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Reducing the energy consumption of heavy goods vehicles through the application of lightweight trailers: Fleet case studies

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ABSTRACT

Reducing the empty weight of articulated heavy goods vehicle trailers is one avenue that needs to be explored in reducing the carbon footprint of the road freight industry as a whole. A statistical analysis of two heavy goods vehicle fleets operating in the United Kingdom has helped to identify double-deck trailers used in grocery haulage and ‘walking-floor’ trailers used in bulk haulage as two examples of trailers that can benefit significantly from lightweighting. Energy consumption of numerous articulated heavy goods vehicles is quantified through an idealised drive cycle analysis reflecting a long haul journey over a highway. This energy analysis allows for a mass energy performance index to be established. The analysis has shown that reducing the empty weight of trailers by 30% can cause reductions of up to 18% and 11% in mass energy performance index for double-deck trailers and ‘walking-floor’ trailers respectively. Using this approach, trailers that will benefit the most from weight reduction can be identified systematically, allowing for lightweighting strategies to be implemented more effectively. Strategies to reduce empty trailer weight and improve vehicle utilisation are also discussed.

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Introduction

Road freight is without doubt the dominant medium for goods transportation throughout the United Kingdom (UK) and there are no indications of this changing in the foreseeable future. In 2010, of the total freight movements within Great Britain, heavy goods vehicles (HGVs) accounted for 68% of the total tonne-kilometres and 82% of total tonnes lifted ([Department for Transport, 2012a](#)). Moreover, predictions suggest that road freight activity will remain of underlying importance to society and the economy alike ([Mckinnon, 2006](#)). Road freight transport however is having an adverse effect on the environment as it accounts for approximately 5% of the UK’s carbon footprint ([Department for Transport, 2012a](#)). New aggressive targets established by the UK government aim to drastically reduce the emissions of greenhouse gases (GHGs) such as carbon dioxide (CO₂) by 2050. The target is an 80% reduction in GHG emissions compared to 1990 levels. Total empty vehicle weight is one factor that contributes to vehicle fuel consumption and CO₂ emissions. The total empty weight of articulated road freight vehicles is the combination of the empty weight of the tractor unit and the empty weight of the trailer. Therefore, by reducing the empty mass of the trailer the energy efficiency of the vehicle as a whole can be improved.

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The main contributors to energy consumption of HGVs can be grouped into three broad categories (Odhams et al., 2010):

- i. Vehicle design factors; such as vehicle dimensions, mass, volume, engine efficiency, rolling resistance, aerodynamic profile and material selection.
- ii. Logistical factors; such as vehicle utilisation, vehicle speed, vehicle routing and supply chain structure.
- iii. External factors; such as the drive cycle, the traffic conditions, driver behaviour and weather conditions.

It has also been noted that we can expect around a 6.5% reduction in fuel consumption from reducing trailer unladen mass by 25% (Odhams et al., 2010). This may seem to be a modest reduction relative to improving logistical factors such as running full by mass or running full by volume, which the analysis suggests can reduce fuel consumption by over 40% through reducing the total number of vehicles in a fleet. However, the estimated reduction of 6.5% in fuel consumption from lightweighting is still significant enough to pursue and may be more readily implemented compared to other measures. In fact, it has been suggested that reducing the unladen mass of the trailer is probably the easiest of the vehicle design changes to implement (Odhams et al., 2010), hence this is the focus of this study. It should be noted however, in order to achieve the ambitious 2050 GHG reduction target a portfolio of measures will be required. Such measures could include: trailer lightweighting, improved trailer aerodynamics, the adoption of alternative fuels and initiatives to improve vehicle utilisation, like those suggested by Léonardi and Baumgartner (2004). Driver training and reward schemes have been shown to have merit in reducing fuel consumption (Lai, 2015). The need for a portfolio of solutions to achieve ambitious long-term GHG emission reductions is well noted in literature (Yang et al., 2009).

The idea of reducing empty trailer mass by the application of lightweight materials in design is not a new one and throughout the last decade there has been a growing appreciation of the potential benefits from doing so. This has ultimately led to the development of a number of lightweight trailer prototypes which utilise lightweight composite materials in their structure. Examples of such lightweight trailers include: the ROADLITE trailer (Turner and Boyce, 2005), the CleanMould trailer (EPL Composite Solutions, 2010), the Compositrailer (Verhaeghe, 2006), the Phoenixx trailer (Jarvis, 2006) and the Walmart prototype trailer (Gardiner, 2014). Lightweight materials have also been applied to refrigerated trailers such as the carbon fibre based refrigerated Aldi trailer (Kaiser, 2010). All of these projects managed to reduce empty trailer weight by between 10% and 30% compared to conventional steel trailers.

Aside from the afore-mentioned trailers that are designed around a majority of lightweight materials, numerous companies have incorporated lightweight subcomponents into trailer designs. For example, composite sandwich panels are now a popular choice for the side walls of box-type trailers and refrigerated trailers. One such example is the VersaMax sandwich panel which is recyclable, impact-resistant and relatively low cost (VersaPlast, 2012). Other lightweight trailer subcomponents such as glass fibre based air suspension running gear systems (Bentfeld, 2012), are yet to enter the mainstream trailer market.

