FOOTPRINT AS UTILITY PARAMETER

A TECHNICAL ASSESSMENT OF THE POSSIBILITY OF USING FOOTPRINT AS THE UTILITY PARAMETER FOR REGULATING PASSENGER CAR CO_2 EMISSIONS IN THE EU

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1 INTRODUCTION – THE SEARCH FOR A UTILITY PARAMETER

In the background research in support of the Commission's Impact Assessment for its proposal for its proposal for a Regulation to reduce CO_2 from cars (COM(2007)856 final) one important component was to identify a suitable 'utility parameter' that could be used in the design of targets for legislation.

A utility parameter is potentially an important tool to allow for differentiated targets for different cars or car manufacturers to reflect the different 'sizes' and hence different degrees of utility of different classes of vehicle. This was perceived to be particularly important because there was clear requirement from the outset to 'respect the diversity' of the European car market. Since different car makers occupy different segments of the market – ie some make mainly small 'family' cars while others make predominantly larger and more luxurious models, with the latter having generally higher average CO_2 emissions – some rational means of giving a larger allowance to the latter than the former, while still ensuring that the latter take on their fair share of the reduction burden, was needed.

It was also clear that it would be most desirable to use a continuously-variable numerical parameter for this purpose. While it might be possible to divide all cars up into a series of categories and set targets for each of these, such categories would necessarily be arbitrary and likely subject to dispute and legal challenge. In contrast a continuously-variable parameter could be used to *normalise* the emissions from each car or company, and thereby arrive at an objectively-set and tailored target for each company that would have more chance of being perceived to be 'fair' and to reflect their particular sales mix.

As set out below, a shortlist of two options for a choice of utility parameter – weight or pan area (the product of the overall length and width of the vehicle) – were selected and used for further analysis. It was however recognised that either of these options had its shortcomings, and it was further suggested in the study that 'footprint' (ie the length of the wheelbase of the vehicle multiplied by its track width) might well prove a superior parameter.

As the relevant data were not available to the study team to allow for its analysis, however, the footprint option was not pursued further at that time. Now, though, additional data on footprint have been obtained and analysed. This paper presents draft findings of this analysis.

The next sections address the following topics:

- The theoretical benefits of footprint as utility parameter;
- Methodology used to derive footprints for the EU vehicle fleet;
- Development of a footprint-based limit function and analysis of distance to target for various manufacturers;
- Analysis of perverse incentives in relation to the slope of the limit function;
- Overall conclusions.

2 THE THEORETICAL BENEFITS OF FOOTPRINT AS A UTILITY PARAMETER

2.1 The Shortlisting of Possible Parameters

In this and the earlier analysis in support of the European Commission's Impact Assessment of its proposed Regulation we have studied the possibility of utilising a wide variety of possible parameters as a basis for a utility function to be applied in a sloped line target with a future legal instrument[1]. We applied a range of criteria to select a shortlist of options, including in particular the following:

- Good measure of 'utility' (ie encourage acceptable aspects of utility rather than controversial or less acceptable ones)
- Preference for a continuously-variable function
- Availability (actually available or easily obtainable) of required data
- Understandable – hence preference against a complex function or variable
- Perverse effects (ie incentive to 'gaming') should be minimised
- Adverse effects (eg reduced vehicle safety) should be avoided
- Should not exclude specific technical options
- Distributional impacts should not unfairly disadvantage any particular manufacturer group on account of the characteristics of their model portfolio

It should be emphasized that in the above list the level of correlation between CO_2 emissions and the utility value of vehicles on the market is *not* included as a criterion for a suitable parameter. Some level of correlation with CO_2 is obviously necessary because without that the utility parameter does not provide a basis for differentiation of the target. But a 100% correlation would simply mean that the chosen parameter is a direct physical determinant of CO_2 emissions, which would not leave any room for optimisation at a given utility value. On the contrary, we are looking for a utility parameter that a significant level of spread in the CO_2 emissions for vehicles with the same utility value, as this shows that there are ways to improve vehicle efficiency without changing the utility value and that some manufacturers build more efficient vehicles than others.

In the work for the European Commission we then agreed a shortlist of options, on the basis of our initial analysis, as follows:

- U = m, vehicle weight (empty) in kg
- U = l x w, pan area = vehicle length x vehicle width in m^2

Footprint (ie U = wb x tw, footprint = wheelbase x average[2] track width in m^2) was also identified as a promising candidate for the future, but could not be pursued at that point because detailed data on the footprint of individual models sold were unavailable – hence they could not be applied in the detailed analysis, and nor would they be available as a basis upon which to base a legal Regulation.

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[1] See: [IEEP 2008]: M. Fergusson (IEEP) et al., *Possible regulatory approaches to reducing CO_2 emissions from cars*, Study carried out by IEEP, CE Delft and TNO on behalf of DG-ENV, contract nr. 070402/2006/452236/MAR/C3, 2008, http://ec.europa.eu/environment/co2/co2_study_ia.htm

[2] ie the average of front and rear wheel track width, as these can differ

Table 1: Summary Qualitative Assessment of the Three Utility Parameters

Criterion	**U=Weight-based**	**U=area-based**	
		Pan area	**Footprint**
Good measure of utility	Proxy for other measures of utility, eg vehicle size, special features, but not generally seen as a virtue in itself[3]	Reasonable proxy for vehicle size	Good proxy for vehicle cabin size (excluding height, but an unnecessarily high cabin is undesirable anyway)
Continuously variable	Yes	Yes	Yes
Available	Yes – reported in Monitoring Mechanism	Yes – available but not reported	Not available up until now – required to be reported in Monitoring Mechanism under proposed Regulation
Understandable	Yes – very	Yes	Yes – fairly
Perverse effects/ gaming	Yes[4]	Yes to an extent – eg deeper bumpers	Limited[4]
Adverse effects	Yes – safety[4]	No	No – safer[4]
Not excluding options	Could exclude weight-reduction measures to reduce CO_2[5]. Tends to favour heavier options eg diesels, hybrids and to penalize e.g. engine downsizing if this also leads to weight reduction.	Not greatly – it does reduce the incentive for reducing the width of the car, but it is generally difficult to do this without sacrificing utility in the form of cabin space and possibly roadholding.	Not greatly – it does reduce the incentive for reducing the width of the car or its wheelbase, but it is generally difficult to do this without sacrificing utility in the form of cabin space, driveability or comfort.
Distributional impacts	Appears 'fair' and quite similar to pan area[6]	Appears 'fair' and quite similar to weight[7]	Not yet known – probably similar to pan area (see below)

Source: Based on [IEEP 2008][1] with additions

[3] Indeed, in car reviews weight is often portrayed as a negative feature; but strictly speaking this is likely to refer to a perception of being 'heavy' caused by poor handling or acceleration characteristics. A heavy car can in fact be very driveable provided it has a commensurate level of power and suitable suspension and steering gear, and most luxury cars are relatively heavy.

[4] See discussion below of the relative merits of different utility options, and of US analysis

[5] But see analysis below of package options

[6] Note 9 of [IEEP 2008] entitled "Quantitative analysis of various options with updated model" shows that the distributional effects of mass and pan area as utility parameters is very similar, although for some manufacturers the sensitivity to the slope of the limit function strongly depends on the parameter chosen. For more details the reader is referred to the Note.

[7] Note 9 of [IEEP 2008] entitled "Quantitative analysis of various options with updated model" shows that the distributional effects of mass and pan area as utility parameters is very similar, although for some manufacturers the sensitivity to the slope of the limit function strongly depends on the parameter chosen. For more details the reader is referred to the Note.

Nonetheless, footprint appeared likely to offer a number of benefits relative to the two parameter options that were analysed in detail in the study referred to above. These are summarised in Table 1.

In summary, there appeared on the face of it to be a number of possible benefits of using footprint rather than weight as a utility parameter, as follows:
- Footprint is a good measure of the 'space' available in the vehicle cabin;
- It appears to limit the possibilities of manipulation or 'gaming' of vehicle characteristics to increase the CO_2 allowance for a particular vehicle;
- It fully rewards and does not penalise efforts towards weight reduction;
- Insofar as US evidence is applicable to Europe, this seemed to suggest that footprint was associated with improved safety, whereas weight *per se* was associated with an increase in fatalities.

In short there may be several clear benefits to using footprint as a utility parameter, and no obvious downsides once the data are available.

2.2 Possible Perverse Impacts of Weight as Utility Parameter

Possible perverse impacts of the choice for a specific utility parameter cover the following aspects:
- Possibilities for 'gaming' the legislation;
- Perverse incentives.

Gaming is possible if there are easy and cheap means of manipulating the utility parameter value of a vehicle to increase the CO_2 target and thereby reduce the need for application of CO_2 reduction measures. Adding 'dead' weight to a vehicle (the proverbial 'brick in the boot' scenario) or mounting bigger bumpers to increase pan area are such perverse gaming options. In the case of adding 'dead' weight it is all the more perverse as it not only reduces the required CO_2 reduction effort but also increases the actual CO_2 emissions.

A utility-based limit that has options for gaming generally also creates perverse incentives in the sense that it rewards manufacturers to develop and sell bigger or heavier cars or discourages manufacturers to apply certain CO_2 reduction measures. The extent to which this is the case generally depends on the slope of the limit function in comparison to the additional CO_2 emissions resulting from an increase in the value of the utility parameter.

Vehicle weight is a strong determinant of a vehicle's CO_2 emissions and as such weight reduction is an important technical option for reducing CO_2 emissions from passenger cars. Choosing weight as utility parameter thus reduces or even potentially cancels the potential of weight reduction as an option for contributing towards meeting any utility-based limit or target. With weight as utility parameter, reducing the weight of a vehicle also leads to a lower CO_2 target for that vehicle, thus reducing the incentive to cut weight. The extent to which weight reduction is discouraged as a CO_2 reduction measure depends on the slope of the weight-based limit function.

