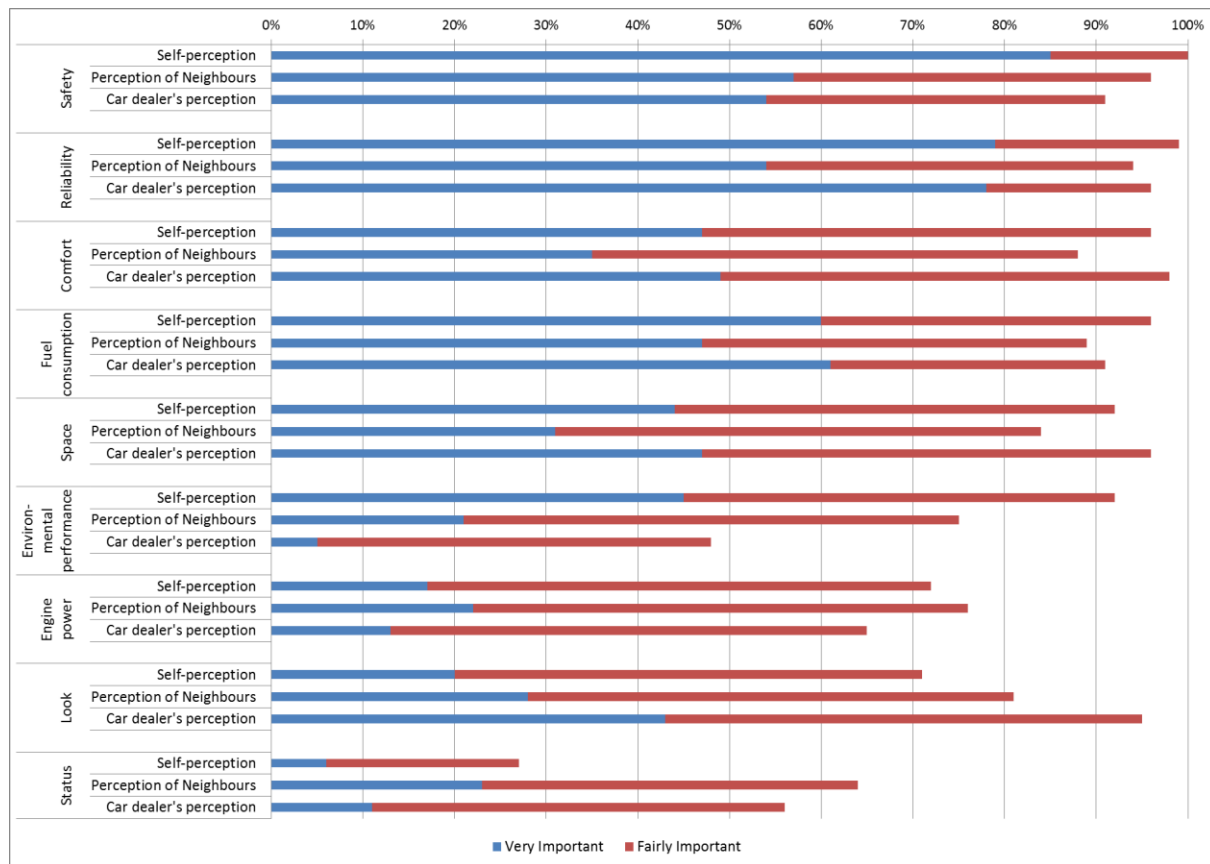
Figure 7-5: Most important car purchase factors. Source: (Lane, B. and N. Banks, 2010)



As can be seen from the figure, consumers *state* that fuel economy is the most important attribute in their car purchasing decisions; other important attributes include size, price, appearance and reliability.

Another challenge in assessing how consumers value vehicle attributes is that even knowing one’s own true preferences is non-trivial. Findings from Johansson-Stenman and Martinsson (2006) suggest that consumers’ willingness to compromise on a car’s aesthetic experience in favour of better environmental performance may in fact be lower than the consumers themselves believe. The survey evaluated 1,300 questionnaire responses broadly representative of the Swedish population aged between 18 and 65 years. The questionnaire asked individuals on the importance they attach to certain new vehicle attributes and how important they thought these attributes would be to their neighbours. 83 car dealers were also asked the same questions. The results show that differences between the three assessments are particularly pronounced with regards to environmental performance, where self-perceived importance is much higher, and status, where self-perceived importance is much lower. The authors argue that both self-perception and the perception of others are likely to be biased for various reasons.

Figure 7-6: Questionnaire results on the importance of various vehicle attributes (Johansson-Stenman and Martinsson, 2006)



Both of these surveys show that mass is not an attribute that influences purchasing decisions, but if it is correlated with any of the key attributes, then it could be viewed as an indirect factor in consumer purchasing decisions.

To test the relationships between mass and key vehicle attributes of interest to consumers, we carried out scatter analysis using a vehicle attribute dataset collected as part of a previous study for the Commission (AEA, 2011). This dataset included information on a wide selection of vehicles sold in the EU in 2010, including:

- Kerb mass
- Price
- Length
- Width
- Maximum engine power output
- Fuel consumption
- Comfort feature content

The outputs from the correlation analysis are presented in the following figures.

Figure 7-7: Relationship between kerb mass and retail price for selected 2010 passenger cars. Principal data source: (AEA, 2011).

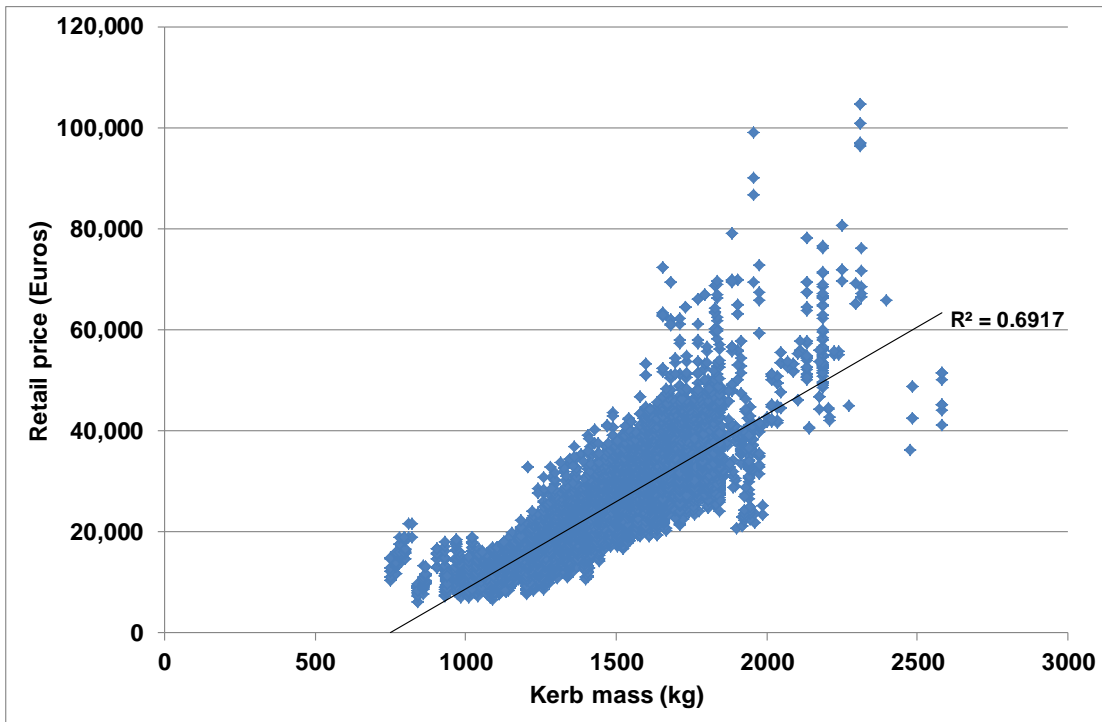
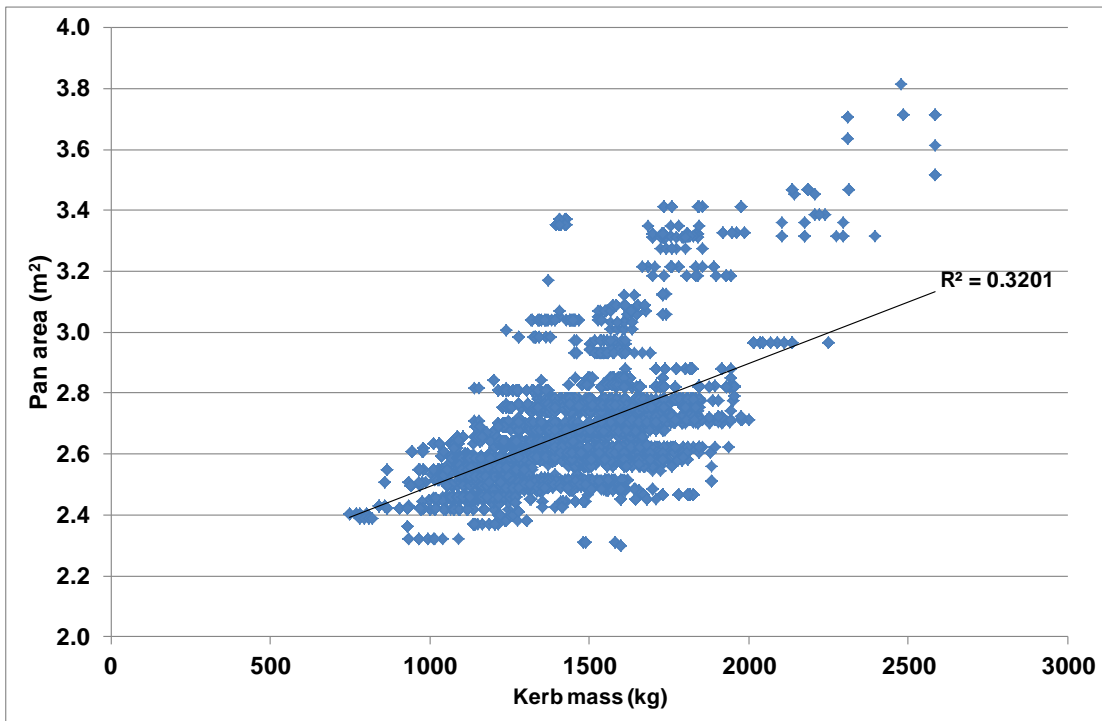


Figure 7-8: Relationship between kerb mass and pan area for selected 2010 passenger cars. Principal data source: (AEA, 2011).



Note: Pan area = vehicle length multiplied by vehicle width

Figure 7-9: Relationship between kerb mass and fuel consumption for selected 2010 passenger cars. Principal data source: (AEA, 2011).

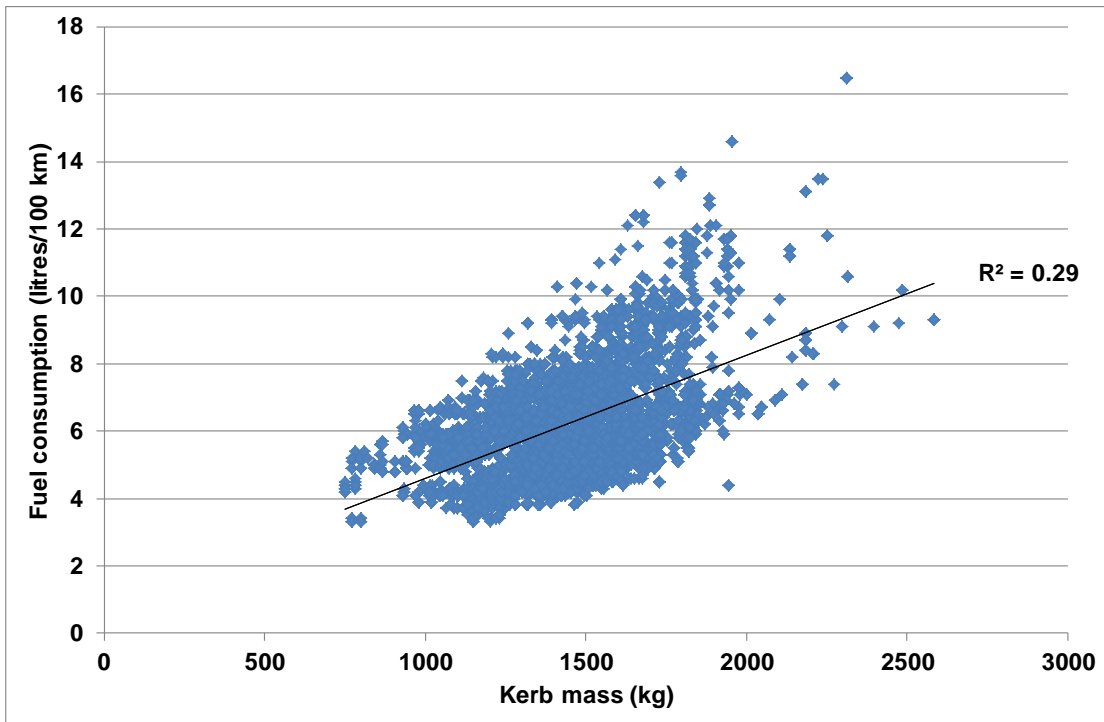


Figure 7-10: Relationship between kerb mass and maximum engine power output for selected 2010 passenger cars. Principal data source: (AEA, 2011)

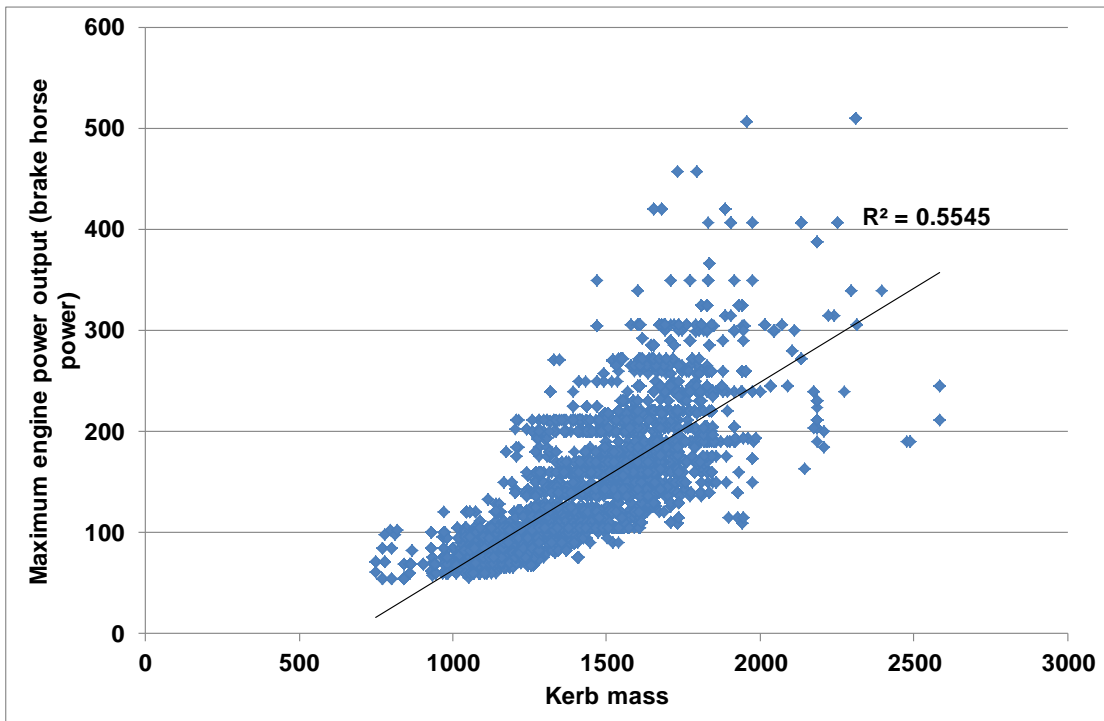
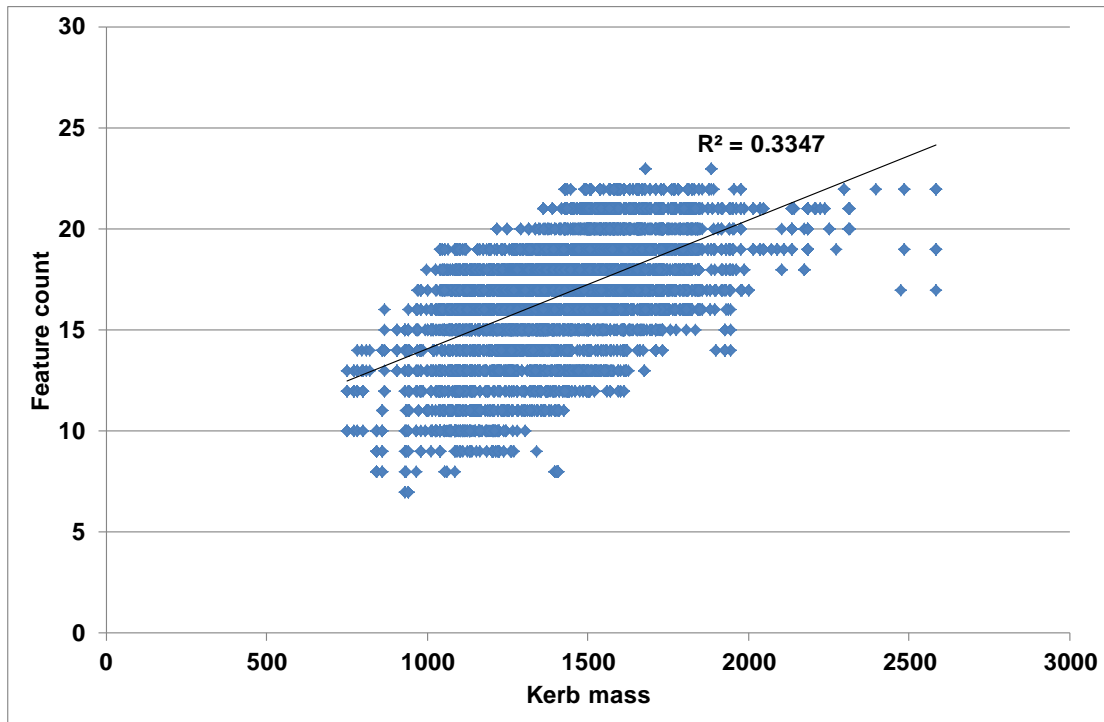