One major obstacle that is thought to be hindering the uptake of lightweight materials in HGV trailers is the difficulty in quantifying the energy consumption benefits that lighter trailers can bring. This is because in most developed economies such as the UK, operations are typically limited by volume rather than gross vehicle weight (GVW) or weight over axle. This is highlighted by Fig. 1 which shows data for the UK. This is largely attributed to the fact that the majority of vehicles move low density fast moving consumer goods (FMCGs). The average density of products that are commonly moved by HGVs are shown in Fig. 2.

The economic and environmental gains from lightweighting will only become relevant in weight-limited applications, as the relative benefits will diminish and become far less quantifiable in operations that are limited by volume. As such, it is proposed that the success of a lightweight trailer will depend heavily on identifying appropriate sectors of the road freight industry which frequently weight-out, that is, operate close to their legal maximum GVW. Whilst there are statistics released by the Department for Transport about GVW and fill-rate, the data lacks important details, such as tractor-trailer combination type and weight over axle, which can be found by examining individual HGV fleets in greater detail.

The aim of this paper is to identify specific logistic operations and corresponding HGV trailers that are prone to weighting-out and to use this information to deduce what energy savings could be realised through reducing empty trailer

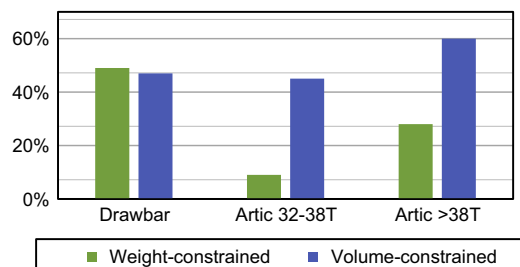


Fig. 1. Percentage of weight and volume constrained heavy goods vehicles operating in the UK, adapted from Mckinnon (2010).

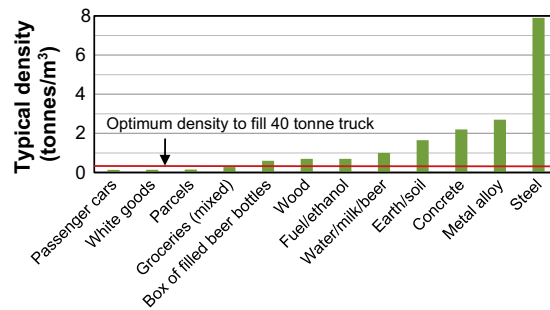


Fig. 2. Approximate densities for a range of common road freight payloads, adapted from Glaeser (2010).

weight. This will assist fleet operators and trailer manufacturers alike in assessing which trailers stand the most to gain from lightweighting. Specific trailers are identified through a statistical study of the weight characteristics of two commercial HGV fleets operating in the UK (Section 'Statistical analysis of two different road freight fleets'). The first fleet (Section 'Heavy goods vehicle fleet used in grocery distribution (non-refrigerated)') primarily distributes FMCGs whilst the second fleet (Section 'Heavy goods vehicles used in bulk haulage') is concerned with bulk haulage. The distribution of FMCGs and bulk haulage generate a significant amount of road freight movements in the UK in terms of both tonnes lifted and tonne-kilometres. Both fleets examined are owned by large companies within these sectors, so they can give a good insight into these sectors as a whole within the UK. The weight data obtained from these case studies are then used in an idealised drive cycle analysis (Section 'Energy consumption estimation through an idealised drive cycle analysis') to predict reductions in energy consumption that result from reducing the mass of trailers by 30%. Ways of achieving this reduction in empty trailer weight, as well as ways to improve vehicle utilisation, will both be discussed in Section 'Discussion'.

Statistical analysis of two different road freight fleets

Heavy goods vehicle fleet used in grocery distribution (non-refrigerated)

The aim of the first statistical case study is to identify the tractor–trailer combinations that tend to be limited by weight in a HGV fleet used to transport non-refrigerated groceries from a distribution centre in the UK. At the distribution centre there are two main types of operation; trunking operations to other distribution centres and store delivery. Trunking operations are typically performed with an articulated combination of a three axle 13.6 m double-deck trailer with box sidewalls combined with a three axle tractor. A three axle 13.6 m single deck curtain side trailer combined with either a two or three axle tractor are the two other less common types of tractor–trailer combination that operate from the distribution centre. All tractor–trailer combinations used in distribution are required to adhere to UK regulations on maximum GVW and maximum weight over axle as shown in Table 1. In addition to weight regulations, volume constraints dictate that double-deck trailers are limited to carrying 75 grocery cages, whilst single deck trailers are limited to 45 cages.

