The application of a systematic approach to material selection for the lightweighting of metro vehicles

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Abstract: With reduced operational energy consumption as the primary driver, a cross-industry consortium of vehicle manufacturers has explored some of the issues surrounding the introduction of lightweight materials into metro vehicles. Taking today’s vehicles as the starting point, the aim of the study was to examine the current barriers that need to be removed or overcome in order to realize the economic and environmental benefits of lightweight materials.

From a technical perspective, the use of a systematic approach to material selection is described that matches the design requirements and constraints of a given application to potentially suitable candidate materials within a large database. The approach is illustrated by a case study in which a 57 per cent mass saving is achieved for a metro vehicle interior grab rail.

Estimates are also provided for the magnitude of the operational energy and cost savings that can be achieved through metro vehicle lightweighting. For the particular scenario considered in this article, a 10 per cent reduction in vehicle mass was estimated to equate to a 7 per cent saving in energy consumption and a corresponding 100 000 £ annual operational cost saving per vehicle. Such data can now be used to support decision making with respect to the benefits of lightweighting.

Keywords: lightweighting, energy saving, metro vehicles, material selection

1 INTRODUCTION

With the rising economic and environmental pressures associated with the generation and consumption of energy, transport operators are increasingly considering the energy efficiency of their fleets. One approach to reducing the energy consumption of a vehicle is to reduce its overall mass. Everything else being equal (e.g. track profile, timetabling, driving style, and so on), a lighter vehicle will consume less energy in operation than a heavier one.

It is theoretically possible to reduce the tare mass of vehicles by employing lightweight materials and design principle. However, before lightweight materials can be specified in practice, it is essential that any potential constraints on their use are removed. Such constraints might be:

(a) technical – perhaps relating to the fitness for purpose of the lightweight material, the availability of design data, or issues associated with manufacturing and assembly;
(b) economic – perhaps relating to the direct cost of the lightweight material, or the costs associated with its qualification or maintenance;
(c) wider constraints – perhaps relating to standards and specifications, supply chain issues, or customer acceptance.

As part of the MODURBAN (MODURBAN – Modular Urban Guided Rail Systems, European Commission Contract No. TIP4-CT-2005-516380. See www.modurban.org for more information) European project, a team of engineers from Alstom Transport, AnsaldoBreda, Bombardier Transportation, Siemens Transportation Systems, and NewRail convened to
consider the various issues surrounding the increased use of lightweight materials in the rail industry. Their findings are presented in this article. The main focus of MODURBAN was metro systems, and that focus is reflected here. However, many of the observations and conclusions will be equally relevant to mainline rail.

2 TODAY’S METRO VEHICLES: MATERIALS AND MASS

As the first phase of the programme, a study was made of the material usage and mass of typical state of the art metro vehicles. The aim was to highlight those components and assemblies that might provide the best opportunities for lightweighting through material substitution. Each of the four vehicle manufacturers provided mass breakdown data for a typical metro vehicle within their current product range. They also provided information on material usage. All four vehicles considered were broadly similar six car sets comprising four motor cars and two trailer cars.

Although there was some variation in the total mass of the four vehicles (varying between 1470 and 1760 kg per linear metre of vehicle length), the relative mass breakdown of each was very similar. Figure 1 shows a typical mass breakdown from the study. It can be seen that five aspects – the bodyshell, the bogies (including gear boxes, wheelsets, suspension elements, and so on), the passenger interior (excluding seats), the external doors, and the heating, ventilation, and air conditioning (HVAC) systems account for ∼80 per cent of the total tare mass.

In terms of material usage, one of the notable trends was the high degree of consensus across the four vehicles for the major structural items. For example, all four vehicles employed aluminium bodyshells and steel bogie frames. Conversely, for the less structural parts there was a much greater diversity in the materials employed. An example was the interior flooring for which a number of different solutions were employed, including plywood-based systems and aluminium sandwich panels. This suggests that manufacturers and operators are more likely to be open to material substitutions for semi-structural or non-structural parts, which is intuitively reasonable.