In principle, these effects tend to discourage the use of weight reduction as an option for manufacturers to meet their CO_2 emission target based on the sales-weighted average utility value, and hence makes the average reductions more expensive than they otherwise would be. In practice, however, the analysis suggested that this effect would not be very large. Excluding weight reduction decreases the maximum reduction potential of the measures identified in [TNO 2006][8], but analysis suggested that this full potential is not necessary for reaching the average target of 130 g/km. At the same time there are other CO_2 reduction options available with similar cost and potential as weight reduction so that the overall costs for meeting the 130 g/km target are expected not to be significantly affected by (partial) exclusion of weight reduction as a CO_2 reduction measure.

That said, the analysis only included three quite basic weight reduction options ('mild, medium and strong weight reduction' on the basis of applying light-weight steel construction to the vehicle's body in white. Although these could not be quantified for the purpose of the [TNO 2006][8] study, there may exist various other options for weight reduction eg through application of lightweight materials in the vehicle's interior or weight reduction in various vehicle components. It seems likely that a weight-based utility parameter would also discourage the development of these possibilities, whereas ideally a CO_2 Regulation should encourage engineers to look for such clever and possibly very cost-effective options in the design of vehicles.

Our earlier analysis did conclude that the perverse effect in favour of increasing vehicle weight could be minimised by keeping the 'slope' of the utility curve fairly flat – ie not fully compensating for weight increases. It was suggested that the use of a slope below 80% would eliminate at least most of the perverse incentives. Nonetheless, Figure 1 above and the Technical Annex to this paper both illustrate that weight is an important determinant of the power requirements and hence CO_2 emissions of a car, being a component of acceleration resistance, rolling resistance and gradient resistance.

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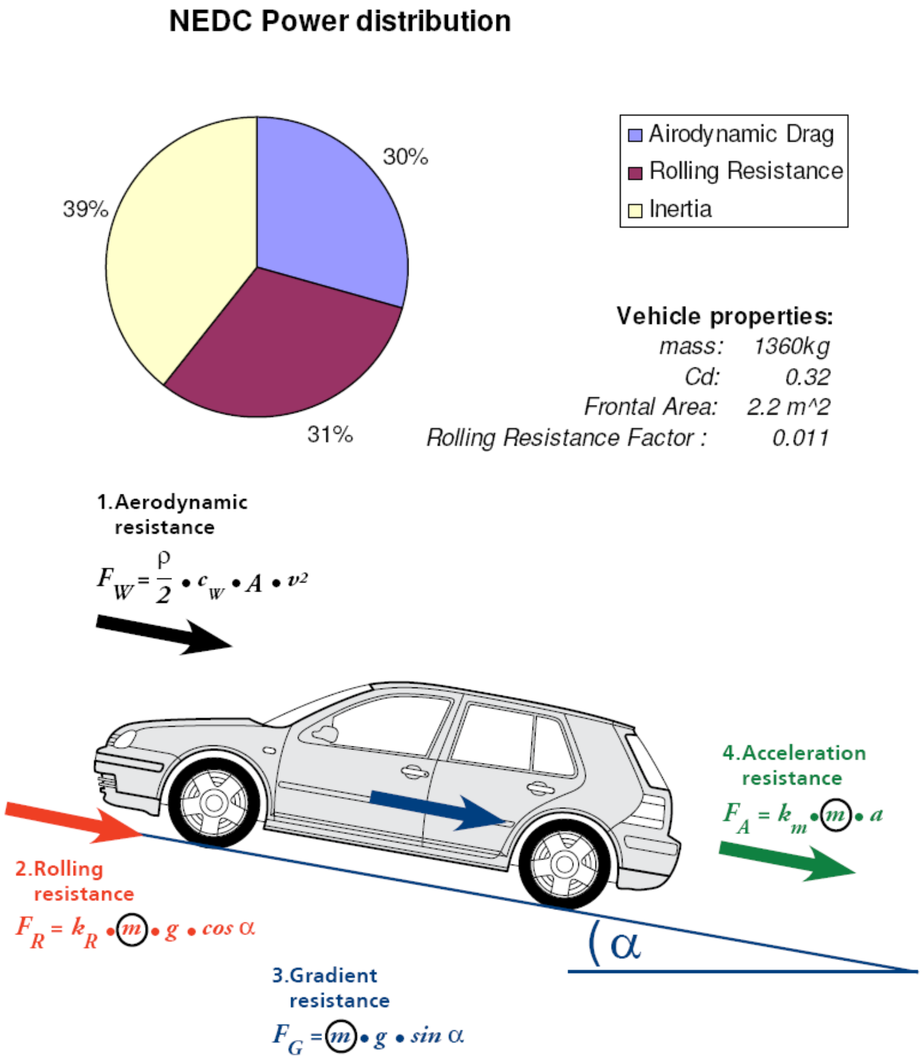
8 [TNO 2006], R. Smokers et al., *Review and analysis of the reduction potential and costs of technological and other measures to reduce CO_2 emissions from passenger cars*, project carried out by TNO, IEEP & LAT on behalf of the European Commission (DG ENTR), contract nr. SI2.4082812, TNO Report 06.OR.PT.040.2/RSM, October 2006 http://ec.europa.eu/enterprise/automotive/pagesbackground/pollutant_emission/index.htm#co2.

Figure 1: Weight as a Component of the Power Requirements of Cars



Source: European Aluminium Industry

The maximum allowable slope depends on the options for 'gaming' and perverse incentives that are considered likely. Basically three options can be discerned where weight is concerned:

- The first option is the proverbial 'brick in the boot' in which weight is added to the vehicle without compensation of the resulting loss in performance by increasing engine power, but thereby gaining extra CO_2 allowance;
- The second option is to add mass to the car while at the same time applying compensating measures to engine and powertrain to maintain vehicle performance;
- The third option is the mechanism that corresponds to upward or downward market shifts, e.g. consumers buying on average larger and better performing cars or smaller and less performing cars. In case of an upward market shift this trend will also lead to an increase of the average mass of newly sold vehicles over time.

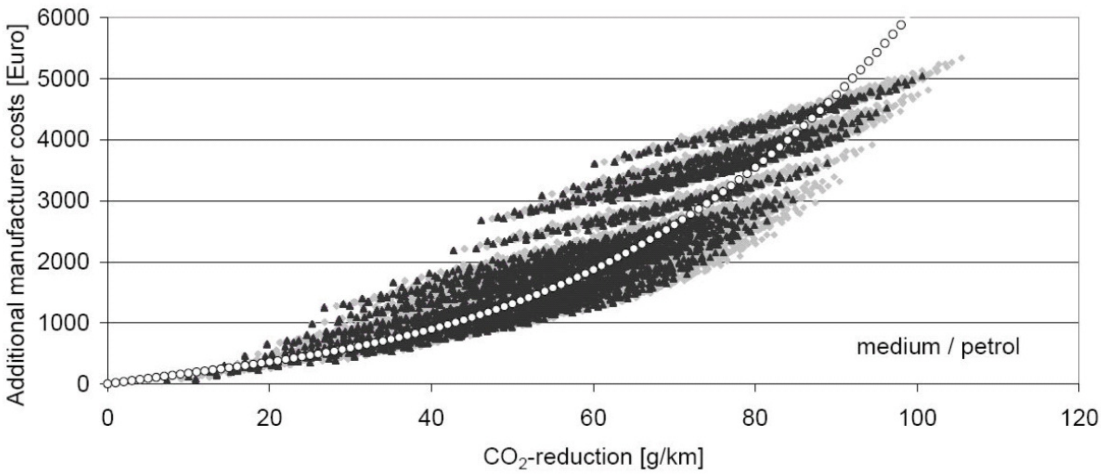
It was suggested that the use of a slope below 80% would for the majority of vehicles sold eliminate most of the perverse incentives posed by the second and third option. To fully exclude the 'brick in the boot' option the slope of the limit function would need to be below 40%, but this would strongly increase distributional impacts on some companies.

2.3 Impact of weight as utility parameter on the cost of meeting the 130 g/km target

As also recognised in [IEEP 2008][1] using mass as utility parameter reduces the effectiveness of weight reduction as an option for complying with a utility-based limit function and as such reduces the number of options available to the industry for meeting the target. This could lead to higher compliance costs depending on whether or not other options with similar cost effectiveness are available alongside weight reduction.

The impact of (fully) excluding weight reduction as a reduction option on the cost curve is shown in Figure 2 below, which is taken from Technical Note 4 of [IEEP 2008]. The light grey dots are the original packages with all possible combinations of individual CO_2 reduction options as discerned in [TNO 2006][8], while the black dots are all packages that do not contain weight reduction as one of the measures.

Figure 2: Impact on The Cost Curve for a Medium Sized Petrol Vehicle of (Fully) Excluding Weight Reduction as a CO_2 Reduction Option (Taken from Figure 4 in Technical Note 4 of [IEEP 2008])



Note: Grey dots are the original packages with all possible combinations of individual CO_2 reduction options. Black dots are all packages that do not contain weight reduction as one of the measures.

Excluding weight reduction significantly reduces the number of packages available for reaching a given CO_2 reduction within a given cost range. Nevertheless it was concluded in [IEEP 2008] that the overall spread of the cloud of possible combinations of options remains similar to the original and would not lead to a significant shift in the cost curve. Only for reductions above 70 g/km (which for most manufacturers is beyond what is necessary to achieve the 130 g/km target) one can observe that a small band with the cheapest options is excluded. As such [IEEP 2008] concludes that exclusion of weight reduction is not likely to significantly influence the costs of reaching the desired levels of CO_2 reduction in most cases, but does reduce the number of approaches available to manufacturers for reaching a certain level of

CO_2 emission reduction in a way that not only serves CO_2 reduction and cost optimisation but also meets other targets set in vehicle design.