Figure 7-11: Relationship between kerb mass and feature count²² for selected 2010 passenger cars



As can be seen from the charts, there is some level of correlation between each attribute and vehicle mass, but the strength of these relationships is highly variable, and in many cases, is weak. The relationship between kerb mass and retail price is strong ($R^2 = 0.69$), a finding that would be expected given that larger, heavier vehicles tend to have a higher market value. Overall, based on this analysis, there is insufficient evidence to use mass as a proxy for any of the vehicle attributes that are important to consumers. Consequently, we conclude that vehicle mass is not a parameter that is important to consumers when making vehicle purchasing decisions.

²² Note: Feature count refers to whether or not a car is fitted with key comfort and safety features. Features covered by this analysis are as follows: (i) Anti-lock braking systems; (ii) driver’s airbag; (iii) passenger airbag; (iv) electronic stability control systems; (v) electronic brake force distribution systems; (vi) automatic gearbox; (vii) side airbags; (viii) leather upholstery; (ix) cruise control; (x) electric front seats; (xi) alarm; (xii) immobiliser; (xiii) electric front windows; (xiv) electric rear windows; (xv) electric door mirrors; (xvi) central door locking; (xvii) fog lights; (xviii) alloy wheels; (xix) power assisted steering; (xx) air conditioning; (xxi) satellite navigation system; (xxii) side-impact bars; (xxiii) on-board computer; (xxiv) four-wheel drive system; (xxv) convertible roof.

8 Costs of vehicle mass reduction to manufacturers and financial benefits to society

8.1 Overview

A key objective of this study was to provide new estimates for the costs associated with vehicle mass reduction. This chapter presents these estimates, drawing on previous research in this area and the findings from Chapters 5 to 7 of this report.

8.2 Previous estimates for the costs of vehicle mass reduction

8.2.1 Passenger cars

TNO et al (2011) carried out a detailed analysis of the costs and potential CO₂ reductions associated with a wide range of vehicle technologies. The work included analysis of the costs and CO₂ impacts associated with vehicle mass reduction. TNO et al (2011) generated estimates for mass reduction on the basis of 10%, 20% and 40% reductions in the mass of the body-in-white (BIW). Mass reductions for other components were examined separately. As discussed in Section 5.1, the BIW represents only about 20-28% of a car's mass. Addressing the BIW alone ignores secondary mass reductions which have been shown in Section 5.6 to be important. The findings from the TNO study are presented in the tables below.

Table 8-1: Previous estimates for the costs associated with passenger car mass reduction. Source: (TNO et al, 2011)

Mass reduction	Small car	Medium car	Large car
BIW lightweighting - mild (~10% reduction)	€128	€160	€192
BIW lightweighting - medium (~25% reduction)	€320	€400	€480
BIW lightweighting - strong (~40% reduction)	€800	€1,000	€1,200
Lightweight components other than body in white	€120	€150	€180

The passenger car size categories used by TNO et al to derive the above figures are as follows. All medium cars are classed as C-segment vehicles²³; small cars are all those in segments below the C-segment; and large cars are all those in segments above the C-segment.

The figures above relate only to percentage reductions in the mass of the body-in-white and not the full vehicle. TNO et al estimated the impacts of the three BIW mass reduction scenarios from the table above on total vehicle mass, as follows:

- 10% reduction in BIW mass equates to between 2% and 3% reduction in total vehicle mass;
- 25% reduction in BIW mass equates to between 5% and 7% reduction in total vehicle mass;
- 40% reduction in BIW mass equates to between 8% and 11% reduction in total vehicle mass.

Furthermore, for lightweight components other than the body-in-white, TNO et al assumed that the application of these technologies would result in total vehicle mass reductions of less than 1%.

As part of the TNO *et al* (2011) study, results from work carried out by the US EPA on vehicle technology costs were analysed (US EPA, 2010). The findings from this analysis indicated that the EPA's cost

²³ We have included CX-segment crossovers and CM-segment MPVs in this definition.

estimate for vehicle mass reduction were significantly lower than the TNO *et al* estimates. TNO *et al* derived an alternative set of cost estimates from the EPA data and these are presented in the table below. Note that these estimates are on the basis of reductions in **overall** vehicle mass, not just the mass of the body-in-white.

Table 8-2: Previous alternative estimates for the costs associated with passenger car mass reduction derived from research carried out by the US EPA. Source: (TNO et al, 2011)

Mass reduction	Small car	Medium car	Large car
10% reduction in total vehicle mass	€25	€31	€38
20% reduction in total vehicle mass	€160	€200	€240
30% reduction in total vehicle mass	€590	€738	€885

It is difficult to compare the two sets of estimates presented in the tables above because the majority of the first set of figures relate only to the costs of reducing the mass of the body-in-white, whilst the second set relate to reductions in the mass of whole vehicles. To be able to compare these datasets, we have estimated the unit costs per kilogram of mass saved for each size category, using information from the EEA CO₂ monitoring database (European Environment Agency, 2013) on the sales-weighted average mass of vehicles by segment to derive average mass values for small, medium and large cars registered in 2012 (see Table 8-3 below).

Table 8-3: Sales-weighted average mass by size category for new passenger cars registered in 2012

	Small car	Medium car	Large car
Sales-weighted average mass	1125 kg	1454 kg	1705 kg

Using these data along with TNO *et al*'s estimates for how BIW mass reduction translates into total vehicle mass reduction (see above) we have converted the cost data presented in Table 8-1 and Table 8-2 into unit estimates for the costs of mass reduction per kilogram saved.

Table 8-4: Average unit costs of passenger car mass reduction. Derived from (TNO et al, 2011)

Average unit costs of mass reduction (€/kg)	Small car	Medium car	Large car
BIW lightweighting - mild (~10% reduction in BIW mass)	€ 3.79/kg	€ 3.67/kg	€ 3.75/kg
BIW lightweighting - medium (~25% reduction in BIW mass)	€ 4.06/kg	€ 3.93/kg	€ 4.02/kg
BIW lightweighting – strong (~40% reduction in BIW mass)	€ 5.93/kg	€ 5.73/kg	€ 5.87/kg
Lightweight components other than body in white	€ 11.85/kg	€ 11.46/kg	€ 11.73/kg

Note: In line with TNO *et al* (2011) assumptions, 10% BIW mass reduction assumed to equate to 3% total vehicle mass reduction; 20% BIW mass reduction assumed to equate to 7% total vehicle mass reduction; 40% BIW mass reduction assumed to equate to 12% total vehicle mass reduction; Lightweight components other than BIW are assumed to give 0.9% reduction in total vehicle mass.

Table 8-5: Alternative average unit costs of passenger car mass reduction. Derived from the TNO et al analysis of US EPA cost estimates (TNO et al, 2011)

Average unit costs of weight reduction (€/kg)	Small car	Medium car	Large car
10% reduction in total vehicle mass	€ 0.22/kg	€ 0.21/kg	€ 0.22/kg
20% reduction in total vehicle mass	€ 0.71/kg	€ 0.69/kg	€ 0.70/kg
30% reduction in total vehicle mass	€ 1.75/kg	€ 1.69/kg	€ 1.73/kg

8.2.2 Light commercial vehicles

Previous estimates for the costs of mass reduction for light commercial vehicles were also developed by TNO et al as part of a separate study (TNO et al, 2012). A similar approach to passenger cars was adopted whereby costs were estimated for different levels of BIW mass reduction and for non-BIW lightweight components. The findings from this previous research are presented in the table below.

Table 8-6: Previous estimates for the costs associated with LCV mass reduction. Source: (TNO et al, 2012)

Mass reduction	Small LCV	Medium LCV	Large LCV
BIW lightweighting - mild (~10% reduction in BIW mass)	€150	€175	€325
BIW lightweighting - medium (~25% reduction in BIW mass)	€750	€875	€1,625
BIW lightweighting – strong (~40% reduction in BIW mass)	€2,400	€2,800	€5,200
Lightweight components other than body in white	€150	€175	€325

TNO et al's research (TNO et al, 2012) showed that for LCVs, mass reduction as a means to reduce CO₂ emissions is less cost effective than for passenger cars. There are a number of reasons for this. For small LCVs, whilst they often share components and systems with passenger cars, the potential for reducing mass is lower because there are (a) fewer components to remove and (b) any reduction in mass must not affect the load carrying ability of the vehicle. Furthermore, medium and large LCVs have high levels of rolling resistance and poor aerodynamic performance compared to passenger cars. This means that the efficiency benefits of mass reduction are lower. It should also be noted that the cost estimates developed by TNO et al for LCVs are based on those developed in the SuperLIGHT-CAR project (SuperLIGHT-CAR, 2009).

8.2.3 Critical review of previous cost estimates

For passenger cars, it is notable that there are very significant differences in the unit costs of mass reduction depending on which set of data from TNO et al (2011) are used. The data presented in Table 8-4 which are based on TNO et al's own analysis of the costs of vehicle mass reduction appear to indicate that the units costs of mass reduction for passenger cars range from €3.67/kg to €11.85/kg, depending on level of ambition with respect to mass reduction and the size of vehicle. It is striking that for passenger cars, the average units costs associated with reducing the mass of non-BIW components are higher than for BIW components. This is surprising as the costs associated with taking mass out of the vehicle body structure are usually higher than for other components.

Furthermore, our derivation of unit costs for mass reduction from TNO's analysis of the US EPA data on the costs of vehicle mass reduction shows that these cost estimates are very significantly (an order of magnitude) lower than the costs identified in TNO's own original research.

For light commercial vehicles, whilst the costs of mass reduction are likely to be higher than for passenger cars (due to the reasons listed above and also because of the much lower production volumes of most LCVs compared to passenger cars), there is also a need to consider whether revised cost estimates are required as the TNO *et al* (2012) figures are very high.

Taking all of the above into account, and the findings from the previous chapters of this study, a new set of cost estimates for vehicle mass reduction are required as it is likely that the previous figures developed by TNO *et al* are too high. The following section presents the findings from analysis to produce new estimates for the costs of vehicle mass reduction.

8.3 Development of new cost estimates based on the findings from this study

8.3.1 Overview

There are many different ways in which vehicle mass reduction can be achieved, as demonstrated by the literature review and the stakeholder consultation. This diversity in the approaches available means that it is difficult to obtain robust estimates of the average costs of reducing vehicle mass. Costs will vary significantly depending on the specific design of the vehicle, its size and the mass reduction technologies already applied.

As described in Section 8.2, previous EU-level research on this topic (TNO *et al*, 2011, TNO *et al*, 2012) focused on the costs of mass reduction for the vehicle body-in-white, and grouped the costs of other types of mass reduction together. Given that any new cost estimates will be used to inform policy analysis rather than deep technical studies on individual weight-saving measures, it is not appropriate to place a specific focus on the costs of reducing the mass of the body-in-white. BIW mass reduction is one of many options that can be applied for reducing vehicle mass. Whilst it is one of the most important options, it is more appropriate to develop generalised cost estimates for overall vehicle mass reduction. This is in line with the approach taken by the US EPA.

The previous research carried out by TNO *et al* identified costs for 10%, 20% and 40% reductions in the mass of the body-in-white. Reductions in BIW mass do not translate into equivalent reductions in the overall mass of the vehicle (as outlined in Section 8.2.1). Whilst achieving a 40% reduction in the mass of the body-in-white is feasible in the 2020 time period, the literature review and discussions with stakeholders indicated that achieving a 40% reduction in overall vehicle mass would be technically very challenging and prohibitively expensive. Furthermore, the US EPA approach is based on estimating costs for 10%, 20% and 30% reductions in total vehicle mass. Taking all of these factors into account, we have developed new cost estimates for achieving 10%, 20% and 30% reductions in overall vehicle mass.

8.3.2 Cost estimates for reducing passenger car mass

It is not straightforward to develop cost estimates for vehicle mass reduction because of the wide variety of different technologies that can be applied to different parts of the vehicle. Furthermore, different manufacturers are applying very different strategies in this area, depending on their experience, their position in the market-place and their willingness to pay for mass reduction. All of these factors make it difficult to develop generalised cost estimates for mass reduction.

The costs of mass reduction also depend on the extent to which manufacturers have already applied mass reduction technologies to their vehicles. As discussed in Chapter 5, in the EU market the majority of new vehicles are already equipped with various grades of high strength steels in the body structure and downsized engines have become increasingly common. Whilst there is limited use of aluminium in smaller vehicles, there is a significant level of uptake for larger vehicles, with many manufacturers planning to increase the amounts used in the body-in-white, closures and chassis systems. Many manufacturers and component suppliers are applying parts integration techniques that allow metallic parts and assemblies to be replaced by cheaper, integrated all-plastic components. All of these factors mean that the costs of mass reduction can vary significantly from manufacturer to manufacturer and from vehicle to vehicle.

Based on the findings of the literature review and from discussions with stakeholders, we have assembled information on the costs of mass reduction. A summary of the cost estimates identified from the literature review is presented in the table below.

Table 8-7: Unit costs for passenger car mass reduction identified from the literature

Literature source	Mass reduction achieved	Cost per kg saved	Secondary mass reduction achieved
Future Steel Vehicle	19% of BIW (ca 5% of whole vehicle)	Approximately €0/kg	No
SuperLIGHT Car	Steel intensive: 20% of BIW (~5% of whole vehicle)	<€2.5 per kg	No
	Universal Light Body Concept: 27% from BIW (~7% of whole vehicle)	Approximately €5 per kg	No
	Super Light Body Concept: 38% from BIW (~9.5% of whole vehicle)	Approximately €10 per kg	No
Lotus Engineering (2010)	Low development: 20% of whole vehicle	-€0.8 per kg	Yes
	High development: 32% of whole vehicle	€0.8 per kg	Yes
FEV (2012)	18% of whole vehicle	-€0.45 per kg	Yes
Electricore et al (2012)	23% of whole vehicle	€0.6 per kg	Yes
McKinsey (2012)	18% of whole vehicle	€3 per kg	Unknown
	30% of whole vehicle	€4 per kg	Unknown
	35% of whole vehicle	€8-10 per kg	Unknown

From the stakeholder consultation exercise information was obtained to indicate that vehicle manufacturers are willing to pay between €1/kg and €20/kg to reduce vehicle mass, but that within this range, the specific figures vary significantly depending on the manufacturer and depending on the types of mass reduction technologies being applied. Furthermore, there is greater scope for applying more costly mass reduction measures to larger vehicles as sales of these vehicles are less sensitive to changes in prices than smaller, cheaper vehicles. This is most clearly demonstrated by the levels of aluminium use by vehicle segment (discussed in Section 5.2.2); small cars have very little aluminium content, whilst many E-segment vehicles have very significant use of aluminium, including in their body structures and closures. This means that for a given percentage reduction in vehicle mass, costs are likely to be higher for larger vehicles. For example, a 20% reduction in mass for an E-segment car will cost more as a percentage of total production costs than for a B-segment car, because the technical solutions required are likely to be more complex and costly per kg of weight saved.