3 MATERIAL SELECTION FOR LIGHTWEIGHTING

If the objective of a lightweighting design exercise is to identify the most suitable materials that fulfil all the essential requirements and constraints of a given application with minimum mass, then it would be useful to have two specific design aids available.

1. A large database of materials that provides a global population of possible material options.
2. A means of sorting through that database in a systematic and rational manner in order to identify and compare only those materials that fulfil the necessary requirements and constraints of the application considered.

Indeed, the current general lack of such design aids within the rail industry could be considered as one of
the constraints to the more widespread specification of lightweight materials.

There are several commercial software packages that fulfil such a function, so there was no need for the MODURBAN partners to develop their own solution. For the purposes of the study described here, the ‘CES Selector’ material selection software of Granta Design Limited was employed. CES’s approach to material selection is well described by Ashby [1] and illustrated by Ashby and Cebon [2]. Very briefly, it can be summarized by the following five steps.

1. Problem definition. The component to be analysed is characterized in terms of:
   (a) its function – the primary purpose of the part;
   (b) the objective of the study. Here it was to ‘minimize mass’;
   (c) the constraints – the requirements of the application that any new design must meet.

2. Definition of the objective function. If the objective of the materials selection exercise is to minimize the mass of a given component, then the objective function will normally be an expression for that component’s mass. The aim will then be to minimize the value of the objective function.

3. Definition of the constraints. In a similar way to the objective function, each of the constraints identified in the problem definition step needs to be quantified. Using the Ashby [1] approach, this is normally achieved through the use of ‘performance indices’ and ‘attribute limits’. Performance indices are derived expressions that characterize the performance of a particular geometry as a function of its material properties. Attribute limits are simply minimum or maximum permitted values of a given material property.

4. Implementation of the material selection using material selection charts. Material selection charts are constructed by plotting two material properties (or combination of properties) against each other on logarithmic axes. The use of logarithmic axes allows all the materials within a database to be conveniently displayed on a single diagram. The performances indices and attribute limits defined in step 3 can then be superimposed on the chart to identify potential candidate materials.

5. Interpretation of the results. Having identified which materials in the database pass the various constraints and, most importantly, which materials pass all of the constraints combined, the result is normally a short list of candidate materials. These candidates then need to be considered further to determine whether they really represent viable options. Common questions that might be considered at this stage include the following:
   (a) Is the candidate material readily available?
   (b) In what forms is the candidate material available?
   (c) Are there viable processing/fabrication routes available for the candidate material?
   (d) Are there any health and safety issues associated with the candidate material?
   (e) Have all the constraints associated with the application been considered in full?
   (f) Does the candidate material provide a sufficiently great advantage over the existing solution to warrant further investigation?
   (g) Does the candidate material bring new issues or compromises that were not a factor with the existing solution?

4 LIGHTWEIGHTING CASE STUDY: METRO VEHICLE INTERIOR GRAB RAIL

In order to illustrate the material selection approach just described, a relatively straightforward example will be considered. Interior grab rails, such as the ones depicted in Fig. 2, are well suited to lightweighting through material substitution. They are self-contained components that are easily replaced, they have well-defined functions and constraints, and they have simple geometries that are easily analysed. Furthermore, a typical six car metro vehicle might have anything up to 200 grab rails of various dimensions weighing a total of >700 kg. Therefore, while an individual grab
rail is not particularly heavy, collectively they represent a sizeable mass and are therefore good candidates for lightweighting.

The grab rails considered in this particular case study were of the straight floor-to-ceiling type. They are typically around 2 m long with an outside diameter of around 35 mm. They must be sufficiently rigid to support passengers during the acceleration and braking phases of the vehicle. Furthermore, they must not exhibit any undesirable vibration characteristics. They must also satisfy requirements with respect to fatigue in bending, as well as fire.

At present the grab rails considered here are made from stainless steel and each weighs 4.8 kg (excluding fittings). Is there an alternative material that would provide a lighter solution at similar cost and performance levels? The five-step material selection approach described previously is followed in order to address this question.

4.1 Step one – problem definition

The material selection problem to be addressed is defined in terms of the component's function, objectives, and constraints. For the grab rail these are specified in Table 1.