For a 2012 target of 130 g/km it is indeed likely that reducing the cost-effectiveness of weight reduction as a CO_2 reduction measure option has a very limited impact on the total cost of meeting the target, i.e. not more than a few percent. Nevertheless it is clear that if reducing the effectiveness of weight reduction would have an impact on costs it would be an increase, and this cost increase will become more prominent with further reduction of the sales averaged target beyond 2012. Above 70 g/km reduction in Figure 2 the outer envelope of the cloud of data points shifts about 6 g/km to the left, independent of the overall reduction. As the cost curve is positioned on a 2/3-1/3 division of the width of cloud, this shift of the outer envelope would lead to a 4 g/km shift to the left of the resulting cost curve. At a reduction of 70 g/km a 4 g/km shift of the cost curve results in a cost increase for achieving that reduction by some 13%. For higher reductions the relative cost increase as a result of excluding weight reduction is smaller.

This indicates that in a worst case (full exclusion of weight reduction) the costs for meeting higher levels of CO_2 reduction could be order of magnitude 11 - 13% higher than what would be assessed based on the assumptions used in [IEEP 2008]. The 60% slope of the weight-based limit function proposed by the European Commission still rewards some 25% of the CO_2 impact of weight reduction[9], leading to a shift of the cost curve by 3 g/km and a corresponding cost increase for meeting the target of maximum 9 - 10%. The exact increase in average costs depends on the CO_2 target level and the amount of autonomous mass increase that is assumed. The latter requires additional CO_2 reduction to compensate for the impact of increased mass on CO_2. For individual manufacturers the cost of meeting the target furthermore depends on their distance to target, which is their average vehicle efficiency relative to that of other manufacturers.

In addition to this is should be mentioned again that besides the options of weight reduction for the body-in-white, which are included in the cost curves from [TNO 2006], there may be a range of other weight reduction options available in the design of a vehicle and its components. The fact that weight as utility parameter does not reward these options, may lead to underutilisation of these options by car manufacturers. These options, however, are expected to be relatively cost effective and may thus lead to lower costs for meeting the target.

Concluding it can be stated that for the 130 g/km target the choice of mass as utility parameter may lead to a few percent higher cost for meeting the target than would be the case for utility parameters (e.g. pan area or footprint) that fully reward the effectiveness of weight reduction as a CO_2 reduction option. For more ambitious future targets the use of pan area or footprint as utility parameter may result in up to 10% lower costs than is the case for a weight-based limit function.

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[9] An 80% slope is roughly equivalent to the CO_2 emission increase per unit weight increase based on the following average relation: $\Delta CO_2/CO_2 = 0.65\ \Delta m/m$, see Annex A of Technical Note 8 of [IEEP 2007].

2.4 The Relative Merits of Pan Area and Footprint as Utility Parameters

It should be stressed that neither pan area nor footprint would present these perverse effects. Pan area does suggest other possibilities for ‘gaming’ the outcome, but footprint apparently much less so. That is, pan area can be increased at low cost, even on existing vehicle models, simply by adding larger bumpers. To increase footprint, in contrast, either track width or wheelbase needs to be increased, and both options require structural changes to the vehicle design that can only be made as part of a major redesign that would typically take place every six years or so. This in turn requires significant cost and effort to be put into the new design, and in this process footprint size and CO_2 emissions would need to be weighed up against a wide range of other desirable features in a highly sophisticated design process. There could still be room in this for some perverse incentives to increase footprint area and hence the CO_2 allowance, but in this case the designer is in effect designing a bigger car, so this is a far cry from the simple ‘brick in the boot’ option.

Track width can only be increased as the width of the vehicle is increased. This adds mass and also increases frontal area, leading to an increase in CO_2 emissions. Over the past years wheelbase length has already increased significantly (at the expense of front and rear overhang) as this increases interior space, driving comfort and vehicle stability. The room to further increase wheelbase without increasing vehicle length is considered limited because the easy options have already been taken up: further increases are likely to involve tradeoffs against other desirable features. Increasing the vehicle length may somewhat reduce air drag, but will also add weight to the vehicle. Increasing footprint is thus difficult to apply to existing vehicle platforms in isolation and when applied to new vehicles will very likely be accompanied by an increase in CO_2 emissions that at least partly offsets the benefit of a higher target.

If the design of a new vehicle does provide the possibility to increase wheel base without increasing the overall length of the vehicle, footprint can be increased without an accompanying increase in CO_2 emissions. This in itself may be considered a form of gaming, as it increases the target and reduces the required effort from the manufacturer to apply CO_2 reduction measures. But as a gaming option it is considered less “perverse” than increasing mass as it does not of itself lead to increased CO_2 emissions, and is likely to be accompanied by genuine utility gains in terms of a more comfortable ride and more internal space.

Reflecting these points, a technical analysis of the impact of increasing width and length on CO_2 emissions is presented in Annex A. The outcome is used in section 5 to determine the maximum slope level that can be applied without creating a perverse incentive for manufacturers to increase footprint in order reduce the required level of CO_2 reduction measures.

A further point to note is that modern manufacturing methods often utilise the same basic vehicle platform for a number of different models with quite different requirements and characteristics. This further restricts the room for gaming.

2.5 Developments in the US

In March 2006 the US National Highway Traffic Safety Administration (NHTSA) issued a 'final rule' reforming the structure of the US CAFE programme for light trucks and establishing higher fuel economy standards for model year (MY) 2008-2011 light trucks and minivans[10]. The reformed CAFE programme also restructures the fuel economy standards such that they now use a completely new utility parameter as the basis for targets, namely a vehicle's 'footprint' (ie the vehicle's wheelbase multiplied by its track width).

Vehicle weight and 'shadow' (ie pan area) had also been considered as possible functions on which to base the standards, but there were concerns that they could more easily be tailored (ie gamed) with the objective of achieving a less stringent target and they were therefore discounted in favour of footprint. The latter is argued to be more integral to a vehicle's design as it is dictated by the vehicle platform (which is typically used for a multi-year model lifecycle), and cannot therefore easily be altered between model years.

Note that the footprint approach also received support in a March 2004 meta-study by Dynamic Research Inc (DRI)[11] which analysed a number of previous studies into the effects of vehicle weight and size on accident fatality risk. All the studies reviewed used data on crashes for both light trucks and passenger cars. The study concluded that reducing wheelbase and track width (ie footprint) generally increased the number of fatalities, whereas reducing vehicle weight tends to decrease the number of fatalities.

Clearly there are differences between Europe and the US as regards average vehicle size, fleet composition and driving conditions; but to the extent that they are applicable in Europe, these findings on safety would be a significant further argument against a utility parameter that could encourage greater weight rather than footprint.

More recently, the NHTSA has confirmed its intention to adopt a continuously-variable function of footprint to regulate cars and light trucks for model years 2011-2015[12]. Thus if the EU were to shift at the earliest available date, there would be a uniform basis for establishing CO_2/fuel economy requirements for models sold on both sides of the Atlantic (in the world's two largest vehicle markets) and similar regulatory pressures on both.

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10 *Final Rule on Average Fuel Economy Standards for Light Trucks Model Years 2008-2011* - http://www.nhtsa.dot.gov/staticfiles/DOT/NHTSA/Rulemaking/Rules/Associated%20Files/2006FinalRule.pdf

11 A Review of the Results in the 1997 Kahane, 2002 DRI, 2003 DRI, and 2003 Kahane Reports on the Effects of Passenger Car and Light Truck Weight and Size on Fatality Risk (DRI-TR-04-02), R. M. Van Auken and J. W. Zellner, March 2004

12 *Average Fuel Economy Standards; Passenger Cars and Light Trucks Model Years 2011-2015*, US NHTSA, Washington, 2008

3 METHODOLOGY FOR ASSESSING FOOTPRINT OF THE EU FLEET

3.1 Obtaining a Footprint Database

The analytical basis of this study is as far as possible identical to that used in [IEEP, 2008] and the same data are utilised in order to allow a direct comparison of footprint to the other two utility parameter options. However, footprint data were not available and no comprehensive and detailed database of the footprints of the EU's new car fleet is known to exist.

It was therefore a first requirement to develop such a database. A first step in this was to obtain and examine two databases of national data with pan area and footprint as well as CO_2 emissions for a large number of car models and variants. The most important of these was a database compiled by the Umweltbundesamt (UBA) in Germany. The two databases were compared in detail and their pan areas were also crosschecked against previously-available data to verify that the data were reliable. From this it was determined that the UBA database was extremely accurate, and that it also included the most representative variants of virtually all of the most popular car models sold in the EU-15. That is, the UBA data covered some variants of 99% of the models in the Polk database (see below), and 75% of actual sales, with only two moderately popular models that were not covered.

However, the data were confined to German car sales, so a detailed database of all EU sales was needed. For this we obtained access to the R. L. Polk Marketing Systems GmbH database of year 2006 sales, which includes detailed information on the sales and technical parameters of approximately 58,000 different car variants. These technical data include number of sales and pan area for each variant, but not footprint.