Based on weighbridge ticket data collected over a typical week of operations, probability distributions have been created for weight over tractor axle, weight over trailer axle, GVW and number of cages carried for the three most common articulated combinations operated out of the distribution centre (Figs. 3–5). Each distribution is created from a kernel smoothing function estimate calculated with the 'kdensity' function in MATLAB. To show the consistency of the smoothing function, a histogram of raw weight data is plotted alongside the smoothed distribution for each of the GVW plots. Note that only histogram plots are shown for the number of cages, as they are more appropriate given the discretised nature of this data. In the few cases where trailers are used to carry a small number of pallets in addition to cages, the distribution of number of cages has been simplified by assuming that one pallet is equivalent to two cages.

Table 1

The current amendments to the Road Vehicles (Construction and Use) Regulations 1986 (SI 1986/1078) relevant to articulated vehicles with a total of five or six axles.

Number of axles in articulated combination	Maximum GVW	Maximum Weight Over Axle	Comments
6	44* tonnes	10.5 tonne limit on drive axle	* Indicates that the tractor must be fitted with a low pollution (at least Euro 2 compliant) engine Tractor and trailer must both have three axles Trailer must be fitted with road friendly suspension
	OR 41 tonnes	24.0 tonne limit on trailer bogie (this equates to 8.0 tonne per axle)	
5	40 tonnes	11.5 tonnes over all axles	Two axle tractor and three axle trailer OR three axle tractor and two axle trailer

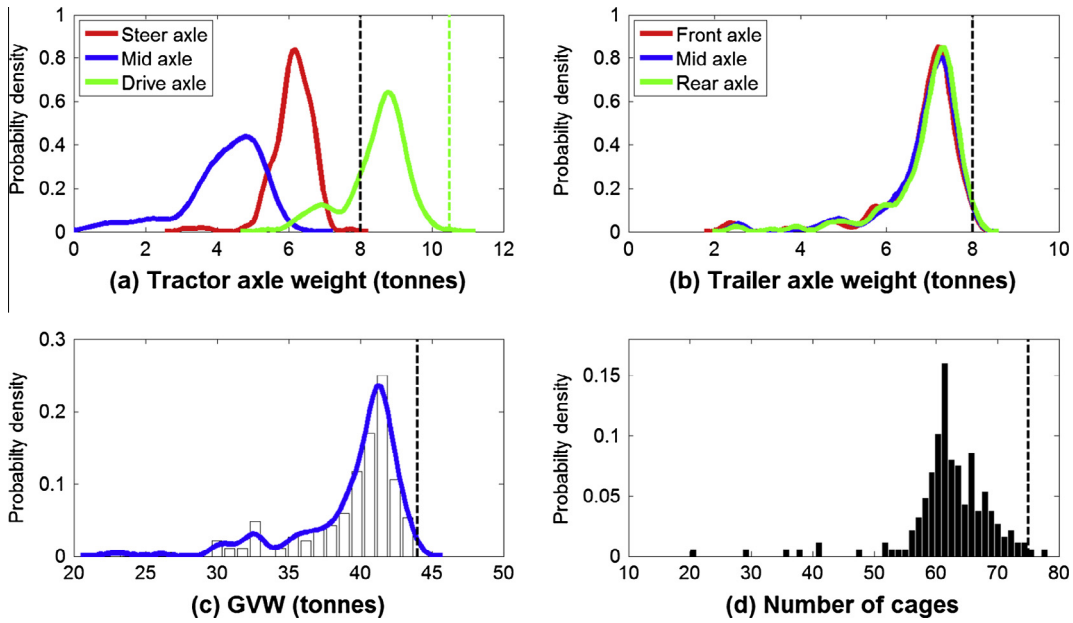


Fig. 3. Probability distributions (with kernel smoothing function applied) for: (a) tractor axle weight, (b) trailer axle weight, (c) GVW and (d) a histogram of number of cages for 13.6 m double-deck box trailers combined with three axle tractors used in non-refrigerated grocery distribution. Dashed lines indicate maximum allowable values. Sample size = 188.