Many stakeholders indicated that the average cost of mass reduction is €5/kg. Based on much of the analysis that we have carried out, we believe that it is likely that the costs for many mass reduction technologies are lower than this. There are also examples where mass reduction has been achieved with a reduction in cost or no increase. Furthermore, the costs of reducing vehicle mass are not constant; greater levels of mass reduction are likely to have higher unit costs (€/kg saved) because the technical complexity of the solutions required increases as the level of mass reduction increases. A number of stakeholders indicated that a 20% reduction in vehicle mass could be achieved for between €200 and €300 in total.

Examples of the variations in costs for different mass reduction technologies can be seen from estimates obtained as part of the consultation process.

Table 8-8: Estimates of the costs associated with constructing a vehicle body-in-white from different materials (source: stakeholder consultation supporting this study)

Material	Mass (kg)	Percentage weight reduction compared to conventional steel	Production costs (€)	Marginal cost compared to conventional steel (€)
Conventional steel	300 kg	N/A	€180	N/A
Ultra-high strength steel	270 kg	10%	€270	€90
Aluminium	180 kg	40%	€540	€360
Carbon fibre	100 kg	67%	€1600	€1420

Based on the above figures, it would appear that a 10% reduction in BIW mass can be achieved for €90, a 40% reduction can be achieved for €360 and a 67% reduction can be achieved for €1420. These figures do not take into account the fact that manufacturers very rarely produce body structures from a single material, but instead use combinations of different materials, which will have an impact on the costs. Furthermore, the costs above do not take into account the costs associated with modifying production facilities and processes to accommodate alternative materials. For example, constructing a full vehicle body structure from aluminium requires very significant changes in production processes. Based on the research carried out for this project, very few vehicles will utilise all-aluminium body structures in future. It is also worth noting that the figures quoted above are significantly lower than TNO *et al*'s previous estimates for the costs of BIW mass reduction. The figures in the table above relate to the body-in-white only; many of the above materials can also be used for body closures, but the costs associated with using advanced materials for closures is usually higher due to the complexities of some body panels and requirements for high quality surface finishes for exterior (skin) panels. Furthermore, reductions in BIW mass often enable secondary mass reductions to be made to other vehicle systems (e.g. powertrain, chassis, interior systems, etc), that can also lead to cost reductions.

Based on the research carried out in this project, we conclude that the previous cost estimates developed by TNO *et al* (2011) are too high. By contrast, we believe that the US EPA estimates referred to in the TNO *et al* study are too low for use in the EU context, due to differences in the US and EU vehicle markets. In particular, a large proportion of EU-market vehicles are already equipped with substantial amounts of high strength steel in their body structures and are already fitted with downsized engines. Hence, the scope for applying these technologies (both of which are relatively cost effective methods for reducing vehicle mass) in future years is more limited. The situation in the USA is different; for example, the extent to which engine downsizing has been applied to date is much more limited than in the European market. For example, the Ford Focus is available in both the US and EU markets, but in the US market, the smallest engine is a 2.0 litre petrol engine, whilst in the EU, the smallest available engine is a 1.0 litre downsized engine; the lightest version of the Focus in the US market weighs 1,334 kg, whereas in the EU, the lightest variant weighs 1,264 kg – a difference of 69 kg. This trend of larger engines in US-market vehicles is observed across many different brands and vehicle size categories, and means that there is a certain amount of untapped low-cost (or cost-saving) mass reduction potential still available in the US market that has already been taken up in the EU.

Other factors that are likely to influence the costs and potential for reducing powertrain mass include the fact that a significant proportion of EU-market vehicles are equipped with diesel engines. In order to comply with the Euro 6 air pollutant emissions standards, most manufacturers have fitted either lean-NO_x traps (LNTs) or selective catalytic reduction (SCR) systems to their medium-sized and large diesel cars (these systems are usually not necessary for smaller vehicles), with knock-on impacts in terms of increasing overall vehicle mass. Whilst the same technologies are required for US-market diesel cars, the very low market penetration of diesel in the US passenger car market means that the impacts of these technologies on the potential for mass reduction across the vehicle fleet are much less important.

With respect to reducing the mass of the body-in-white and other body components, in both the EU and US markets there has been significant uptake of high strength steels in recent years, with many newer vehicles already being predominantly constructed from various AHSS steel grades (for example, 80% of the steel content in the 2012 Golf VII comprises high strength steel, and of this, 28% is ultra-high strength steel). So, whilst there is still some potential for reducing mass through further application of different types of ultra-high strength steel, in order to achieve significant mass reductions, other higher-cost materials will be required.

Given all of the above, we have used the EPA figures as the basis for developing new estimates for the costs of mass reduction for EU-market vehicles. The EPA figures have been scaled up by 25% to reflect our findings that costs for reducing the mass of EU-market vehicles are likely to be higher than previous estimates of the costs of mass reduction for US-market vehicles. The approach of scaling the EPA costs up by 25% is an approximation, but to develop more detailed cost estimates would require a much more comprehensive study than is possible within the constraints of this project. Our new estimates for the costs of mass reduction in passenger cars are presented in Table 8-9. These estimates assume that the baseline vehicle is an average 2010 new car in Europe and that only the mass reduction technologies that will be available for mass production before 2020 will be applied; all other factors remain unchanged.

Table 8-9: New estimates for the costs of whole-vehicle mass reduction for passenger cars

	Absolute costs			Unit costs
	Small cars	Medium cars	Large cars	
10% reduction in total vehicle mass	€31	€39	€48	€0.3/kg
20% reduction in total vehicle mass	€200	€250	€300	€0.9/kg
30% reduction in total vehicle mass	€738	€923	€1,106	€2.2/kg

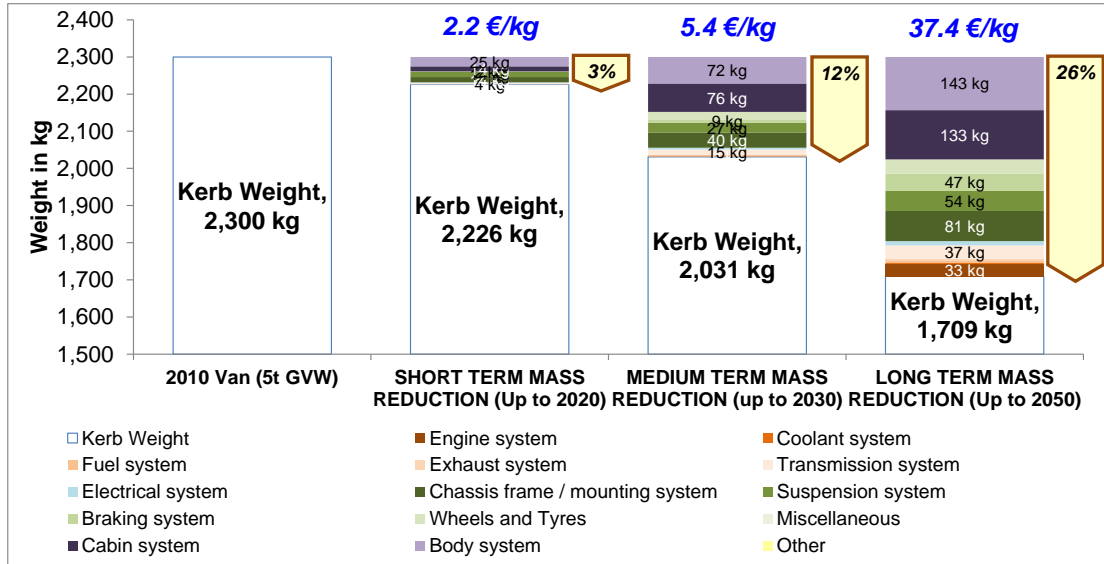
8.3.3 Cost estimates for reducing the mass of light commercial vehicles

The costs for reducing the mass of light commercial vehicles are likely to be higher than for passenger cars for at least two reasons. Firstly, the sales volumes of light commercial vehicles are much lower than for passenger cars, meaning that the unit costs of applying mass reduction technologies will be higher. This is particularly the case for reductions to the mass of the body structure, where tooling costs are very significant contributors to overall cost (e.g. the tooling costs for hot-formed ultra-high strength steel body panels are higher than for panels made from cold-formed conventional and high strength steels). As the sales volumes of LCVs are much lower than for cars, the production life-cycles of these vehicles tend to be much longer to make the vehicles economically viable in the market place. However, this means that the opportunities for applying mass reduction technologies are also lower, as major changes can usually only be made when a new model is introduced. Furthermore, the range of available mass reduction techniques is smaller for light commercial vehicles because these vehicles are designed around providing the maximum possible payload. This means that even if the mass of the unladen vehicle is reduced, it still has to be designed to cope with the same payload (or preferably a greater payload) as a vehicle that does not have any mass-reducing measures applied. This is particularly the case with modern vehicles where legislative and market requirements for additional equipment in LCVs (e.g. emissions control equipment, safety systems, comfort features, etc) have led to reductions in the available payloads for the latest version of many LCVs compared to their predecessors. Hence, the scope for secondary mass reduction is much smaller for LCVs than it is for passenger cars.

As part of a parallel study for the European Commission on mass reduction for heavy duty vehicles, (Ricardo-AEA, 2015 (forthcoming)), we have carried out a detailed assessment of the scope and costs associated with reducing the mass of large vans (gross vehicle mass of 5 tonnes). These types of vehicles are very similar to medium and large light commercial vehicles (in many cases, they are simply larger versions of standard LCVs – e.g. variants of the Ford Transit, Mercedes Sprinter and VW Crafter with a gross vehicle mass of 5 tonnes are all available on the market) and hence the findings from this parallel study are very relevant in this context.

The analysis was based on a typical 5 tonne large van with a kerb mass of 2,300 kg, and examined three different scenarios of mass reduction (short-term, medium-term and long-term). For each scenario, mass reduction options for the key vehicle systems and subsystems were analysed in detail. This analysis included developing quantified estimates of the mass reduction potential and costs associated with each option, using the expertise of Ricardo’s vehicle lightweighting engineers. A summary of the results of this analysis is presented in the figure below.

Figure 8-1: Mass reduction potential (and associated costs) for large vans (5 tonne gross vehicle mass) (Source: Ricardo-AEA, 2015 (forthcoming))



As can be seen from the chart, the potential for mass reduction in the short term is very limited; only a 3% reduction in mass is thought to be achievable before 2020, primarily because many of the factors that influence the mass of vans are acting to increase, rather than reduce kerb mass. In the medium term (to 2030), mass reductions of up to 12% are thought to be feasible through the use of alternative materials. In the long term (to 2050), more significant reductions in mass of up to 26% could be achieved, but this relies on the extensive use of fibre-reinforced plastics in the body structure.

Body structure and closures

In the short term (to 2020), the mass of the body structure and closures could be reduced by 39 kg (1.7% reduction in vehicle mass) through changes to the grades of steel used (increased use of AHSS grades). This could be achieved at a cost of €97 per vehicle. In the medium term (to 2030), more significant reductions in mass could be achieved by making the bodyshell and closures from aluminium. This would reduce vehicle mass by 111 kg (4.8% reduction) at a cost of €555 per vehicle. In the longer term (to 2050), significant mass reductions to the body structure and closures could be achieved through the use of carbon fibre reinforced body components. Reductions in mass of more than 220 kg could be achieved, but at very high cost (more than €10,000 per vehicle).

Powertrain

The mass reduction potential for powertrain systems is thought to be quite limited in the short-term and medium term. In particular, more stringent emissions control standards that have required additional exhaust after-treatment equipment mean that overall mass has been increasing. The opportunities for engine downsizing are also currently much more limited for vans, and Ricardo’s analysis indicates that in the short term and medium term, there are no tangible options for reducing the mass of the engine. Small reductions in the mass of the transmission system of around 4 kg (0.2% reduction) could be achieved in the short term at no cost, whilst improvements to the coolant system, changes to the material used for the fuel tank and further design improvements and material changes for the transmission system could be made in the medium term that would yield mass reductions of 20 kg (0.9%) at a cost of €64 per vehicle. In the longer term, engine downsizing becomes available as an option, reducing mass by 36 kg (at zero cost), primarily because significant reductions in mass elsewhere on the vehicle allow the engine to be downsized and downpowered. Additionally, further reductions in mass of around 42 kg could be achieved through the use of alternative materials for key components (e.g. fuel tank and transmission casings made from fibre reinforced plastic, downsized exhaust system, etc).

Chassis system

For the chassis system, design modifications and changes to the grades of steel used in the short term could give savings of around 29 kg (1.2% reduction in vehicle mass) for a cost of €69 per vehicle. In the medium term, a switch to using aluminium for the majority of the chassis components (including brake and suspension components) could yield reductions in mass of 96 kg (4.2% reduction in vehicle mass) at a cost of €504 per vehicle. In the longer term, the use of fibre reinforced plastics for the wheels, and key chassis and suspension components, along with carbon fibre/ceramic brakes could reduce mass by up to 220 kg. However, the costs associated with achieving this level of mass reduction would be exceptionally high at more than €7,800 per vehicle.

Electrical system

Minor reductions in the mass of the electrical system are possible in the short-term at no cost that would give a mass reduction of 1.4 kg (0.06% reduction in vehicle mass). In the medium term, further improvements could give mass reductions of around 4.6 kg (0.2% reduction in vehicle mass) at a cost of €46 per vehicle.

Interior systems

In the short term, the scope for applying mass reduction techniques is very limited, with no options identified. In the medium term, by fitting various lightweight components including seats with magnesium frames, interior trim materials, and dashboard materials could give mass reductions of 37 kg (1.6%) at a cost of €270 per vehicle. In the longer term, mass reduction of around 54 kg could be achieved through the use of fibre-reinforced plastics for components such as seat frames and through the use of polycarbonate glazing. However, the costs of achieving this level of mass reduction for interior systems is estimated to be very high, at more than €2,140 per vehicle.

Summary

The results of this analysis provide an indication of the costs associated with achieving different levels of mass reduction for a large van (5 tonne gross vehicle mass). The key findings are as follows:

- For the 2020 timeframe, reductions in mass of around 3% (74 kg) can be achieved at a cost of €166 per vehicle. This equates to a cost of €2.2 per kg saved.
- For the 2030 timeframe, reductions in mass of around 12% (269 kg) can be achieved at a cost of €1,439 per vehicle. This equates to a cost of €5.4 per kg saved.
- For the 2050 timeframe, reductions in mass of around 25% (590 kg) can be achieved at a cost of €22,123. This equates to a cost of €37.4 per kg saved.

Based on this analysis, the costs of achieving a 25% reduction in vehicle mass are not currently economically viable, primarily because achieving this level of mass reduction would require a significant proportion of the vehicle to be constructed from expensive fibre-reinforced plastics.