There are however many body-size variants in the Polk list – many more than in the UBA database, so it was necessary to approximate the footprint from the pan area and model details in each case. This was achieved by mapping the UBA footprint data onto the Polk database using a cascading series of approximations as follows:

- Where the pan area sizes matched to within $100mm^2$ (as they did for most common models and variants), the UBA footprint value was applied directly;
- For variants with pan areas that did not match exactly, footprint was approximated by multiplying the pan area value in the Polk data by the unweighted average ratio of footprint to pan area for the model as a whole as obtained from the UBA database ;
- For models where there were no exact size matches in the UBA database, the model's unweighted average ratio of footprint to pan area in the UBA database was multiplied by the Polk pan area for each variant to give a derived footprint.
- For models that were not recognised in the UBA database, the manufacturer's overall unweighted average ratio of footprint to pan area from the UBA database was applied to the Polk pan area values for each variant.
- For the minor manufacturers that were not in or not recognised in the German database, the fleet unweighted average ratio of footprint to pan area from the UBA database was applied to the Polk pan area values for each variant to approximate the footprint.

As illustrated below, this method gave very accurate results, especially for the most common models and variants sold, and gave a good fit to the original UBA database. We can thus have good confidence that this accurately reflects the sales-weighted footprint values for each vehicle holding company.

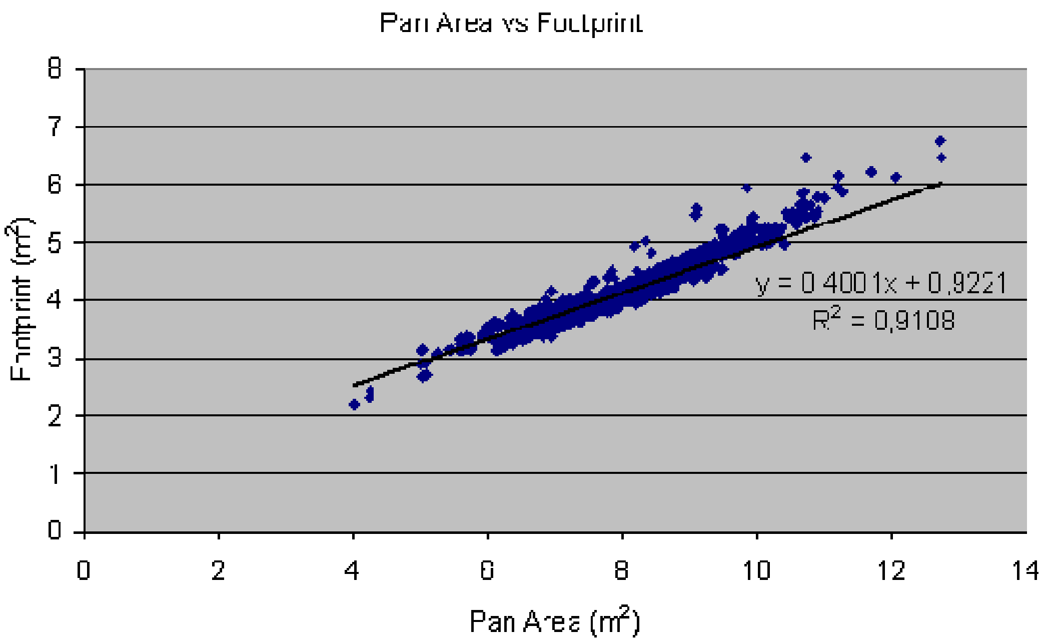
Note: Detailed analysis of the database used has revealed some inconsistencies in the vehicle width data of some models. The most significant of these have been manually corrected, with a high degree of confidence in the changes made. Remaining issues are not of sufficient magnitude to significantly affect the overall results or conclusions of this analysis. Note however that company results for Renault and DaimlerChrysler in particular are affected and should be regarded as provisional. On the basis of the various data sources available to us, it appears that fully corrected footprint data would result in a somewhat more stringent (ie lower) target for Renault, and a slightly easier (ie higher) target for DaimlerChrysler. It also appears likely as a consequence that the distance to target for Renault would be greater and for DaimlerChrysler would be less, thereby further reducing the differences in distance to target between the weight and footprint-based utility functions.

4 DEVELOPMENT OF A FOOTPRINT-BASED LIMIT FUNCTION

4.1 Footprint and Pan Area Compared

Figure 3 below illustrates the relationship between pan area and the footprint data derived from the merging of the two databases for each model and variant sold in the EU in 2006.

Figure 3: Footprint vs Pan Area for all 2006 Model Variants



This illustrates that there is a very close relationship between footprint and pan area for all cars. The unweighted least squares fit gives an R^2 value of 0.91, which matched very closely to the value of 0.92 reported for the original UBA database. That is, most of the values fall very close to the regression line. For reasons of simple geometry, however, some larger vehicles tend to have ratios that fall above the line, while small vehicles in particular tend to fall slightly below. That is, large vehicles have better possibilities to have a very long wheelbase relative to overall vehicle length, but for small vehicles such options are constrained by the wheel radius.

Figure 4: Footprint vs CO_2 Emissions for All 2006 Model Variants

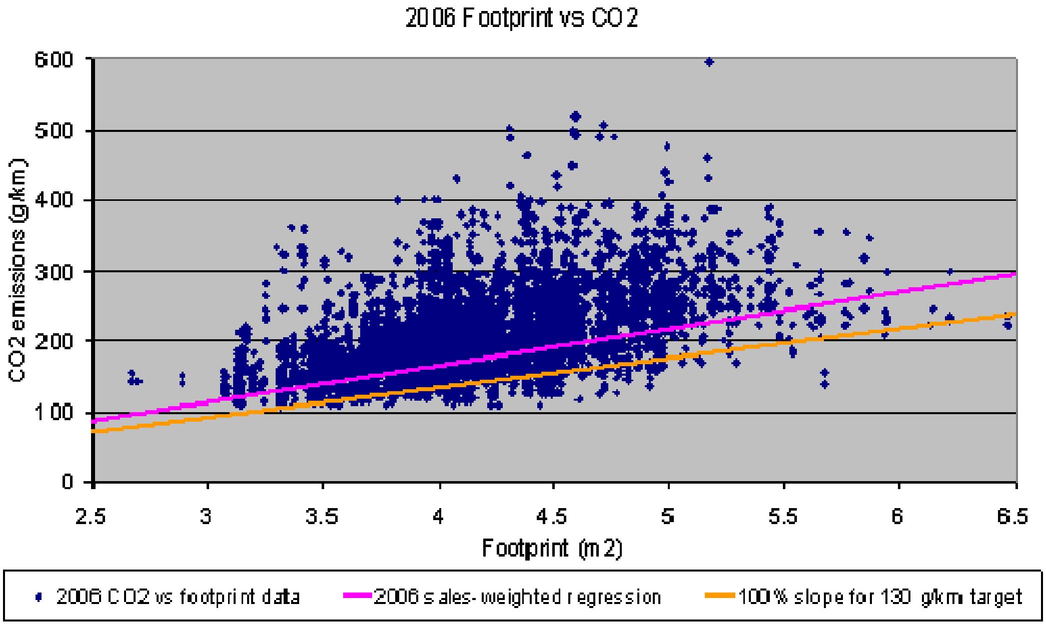


Figure 4 above illustrates the scatter of CO_2 emissions against footprint for all 2006 sales models and variants. As with the other two parameters studied previously, this illustrates a significant scatter of both footprint values and CO_2 emissions across the fleet. Not surprisingly given the close fit to pan area, the scatter pattern is quite similar for these two variables.

Figure 4 also illustrates the sales weighted fit of 2006 emissions. As with the other parameters studied, this gives a fit close to the bottom of the 'cloud' of scatter points, reflecting the fact that the most common models (ie most-sold models) tend to fall towards the bottom of the CO_2 emissions range for all footprint values.

Figure 4 also includes the '100%' target line for reaching a 130g/km overall target. That is, it illustrates the degree of improvement needed at all footprint values if full credit is given for the footprint utility value. Lower percentages would imply only partial credit being given for higher footprint values, while a zero percentage implies no credit being given for a larger footprint value – in effect giving all vehicle sizes the same target.

Table 2 below presents the a and b values needed to generate slopes for a representative range of slopes for the footprint utility curve for the formula a x + b.

Table 2: a and b Values for the Sales-Weighted Least Squares Fit through the 2006 Footprint vs CO_2 Data and a Range of Target Slopes for the Footprint-Based CO_2 Limit Function

		a	b
least squares fit 2006		52,106	-43,0
slope 120%	*120%*	50,591	-67,7
slope 100%	*100%*	42,159	-34,8
slope 80%	*80%*	33,727	-1,8
slope 60%	*60%*	25,295	31,1
slope 40%	*40%*	16,864	64,1
slope 20%	*20%*	8,432	97,0
slope 0%	*0%*	0,000	130,0

4.2 Footprint and Holding Company Average CO_2 Emissions

Figure 5 below illustrates the 2006 average emissions for each of the main manufacturer holding companies in the context of the overall scatter of vehicles and the two lines shown in Figure 4 above.

This illustrates that for footprint, even more so than for pan area, company averages are much less widely scattered than the overall scatter of vehicle results, or indeed the scatter based on vehicle weight. The two outlying companies with the highest average CO_2 emissions are Porsche and Subaru respectively; the two with the smallest footprint are Fiat and Suzuki. All others are relatively closely grouped, with most falling close to the 2006 average regression line, but all falling above the 130g/km target line (at 100% and all other possible slope values).