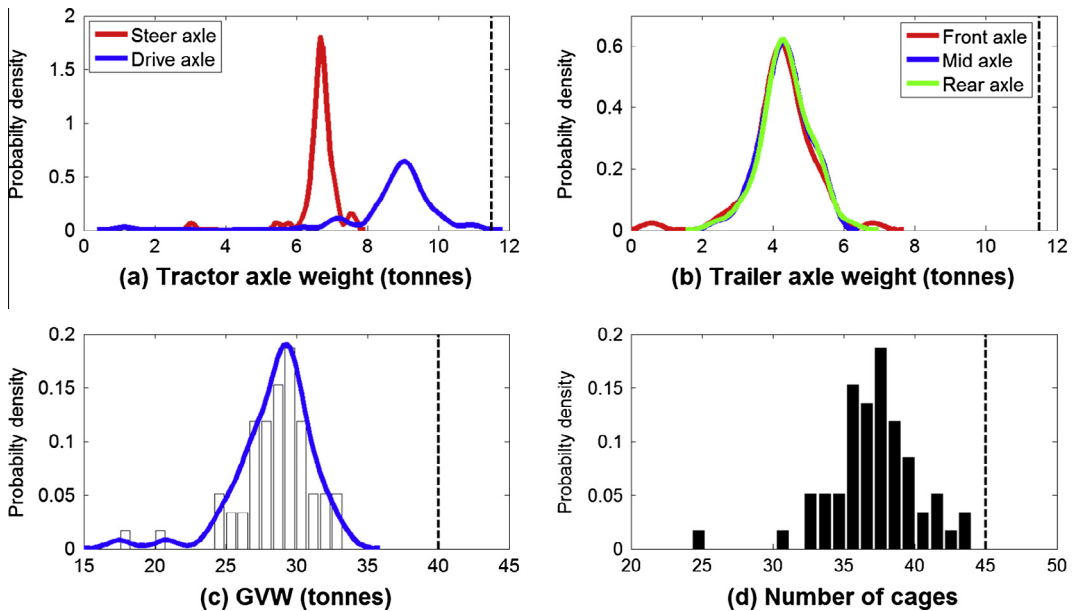


Fig. 4. Probability distributions (with kernel smoothing function applied) for: (a) tractor axle weight, (b) trailer axle weight, (c) GVW and (d) a histogram of number of cages for 13.6 m single deck curtain side trailers combined with two axle tractors used in non-refrigerated grocery distribution. Dashed lines indicate maximum allowable values. Sample size = 59.

Plotted over each of the distributions are the maximum allowable values as described previously, which help to identify the limiting factor in operation for each of the different combination types. It is assumed that combinations using a three axle tractor are fitted with at least a Euro 2 compliant engine so that the maximum legal GVW will be 44 tonnes. Note that median values rather than mean values are reported as they provide the best indicator of an average value since there are outliers in the distributions and the data is not symmetrically distributed.

Fig. 3 indicates that weight, rather than number of cages, is more likely to be the limiting factor in the operation of the double-deck trailers. In particular, the average GVW (Fig. 3(c)) of the double-deck trailers is 40.8 tonnes, which is 93% of the maximum allowable value of 44 tonnes. Similarly, the weight over trailer axle (Fig. 3(b)), was found to have an average value

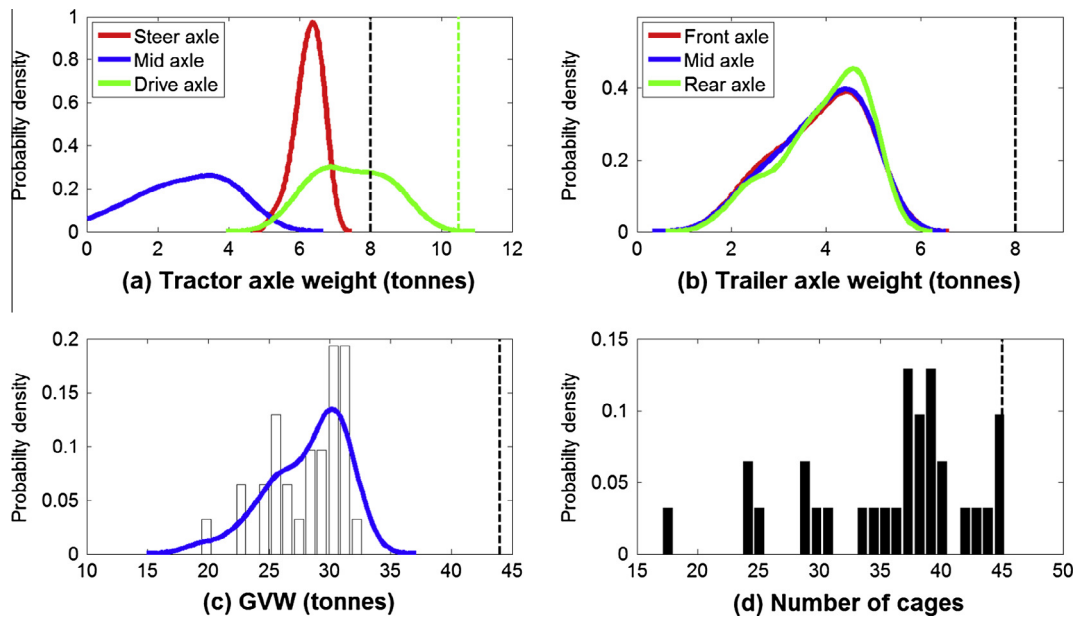


Fig. 5. Probability distributions (with kernel smoothing function applied) for: (a) tractor axle weight, (b) trailer axle weight, (c) GVW and (d) a histogram of number of cages for 13.6 m single deck curtain side trailers combined with three axle tractors used in non-refrigerated grocery distribution. Dashed lines indicate maximum allowable values. Sample size = 31.

of 7.1 tonnes, 89% of the maximum allowable value of 8.0 tonnes. However, the average number of grocery cages (Fig. 3(d)) carried for double-deck trailer operations was found to be 62, which is only 83% of the maximum allowable value of 75 cages. This is to be expected, as numerous fleet operators report that the double-deck trailers tend to reach their maximum allowable weights before they can be completely filled, owing to their increased size and volume.