8.3.3.1 Costs for reducing the mass of small, medium and large LCVs

Drawing on the above analysis, we have developed estimates for the costs of achieving different levels of mass reduction for small, medium and large LCVs by scaling the values set out above in accordance with typical kerb mass values for Class I, Class II and Class III LCVs. The kerb mass values for the following LCVs were used to represent each of these classes:

- Class I: Ford Transit Courier 1.5 TDi start-stop (kerb mass = 1140 kg)
- Class II: Renault Trafic (kerb mass = 1665 kg)
- Class III: Ford Transit 350 L4 rear-wheel drive van (kerb mass = 2300 kg)

The kerb mass value of the representative Class III LCV is the same as the kerb mass for the typical large 5 tonne van used for the analysis described in the previous section, and hence the same estimates for the potential for, and costs of mass reduction have been used for both types of vehicles. For Class I and Class II LCVs, the absolute levels of mass reduction potential and the associated costs have been scaled down in line with the kerb mass values for the representative Class I and Class II vehicles when calculated as a ratio of the kerb mass of the 5 tonne large vans. For example, for Class I LCVs, costs and mass reduction potential have been estimated by multiplying the results presented in the previous section by a factor of 0.5 (equivalent to 1140 kg divided by 2300 kg). This assumes that mass reduction potential can be scaled with vehicle size, which is an approximation, but within the constraints of this study, we believe that this is an appropriate method to use. The results of this analysis are presented in the table below.

Table 8-10: New estimates for the costs of whole-vehicle mass reduction for light commercial vehicles

	Absolute costs			Unit costs
	Small LCVs	Medium LCVs	Large LCVs	
3% reduction in total vehicle mass	€83	€115	€166	€2.2/kg
12% reduction in total vehicle mass	€719	€1,010	€1,439	€5.4/kg
25% reduction in total vehicle mass	€10,809	€15,053	€22,123	€37.4/kg

We stress that the availability of cost data for reducing the mass of light commercial vehicles is very limited as there have been few studies carried out specifically on this topic.

8.4 Financial benefits of vehicle mass reduction to vehicle users

The previous sections in this chapter have presented new estimates for the incremental costs to vehicle manufacturers of implementing mass reduction strategies. Given that mass reduction leads to improvements in vehicle fuel economy and CO₂ emissions, there will also be reductions in fuel costs for consumers and businesses that use vehicles. In this section, we present estimates for the lifetime impacts of mass reduction on fuel costs for average petrol and diesel cars and for an average diesel light commercial vehicle.

8.4.1 Passenger cars

A 10% reduction in vehicle mass typically yields between 6% and 7% improvement in fuel economy (averaged at 6.5%). Using these figures, in combination with data on typical fuel consumption, CO₂ performance, mass and lifetime mileage for average petrol and diesel cars, it is possible to estimate the total lifetime savings in fuel costs associated with mass reduction and a fuel cost saving per kilogram of mass removed from the vehicle. The tables below present analysis for typical vehicles with average mass (1,390 kg) in line with 2013 data from the CO₂ monitoring database (European Environment Agency, 2013) and lifetime mileage data from a recent study carried out for the European Commission (Ricardo-AEA, 2014). CO₂ performance and the related fuel consumption data for the petrol and diesel vehicle were chosen to be in line with typical values for new medium-sized (C-segment) vehicles on the market today (NEDC values of 120 gCO₂/km for petrol cars and 100 gCO₂/km for diesel cars, equating to 5.2 litres/100 km and 4.8 litres/100 km respectively). The results of this analysis are presented in the tables below; fuel prices have been assumed to be €1.50 per litre.

Table 8-11: Impacts of mass reduction on fuel costs for a typical current (2015) petrol car

Vehicle configuration	Mass (kg)	CO ₂ performance	Fuel consumption (litres/100 km)	Lifetime distance travelled (km)	Lifetime fuel costs (€)
(1) Baseline petrol car	1,390 kg	120 g/km	5.1 l/100 km	150,578	€11,708
(2) 10% mass-reduced petrol car	1,251 kg	112 g/km	4.8 l/100 km	150,578	€10,947
Difference between (1) and (2)	139 kg	8 g/km	0.3 l/100 km	N/A	€761
Unit cost saving per kg mass reduction			€5.5/kg		

Note: Fuel price = €1.50 per litre

For an average petrol car, the lifetime saving in fuel costs is €761 for a vehicle that weighs 10% less than the baseline vehicle. This equates to a unit cost saving of €5.5 per kg mass reduction. We stress that the lifetime fuel cost savings are sensitive to the absolute mass of the baseline vehicle, the specific fuel consumption of the baseline vehicle and the price of fuel. For a baseline vehicle with higher (worse) fuel consumption than the example above, but that has the same baseline mass, the lifetime fuel cost savings (and hence the unit fuel cost saving, in €/kg) would be higher. By contrast, for a baseline vehicle that has the same fuel consumption as the example above in Table 8-11, but that has a higher baseline mass, the unit fuel cost saving (€/kg) would be lower. The results are also sensitive to changes in fuel prices, with higher fuel prices yielding greater cost savings.

Table 8-12: Impacts of mass reduction on fuel costs for a typical current (2015) diesel car

Vehicle configuration	Mass (kg)	CO ₂ performance	Fuel consumption (litres/100 km)	Lifetime distance travelled (km)	Lifetime fuel costs (€)
(1) Baseline diesel car	1,390 kg	100 g/km	3.8 l/100 km	219,934	€12,544
(2) 10% mass-reduced diesel car	1,251 kg	93 g/km	3.5 l/100 km	219,934	€11,728
Difference between (1) and (2)	139 kg	7 g/km	0.3 l/100 km	N/A	€815
Unit cost saving per kg mass reduction				€5.9/kg	

Note: Fuel price = €1.50 per litre

Table 8-12 above presents equivalent analysis for a typical diesel car. The lifetime mileage for diesel cars is significantly higher than for petrol cars (Ricardo-AEA, 2014), but the baseline fuel consumption is significantly lower. The resultant unit cost saving associated with mass reduction for a typical diesel car is €5.9/kg. A typical diesel car is 40-60 kg heavier than an equivalent petrol car but for the above example, we have not taken this into account. If we were to assume a baseline vehicle mass of 1,450 kg (i.e. 60 kg heavier), the unit fuel cost saving for mass reduction would decrease to €5.6/kg.

Rerunning the analysis presented above to take into account likely improvements in fuel efficiency and tailpipe emissions that will occur between now and 2020, we can see that the value of mass reductions to consumers will decline as overall fuel efficiency improves. The table below provides an example of the cost savings associated with a typical 2020 petrol passenger car with the same mass as in the examples above, but with tailpipe emissions of 95 gCO₂/km.

Table 8-13: Impacts of mass reduction on fuel costs for a 2020 petrol car

Vehicle configuration	Mass (kg)	CO ₂ performance	Fuel consumption (litres/100 km)	Lifetime distance travelled (km)	Lifetime fuel costs (€)
(1) Baseline petrol car	1,390 kg	95 g/km	4.1 l/100 km	150,578	€9,269
(2) 10% mass-reduced petrol car	1,251 kg	89 g/km	3.8 l/100 km	150,578	€8,666
Difference between (1) and (2)	139 kg	6 g/km	0.3 l/100 km	N/A	€603
Unit cost saving per kg mass reduction				€4.3/kg	

Note: Fuel price = €1.50 per litre

As can be seen from the table, by 2020, the unit fuel cost savings associated with mass reduction drop from €5.5/kg to €4.3/kg for a typical petrol car. Similar reductions will also occur for diesel cars.

8.4.2 Light commercial vehicles

The same type of analysis was carried out for a typical light commercial vehicle. For this scenario, a typical diesel LCV was analysed with a mass of 1,850 kg, which is in line with the sales-weighted average mass for LCVs registered in 2012 (European Environment Agency, 2013b). The lifetime mileage was taken from previous research carried out for the European Commission on LCVs (TNO *et al*, 2012), which assumed an annual mileage of 23,500 km and a total vehicle lifetime of 13 years. Tailpipe CO₂ emissions for the baseline vehicle were assumed to be 175 gCO₂/km, which equates to 6.7 litres/100 km. The results of this analysis are presented in Table 8-14.

Table 8-14: Impacts of mass reduction on fuel costs for a typical current (2015) diesel LCV

Vehicle configuration	Mass (kg)	CO ₂ performance	Fuel consumption (litres/100 km)	Lifetime distance travelled (km)	Lifetime fuel costs (€)
(1) Baseline diesel LCV	1,761 kg	175 g/km	6.7 l/100 km	305,500	€30,492
(2) 10% mass-reduced diesel LCV	1,585 kg	164 g/km	6.2 l/100 km	305,500	€28,510
Difference between (1) and (2)	176 kg	11 g/km	0.5 l/100 km	N/A	€1,982
Unit cost saving per kg mass reduction			€11.3/kg		

Note: Fuel price = €1.50 per litre

As can be seen from Table 8-14, the unit cost saving per kg mass reduction, at €11.3 per kg, is significantly higher for LCVs than for passenger cars. This is due to the higher (worse) fuel consumption of LCVs compared to cars and the much greater lifetime distances travelled by these types of vehicles, which together mean that total lifetime fuel consumption is much greater than for passenger cars.

Table 8-15: Impacts of mass reduction on fuel costs for a 2020 diesel LCV

Vehicle configuration	Mass (kg)	CO ₂ performance	Fuel consumption (litres/100 km)	Lifetime distance travelled (km)	Lifetime fuel costs (€)
(1) Baseline diesel LCV	1,850 kg	147 g/km	5.6 l/100 km	305,500	€25,787
(2) 10% mass-reduced diesel LCV	1,665 kg	137 g/km	5.3 l/100 km	305,500	€24,111
Difference between (1) and (2)	185 kg	10 g/km	0.3 l/100 km	N/A	€1,676
Unit cost saving per kg mass reduction			€9.5/kg		

Note: Fuel price = €1.50 per litre

Table 8-15 presents the results of analysis on fuel cost savings associated with mass reduction for a 2020 diesel LCV that has CO₂ emissions performance of 147 gCO₂/km. As for passenger cars, the value of fuel cost savings associated with mass reduction declines between now and 2020, in this case dropping to approximately €9.1 per kg.

It should be stressed that for LCVs, our analysis in Section 8.3 indicates that achieving a 10% reduction in mass by 2020 could be challenging, and that a 3% reduction in mass is more feasible for the period between now and 2020. Whilst this doesn't change the unit cost saving per kg mass reduction, it would reduce the total savings in lifetime costs experienced by vehicle users. A 3% reduction in mass would give lifetime fuel cost savings of €595 for a 2015 LCV, and lifetime fuel cost savings of €503 for a 2020 LCV.

8.4.3 Summary

The foregoing analysis shows that there are useful fuel cost savings for vehicle users associated with mass reduction for both cars and LCVs. The absolute levels of cost savings are dependent on a number of factors including baseline vehicle mass, baseline vehicle fuel consumption, levels of mass reduction achieved, lifetime distance travelled and fuel prices. The examples above show that the level of fuel cost saving per kg mass reduction is much higher for light commercial vehicles than it is for passenger cars; this is due to significant differences in the mass, fuel consumption performance and lifetime mileages travelled by these types of vehicles compared to passenger cars.

The analysis shows that the value of fuel cost savings for vehicle users will decline in future years as vehicle manufacturers make cars and vans more fuel efficient in response to the LDV CO₂ Regulations. For passenger cars, the unit cost savings associated with vehicle mass reduction (€/kg) are likely to decline by around 20% between 2014 and 2020, whilst for LCVs, the unit cost savings are likely to decrease by approximately 15%.

9 Comparison of the impacts and costs of using mass and footprint as a utility parameter

9.1 Overview

The current CO₂ emissions performance targets for passenger cars and light commercial vehicles in the EU are based on a linear target line, which directly relates the CO₂ emissions of a vehicle (and also each manufacturer's target) to vehicle mass in running order (the utility parameter). As discussed in Chapter 4, the use of mass as the utility parameter has the potential to disincentivise mass reduction as a means for reducing vehicle CO₂ emissions. Using footprint as an alternative utility parameter avoids these issues. The objective of this chapter is to compare the impacts and costs of using (i) mass and (ii) footprint as the utility parameter in the car CO₂ regulations.

TNO *et al* (2011) carried out previous work on this topic; this new research uses that previous work as a starting point and develops it further using new information on costs and the potential for vehicle mass reduction gathered over the course of this study.

The research presented in this chapter assesses impacts and costs in the context of possible post-2020 CO₂ targets for light duty vehicles. Such targets will also be based on emissions tests conducted using the World-harmonised Light-duty Test Protocol (WLTP), which will replace the New European Drive Cycle in the coming years; with this in mind, the possible post-2020 targets used were based on the WLTP procedure. Targets beyond 2020 (or 2021 for cars) have yet to be set and all of the analysis presented below is performed using hypothetical future targets for light duty vehicles. Hence, the results and charts published here are for illustrative purposes only. Appendix 6 explains how vehicle simulation techniques were used to estimate the impacts of the WLTP on CO₂ emissions and targets for vehicles fitted with different technologies.

The remainder of this chapter is structured as follows:

- Section 9.2 identifies the effort required for vehicle manufacturers to achieve possible post-2020/21 CO₂ targets under regulatory systems that use (a) mass and (b) footprint as the utility parameter;
- Section 9.3 examines the additional cost per vehicle for manufacturers to reach these targets; and
- Section 9.4 sets out the conclusions of the research presented in this chapter.

9.2 Comparison of efforts needed by manufacturers to achieve possible post-2020 CO₂ reduction targets

9.2.1 Overview

The aim of this section is to demonstrate how the level of abatement effort required by manufacturers to meet their illustrative post-2020 WLTP-based CO₂ targets might differ depending on whether 'mass' or 'footprint' is used as the utility parameter. For a truly robust analysis of the impacts on manufacturers of using 'mass' and 'footprint', multiple slopes would need to be evaluated to enable a thorough understanding of the differences. As noted above, all of the numbers presented in this section should be taken to be indicative only.

9.2.2 Definition and level of effort required to achieve post-2020 car CO₂ targets

In defining the hypothetical post-2020/21 target line, the same approach was taken as when the 2020 target line was identified in the Impact Assessment for the 2020 modalities. In other words, an "equal effort" measure was adopted whereby the post-2021 target line was defined simply by lowering all points on the 2021 target line by the percentage reduction in the overall post-2021 target compared to the 2021 target of 95 gCO₂/km. For footprint, the situation was more complex since a target line for 'footprint' has never been defined in legislation. In the impact assessment for the 2020 modalities, a footprint slope was defined (European Commission, 2007), although this was based on a slope for a mass-based system in 2015, which was not the one used in the eventual Regulation. Hence, it was necessary to

scale the slope of this ‘footprint’ target line to the correct 2015 slope and then take the same approach with this slope line as with a mass based system (i.e. the 2021 footprint slope is defined by reducing every point on the 2015 line by the percentage reduced from 2015 to 2021 for a mass based system and then reduced again to reach the post 2020/21 slope using the same approach). As the respective targets are hypothetical, their values are not explicitly stated in this report.

As noted in Section 9.1, the current NEDC values were translated to WLTP values using vehicle simulation techniques and these were compared for each vehicle manufacturer to a hypothetical future post 2020/21 WLTP target. The analysis was conducted for both mass-based and footprint-based utility parameters.

Bubble plot charts showing individual manufacturer positions and manufacturer pool positions relative to a possible post 2020/21 target line are provided in Figure 9-2. Looking at the distance (or effort) to target (Figure 9-1) it can be seen that seven manufacturers would benefit from a footprint based system. The overall effort across all manufacturers is the same when comparing the two utility parameters. This is because the two slopes (mass and footprint) have been defined to achieve the same overall reduction in emissions.