Figure 5: Holding Company Average Footprint and CO_2 from 2006

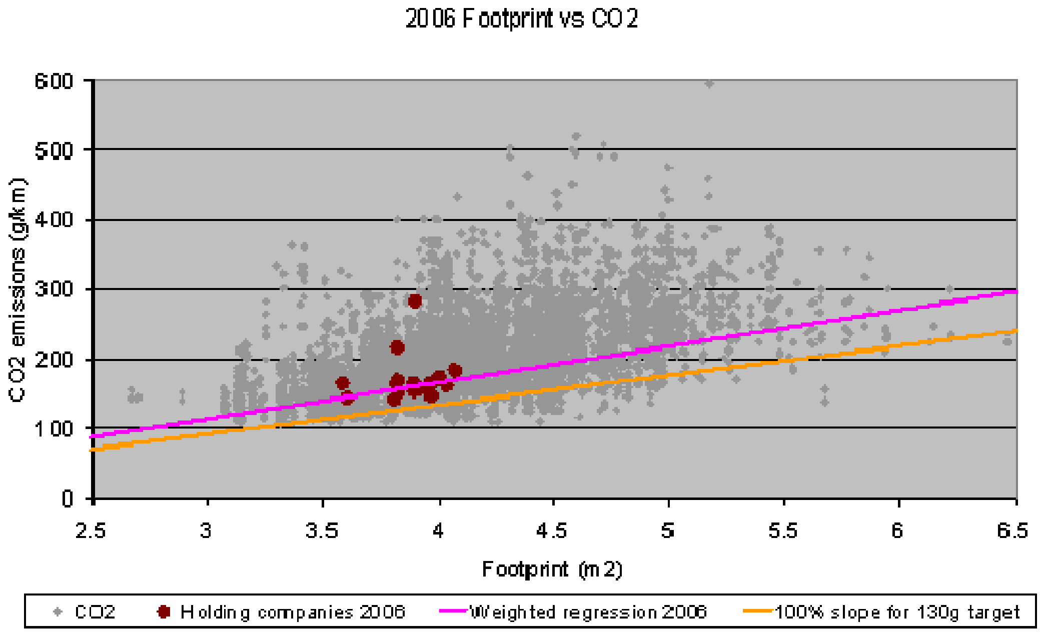
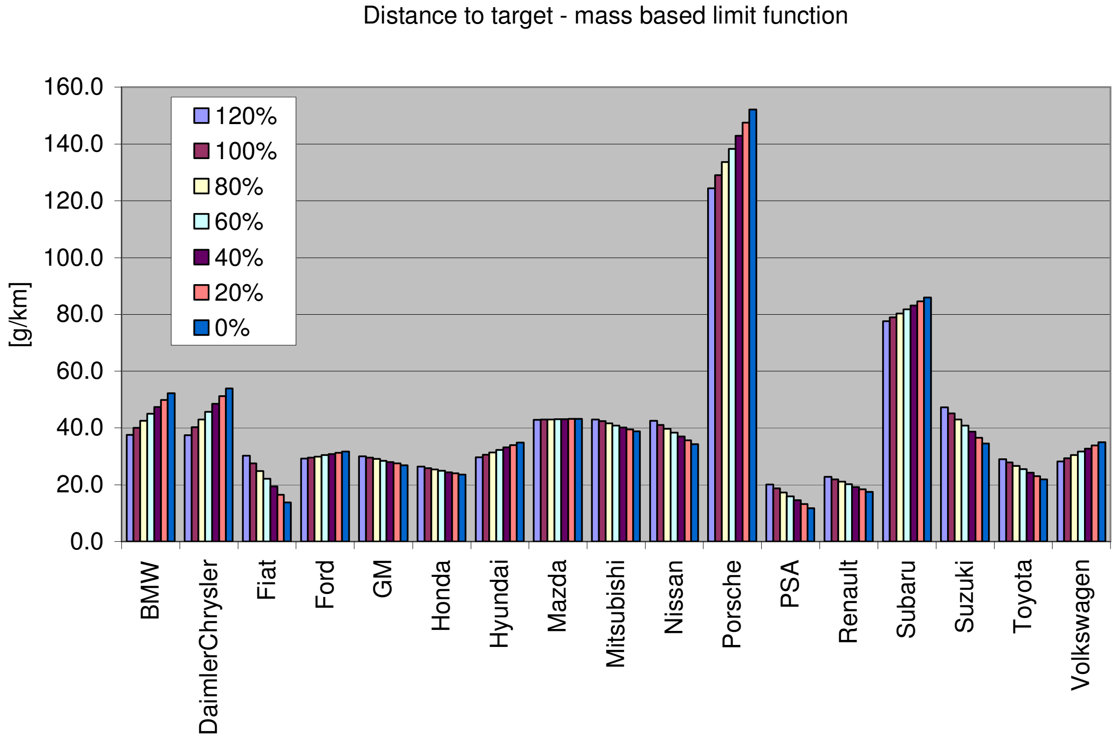


Figure 6 below compares the distance to target for the proposed mass-based utility curve with that for footprint for each holding company in relation to a range of possible slope values for the target curve. This illustrates that a footprint-based target gives a very similar overall target distribution between holding companies as does vehicle mass. In almost all cases the distribution also varies in the same direction in relation to the slope of the chosen curve, showing that in almost all cases it is the same companies that would benefit from a steeper or a flatter curve.

A key difference, however, is that in almost all cases the variation across slope values is less for footprint than for mass – ie the tops of the grouped bars for each holding company are flatter. This illustrates that the distributional impacts of the footprint target line are generally much less sensitive to the curve slope value chosen, which in turn reflects the close grouping of the companies shown in Figure 5.

Figure 7 below also compares the effort required under each slope value as a percentage of current emissions. This illustrates that the required effort under all slope values is much more evenly distributed when expressed as a percentage reduction requirement – typically around 30% except for those companies with the highest and lowest current averages. In the latter cases it is those with highest emissions that are required to do most, and those with the lowest to do least. Thus this suggests that footprint is capable of delivering a fairly equitable distribution of effort required to meet differentiated targets.

Figure 6: Distance to Target Compared for Mass and Footprint-Based Targets with Different Slopes



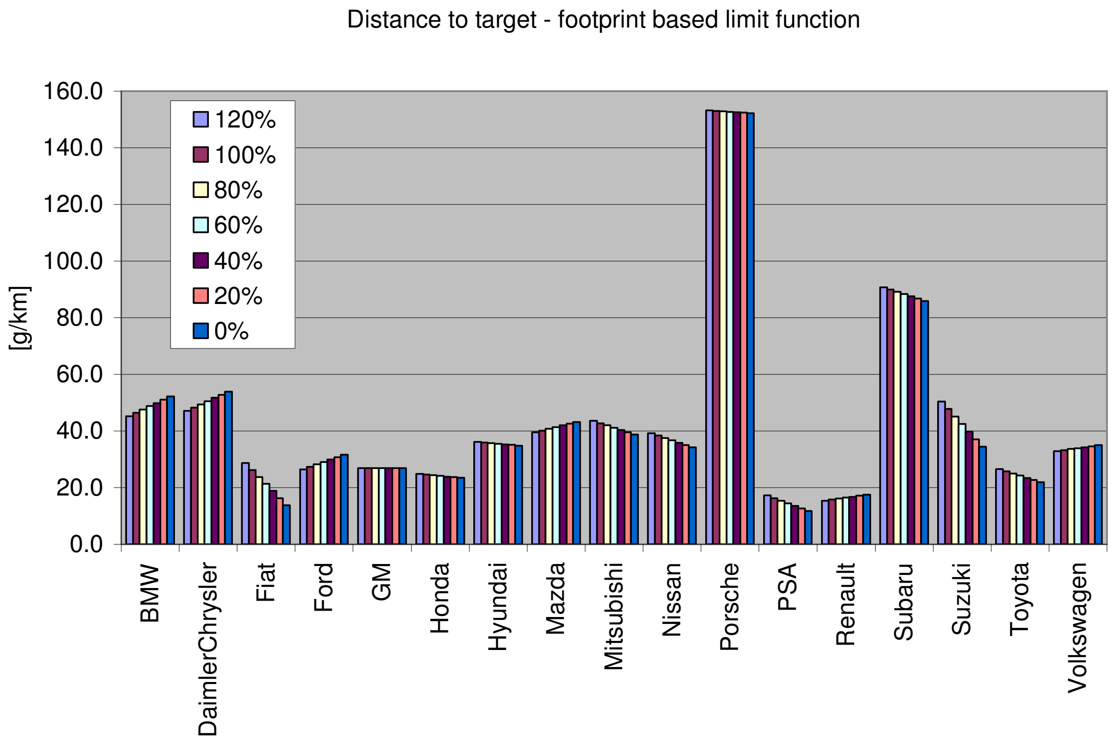
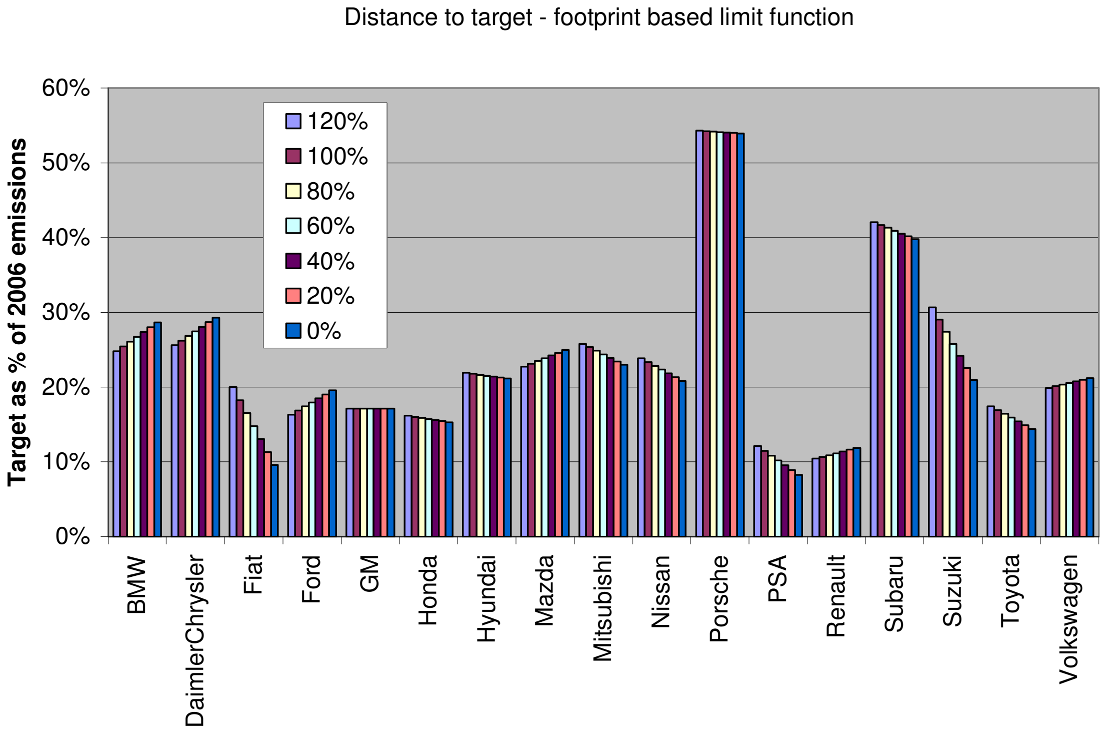