Different to double-deck trailer operation, Figs. 4 and 5 show that both types of single deck trailer combinations operate far from their maximum allowable axle weight and GVW. For example, the average GVW for both types of single deck trailer operations is 29 tonnes, which is far short of the maximum allowable limit of both combinations. On the other hand, the number of cages carried by single deck trailers is closer to the maximum allowable limit, though it is still somewhat far from it. For both types of single deck trailer operations, the average number of grocery cages carried was found to be 37, which is 82% the maximum allowable value of 45 cages.

Heavy goods vehicles used in bulk haulage

The aim of the second statistical case study is to investigate the HGVs that tend to be limited by weight in a commercial bulk haulage fleet operating in the UK. Within the fleet there are two categories of vehicles; rigid '8 wheeler tippers' which have a maximum legal GVW of 32 tonnes and articulated combinations with a total of six axles which have a maximum legal GVW of 44 tonnes. The rigid tipping vehicles are typically comprised of aluminium tipping bins, whilst the 44 tonne vehicles are articulated combinations with three axle tractor units and three axle trailer units with either an aluminium 'walking-floor' or a steel tipping bin.

As in the previous case study, weighbridge ticket data is collected to create probability distributions for GVW for both 32 and 44 tonne vehicles (Fig. 6(a)). To examine the effect of payload type on GVW, the weight data is broken down further to show average GVW by payload type for both weight categories of vehicles (Fig. 6(b) and (c)). Note that for the same reasons as in the previous case study, median values are used to average.

Fig. 6 shows that the 44 tonne capacity vehicles operate close to their maximum allowable weight with an average GVW of 43.0 tonnes. This is in contrast to the rigid 32 tonne capacity tipping vehicles which operate far from their maximum allowable weight with an average value of 22.9 tonnes. The analysis also shows whilst the two different weight class of vehicles are carrying similar payload types, the 44 tonne vehicles are much more frequently operating near their maximum legal GVW. This is attributed to the fact that the 32 tonne vehicles are deployed more flexibly in operations; for example, they are frequently used in jobs that are paid by trip rather than payload weight.

Energy consumption estimation through an idealised drive cycle analysis

This section attempts to quantify the energy consumption reductions that can be brought from lightweighting the trailers (in articulated combinations) presented in the previous case studies by applying an idealised drive cycle analysis.

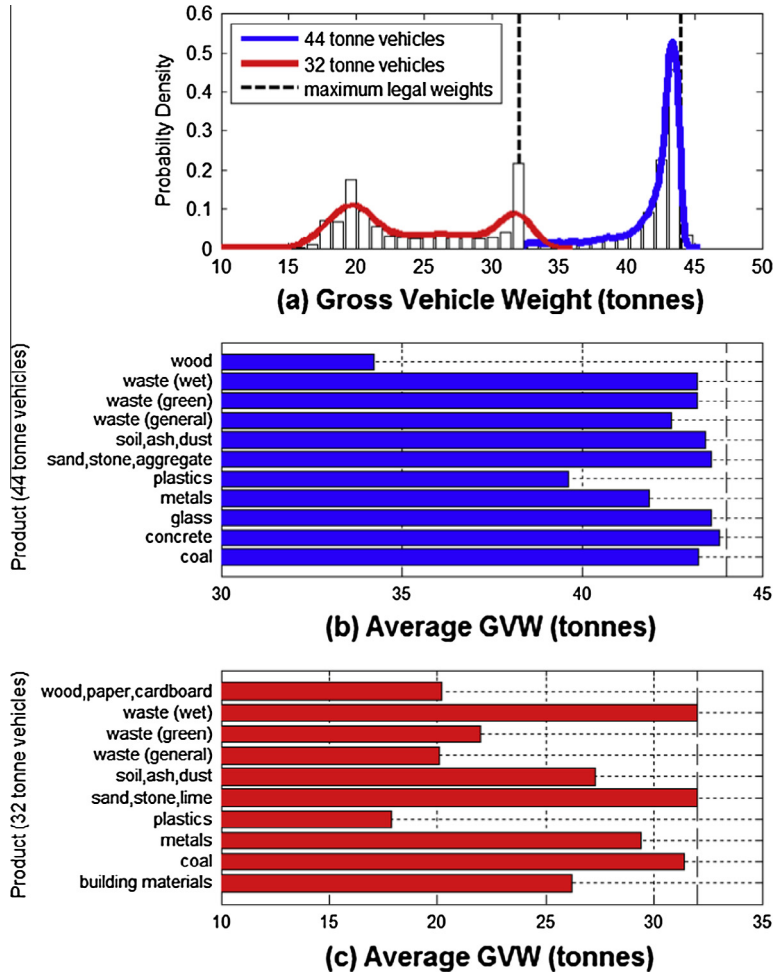


Fig. 6. (a) Probability distribution (with kernel smoothing function applied) for GVW for 44 tonne vehicles (sample size = 5773) and 32 tonne vehicles (sample size = 3572) used in bulk haulage. (b) Average GVW by payload type for 44 tonne articulated combinations (sample size = 4719). (c) Average GVW by payload type for rigid tipper trucks with a maximum legal GVW of 32 tonnes (sample size = 2855).