Figure 9-1: Effort to achieve post 2020/21 target for passenger cars

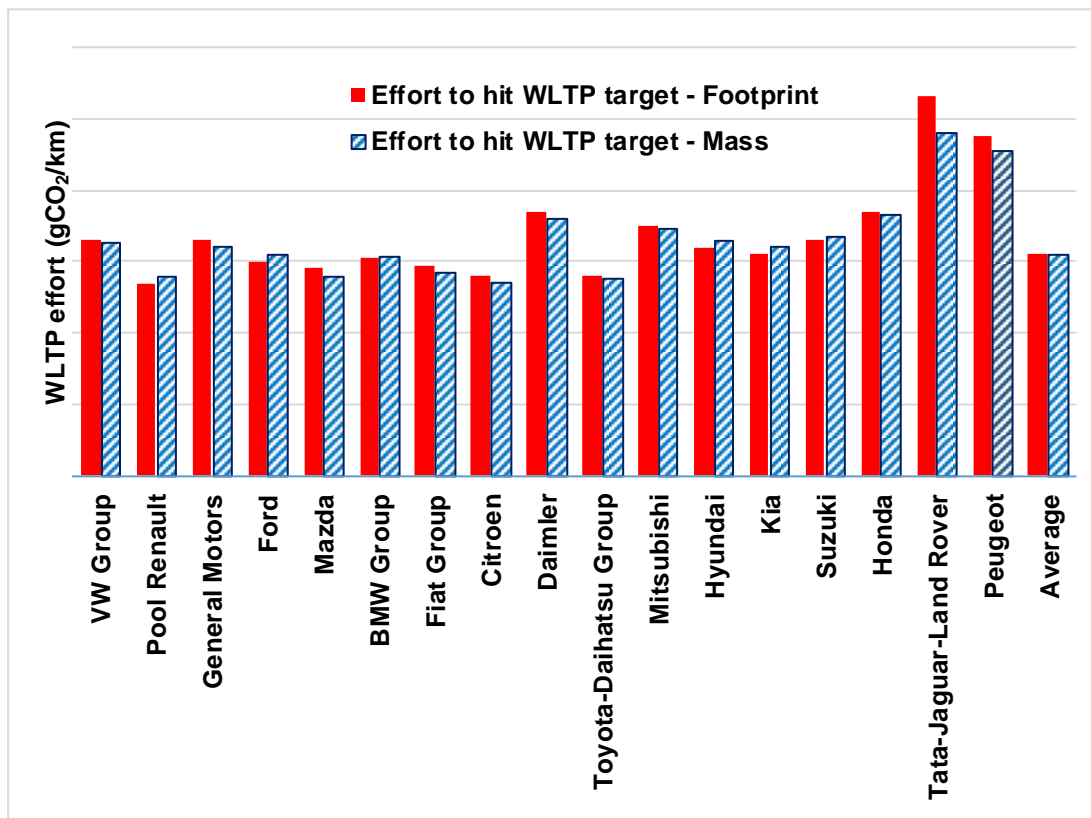
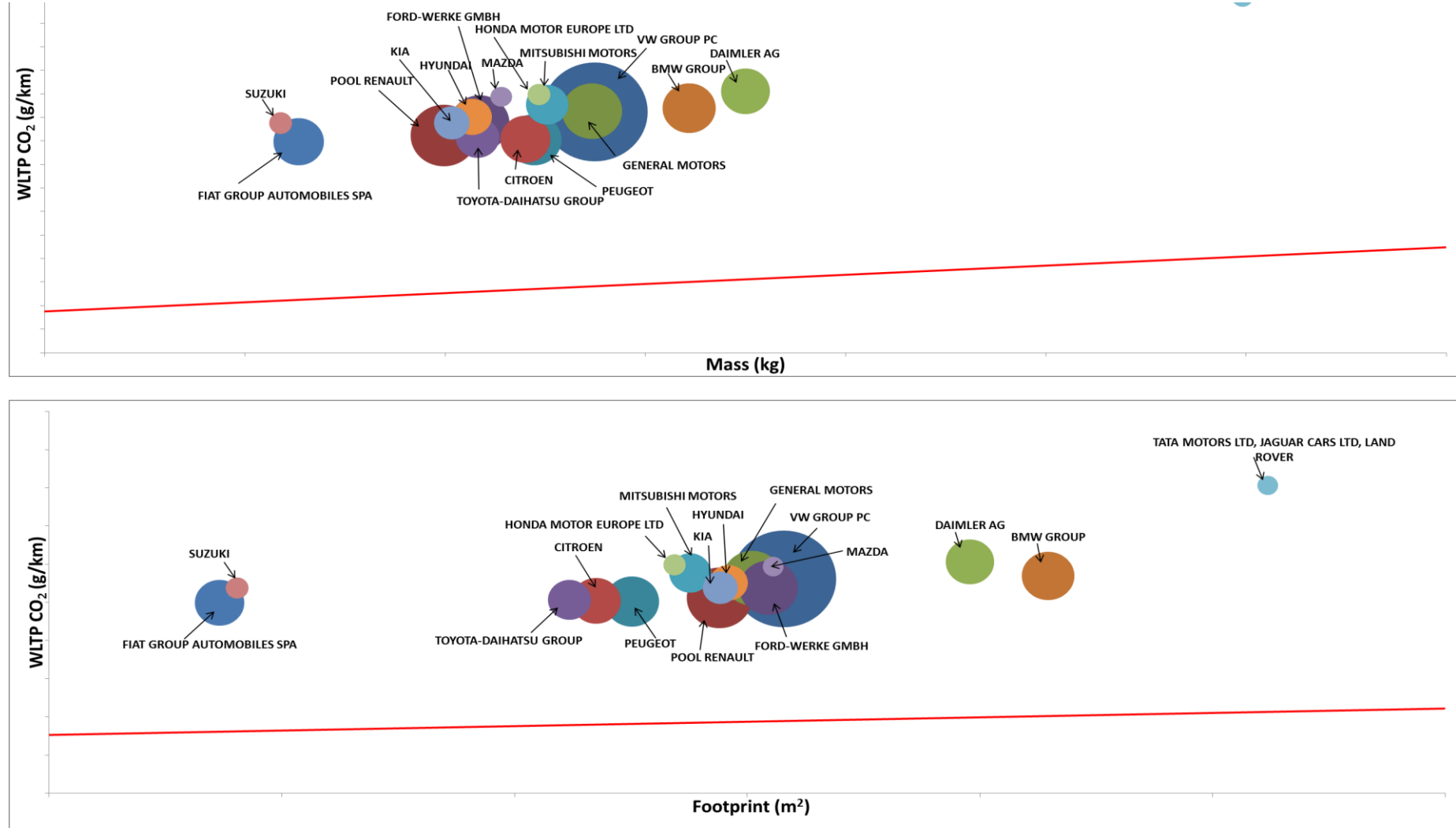


Figure 9-2: Comparison of relative positions of passenger car manufacturer groupings under a mass based (upper diagram) and footprint based (lower diagram) utility parameter



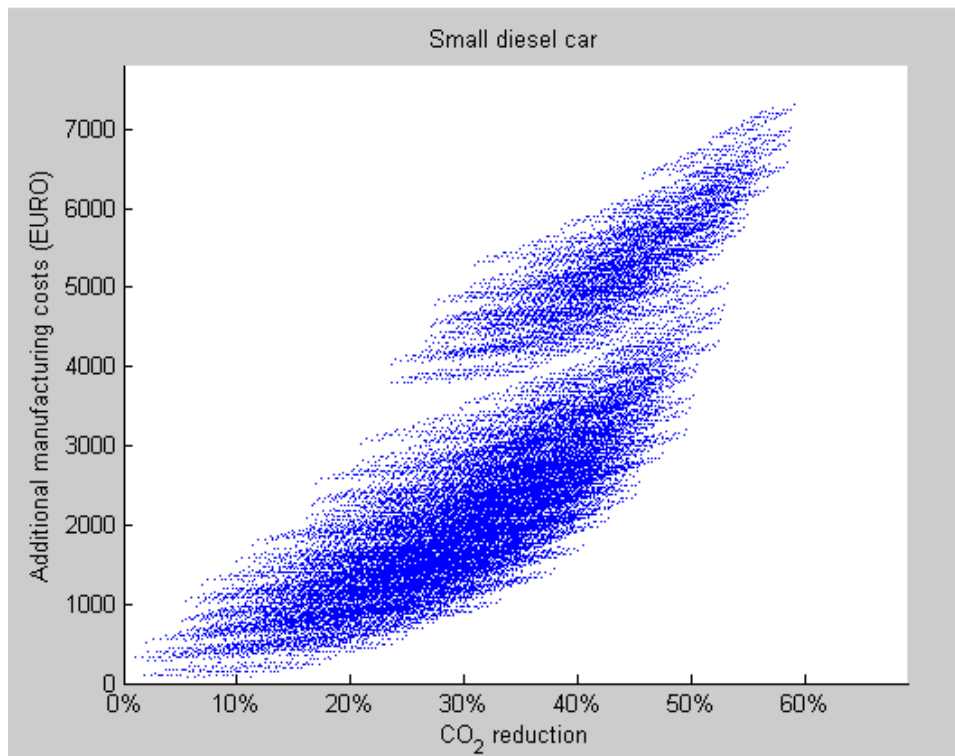
9.3 Comparison of costs that might be incurred by manufacturers in achieving possible post-2020 CO₂ reduction targets

The aim of this section is to demonstrate how the costs incurred by manufacturers in meeting their respective post-2020 targets might differ depending on whether ‘mass’ or ‘footprint’ is used as the utility parameter.

9.3.1 Methodology to calculate costs to achieve possible post 2020/21 targets

The methodology used to calculate the total costs for achieving possible post 2020/21 targets was based on TNO *et al* (2011), but used a modified list of technical options for reducing CO₂ emissions from cars (see Appendix 7). The costs for each technology option (aside from vehicle mass reduction) were taken directly from TNO *et al* (2011). The costs for mass reduction used were those presented in Chapter 8 of this report, which were developed from the research carried out over the course of this study. On the basis of these costs, Ricardo-AEA’s in-house vehicle technology cost curve tool was used to produce new cost curves using these updated lists of technological options. The cost curve tool was then used to analyse all feasible combination of technologies²⁴ to create “packages” (or groups) of individual technologies. This analysis produced a large number of possible technology packages, each with different overall CO₂ reduction potentials and costs which were used as the basis for developing the new cost curves. The theory behind this analysis is straightforward and is explained in the Appendix 7. An illustrative example of the output chart of such analysis is show below in Figure 9-5.

Figure 9-5: Cost cloud illustrative example



²⁴ Exclusions criteria for all technologies can be found in Appendix 8

The baseline passenger car data used for this analysis were taken from the 2012 EEA CO₂ monitoring database (European Environment Agency, 2013a). After an extensive cleaning process to remove unnecessary and invalid data, the remaining 85% of passenger car registrations from the database were retained for further analysis. Each vehicle from the database was assigned to one of the six vehicle segments that have previously been used for cost curve analysis of the Regulations (i.e. three size categories (small, medium and large cars), with two fuel types (petrol, diesel) for each of the size categories).

Baseline NEDC CO₂ emissions for each vehicle were taken from EEA database and sales-weighted average CO₂ values were calculated for each car segment. These baseline NEDC CO₂ values for each segment were then translated into WLTP CO₂ values using the results of vehicle simulation work carried out using the PHEM model (see Appendix 6 for more details). The CO₂ emissions abatement performance values for each of the technical options were also translated from the NEDC to the WLTP using the results of the PHEM simulation analysis.

The baseline WLTP CO₂ sales-weighted average emissions values for each vehicle segment are presented in the tables below.

Table 9-1: Baseline sales-weighted WLTP-based CO₂ emissions performance for each car segment

Baseline values	Petrol, Small	Petrol, Medium	Petrol, Large	Diesel, Small	Diesel, Medium	Diesel, Large
WLTP CO ₂ emissions (g/km)	141.0	163.9	191.8	127.3	151.1	174.6
Vehicle Mass (kg)	1084.1	1421.8	1700.2	1241.9	1578.5	1898.0
Vehicle Footprint (m ²)	3.6	4.1	4.4	3.7	4.2	4.6

Using the baseline data as well as the costs and performance data for each technology option, a “cloud” matrix of possible vehicle configurations for achieving different levels of CO₂ emissions reductions can be generated for each vehicle segment (similar to Figure 9-5). Once the “cloud” has been generated, the cost curve is defined by its lower horizon. The lower horizon is described by a set of anchor points defined as the lowest cost at specified CO₂ reduction potentials. This process assumes that manufacturers will always choose the cheapest method to achieve the maximum CO₂ reduction.

The final cost curve is defined using the concept of a safety margin. This takes into account the first order nature of the CO₂ reduction potential equation which may overestimate the overall reduction achieved by two measures that target the same losses. This safety margin is defined in Box 9-1.

Box 9-1: Definition of the safety margin

To obtain the final cost curve, the x-value (percentage reduction in CO₂ emissions) of every anchor point on the lower horizon is multiplied by (1 – β) with β linearly scaling from zero to its maximum value between x = 0 and the maximum reduction potential indicated by the outer envelope. This creates a set of anchor points for the cost curve. This study assumes a β of 0.85 for petrol cars and 0.95 for diesel cars and vans as in TNO *et al* (2011).

Once the final cost curve is defined a polynomial function can be fitted to the curve. These polynomials take the form:

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

With x the CO₂ reduction in % and y the additional manufacturer costs in Euros.

The form of this polynomial function ensures that the curves pass through the origin and increase monotonically.

9.3.2 Cost curves for passenger cars

A summary of the cost curves for passenger cars is presented in Figures 9-6 and 9-7, with information on the maximum abatement potential presented in Table 9-3.

Figure 9-6: Summary of cost curves for petrol passenger cars

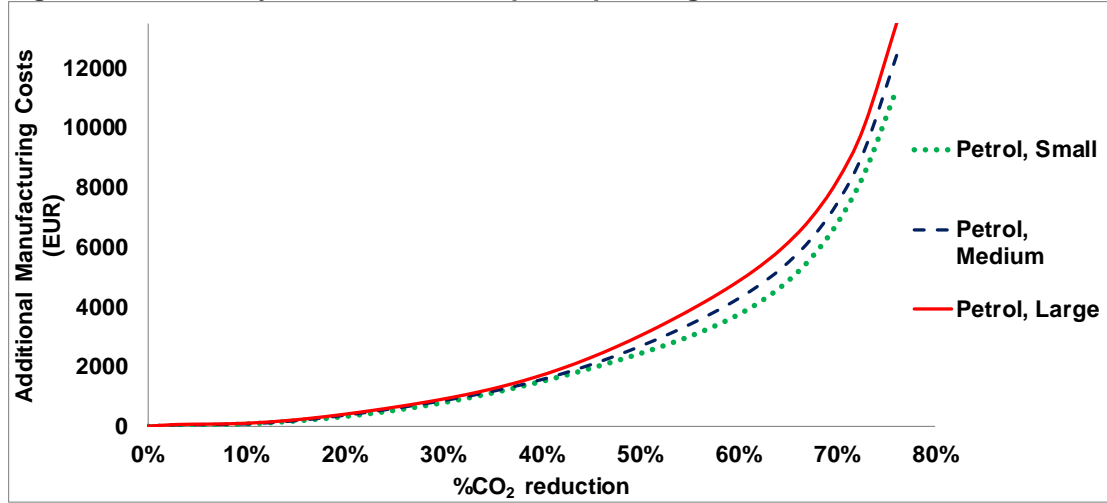


Figure 9-7: Summary of cost curves for diesel passenger cars

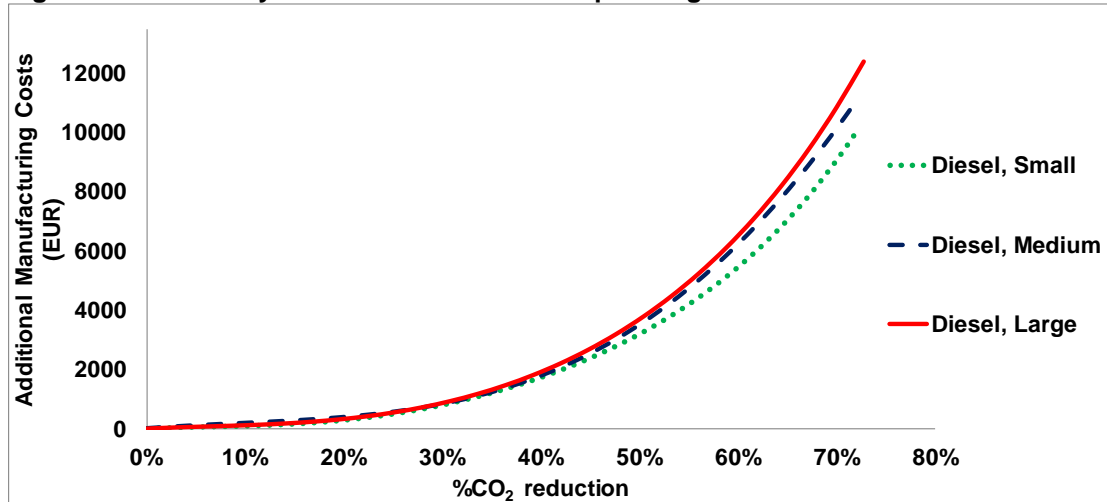


Table 9-3: Maximum CO₂ abatement and associated cost for each car segment

Vehicle segment	PS	PM	PL	DS	DM	DL
Max CO ₂ reduction against baseline values (%)	75.8%	76.1%	76.4%	71.8%	72.2%	72.8%
Cost for achieving maximum CO ₂ reduction (EUR)	€ 11,100	€ 12,450	€ 13,890	€ 9,910	€ 11,150	€ 12,400

Note: PS = small petrol; PM = medium petrol; PL = large petrol; DS = small diesel; DM = medium diesel; DL = large diesel

9.3.3 Estimated costs associated with meeting a possible post 2020/21 targets for passenger cars

Using the above cost curve analysis, the costs associated with achieving possible post-2020/21 CO₂ targets for cars and light commercial vehicles can be estimated for each vehicle manufacturer. The analysis was used to estimate the differences in such costs depending on

whether mass or footprint is used as the utility parameter. The methodology for this analysis had to take into account the fact the baseline vehicles used in this analysis may already include some of the technologies that are being analysed. To counter this issue, it was necessary to re-define the origin along the x-axis of the cost curves (see Box 9-2).