Figure 7: Distance to Target Expressed as a Percentage of 2006 Emissions



4.3 Distribution of Costs for Individual Manufacturers under a Footprint-Based Utility Function

A possible impact of using footprint on the overall cost of meeting the target is discussed in Section 2.3. Apart from this possible shift of the cost curves, the overall average effort required to fulfil a Regulation based on a footprint-based utility function is the same as for any other parameter. The reason for this is that the total average distance to target is the same. Therefore the overall cost of the measure would remain quite similar to what is set out in the Commission's Impact Assessment.

However, using footprint instead of weight will lead to somewhat different distances to target for the various manufacturers. Any differences in the distribution of the distances to target for each holding company, as suggested by Figure 6, will lead to comparable or greater changes in the total cost to that company. This is because the companies can in principle optimise the costs incurred in each vehicle segment such that they make reductions in CO_2 emissions wherever the marginal cost of doing so is cheapest; but if they are required to make greater reductions overall because they have a tougher target, they will have to move further up the cost curve in some or all vehicle segments and will thus incur higher marginal costs in doing so. Conversely, a company with a less demanding target will have to move less far up the curve than it otherwise would, so both their marginal and average abatement costs will be lower.

The comparison of distances to target for weight- and footprint-based limits, as presented in Figure 6, shows that the spread in costs for individual manufactures (so called "distributional impacts") is very similar for both cases. Using footprint as utility parameter is thus not expected to lead to major changes in the distribution of costs for meeting the target over the different holding companies.

If the distributional impacts would be smaller under a footprint-based target than under a weight-based target, the overall costs may be somewhat lower. A smaller spread in costs per manufacturer means that the sum of cost optimisations per manufacturer is closer to the minimum average costs, which is obtained when sales of all manufacturers are pooled for the cost optimisation.

5 ANALYSIS OF PERVERSE INCENTIVES IN RELATION TO THE SLOPE OF THE FOOTPRINT LIMIT FUNCTION

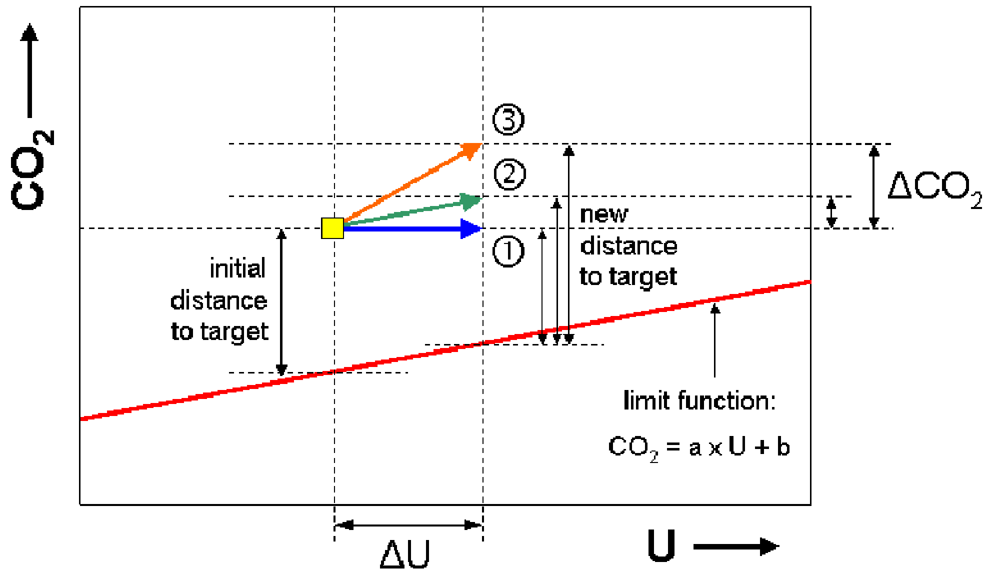
As stated above there are different ways in which an increase in footprint may affect a vehicle's CO_2 emissions:

- If the wheelbase for a new model can be increased without changing the length of the vehicle footprint can be increased without an impact on CO_2 emissions;
- For most models, however, a significant increase in wheelbase is only possible if it is accompanied by a similar increase in the length of the vehicle. This will add weight, leading to increased CO_2 emissions. Increasing length may somewhat reduce air drag (C_w), which may compensate some of the CO_2 emission increase resulting from increased weight.
- Increasing footprint by increasing track width is only possible if the vehicle width is also increased. This will lead to an increase in frontal area and a mass increase, which both result in increased CO_2 emissions.

Annex A provides a quantitative, technical analysis of the impact of increasing width and length on CO_2 emissions. Table 3 below summarizes the main results obtained for three typical vehicles. An analysis in Annex A based on the mass decomposition of an average indicates that a 10% increase in length or width leads to mass increase of 4 to 5%. CO_2 impacts are assessed for these two values to indicate a bandwidth. For details of the assessment the reader is referred to Annex A.

Increasing footprint by increasing width or length of the vehicle is rewarded if the relative increase of CO_2 emissions resulting from a given relative increase in width or length is smaller than the relative increase of the CO_2 target for the same relative increase in width or length. In that case increasing footprint brings a vehicle closer to the target line. This is illustrated in Figure 8.

Figure 8: Illustration of the Possible Impact of Changing the Utility Value on CO_2 Emissions and Distance to Target



In case ① in Figure 8 an increase in the value of the utility parameter U of a given vehicle model is realised without an increase in CO_2 emissions. Such action can be considered gaming if it reduces the distance to target without realising a net CO_2 reduction or a real increase in utility. But is arguably legitimate if it increases utility for the consumer without increasing the CO_2 emissions. Case ② represents the situation in which an increase in the value of U is accompanied by an increase in CO_2 emissions which is equal to the increase in the CO_2 target related to the ΔU. In this case increasing the utility value does not bring a vehicle closer to the target line and therefore does not reduce the required effort to meet the target. If the CO_2 emission increase associated with an increase in U ($\Delta CO_2/\Delta U$) is larger than the slope of the CO_2 limit function (target line), then increasing U also increases the distance to target and the required effort for meeting the target in terms of applying technical CO_2 reduction measures. In other words: the possibilities for gaming as well as possible perverse incentives for building larger and more CO_2 emitting cars are eliminated if the slope *a* of the CO_2 limit function is smaller than the increase in CO_2 emissions per unit utility that is determined by the physical relationship between CO_2 and U.

For the three vehicles the physical relations between CO_2 and width as well as length have been calculated. By comparing the increase in CO_2 emission due to increase in width or length to the increase in CO_2 target for the different slopes one can derive the maximum slope values for which increasing width or length is not rewarded by reducing the distance to target.

Table 3: Comparison of the Impact of Changing Vehicle Width and Length on CO_2 Emissions with the Slopes of Footprint-Based CO_2 Limit Functions

			Smart fortwo	VW Passat	BMW X5 4.8i	
scale factor length-to-mass	0.40					
scale factor width-to-mass	0.40	ΔCO2/CO2=	0.1978	0.2835	0.2764	x Δl/l
scale factor length-to-Cw	0.05	ΔCO2/CO2=	0.7466	0.5998	0.6119	x Δw/w
scale factor length-to-mass	0.50					
scale factor width-to-mass	0.50	ΔCO2/CO2=	0.2400	0.3502	0.3411	x Δl/l
scale factor length-to-Cw	0.05	ΔCO2/CO2=	0.7889	0.6665	0.6766	x Δw/w
slope of limit function	120%	ΔCO2/CO2=	1.0321	1.6281	1.1513	x Δfp/fp
	100%		0.8601	1.3567	0.9594	
	80%		0.6880	1.0854	0.7675	
	60%		0.5160	0.8140	0.5756	
	40%		0.3440	0.5427	0.3838	
	20%		0.1720	0.2713	0.1919	
	0%		0.0000	0.0000	0.0000	

From Table 3 and the above reasoning the following conclusions can be drawn:

- Changing footprint in existing models is hardly possible as it interferes with the whole design of the vehicle (platform and body). Gaming or responding to perverse incentives is thus hardly possible with existing models.
- Changing footprint with the intention of gaming or responding to perverse incentives is possible with new models or model versions, but there are no cheap gaming options equivalent to the 'brick in the boot' where footprint is concerned, as the changes needed are more complex and costly, and increasing footprint may well be associated with a genuine increase in utility through a smoother ride or greater internal space.
- Increasing track width of new models always leads to increased vehicle width, and thus has a serious CO_2 penalty due to increased frontal area and mass. This option is discouraged by slopes below 60% if one assumes that an n% increase in width leads to an n% increase in frontal area. If manufacturers can realise an increased width in combination with a reduction in height (while meeting all other customer requirements, which at the moment tend to go for higher vehicles) the slope would need to be smaller.
- Increasing the wheelbase of new models may to some extent be done without increasing overall vehicle length and thus without CO_2 penalty. There is no 'safe' slope percentage for the limit function that can prevent this type of gaming, but owing to recent trends in car design it is believed that the scope for pursuing this option further is now very limited. The issue of whether such increase in wheelbase interferes with driveability, vehicle handling and safety is beyond the scope of this analysis.
- One may expect, however, that for most vehicle models increasing wheelbase does require increasing vehicle length, in which case the additional mass involved gives a CO_2 penalty. This is only discouraged by slope percentages below 20%. If the impact of increased length on the air drag coefficient C_w is higher than assumed the required slope percentage may be even lower. However, it has been argued above that such changes can only be achieved as part of a more complex vehicle design involving significant cost, so it is not considered necessary to have a slope flat enough to eliminate such perverse incentives completely.