As vehicles become lighter it is prudent from an operations perspective to use the extra weight saved to increase the payload weight of the vehicle. However, this can act to mask the energy benefits from lightweighting as the GVW will be roughly the same as before the trailer weight reduction. Hence in this case we will observe that a similar amount of fuel has been consumed. To overcome this issue, Odhams et al. (2010) quantified energy consumption through an energy performance index. They define mass energy performance index (EI_m) with units of kJ/tonne km, for vehicles that are mass-limited (Eq. (1)):

$$EI_m = \frac{\text{Total energy used}}{\text{Mass payload} \times \text{Distance travelled}} \tag{1}$$

Here the total energy used equates to the tractive energy (E_{trac}) of the vehicle required to overcome the energy associated with aerodynamics (E_{aero}), rolling resistance (E_{RR}) and kinetic energy. These energies can be determined by first considering a simple force balance on a vehicle travelling on a straight and level road as shown in Fig. 7.

A force balance determined from the free body diagram yields a formula for tractive force (F_{trac}) (Eq. (2)), in terms of aerodynamic force (F_{aero}), rolling resistance force (F_{RR}) and linear momentum. This equation can then be expanded (Eq. (3)). Tractive power (Eq. (4)) is then determined by multiplying tractive force (Eq. (3)) by the vehicle velocity (v). Integration of the positive values of tractive power over an idealised drive cycle (Fig. 8) yields the tractive energy required to travel a certain distance (s) in that time (t) (Eqs. (5) and (6)). To simplify the analysis, only positive tractive energy is accounted for. Because tractive force is negative throughout the entire braking period at the end of the drive cycle, the tractive energy here is negative, hence the fuel consumed during this period is neglected. The engineering constants used throughout the drive cycle analysis are defined in Table 2 and the vehicle mass (m) in the equations refers to GVW.

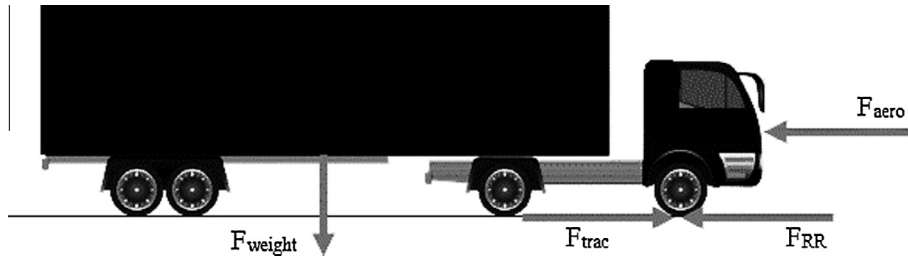


Fig. 7. Free body diagram of a lorry travelling along a straight level road.

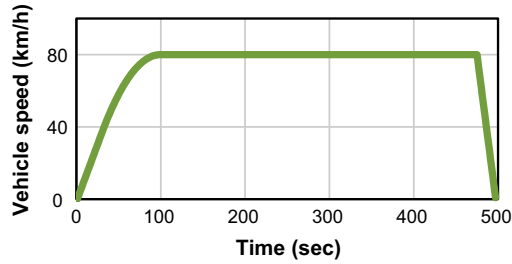


Fig. 8. Idealised long haul drive cycle over a distance of 10 km, adapted from Odhams et al. (2010).

$$F_{\text{trac}} = F_{\text{aero}} + F_{\text{RR}} + m \frac{dv}{dt} \quad (2)$$

$$F_{\text{trac}} = \frac{1}{2} C_D A \rho_{\text{air}} v^2 + C_{\text{RR}} mg + m \frac{dv}{dt} \quad (3)$$

$$P_{\text{trac}} = \frac{1}{2} C_D A \rho_{\text{air}} v^3 + C_{\text{RR}} mg v + m v \frac{dv}{dt} \quad (4)$$

$$E_{\text{trac}} = E_{\text{aero}} + E_{\text{RR}} + E_{\text{kinetic}} \quad (5)$$

$$E_{\text{trac}} = \frac{1}{2} C_D A \rho_{\text{air}} \int_{t_0}^{t_1} v^3 dt + C_{\text{RR}} mg s + \frac{1}{2} m (v_2^2 - v_1^2) \quad (6)$$

The corresponding volume of fuel burnt for the journey can then be estimated by multiplying the tractive energy by the inverse of the lower heating value of diesel, with the engine and transmission efficiencies also being accounted for (Eq. (7)). The effect of vehicle accessories and gear ratios on fuel consumption have both been neglected for this simple comparative analysis.

$$\text{Fuel Consumed (L)} = \frac{1}{\eta_{\text{eng}} \eta_{\text{trans}} \text{LHV}} E_{\text{trac}} \quad (7)$$

All the vehicles in both case studies are typically being operated outside of urban areas on long haul journeys over highways. With this in mind, an idealised drive cycle to reflect this kind of journey was chosen for use in the tractive energy analysis. The drive cycle used is shown in Fig. 8 and has been adapted from Odhams et al. (2010).

Table 2
Engineering constants used in the drive cycle analysis.