Box 9-2: Redefinition of the origin on the x-axis of the cost curves

The baseline passenger cars used in TNO et al (2011) were compared to the baseline vehicles used in this study. The emissions performance of the previous baseline vehicles was first translated to WLTP using the translation function to perform this comparison and for each segment; the percentage difference between the two baselines is the point at which the new origin on the cost curves is defined.

For example, the CO₂ emissions performance of the previous baseline vehicle for a small petrol passenger car was around 14% higher than the baseline vehicle used in this study. Therefore the new origin for the small petrol passenger car cost curve is 14% along the x-axis.

In addition to redefining the origin, we have also taken NEDC test cycle flexibilities into account. Research shows that over the last few years, part of the reduction observed in the CO₂ emissions of new cars in Europe may not be attributable to the application of identifiable CO₂ reducing technologies. For passenger cars it is estimated that the potential CO₂ reduction in 2010 due to additional use of flexibilities since 2002 is around 11% (TNO et al, 2012b).

To estimate the costs for achieving the post-2020/21 targets, it was necessary to look at each manufacturer individually, analyse their fleets according to the EEA CO₂ monitoring database and use optimisation methods to calculate the minimum cost to reach the manufacturer-specific targets using data from the segment-specific cost curves.

To do this accurately for both a mass-based system and a footprint-based system, two different sets of cost curves were used. The reason for this is to account for the anomaly that exists in mass based target systems whereby technical options for reducing vehicle mass are not fully credited (see Chapter 4 for further information).

The two sets of cost curves used were as follows:

1. **Cost curves that fully credit the CO₂ improvements associated with vehicle mass reduction (shown above in Figures 9-6 and 9-7).** These cost curves were used to calculate the costs associated with meeting the post-2020/21 CO₂ targets for each manufacturer under a regulatory system where footprint is used as the utility parameter.
2. **Cost curves that do not fully credit vehicle mass reduction** (although note that vehicle mass reduction is not completely discounted). This approach was used to calculate the costs associated with meeting the post-2020/21 CO₂ targets for each manufacturer under a regulatory system where mass is used as the utility parameter.

Figure 9-8 presents the estimated additional costs per vehicle for each car manufacturer to meet possible post 2020/21 targets under possible future regulatory systems that use (a) mass and (b) footprint as the utility parameter. The results indicate that the total costs associated with meeting the target for passenger cars are more than 16% lower under a footprint-based system than under a mass-based system. A footprint-based CO₂ regulatory structure would therefore be expected to result in significantly greater benefits for society than the current mass based system. Only one manufacturer (Tata/Jaguar/Land Rover pool) would incur higher compliance costs under a footprint-based CO₂ regulatory system. Given the large size of vehicles in this manufacturer's fleet, this result was to be expected. For all other manufacturers, there would be significant cost savings associated with a footprint-based regulatory system. As can be seen from Figure 9-9, costs would be between 8% and 20% lower depending on the manufacturer.

Figure 9-8: Estimated marginal costs for each manufacturer to achieve possible post-2020/21 CO₂ targets for passenger cars under regulatory systems where (a) mass is the utility parameter and (b) footprint is the utility parameter

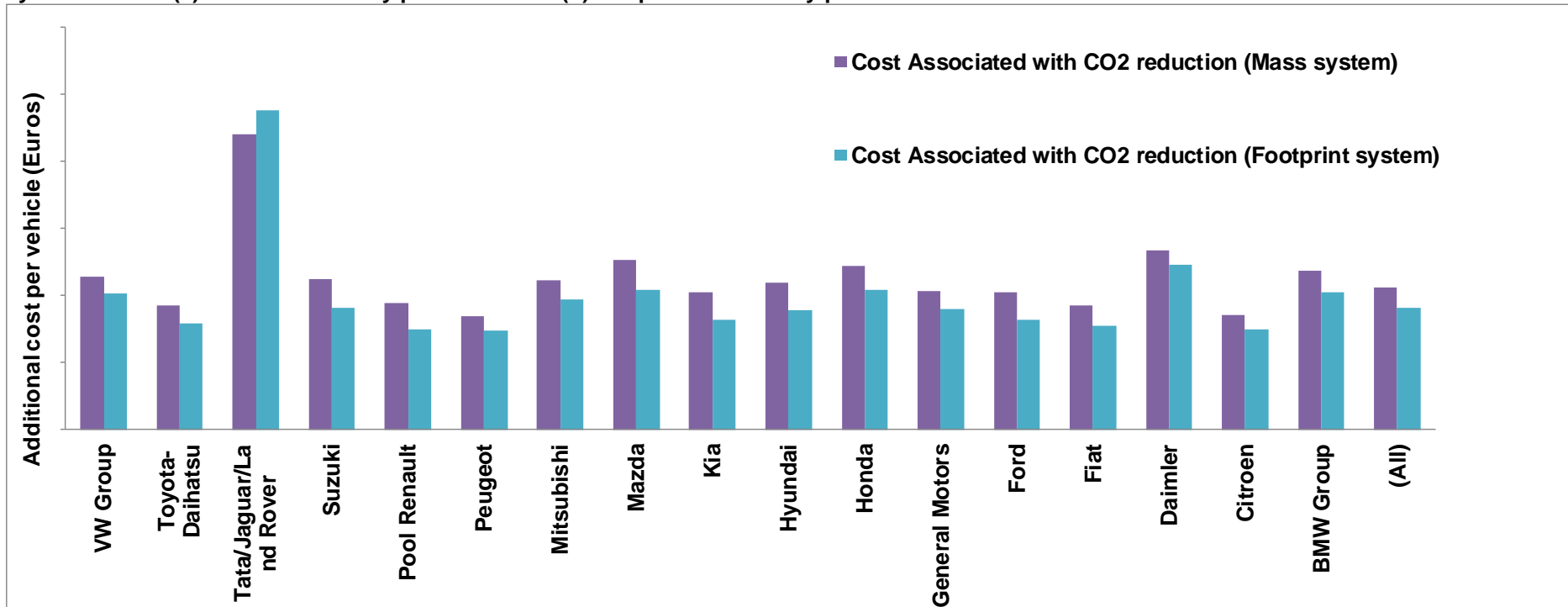
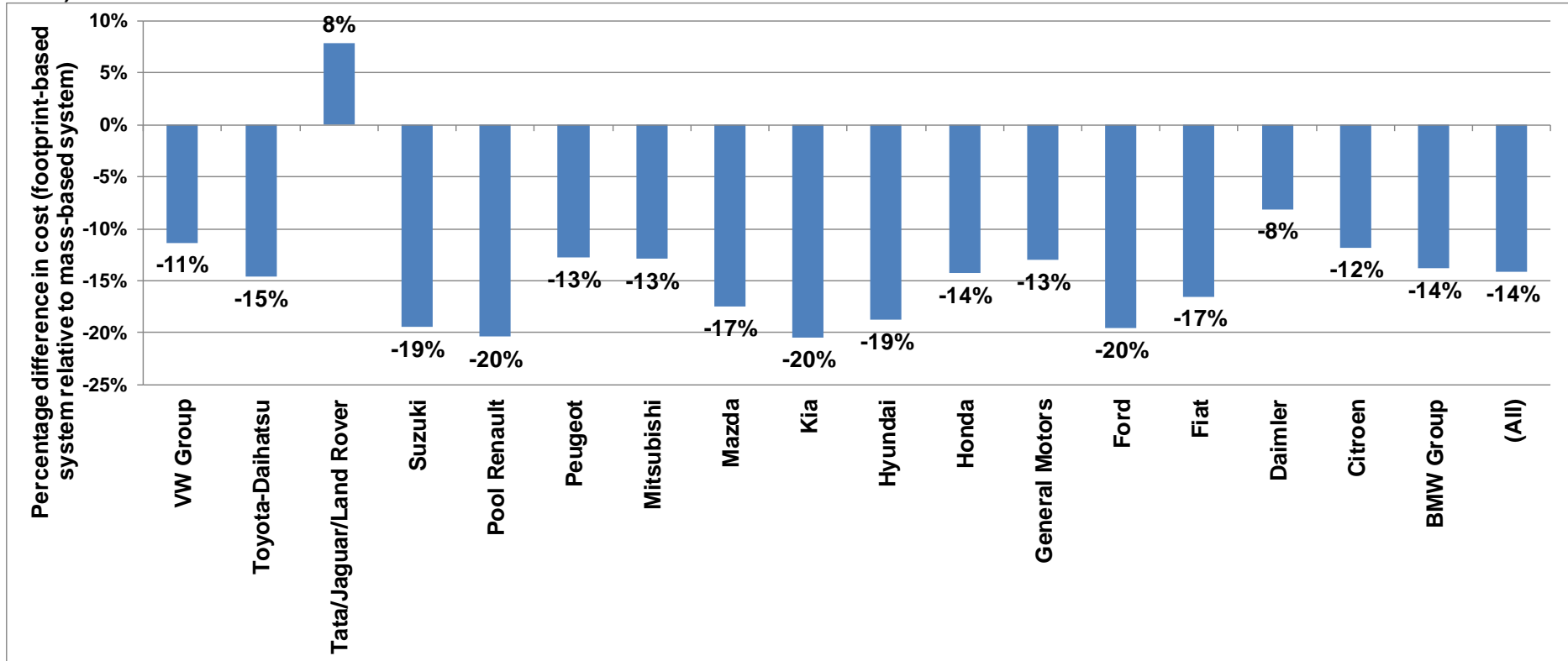


Figure 9-9: Percentage difference in costs to achieve possible post-2020/21 car CO₂ targets for a regulatory system where footprint is the utility parameter relative to a regulatory system where mass is the utility parameter (negative numbers indicate that footprint-based approach has lower costs)



9.4 Summary

Chapter 4 of this report showed how the current CO₂ regulatory system for light duty vehicles disincentivises the take-up of vehicle mass reduction measures because the CO₂ benefits of such measures are not fully rewarded. This chapter has taken the findings from Chapter 4 and examined the cost implications for each car manufacturer associated with meeting possible post-2020/21 CO₂ targets under future CO₂ regulatory systems that use (a) mass and (b) footprint as the utility parameter. The key finding from this research is that the cost to manufacturers for achieving the possible future CO₂ target would be 14% lower if the car CO₂ Regulation used footprint instead of mass as the utility parameter; for all manufacturers except one, costs would be between 8% and 20% lower under a footprint-based system. The one manufacturer that would be faced with increased costs under a footprint-based system is the Tata/Jaguar/Land Rover pool, where costs are likely to be 8% higher.

10 Alternative options for ensuring that vehicle mass reduction is as attractive as other CO₂ reduction options

10.1 Overview

The aim of this section is to identify and evaluate options for making mass reduction technologies as attractive to manufacturers as other CO₂ reduction options if a mass-based utility parameter remains in place beyond 2020. This is potentially important as it may be difficult to get agreement from all relevant parties to move from a mass-based utility parameter to a footprint-based parameter for the post-2020 targets. Additionally, as noted in Section 4.2, when 'mass' is the utility parameter, any manufacturer applying technologies to reduce the mass, and therefore the CO₂ emissions, of its vehicle fleet would not benefit in full (in terms of moving closer to its target) from such an approach. Indeed, having 'mass' as the utility parameter disincentivises manufacturers from applying mass reduction technologies. Hence, if 'mass' was retained as the utility parameter post-2020, alternative methods would be required so as not to discourage manufacturers from applying mass reduction technologies.

The work was undertaken in three stages:

- **Literature review/stakeholder consultation:** An extensive review of the wider literature was undertaken, supported by the stakeholder consultation, to identify possible measures that might be implemented to make mass reduction technologies as attractive to manufacturers as other CO₂ reduction options.
- **Evaluation of a long-list of possible options against important conditions:** On the basis of the literature review and suggestions from stakeholders, a long-list of possible options was evaluated against a set of conditions that it was considered important for any additional option to meet. This resulted in a short-list of possible options.
- **Detailed assessment of a short-list of options:** This was undertaken against the standard list of assessment criteria used by the Commission in Impact Assessments, to identify whether there was a preferred option.

The long-list and short-list of options, as well as the respective evaluations and assessments, were developed in an iterative fashion within the project, which included sharing draft findings with the Commission. The sections below present the conclusions with respect to each of the stages of the work listed above.

10.2 Long-list of options identified as a result of the literature review and stakeholder consultation

Various scenarios might be foreseen post 2020 in the event that mass is retained as the utility parameter:

- The introduction of mass reduction technology occurs and the mass of LDVs declines.
- The introduction of mass reduction technology occurs, but the mass of LDVs does not decline and even increases.
- Mass reduction technology is not introduced and the mass of vehicles does not decline or even increases.

In the first and second scenarios, additional options to make mass reduction as attractive as other CO₂ reduction technologies might still be appropriate if either mass reduction technology is not being used to its full potential and/or (some of) the mass reduction benefits associated

with such technologies are being lost due to the addition of more features that increase the mass of vehicles. Hence, for all of the above scenarios, it might be useful to explore whether there are other options that might be introduced to make mass reduction technologies as attractive as other CO₂ reduction technologies.

Additional options could aim to make mass reduction options as attractive as other CO₂ reduction options by:

- Easing the requirements of the Regulation for those that introduce mass reduction measures.
- Making the requirements of the Regulation more stringent for those that do not introduce mass reduction measures.
- Introducing new elements to the Regulations.
- Introducing – or amending – complementary EU legislation.
- Introducing – or amending – complementary national/regional legislation.

To identify potential options that might be used to incentivise mass reduction, a literature review was undertaken of studies and legislation that focused on improving the energy consumption or CO₂ emissions of:

- Vehicles around the world, which included studies and legislation relating to both light and heavy duty vehicles
- Products covered by EU legislation on energy consumption

The starting point for the literature review was the range of flexibilities that are in place in the existing car and LCV CO₂ Regulations. The most relevant ones are listed below, along with an initial assessment of the potential to use these for the purposes of making mass reduction as attractive as other technologies:

- **Manufacturers are allowed to average their emissions performance across their entire fleet as a limit function is used to define their fleet-wide target.** The limit function is used to identify each manufacturer's CO₂ target by relating the average mass of each manufacturer's new vehicle fleet to that of the overall CO₂ target and the average mass of the entire new vehicle fleet. ***It might be possible to introduce a weaker (or more stringent) target for a manufacturer that applies (or does not apply) specified mass reduction technologies.***
- **Eco-innovations.** These aim to capture measurable CO₂ reductions associated with a particular innovation that are not captured in the test cycle. Mass reductions would be captured by the test cycle even where 'mass' is used as the utility parameter. If a manufacturer could demonstrate "additional" benefits of mass reduction (i.e. that are not fully captured in the test cycle) it could seek credit for an eco-innovation. Other than the requirement for the technology to be innovative, there is no barrier to manufacturers doing this anyway, so it is not clear how eco-innovations, in the format used in the Regulations, might be used to further incentivise mass reduction.
- **Super credits.** These allow vehicles emitting less than 50 gCO₂/km to be counted as more than one vehicle. ***It might be possible to use some form of a credit or a debit to ensure that mass reduction is as attractive as other CO₂ reduction technologies,*** e.g. a credit could be given for vehicles weighing less than a certain amount; or where a manufacturer is able to demonstrate a significant reduction in the mass of its new vehicle fleet; or for vehicles using a specified mass reduction technology. The latter might be justified for technologies that have CO₂ reductions that are not fully accounted for on the test cycle.
- **Different approaches to estimating CO₂ reduction targets for small manufacturers.** It is not clear how options focusing on smaller manufacturers might be relevant to making mass reduction options as attractive as other CO₂ reduction options. More generally, the case where a derogation is given to a manufacturer taking action on mass reduction is discussed above.