For footprint the slope percentage at which perverse incentives are eliminated thus tends to be smaller than for weight. The other side of the coin in this case, however, is that a given relative increase in footprint leads to lower additional CO_2 emissions than the same relative increase in weight, so that gaming and perverse trends related to footprint have a smaller environmental impact than in the case of weight.

Also it is always desirable on environmental grounds to have a slope of less than 100% for any utility parameter, to discourage a drift towards ever-larger and more luxurious vehicles which would have negative CO_2 and resource implications. Therefore it is concluded that a slope of around 60% appears technically most suitable for use with the footprint-based utility parameter; the exact choice of value is likely to involve a political judgement based on the distributional impacts of the choice of slope.

It has been argued that nothing beyond a very low slope value could completely eliminate perverse incentives to increase footprint, as with any other utility parameter. But at a given slope percentage the size of this incentive is believed to be much smaller with footprint than with weight as utility parameter.

Also, it is not necessary to eliminate such incentives altogether. Provision has been made in the draft Regulation to adjust the utility function in future years to compensate for any upward drift in utility (ie weight in the proposal as it stands), in order to ensure that the 130 g/km target is still met even if average weight does drift upwards. This would compensate for any increase in average vehicle weight, whether this reflects a continuation of the autonomous upward shift in weight of recent years, or a specific result of perverse incentives in the shape of the utility function. For footprint there has also been an upward trend historically, and there may also be some perverse incentives in what is proposed here; but in both cases these effects are believed to be smaller for footprint than for vehicle weight, and so the necessary adjustment should also be smaller and easier to accommodate.

6 CONCLUSIONS FROM ANALYSIS OF FOOTPRINT DATA

Since the time that the Impact Assessment was completed, we have been able to acquire several different data sources that contain reliable data on footprint, and we have now been able to extend our analysis to cover a footprint-based utility function based on these. Our main conclusions are as follows:

- It has been possible to approximate the footprint data for all fleet sales in 2006 in great detail and with a high level of accuracy. This has allowed the definition of footprint-based limit functions and the analysis of distance to target for different manufacturers.
- Technical analysis suggests that footprint performs at least as well as weight or pan area as a possible utility function, and in several important respects, better.
- Using weight as a utility function does exclude or reduce the incentive for deploying weight reduction techniques to cut CO_2 emissions. In the short term this is unlikely to have a significant impact on the cost of meeting targets, but it could significantly increase (by up to 10%) the cost of larger reductions in emissions in the medium to long term. Using footprint avoids this problem.
- Footprint is not necessarily better than weight with respect to avoiding all possibilities of perverse incentives, but the possibilities of cheap gaming options are much reduced. In fact the possible impact of changing footprint on CO_2 is

weaker than that for mass and as a consequence does not provide a better threshold against gaming or perverse incentives than is the case for mass. But the scale of the perverse incentives appears much less as utility can only be increased by effectively increasing the size of the vehicle, with all the cost and complexity that that entails, and resulting in what is essentially a different vehicle. Also, incremental increases in footprint result in proportionately smaller increases in CO_2 emissions than increases in weight, so the adverse environmental impact is less.

- On balance the slope of the limit function that does not excessively reward gaming and does not create significant perverse incentives for selling bigger cars is considered to be around 60%, although the precise choice of slope value is in the end a political judgement.
- A footprint-based utility function has now been developed, and the CO_2 reduction values required per manufacturer to meet a 130g/km target have been successfully generated and presented for a range of slope assumptions.
- Comparison of distance to target for a mass-based and a footprint-based utility target indicates a similar distribution of efforts between the main holding companies, but the footprint-based function is less sensitive to the slope chosen.
- Our analysis also suggests that the overall cost of using the footprint-based utility function would not be larger than that for a weight-based system as the overall effort required is the same. As a footprint-based system fully rewards weight reduction as a measure to reduce CO_2 emission, the cost for meeting future targets may even be lower than for a weight-based system. Any differences in distributional impact would be similar to the changes predicted in the distance to target for individual holding companies. The overall distributions of CO_2 reduction efforts and associated costs, however, look very similar for weight and for footprint.

ANNEX A

Impact of change in footprint on CO_2 emissions of passenger cars

Technical note

Maurice Snoeren – TNO Automotive
Richard Smokers – CE Delft

Introduction

There are different ways in which an increase in footprint (product of wheelbase and track width) may affect a vehicle's CO_2 emissions:

- If the wheelbase for a new model can be increased without changing the length of the vehicle footprint can be increased without an impact on CO_2 emissions;
- If increasing the wheelbase is accompanied by an increase in vehicle length this will add weight, leading to increased CO_2 emissions. Increasing length may somewhat reduce air drag (C_w), which may compensate some of the CO_2 emission increase resulting from increased weight.
- Increasing footprint by increasing track width is only possible of also the vehicle width is increased. This will lead to an increase in frontal area and a mass increase, which both result in increased CO_2 emissions.

This annex examines the possible impacts on the CO_2 emission of a passenger car resulting from a change in its footprint which is accompanied by a change in overall width and/or length of the vehicle – ie the second and third of the three cases set out above. The first case is believed to be of limited relevance because recent trends in vehicle design have greatly reduced the scope of further moves in this direction.

A relationship between the change of CO_2 emissions resulting from a change in footprint is necessary to determine the slope of a footprint-based CO_2 limit function which does not create perverse incentives for reducing the required efforts for meeting the CO_2 target by increasing the footprint. As the analysis focuses on the effects of changing width and length it is equally valid for assessing the impact of increasing pan area (length x width) on CO_2.

When footprint is used as a utility parameter for a utility-based CO_2 limit function, the incentive for changing footprint as a means to increase the CO_2 limit and reduce the required effort to meet that limit is expected to be less than for the case of using weight or pan area (length x width). For the manufacturer it is generally more difficult to change the wheel base or track width than it is to change mass or pan area, especially on existing vehicle models. This is because the footprint parameters are strongly correlated to vehicle design and to the comfort and stability of the vehicle.

In this annex we analyze the influence of a change in footprint on the extra energy that is needed to power the vehicle over the NEDC test cycle. Under assumptions regarding possible scaling of the engine this is translated into an estimate of the impact of changes in footprint on CO_2 emissions.

Influence on vehicle parameters when footprint changes

An increase in vehicle weight has a direct impact on fuel consumption and CO_2 emissions through an increase in the power required for acceleration and hill climbing, and through an increase in the rolling resistance (see equation 1). The impact of increased required driving power on fuel consumption and CO_2 emissions is somewhat indirect as is depends on the extent to which the engine power is adjusted to maintain vehicle performance and the sensitivity of the average engine efficiency over the NEDC cycle to a change in engine loads.

The impact of a change in footprint is more indirect. Footprint is changed by changing the track width and/or the wheel base of the vehicle. Increasing the track width will be accompanied by an increase in vehicle width. This will increase the vehicle's frontal area, leading to an increase in air drag. Making the vehicle wider will in principle also require more material for the vehicle body, so that an increase in track width will also lead to an increase in weight. Changing the wheel base may also influence the air drag and vehicle weight. Both impacts depend on the extent to which an increased wheelbase also leads to an increase in vehicle length.

The wheelbase of modern vehicles has already increased significantly over the last decades relative to pan area, accompanied by a reduction in front and rear overhang. In other words, footprint and pan area have converged. It is therefore reasonable to assume that further increase in wheelbase is generally only possible if it is accompanied by an increase in vehicle length.

In principle, changing the length of a vehicle while maintaining the overall shape leads to a reduction in the air drag coefficient C_w. However, as the drag coefficient depends on a lot of other vehicle parameters, it is difficult to make an exact correlation to vehicle length.

Based on the above it is assumed for the analysis in this paper that a relative change in footprint leads to an equal relative change in the product of width and length (pan area). The impact of footprint on CO_2 can then be examined by studying the impact of width and length on CO_2.

In the paragraphs below the impacts on CO_2 emissions are analysed of changes in mass, frontal area and drag coefficient C_w resulting from changing the width or length of the vehicle. The analysis is equally valid for footprint and for pan area, as it is assumed that a change in footprint is now only possible in most cases by an equivalent change in pan area. The analysis is based on the physical relationship between footprint and CO_2. It should not be based on the statistical relationship that can be derived from databases with vehicles on the market as in general larger vehicles emit disproportionately more CO_2 because they also tend to have better performance (i.e. higher power-to-weight ratio) than small cars.