Property	Value
Coefficient of aerodynamic drag ($C_D A$)	6.62 m ² (Laclair, 2011)
Coefficient of rolling resistance (C_{RR})	0.0066 (Odhams et al., 2010)
Density of air at sea level (ρ_{air})	1.225 kg/m ³ (Laclair, 2011)
Acceleration due to gravity (g)	9.81 m/s
Lower heating value of diesel (LHV)	35,500,000 J/L (Laclair, 2011)
Efficiency of engine (η_{eng})	0.4 (Laclair, 2011)
Efficiency of transmission (η_{trans})	0.9 (Laclair, 2011)

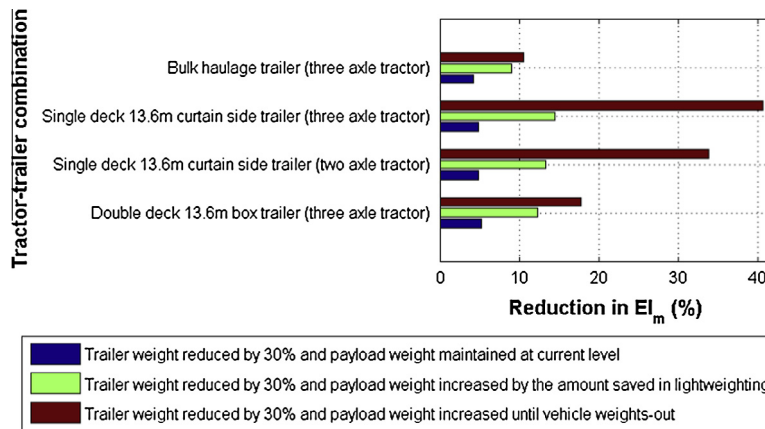


Fig. 9. Estimates of energy consumption reductions that can be achieved through three scenarios involving lightweighting. Note that the third scenario, which involves reducing trailer weight by 30% and increasing the payload until the vehicle reaches its maximum legal GVW (weights-out), will be difficult to achieve for single deck trailers used in grocery distribution because of their volume restrictions. However, this scenario should be achievable in bulk haulage trailers and double-deck trailers used in grocery distribution.

This procedure was then used to evaluate the potential reductions in mass energy performance index for the articulated vehicle combinations from the two case studies presented in Section ‘Statistical analysis of two different road freight fleets’ for the following three scenarios (Fig. 9):

1. Reducing trailer weight by 30% and maintaining payload weight at its current level. In this scenario the reduction in mass energy performance index is directly related to the reduction in fuel consumption.
2. Reducing trailer weight by 30% and increasing payload weight by the amount of weight saved in trailer lightweighting. In this scenario fuel consumption will reflect current levels though payload weight will increase, thus resulting in an overall reduction in mass energy performance index.
3. Reducing trailer weight by 30% and increasing payload weight until the vehicle weights-out (reaches its maximum legal GVW). Here fuel consumption will increase slightly and payload weight will increase markedly producing an overall reduction in mass energy performance index.

Note that 30% weight reduction assumed in the scenarios reflects the weight saving achieved by lightweight prototype trailers outlined in Section ‘Introduction’. The different levels of mass fill rates in each of the scenarios correlates to different levels of improvement to the logistics side of operations.

Discussion

The statistical analysis in Section ‘Heavy goods vehicle fleet used in grocery distribution (non-refrigerated)’ has identified the articulated combination of 13.6 m double-deck box trailers with a three axle tractors as being the tractor-trailer combination that operates closest to its maximum allowable weight limits. This seems reasonable as these trailers have a larger volume and empty weight compared to that of single deck trailers. This suggests that the double-deck trailers in this fleet in particular are good candidates for weight reduction, subject to logistics constraints such as time. This notion is supported by the fact that the analysis in Section ‘Energy consumption estimation through an idealised drive cycle analysis’ suggests that we can expect a reduction of up to 18% in mass energy performance index by reducing the weight of the double-deck trailers by 30% and increasing their payload until the vehicle reaches its maximum legal GVW. The analysis in Section ‘Energy consumption estimation through an idealised drive cycle analysis’ also suggests that we could potentially reduce the mass energy performance index of single deck trailers by up to 41% through the same scenario. However, this scenario is significantly more difficult to achieve in practice largely because of the limited volume of single deck trailers.

The increase in average payload weight that is assumed by two of the three scenarios in Section ‘Energy consumption estimation through an idealised drive cycle analysis’ will most likely require significant improvement to the logistics side of fleet operations. Such improvements could include (but are not limited to): more accurate knowledge of individual cage weight data through refinement of the warehouse management system, refinement of route planning and improving vehicle utilisation. The need to improve vehicle utilisation is not only indicated by the two fleet case studies in Section ‘Statistical analysis of two different road freight fleets’ but also national statistics. For example in the UK in 2010, up to 29% of the tonne-kilometres moved by road freight were not limited by either weight or volume (Department for Transport, 2012a). This suggests that there is a large scope for improvement in vehicle utilisation across many HGV fleets.