- **Pooling.** This allows manufacturers to pool with other manufacturers to meet a joint target and thus reduce marginal costs and improve cost-effectiveness. It is not clear how this might be amended to make mass reduction options as attractive as other CO₂ reduction options.

The review of other vehicle CO₂ reduction legislation around the world yielded little in the way of additional ideas for options. In a review of schemes, IEA (2012) identified a number of potential flexibilities, including some, such as super-credits and special regulations for small manufacturers, mentioned above. Additional flexibilities identified included the banking of credits, under which overachievement in a particular year can be 'banked' for (usually a limited number of) future years, and trading credits, where a manufacturer that overachieves in a particular year can trade the overachievement with a manufacturer that has underachieved²⁵.

In the US, the LDV fuel economy and GHG standards covering the period 2017 to 2025 include a number of flexibilities that are similar to those in the EU Regulations. These flexibilities include provisions for smaller manufacturers to set alternative CO₂ standards, multipliers for electric and gas vehicles along the lines of the EU's super-credits and off-cycle credits that are similar to the EU's eco-innovations. The US Regulations also allow for the banking and trading of credits. Credits can be banked for up to five years or carried back over three years to cover previous underachievement, while credits can also be traded between companies²⁶. These are similar to flexibilities in place for the 2012-2016 standards in the US. Studies supporting the development of the Regulations in the EU have not ruled out the possibility of allowing the banking and borrowing (but not trading) of credits, as this was considered to be a flexibility that enabled the overall target to be met in a more cost-effective manner (TNO *et al*, 2011²⁷).

The LDV fuel economy and GHG standards for California, Canada and Mexico are aligned with the federal US standards, and so contain similar flexibilities, although the flexibilities in Mexico are more generous. In Japan, vehicles in different categories are set different emission reduction targets; the main flexibility allows each manufacturer to accumulate credits in a particular mass category that can be used to make up for underachievement in another category, which is analogous to the averaging allowed by the EU Regulations. In South Korea, credits can be gained for introducing selected driving aids, such as tyre pressure monitoring systems, while there is also a credit available for eco-innovations similar to that in place in the EU. The equivalent Chinese legislation awards credits similar to super-credits for vehicles with certain levels of fuel consumption and ranges (for electric vehicles), as well as allowing the banking of credits for up to three years²⁸. From this discussion, it appears that an additional flexibility of relevance might be **to allow the banking of credits for those manufacturers that demonstrate appropriate levels of mass reduction.**

As noted above, within the context of the work undertaken for this section of the report, it has been assumed that 'footprint' will not be the utility parameter on the basis of which post-2020 targets for cars will be calculated. Consideration was given to whether 'footprint' might be used in some form as part of an option to make mass reduction technologies as attractive as other CO₂ reduction technologies. As using an option that contained 'footprint' on its own would have little impact on the mass of a car, it was considered how 'footprint' might be combined with 'mass' as a measure that might be used in the context of an additional option. The conclusion was to combine the two measurements to create a measure of 'density', defined as mass over footprint (and so measured in kg/m²). It was considered that the **most appropriate use of 'density' would be in some form of credit**, and so a number of relevant options were explored.

The review of complementary measures did not identify any good candidates for legislation that might be adapted, or new legislation that might be introduced, to make mass reduction as attractive as other CO₂ reduction technologies, other than by encouraging CO₂ emissions reductions. From the perspective of EU legislation, the CO₂/fuel efficiency label is targeted at consumers and although it indirectly affects manufacturers, it is difficult to see how any inclusion

²⁵ IEA (2012) *Improving fuel economy of road vehicles*

²⁶ EPA (2012) EPA and NHTSA set standards to reduce greenhouse gases and improve fuel economy for model years 2017-2025 cars and light trucks, EPA-420-F-12-051

²⁷ 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

²⁸ Various entries on ICCT's website: http://transportpolicy.net/index.php?title=Category:Fuel_Efficiency_and_GHG

of mass on the label would affect the decisions that manufacturers take with respect to mass reduction technologies. Similarly, with other legislation that might influence the choice or use of vehicles, such as the Clean Vehicle Directive and any CO₂ component in either the Energy Taxation Directive or the Eurovignette Directive, it is not obvious how these might be adapted to influence manufacturers' decisions about mass reduction technologies, as these do not directly affect manufacturers. Additionally, adding such a dimension to these pieces of legislation would not be consistent with their respective objectives, risks confusing their respective messages and would potentially deliver perverse impacts.

At the national level, Member State vehicle taxation schemes are clearly important for incentivising lower emission vehicles, but again it is not clear how such schemes could be adapted to influence manufacturers' decisions about mass reduction technologies. Targeting CO₂ emissions generally, as many countries do with vehicle taxes, is clearly a more effective means of reducing CO₂ emissions. Similarly, with road pricing schemes²⁹ it is difficult to see how an additional mass-related factor would be any more beneficial than simply adding a strong CO₂ dimension to such a scheme. The IEA (2012) discussed a number of complementary measures that might be introduced to avoid the mass of vehicles increasing, including the introduction of relatively more stringent targets on heavier vehicles, which is discussed further below, and the introduction of taxes based on absolute values for fuel economy or CO₂ emissions.

On the basis of this discussion, it might be concluded that if mass reduction technologies are not being used to their full potential (i.e. options that are relatively cost-effective are not being introduced), the range of measures in place, including the complementary ones, are not a sufficient incentive to encourage their uptake. Consequently, if mass is retained as the utility parameter, an option to incentivise vehicle mass reduction post 2020 might be to ***make the targets more stringent than otherwise would have been the case.***

The review of other EU legislation that aims to improve the energy performance of energy consuming products focused on those products for which EU eco-design legislation has been developed³⁰. Many of these Regulations focus on setting maximum limits for energy consumption or for energy efficiency indices, or on minimum energy efficiency standards, and have little in the way of additional flexibilities. For some products energy consumption limits vary based on different utilities, e.g. those for washing machines are more stringent for machines with a larger capacity. Hence, an additional option to incentivise mass reduction might be ***to split up the vehicle fleet according to mass and then set relatively more lenient CO₂ reduction targets for lighter vehicles (i.e. those that are below a specified mass) and relatively more stringent CO₂ reduction targets for heavier vehicles (i.e. those that are above a specified mass).*** This is consistent with the option proposed by IEA (2012) of making targets more stringent for heavier vehicles.

On the basis of the above discussion, a long-list of options for the post-2020/21 time period aimed at making mass reduction options as attractive as other CO₂ reduction options if mass is retained as the utility parameter was developed. This long-list was as follows:

- **Amended manufacturer targets**, e.g.
 - Less stringent targets for manufacturers using specified mass reduction technologies (which will be considered as **Option A** in the following section); or
 - More stringent targets for manufacturers that do not use specified mass reduction technologies/delivering mass reduction (**Option B**).
- **Mass reduction credits** for:
 - Vehicles weighing less than a certain amount (**Option C**);
 - Manufacturers demonstrating a downward mass trend (on sales weighted average) in the mass of its new vehicle fleet (**Option D**);
 - Vehicles using a specified mass reduction technology (**Option E**).

²⁹ These would probably have to be larger than a city to influence manufacturers significantly.

³⁰ For a list of legislation, see: http://ec.europa.eu/energy/efficiency/ecodesign/doc/overview_legislation_eco-design.pdf

- **Allowing banking** of CO₂ emissions reductions for manufacturers that exceed an annual target and demonstrate a downward mass trend (on the sales-weighted average) (**Option F**).
- **Link reduction target to vehicle mass** by setting:
 - Less stringent CO₂ reduction targets for lighter vehicles, e.g. by introducing a floor that affects only the lightest vehicles (**Option G**);
 - More stringent targets for heavier vehicles, e.g. by setting a ceiling that affects only the heaviest vehicles (**Option H**).
- **Mass reduction credits (and debits) based on ‘density’ for vehicles:**
 - Having a ‘density’ of less than a certain amount (compared to the overall average fleet density) (**Option I**);
 - Having a ‘density’ of less than a certain amount (compared to other vehicles of their size/mass) (**Option J**);
 - Based on their ‘density’ relative to the overall average ‘density’ (**Option K**).
- **More stringent overall CO₂ reduction target** to ensure that relatively cost-effective mass reduction options are taken up (**Option L**).

10.3 Evaluation of the long-list of options against important conditions

The long-list of options identified in the previous section was then assessed against a set of conditions that were considered important for any specific option to meet. This was important as the introduction of any of the options would have to reinforce the message to manufacturers that CO₂ emissions need to be reduced, rather than mass, as CO₂ emissions reduction – rather than the introduction of mass reduction technologies or lighter vehicles per se – is the objective of the Regulations. Hence, the first condition was that any additional option should deliver net CO₂ emissions reductions.

For an additional option to encourage mass reduction it must provide some additional incentive to manufacturers (or a disincentive to increase mass) AND the average mass of their new vehicles must decline. This is important to ensure that mass reductions from the introduction of new technologies are not offset by the inclusion of additional features. Hence, the second condition is that any additional option should reduce the average mass of the new vehicle fleet.

There is clearly a risk that any additional incentive would provide benefits for something that a manufacturer might (or should) do anyway. This leads to the third condition that the additional option should not provide benefits for something that a manufacturer would have done anyway. Finally, there is the issue of how the benefits from applying mass reduction technologies would be verified and credited. It was considered important that any additional option did not significantly increase the complexity of the Regulations, so as to not increase the associated administrative burden and not require additional, significant monitoring and reporting. Hence, a final condition was that under any additional option, the necessary information should be clearly defined and verifiable on the basis of information that is already collected and available, or which could be relatively easily obtained.

In summary, any additional option should:

- Deliver net CO₂ emissions reductions;
- Reduce the average mass of the new vehicle fleet – otherwise any reduction in mass (for which a benefit might be given) could simply be used to add additional features;
- NOT provide benefits for something that would have been done anyway; and
- Be clearly defined and verifiable.

Other conditions could be included in this list, such as cost-effectiveness and equity, but as the short-list of options was going to be assessed against the set of criteria typically used in

European Commission's Impact Assessments, which includes cost-effectiveness and equity, the set of conditions was restricted to those listed above.

An evaluation of the long-list of options against the above criteria is presented in Table 10-1. No option was guaranteed to meet all of the conditions, although some were clearly better than others. Some options do not ensure that there is a net reduction in CO₂ emissions or ensure that the average mass of the new vehicle fleet declines. For many of the options, the introduction of an additional incentive linked to mass reduction risks – to varying degrees – that manufacturers might become distracted from the overall objective of reducing CO₂ emissions and instead focus on reducing mass of certain vehicles to gain the associated benefits. Additionally, some of the options cannot be considered to be technology-neutral and some would adversely interfere with the market. The options that require the identification of specific technologies for which a benefit would be awarded have many risks associated with this process, particularly how to identify such technologies. On the other hand, options that only address a portion of the new vehicle fleet cannot guarantee either net CO₂ reductions or average mass reductions, as the overall impact depends on the whole fleet.

Options worthy of further consideration were identified as a result of their assessment against the specified conditions. The options that require the demonstration of a downward mass trend (D and F) are promising in that they will reduce fleet-average masses and so probably further reduce CO₂. The details of the design of these options, particularly in terms of how to define a 'trend', and the extent to which these will make mass reduction as attractive as other CO₂ reduction technologies would require more detailed assessment.

The most promising options are arguably those that could include 'sticks', i.e. those that impose a penalty in the case of inaction. Even most of these risk being a distraction from the primary objective of CO₂ reduction and would be politically difficult as they would actively influence technology choice and also intervene in the market. Options that involve credits for lower 'density' vehicles add complexity that would need to be further explored to ensure that there are no perverse incentives. The simplest option would be to make the overall CO₂ target lower (more difficult to achieve), but this would not result in any increase in overall cost effectiveness due to the increasing slope of the cost curves. Further, tightening the overall target in this way would not increase the relative attractiveness of mass reduction technologies compared to other CO₂ reduction technologies.

On the basis of the evaluation, it was concluded that the following short-list of options should be taken forward for further consideration:

- Mass reduction credits for manufacturers demonstrating a downward trend in sales-weighted average mass (**Option D**)
- Banking of CO₂ emissions reductions where a downward sales-weighted average mass trend is demonstrated (**Option F**)
- Link targets to mass by setting more stringent targets for heavier vehicles (and more lenient targets for smaller vehicles), e.g. by setting a ceiling that affects only the largest vehicles (and a floor for smaller vehicles) (**Options G and H**)
- Mass reduction credits (and debits) for vehicles based on their 'density' relative to the overall average 'density' (**Option K**)

10.4 Assessment of short-list of options

An evaluation framework, based on the criteria that the Commission typically uses to evaluate its policy proposals and informed by the evaluation of the car and LCV CO₂ Regulations, was developed to include the following criteria:

- **Effectiveness** (of the additional option):
 - In incentivising mass reduction
 - In not introducing perverse incentives, including for gaming

- **Coherence (of the additional option) with the (other elements of the) Regulation**, e.g. working towards delivering CO₂ emissions reductions
- **Efficiency:**
 - Implementation and administration costs
 - Cost efficiency of CO₂ reductions
- **Equity:**
 - Likely distribution of effects across manufacturers
 - Impacts on early movers

A number of potential criteria that are often used to assess and evaluate EU policies were not included in this assessment, as it was considered that their assessment would not add any additional value, not least as the findings would be the same for all options. This includes:

- **Relevance**, as this was confirmed by the previous analysis on the long-list of options. Only those options of relevance are assessed in this part of the evaluation.
- **Coherence with other EU policy objectives**, as the relevant issues are covered by other criteria. Additionally, the options amend an existing Regulation, which has been assessed as being coherent with wider EU policy objectives.
- **EU added value**, as the options considered would all improve an existing Regulation, which has been put in place as it brings EU added value.

An overview of the evaluation of the short-listed options against the identified criteria is given in Table 10-1. From this table it is evident that the short-listed options also have a number of issues. Option G is ruled out, as it has limited scope and potentially high costs for some manufacturers of heavier vehicles. Options D and F have a major problem in that they disadvantage early movers. For other criteria, e.g. the avoidance of perverse incentives and coherence, a positive assessment would depend on the details of the design of the respective options. Option K appears to have the greatest potential, as it has no significant downsides, while having some positive impacts. If this option is explored further, it will be important to explore more fully the potential interactions between footprint and mass to ensure that perverse incentives are avoided and that it would be possible to implement this option in a way that is equitable to all manufacturers. Furthermore, the design of the option in relation to the credits and debits would need to make sure that they incentivise mass reduction by making mass reduction options as attractive to manufacturers in terms of costs as other CO₂ reduction technologies.