Vehicle lateral dynamics

The lateral vehicle dynamics can be described by the following equation (force balance):

$$F = F_{acc} + F_{air} + F_{roll} + F_{grade} = ma + \frac{1}{2} \cdot C_w \cdot A \cdot \rho \cdot v^2 + f_r mg \cos(\alpha) + mg \sin(\alpha) \qquad (1)$$

For the case of the NEDC test cycle the last term (gradient) can be neglected because there is no hill-climbing component in the test. It is easily seen that the mass *m* of the vehicle influences most of the force resistances, except the air resistance. Weight has a strong relationship with the required engine power and the CO_2 emissions. As explained above, a change of the footprint influences the weight and the air drag resistance of the vehicle. Unlike weight change, therefore, the change of footprint will thus influence all parts of the equation and footprint changes will affect the fuel consumption and the CO_2 emissions.

Integrating formula (1) over the *v(t)* pattern of the NEDC cycle yields the total energy required at the wheels for driving the type approval test. Assuming an average engine efficiency over the NEDC cycle the energy at the wheels can be translated into fuel consumption and resulting CO_2 emissions. Such assumption of constant average engine efficiency is consistent with the assumption of constant performance. If changes to the vehicle design lead to higher energy and power demands, the engine power will have to be increased to maintain performance. A more detailed analysis, for this and for other assumptions of what happens to engine power if other utility parameters are changed, would require detailed power train simulations, but these are considered unnecessary for the purpose of this analysis. That is, it is necessary to assume an adjustment in engine power to maintain performance, but other parameters are held constant to give results on a *ceteris paribus* basis.

Impact of changes in width on frontal area

It is assumed that frontal area changes proportionally to the vehicle width, i.e. a 10% increase in width leads to a 10% increase in frontal area *A*. This is because there is no strong reason to assume that a change in vehicle height should accompany a change in width.

Impact of changes in length on C_w

For the moment we do not have a mathematical relation between vehicle length and C_w. In the analysis below it is assumed conservatively that a 10% increase in length leads to a 0.5% decrease in the value of C_w.

Impact of changes in length and width on mass

The table below shows a breakdown of the vehicle mass into contributions from different parts of the vehicle. When the width or length of a vehicle is increased not all parts are affected in the same way. Some parts will remain unaltered while the mass of other parts will increase to different extents. It is assumed that the mass of the body-in-white scales proportionally with width and length, but that e.g. closures, glazing, interior and suspension change less then proportionally. Scaling factors are based on expert judgement. The scaling factor for engine mass is derived from calculation of the maximum required power over the NEDC s with formula (1) and assuming that the total engine power is changed proportional to that in order to maintain overall performance.

	share in vehicle mass	part of mass that changes with width	length
BIW	23%	1.0	1.0
closures	7%	0.0	1.0
glass/trim/hardware	6%	0.5	0.5
interior	10%	0.3	0.2
electrical	4%	0.0	0.0
fluids	5%	0.0	0.0
power unit	17%	0.8	0.3
suspension	12%	0.2	0.1
wheels/tyres	6%	0.0	0.0
steering/brakes	3%	0.0	0.0
fuel/exhaust	6%	0.0	0.0
	100%	46%	42%

The above back-of-the-envelope analysis indicates that a 10% change in width or length (or equivalently in pan area or footprint (under assumption that this can only be changed if also pan area is changed) leads to a 4 to 5% change in vehicle mass. This relation can be used to adapt the mass in equation 1 to model the impacts of changes in length and width. In the analysis presented below different values for the scaling factors between length and width respectively and mass will be used to analyse the bandwidth.

Comparing the effect of changing footprint on CO_2 to the footprint based CO_2 limit function

Using the above relationships between length, width, frontal area, C_w and mass, equation (1) can be used to quantify the impact of changes in length and width on CO_2 emissions for a number of typical vehicles. Calculations have been made using variations on the actual values for the various vehicle parameters. The table below shows the results for different sets of assumptions (scenarios A to E) regarding these relationships. The variant cases are as follows:

- **A**: models the effects of changing length and width on CO_2 through the change in C_w and frontal area respectively, but assumes that changes in length and width do not lead to a change in vehicle mass;
- **B**: models the effects of changing length and width on CO_2 assuming that a 10% change in length and width each leads to a 4% change in vehicle mass;
- **C**: models the effects of changing length and width on CO_2 assuming that a 10% change in length and width each leads to a 5% change in vehicle mass;
- **D**: models the effects of changing length and width on CO_2 assuming that a 10% change in length and width each leads to a 10% change in vehicle mass;
- **E**: models the effects of changing length and width on CO_2 assuming that:
    - a 10% change in length or width leads to a 10% change in vehicle mass;
    - length does not affect C_w and width does not affect A.

case				Smart fortwo	VW Passat	BMW X5 4.8i	
A	scale factor length-to-mass	0.00					
	scale factor width-to-mass	0.00	ΔCO2/CO2=	0.0289	0.0166	0.0177	x Δl/l
	scale factor length-to-Cw	0.05	ΔCO2/CO2=	0.5777	0.3329	0.3532	x Δw/w
B	scale factor length-to-mass	0.40					
	scale factor width-to-mass	0.40	ΔCO2/CO2=	0.1978	0.2835	0.2764	x Δl/l
	scale factor length-to-Cw	0.05	ΔCO2/CO2=	0.7466	0.5998	0.6119	x Δw/w
C	scale factor length-to-mass	0.50					
	scale factor width-to-mass	0.50	ΔCO2/CO2=	0.2400	0.3502	0.3411	x Δl/l
	scale factor length-to-Cw	0.05	ΔCO2/CO2=	0.7889	0.6665	0.6766	x Δw/w
D	scale factor length-to-mass	1.00					
	scale factor width-to-mass	1.00	ΔCO2/CO2=	0.4512	0.6837	0.6645	x Δl/l
	scale factor length-to-Cw	0.05	ΔCO2/CO2=	1.0000	1.0000	1.0000	x Δw/w
E	scale factor length-to-mass	1.00					
	scale factor width-to-mass	1.00	ΔCO2/CO2=	0.4223	0.6671	0.6468	x Δl/l
	scale factor length-to-Cw	0.00	ΔCO2/CO2=	0.4223	0.6671	0.6468	x Δw/w
	frontal area kept constant						
	slope of limit function	120%	ΔCO2/CO2=	1.0321	1.6281	1.1513	x Δfp/fp
		100%		0.8601	1.3567	0.9594	
		80%		0.6880	1.0854	0.7675	
		60%		0.5160	0.8140	0.5756	
		40%		0.3440	0.5427	0.3838	
		20%		0.1720	0.2713	0.1919	
		0%		0.0000	0.0000	0.0000	

Results for CO_2 are valid under the assumption that a relative change in the propulsion energy required at the wheels leads to an equal relative change in CO_2 emissions. For each scenario physical relations between the relative change of length and width and the relative change of CO_2 emissions have been determined. These are compared to the relations between the relative change of footprint and the relative change of CO_2 emissions as given by the footprint-based limit functions derived in the main document.

Cases B and C present a realistic bandwidth for the impacts of changes in footprint / pan area on mass. Cases A and D are extreme cases, while case E provides a gauging with the relation between mass and CO_2 as used in previous studies. The relationships between CO_2 and length and width respectively in case E are entirely based on the impact of mass on CO_2. Except for the relatively small Smart car this relationships is very well in line with the formula $\Delta CO_2/CO_2 = 0.65\ \Delta m/m$ as used in [TNO 2006] and [IEEP 2008].

Because of the assumed relatively week relation between length and C_w the impact on CO_2 of changing width is much stronger than the impact of changing length.

A utility-based limit function creates perverse incentives when an increase in the value of the utility parameter reduces the distance to target (and thus reduces the required CO_2 reduction effort) without leading to actual CO_2 reduction. In relation to the table above this means that the slope of the limit function must be smaller than the slope of the physical relation between the utility parameter and CO_2.

Conclusions

Under the assumption that a relative change in the propulsion energy required at the wheels leads to an equal relative change in CO_2 emissions it can be conclude that the slope of the footprint-based limit function should not exceed 20 to 30% if one wants to avoid gaming by increasing the length of the vehicle. Gaming by changing the width of the vehicle reduces the distance to target for slopes over 60%.

If manufacturers increase vehicle size (length and/or width) without adapting the engine power to maintain performance the impact of mass increase on CO_2 becomes weaker. In Technical Note 4 of [IEEP 2008] it is shown that for this case the relation between CO_2 and mass may be $\Delta CO_2/CO_2 = 0.35\ \Delta m/m$. In this case the footprint-based limit function would need an even flatter slope to remain below the slope of the physical relation between footprint and CO_2. In the case of a mass-based limit this "brick-in-the-boot" gaming option may be very cheap and can be realised in existing vehicles. It should be noted that the equivalent option of changing footprint on existing vehicles is hardly possible, while it leads to significant costs on new vehicles if the vehicle dimensions need to be adapted to allow an increase in footprint.

The exact slope at which increasing footprint bring a vehicle closer to the target line depends strongly on vehicle size and on vehicle shape / model.

The above analysis assumes that especially wheelbase has already been stretched to the limit over the past decade, so that increasing wheelbase is not possible without increasing vehicle length. For an increase in track width always an increase in vehicle width is necessary. For those cases, however, in which footprint can be changed without increasing especially the length of the vehicle the impact on CO_2 will be negligible.

All in all it appears that the possible impact of changing footprint on CO_2 is weaker than that for mass and as a consequence does effectively not provide a better threshold against gaming than is the case for mass. The maximum slope of the limit function that does not reward gaming appears to be lower than in the case of a mass-based limit function. On the other hand this means that a given relative increase in footprint leads to lower additional CO_2 emissions than the same relative increase in weight, so that gaming and perverse trends related to footprint have a smaller environmental impact than in the case of weight.