One way of improving vehicle utilisation is through the application of double-deck trailers. Indeed, these trailers are growing in popularity and both market research and case studies show that they can provide noteworthy improvements to vehicle utilisation (Piecnyk and McKinnon, 2010). Moreover, market research suggests that investment in double-deck trailers may rise particularly within the retail, road haulage and grocery store sectors (Piecnyk and McKinnon, 2010). These factors all reiterate that double-deck trailers are a prime candidate for lightweighting by greater investment in lightweight designs and technologies. It should be noted however, whilst double-deck trailers are particularly appropriate for the UK where there are high bridge and tunnel clearances, the lesser height clearances that feature in many other European countries means their application are limited in mainland Europe. Indeed, previous lightweight prototype trailers mentioned in Section 'Introduction' have been built primarily with the mainland European market in mind, which would suggest that the concept of a lightweight double-deck trailer has been largely neglected to date.

Another way of improving vehicle utilisation is through the application of longer trailers, which have started a 10 year trial in the UK in January 2012 (Department for Transport, 2012b). These longer trailers, like double-deck trailers, have a typically high empty weight which also makes them a good candidate for lightweighting, especially if they are to be permitted for use beyond the trial period.

Whilst the grocery fleet analysed in Section 'Heavy goods vehicle fleet used in grocery distribution (non-refrigerated)' has not taken into consideration refrigerated trailers, it can be expected that these trailers will be operating even closer to their maximum legal GVW, as the trailers carry the additional weight of the refrigeration system.

The analysis of the bulk haulage fleet in Section 'Heavy goods vehicles used in bulk haulage' has shown that the articulated vehicles with a maximum legal GVW of 44 tonnes are much more likely to be limited in operation by weight compared to the rigid tippers that have a maximum operating weight of 32 tonnes.

Section 'Energy consumption estimation through an idealised drive cycle analysis' showed that up to an 11% reduction in mass energy performance index of 44 tonne bulk haulage vehicles is achievable by reducing empty trailer weight by 30% and increasing payload weight until the vehicle reaches its maximum legal GVW. This significant energy saving combined with the fact these vehicles operate close to their maximum allowable GVW make them another good candidate for lightweighting. Moreover, it is thought that 'walking-floor' trailers used in the 44 tonne articulated combinations pose a strong candidate for lightweighting as they are commonly used to haul general waste and green waste materials that are not as dense and damaging as the materials carried by steel tipping bins. Because 44 tonne steel tipping bins are often used to carry heavy bulk products such as stone and scrap metal they need to be extremely robust in construction, meaning that they are potentially a poor candidate for lightweighting. Whilst employing a lightweight 44 tonne articulated tipper only on jobs with less damaging payloads could overcome this issue, this is unlikely in practice since the trailer will become significantly less flexible in its operation, which is often of prime importance to fleet operators.

The analysis of reduction in mass energy performance index carried out in Section 'Energy consumption estimation through an idealised drive cycle analysis' relies on the fact that empty trailer mass for all the articulated combinations can be reduced by 30%. This weight reduction could be achieved through a number of different measures, including:

- Applying lightweight composite materials to the trailer chassis and/or main subcomponents such as: sidewalls, decking and wheels.
- Implementing a steerable wheel trailer, like that developed by Jujnovich et al. (2008), which would allow for larger spacing between trailer axles and hence a reduction in chassis size and weight.
- Removing the lifting deck on double-deck trailers where they are not needed.

Conclusions

Reducing the empty weight of HGV trailers used in mass-limited operations can bring significant energy consumption savings which will lead to a reduction in both operation costs and carbon footprint. The mass energy performance index defined by (Odhamms et al., 2010) is a useful way to quantify the energy consumption of mass-limited heavy goods vehicles. By using this index in conjunction with fleet weight statistics and a simplified drive cycle analysis, it is possible to quantify the reductions in energy consumption caused by hypothetical reductions in empty trailer mass. Using this approach, trailers that will benefit the most from weight reduction can be identified systematically, allowing for lightweighting strategies to be implemented more effectively.

The statistical analysis of two HGV fleets that are operated in the UK identifies double-deck trailers used in grocery distribution and 'walking-floor' trailers used in bulk haulage as two examples of HGV trailers that are good candidates for lightweighting, as they operate relatively close to their legal weight limits. Whilst the analysis here is limited to two HGV fleet case studies, these fleets are owned by large companies that represent a significant proportion of road freight tonne-kilometres within their respective sectors.

To reduce empty trailer mass in practice, applying lightweight composite materials to trailer subcomponents such as decking and side walls seems a logical way to begin the process as this can be implemented in short time frames and for a minimal increase in cost. However, for a long-term solution more radical design changes will be needed to drastically reduce empty trailer weight. Despite the fact that holistic lightweight composite trailers have failed to gain any significant market acceptance, these trailers will become increasingly viable as a greater emphasis is placed on reducing the energy consump-

tion of the road freight industry. An in-depth understanding of fleet operations gained by examining representative fleet data like that presented here, will aid the development and application of lightweight trailers that are economically viable.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.trd.2015.09.010>.

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