Table 10-1: Evaluation of the selected options that could be used to ensure that mass reduction technologies are as attractive to manufacturers as other CO₂ reduction technologies (if mass was retained as the utility parameter for the post-2020) against policy criteria

Key:	Would contribute to meeting criteria: ✓	Contribution to meeting criteria is not clear at this point, as it would require further analysis: ?	Would not contribute to meeting criteria: ✗				
	Effectiveness in incentivising mass reduction	Effectiveness in avoiding perverse incentives	Coherence with other elements of the Regulation	Efficiency re implementation and admin costs	Efficiency of cost of CO₂ reductions	Equity across manufacturers	Equity impact on early movers
D. Downweighting credits for manufacturers demonstrating a downward mass trend (on the sales-weighted average)	✓ Demonstrating a fleet-wide downward mass trend would deliver mass reduction on average.	? Depends on its design, particularly how a downward 'trend' in mass is defined.	? Depends on the size of the credits and the link to the trend.	✓ Small – need to monitor.	? Low certainty as credit only available at end of period.	? If credits granted on % reduction, should be equitable.	✗ Disadvantages early movers as they won't have received credit.
F. Banking of CO₂ emissions reductions allowed where an annual target is exceeded and where downward mass trend is demonstrated (on the sales-weighted average)	✓ Demonstrating a fleet-wide downward mass trend would deliver mass reduction on average.	? Depends on its design, particularly how a downward 'trend' in mass is defined and the extent of banking allowed.	? Depends on extent of banking allowed and how it is linked to the trend.	✓ Small but larger than D.	✓ Lowers costs as all of a manufacturer's CO ₂ emissions reduction 'count', as they can be moved to future years.	? If credits granted on % reduction, should be equitable.	✗ Disadvantages early movers as they won't have received credit.

	Effectiveness in incentivising mass reduction	Effectiveness in avoiding perverse incentives	Coherence with other elements of the Regulation	Efficiency re implementation and admin costs	Efficiency of cost of CO ₂ reductions	Equity across manufacturers	Equity impact on early movers
G./H. Link targets to mass by setting more lenient (and more stringent) targets for lighter (heavier) vehicles, e.g. by introducing a floor (ceiling) that affects only the smallest (largest) vehicles	✖ Most vehicles unaffected. Very few at upper and lower level.	? Risk of perverse impacts around the inflection points of the limit value curve.	? The option needs to be designed so that the impact of the ceiling is not undermined by the impact of the floor.	✓ Small.	✖ High cost for affected manufacturers of heavy cars. Small CO ₂ benefits.	✖ Only benefits manufacturers predominantly at lower mass end of market and disadvantages those at higher end of market.	✓ Early movers unaffected
K. Downweighting credits (and debits) for vehicles based on their 'density' relative to the overall average 'density'	? Balance of credits and debits could be designed to incentivise mass reduction.	? It would be important to fully explore the interplay between mass and footprint in the context of 'density' to identify any perverse incentives and to ensure that these are avoided. It will also be important to explore the balance of the credits and debits	? OK provided credits and debits do not over-value mass reduction compared to other technologies.	✓ Small.	✓ Should lead to more comparable cost of CO ₂ reductions from mass reduction as other technologies.	? As 'density' varies by segment (see Figure 3-19), an equitable approach may not be possible.	✓ Early movers unaffected

	Effectiveness in incentivising mass reduction	Effectiveness in avoiding perverse incentives	Coherence with other elements of the Regulation	Efficiency re implementation and admin costs	Efficiency of cost of CO ₂ reductions	Equity across manufacturers	Equity impact on early movers
		and to ensure that these exactly compensate for disadvantage caused by mass as utility parameter.					

10.5 Conclusions

The section has considered a number of additional options that might be used to ensure that mass reduction technologies are as attractive to manufacturers as other CO₂ reduction technologies, if mass was retained as the utility parameter for the post-2020/21 time period. On the basis of this assessment, it is difficult to see how introducing a mass component in complementary legislation would be better than simply having a strong CO₂ component. Hence, amending such legislation – either at the EU or national levels – to make mass reduction as equally attractive as other CO₂ reduction technologies was ruled out at an early stage of the work.

On the basis of a review of similar legislation elsewhere in the world, as well as studies supporting the development of the passenger car CO₂ Regulation itself, a long-list of options for amending the Regulation were identified and evaluated. Many of these did not meet a set of necessary conditions, while others were considered to be inequitable in some way.

The option that was considered to have the most potential, i.e. mass reduction credits (and debits) for vehicles based on their ‘density’ relative to the overall average ‘density’, would need to be explored further quantitatively to ensure that it provides the right incentives and avoids perverse incentives, as well as providing an equitable treatment for manufacturers. Having said that, this option would introduce an additional layer of complexity to the Regulation, which brings with it the possibility that there might be impacts that it is not possible to foresee prior to implementation. At the stakeholder workshop held as part of the project there was little enthusiasm for such an additional option.

11 Summary and conclusions

The aim of this report was to explore the potential for mass reduction in passenger cars and LCVs and its contribution to achieving desired LDV CO₂ reductions in the EU. This included analysing the implications for cost-effectiveness, in the context of potential post-2020/21 CO₂ emissions reduction targets for such vehicles, including the implications for the choice of utility parameter. To achieve these aims it was necessary to explore ongoing market trends in vehicle characteristics such as mass and footprint, as well as trends in the uptake of lightweight materials. It was also necessary to understand the mechanisms within the existing Regulations that link manufacturers' targets to vehicle mass. The potential for mass reduction, including the implications for CO₂ emissions and costs, was identified by reviewing the relevant literature, including major US studies. The attitudes of manufacturers and consumers to mass reduction were identified through a combination of literature review and stakeholder engagement. On the basis of the analysis carried out, updated estimates of the costs of vehicle mass reduction in the EU were developed. These estimates were used to assess the implications for manufacturers, in relation to the respective distances to their CO₂ targets and the costs associated with meeting these targets. Finally, the potential to use an alternative option was explored that would make mass reduction technologies as attractive to manufacturers as other CO₂ reduction options if a mass-based utility parameter remains in place beyond 2020.

Based on the data analysed, the average mass of new cars and LCVs registered in the EU is increasing and the average footprint of new cars is also increasing. The drivers for the mass increase in cars include an increase in sales of crossover vehicles and MPVs (these vehicles are typically as heavy as a conventional passenger car from the next segment up) and an increase in the market share of diesel cars, which are typically heavier than similar cars that use petrol. For LCVs, it appears that many of the most popular models have increased in mass, thus moving them up into the next mass class.

The literature review and stakeholder engagement suggested that mass reduction is becoming an increasingly important element of manufacturers' CO₂ reduction strategies. According to industry stakeholders, the targets set in the car and LCV CO₂ Regulations were one of the main drivers of mass reduction, while the forthcoming change in the test procedure (to the WLTP) will make mass reduction more important. As is clear from the results mentioned above, such strategies are not yet leading to a significant reduction in the average mass of the new vehicle fleet. There was no evidence from the literature to suggest that consumers have strong opinions on lighter vehicles, as long as the overall performance of vehicles was not adversely affected. The literature review also suggested that while many mass reduction technologies are already beginning to be taken up for LDVs, there is still significant potential for further mass reduction, although at higher costs than have been suggested for the US. The literature and the engagement with stakeholders suggested that there will be a multi-material approach to reducing the mass of vehicles in the future, with different strategies being adopted by different manufacturers.

On the basis of the literature reviewed and the stakeholder engagement undertaken in the course of this study, we conclude that reductions of up to 30% of the overall mass of European light duty vehicles could be achieved. This assumes that the baseline vehicle is an average 2010 new car in Europe and that only the mass reduction technologies that will be available for mass production before 2020 will be applied; all other factors remain unchanged. For passenger cars, based on the research carried out during this study, new estimates for the costs associated with achieving different levels of mass reduction against a 2010 average baseline new car were estimated to be as follows:

- 10% mass reduction: €0.3 per kg
- 20% mass reduction: €0.9 per kg
- 30% mass reduction: €2.2 per kg

These estimates are in line with other research that has been considered.

Whilst the majority of stakeholders, including Tier 1 suppliers, believed that achieving such a mass reduction for the stated level of costs was achievable, several manufacturers believed that the costs associated with achieving this level of mass reduction would be much higher.

For LCVs, there is very limited existing research on the costs of mass reduction and new analysis has been carried out during this study. The scope for applying mass reduction to LCVs is much lower than for passenger cars, because the production volumes are much lower, the model life-cycles are generally

much longer and there is limited potential to apply secondary mass reduction techniques. For all of these reasons, the mass reduction potential for LCVs is lower than for cars and the costs are significantly higher. The analysis carried out in this study indicates that in the medium term (out to 2030) it is possible to reduce LCV mass by up to 12%. In the longer term, mass reductions of up to 25% may be possible, but this would require extensive use of fibre-reinforced plastics, which are currently very expensive. The estimates for the costs of reducing the mass of LCVs developed during this study are as follows:

- 3% reduction in mass: €2.2 per kg
- 12% reduction in mass: €5.4 per kg
- 25% reduction in mass: €37.4 per kg

As mass reduction leads to improvements in vehicle fuel economy and CO₂ emissions, there will also be reductions in costs to society as a whole in terms of decreases in fuel costs for consumers and businesses that use vehicles. The lifetime savings in fuel costs associated with mass reduction for average petrol and diesel cars and for an average diesel light commercial vehicle were estimated. For an average current petrol car, lifetime fuel cost savings of around €5.5 per kg of mass reduction could be achieved. For an average diesel car, the saving is €5.9 per kg of mass reduction and for an average diesel LCV, it is €11.3 per kg of mass reduction. The absolute levels of cost savings are dependent on a number of factors including baseline vehicle mass, baseline vehicle fuel consumption, lifetime distance travelled and fuel prices. Estimates for how these unit cost savings are likely to change between now and 2020 were also developed, in line with anticipated improvements in fuel efficiency for cars and LCVs; this showed that the unit cost savings are likely to decrease as vehicles become more fuel efficient, with likely declines in cost savings of 20% and 15% for passenger cars and LCVs respectively.

For cars, the estimated costs to manufacturers of applying mass reduction strategies were integrated into the cost curves used for the 2020 targets. These cost curves were also adjusted to include plug-in hybrid electric vehicles and the WLTP was used instead of the NEDC. The implications for manufacturers of achieving a hypothetical post-2020/21 CO₂ reduction target (measured on the WLTP) were estimated for cases where (i) mass and (ii) footprint are the utility parameters. This analysis showed that, in terms of distance to their CO₂ targets, more manufacturers would benefit from a mass-based system than a footprint-based system (the overall CO₂ emissions reductions across the whole new car fleet to be achieved under the alternative systems were designed to be the same). From a manufacturer's perspective it is the costs of meeting the target rather than the emissions reductions needed that are more important. In this respect, all but one manufacturer would face significantly lower costs if 'footprint' was the utility parameter. For these manufacturers, costs would be between 8% and 20% lower under a footprint-based system compared to a system where mass is the utility parameter. Overall, the costs to manufacturers for achieving the possible future CO₂ target would be 16% lower if the car CO₂ Regulation used 'footprint' instead of 'mass' as the utility parameter for the post 2020/21 target.

The findings from this study indicate that the costs associated with vehicle mass reduction in the EU are lower than had been estimated in previous studies for the European Commission. Additionally, the analysis suggests that delivering the same overall level of CO₂ reduction would be cheaper if 'footprint' rather than 'mass' was used as the utility parameter for a hypothetical post 2020/21 target. This suggests that 'footprint' should be the preferred option for the utility parameter to be used for any post 2020/21 targets in the LDV CO₂ Regulations.

The above conclusion is linked to the way in which the sales-weighted average vehicle mass interacts with manufacturers' targets within the Regulations. From a purely mathematical perspective, manufacturers should favour 'footprint' as the utility parameter to be used in the Regulations, as they would benefit in full from the application of mass reduction technologies. Under the assumptions used in this report, an average mass reduction of 10% would move an average manufacturer 8.7 gCO₂/km closer to its target if 'footprint' was used as the utility parameter, compared to being only 4 gCO₂/km closer to its target if 'mass' was the utility parameter. This suggests that the application of mass reduction technologies is penalised when 'mass' is the utility parameter.

A further disincentive to the use of mass reduction technologies exists where the average mass of the new vehicle fleet is increasing, as has been the case in recent years, as the 'M₀ adjustment', and the subsequent more stringent (tougher) targets, could effectively negate any CO₂ reductions resulting from the introduction of mass reduction technologies. Hence, it would be in policy-makers' interests, at least

in the short-term, to use 'footprint' as the utility parameter to ensure that the policy framework does not disincentivise the application of technologies that could yield benefits for consumers and for society. In future years (perhaps prior to 2020), the existence of the M_0 adjustment could begin to increase the incentive to use mass reduction technologies, as increases in the value of M_0 lead to more stringent targets.

To counter such disincentives, alternative options that would make mass reduction technologies as attractive to manufacturers as other CO₂ reduction options were explored to identify whether any of these might be used if a mass-based system remains in place beyond 2020. This exploration did not yield an obvious alternative option that might be implemented. Additionally, stakeholders did not support the inclusion of such an additional option.

In the course of the engagement with stakeholders, the majority accepted that having 'mass' as the utility parameter discouraged mass reduction *in theory*, but most manufacturers thought that this was not the case in practice and so preferred to keep 'mass' as the utility parameter for any post 2020 targets. Most suppliers believed that changing the utility parameter to 'footprint' would put greater emphasis on mass reduction.

In terms of the future choice between 'mass' or 'footprint' as the utility parameter for any post 2020/21 CO₂ reduction target for cars, two of the three original reasons why the Impact Assessment accompanying the original proposal for the passenger car CO₂ Regulation chose 'mass' over 'footprint' are no longer valid. There are no longer issues over data availability and international compatibility, as data to calculate 'footprint' are now collated in the EU in a consistent manner, while legislation regulating the CO₂ emissions of light duty vehicles in North America now uses 'footprint'. The one remaining original argument in favour of 'mass' is that it is more understandable than footprint as a concept, which was mentioned as a reason for retaining 'mass' as the utility parameter in the course of the stakeholder engagement. This may still be the case amongst the general public (although they are not required to understand the workings of the Regulations), but those involved in reducing CO₂ emissions from cars, including policy-makers and manufacturers, will have become increasingly familiar with the concept of 'footprint' in recent years, not least as a result of the various reports that have been undertaken on the issue of the utility parameter.

Consequently, it is worth identifying whether there are now additional reasons in favour of keeping 'mass' as the utility parameter for any post 2020 CO₂ reduction targets for cars. The majority of manufacturers support the continued use of 'mass' as the utility parameter in any post 2020 regulatory regime for passenger car CO₂ emissions. The argument that having 'mass' as the utility parameter does not penalise mass reduction in practice might be supported by the various statements that manufacturers have made in support of mass reduction and its importance to meeting their respective CO₂ reduction targets. Until 2012, this commitment had not translated into a lower average mass of new cars. However, in 2013, there was a small reduction (0.9%) in the sales-weighted average mass of new cars; it remains to be seen whether there will be further reductions in future years. The might be because the effect of the strategies has not yet had the time to have an impact on the vehicles that are put on sale, or because the strategies are not yet delivering mass reduction to a sufficiently wide range of vehicles, or because the use of lightweight materials is being offset by increased mass elsewhere. Whichever is the explanation, it can be concluded that having mass as the utility parameter between 2009 and 2012 did not result in a reduction in the average mass of the new car fleet. For many of the other reasons put forward by stakeholders for retaining 'mass' as the utility parameter, it was often not clear why a similar argument could not be made for changing to 'footprint'.

What is clear is that a change from having 'mass' as the utility parameter for cars for 12 years, i.e. from 2009 (i.e. when the Regulation was published) until 2021 (the year in which the 95 gCO₂/km target has to be met by the entire new car fleet), to footprint, e.g. for a 2025 target, would require manufacturers to revise the parameters within which they make decisions about the most cost-effective means of reducing the CO₂ emissions of their new vehicle fleets. It is perhaps the uncertainty that such a change would entail that underlies the desire amongst most manufacturers to retain 'mass' as the utility parameter for any post-2020/21 CO₂ emissions reduction target, although how this uncertainty can offset a 16% cost reduction for them is less evident. To put this in a wider context, the modalities for any post-2020/21 targets would need to be developed with the potential market for the respective year in mind, which is likely to include a much higher proportion of electrified and hybrid vehicles. Hence, it is distinctly possible that the form of the respective Regulation for any post 2020/21 targets will be

different from that used for the 2015 and 2021 targets. In this context, any change in the utility parameter used would just be one of many factors that manufacturers would need to take into account.

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