4.2 Step two – definition of the objective function

The objective of the material selection exercise is to reduce the mass of the grab rail. Therefore, the objective function is simply an expression for the grab rail's mass. It can be written as

\[ m = AL\rho \approx 2\pi rtL\rho \]  

(1)

where \( m \) is the mass of the grab rail, \( A \) is the cross-sectional area of the grab rail, \( L \) is the length of the grab rail, \( \rho \) is the density of the material from which the grab rail is made, \( r \) is the radius of the grab rail, and \( t \) is the wall thickness of the grab rail. In the subsequent analysis, the overall objective is then to minimize the value of equation (1).

4.3 Step three – definition of the constraints

The constraints of the grab rail need to be defined in terms of 'performance indices' and 'attribute limits'.

Starting with the stiffness constraint, the stiffness, \( S \), of a rigidly constrained beam under a perpendicular mid-span load can be written as [1]

\[ S = \frac{192EI}{L^3} \]  

(2)

where \( E \) is Young's modulus of the material from which the beam is made and \( I \) is the second moment of area of the beam.

For a thin-walled hollow circular beam, \( I \) can be approximated as [1]

\[ I \approx \pi r^4t \]  

(3)

Variables \( L \) and \( r \) are fixed; they are constraints (Table 1). Similarly, the beam stiffness \( S \) is specified – this must be sufficient to support the passengers. The free variable is \( t \), the wall thickness of the grab rail. Therefore, using equations (2) and (3) to eliminate \( t \) in equation (1) (the objective function) gives

\[ m \approx \left( \frac{2SL^4}{C_1r^2} \right) \left( \frac{\rho}{E} \right) \]  

(4)

Hence the mass, \( m \), of the grab rail is minimized by choosing materials with a large ratio of Young's modulus to density. The performance index, \( M_1 \), is

\[ M_1 \approx \frac{E}{\rho} \]  

(5)

It can be seen from the above analysis that the derivation of performance indices is reliant on the ability of the component to be characterized using simple analytical expressions. Clearly this approach is not going to be directly transferable to more complex geometries that cannot be readily characterized in such a way. However, when used as a preliminary design tool in the early stages of a component's development, it is often possible to reduce a complex piece into simpler parts to facilitate the derivation of ballpark performance indices. For example, the authors also examined case studies in which a gear-box casing was approximated as a closed, hollow, circular cylinder, and in which an external door leaf was approximated as an assembly of rectangular beams. Such simplifications allow material options to be quickly explored using CES prior to the use of more detailed design tools such as finite element analysis.

It can also be shown that the stiffness constraint performance index in equation (5) is applicable to the vibration constraint. In other words, it can be shown that for the particular grab rail geometry considered here, a material that performs better than stainless
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Steel as a light stiff beam would also be expected to satisfy the requirement of having a natural frequency above 30 Hz.

The other constraints are handled as ‘attribute limits’; specifically the following.

1. For the fatigue constraint, a minimum endurance limit of 150 MPa is specified. The ‘endurance limit’ attribute in CES is defined as the maximum applied cyclic stress amplitude for a fatigue life of more than $10^7$ cycles. This is actually considerably harsher than the actual required fatigue life of the grab rail, which is of the order of $10^6$ cycles. However, as a conservative estimate it is assumed that fatigue properties of any alternative material employed should be at least similar to those of the current stainless steel, which has a CES endurance limit of 170–310 MPa.

2. For the fire performance constraint, only materials with flammability ratings of ‘good’ or ‘very good’ will be considered.

3. For the cost constraint, only materials with a price $< 7 \, \text{€/kg}$ will be considered. For comparison, the price of stainless steel in the CES database is in the range of 3.7–4.7 €/kg, so for investigative purposes a modest premium is allowed. The limitations of using ‘material price’ as the basis of the cost constraint are acknowledged. A better indicator would be the total cost of the finished grab rail. For example, a more expensive material might facilitate more cost-effective production or assembly techniques, thereby leading to an overall lower cost for the finished part. The allowance in the constraint of a price premium over stainless steel partially compensates for this limitation.

4. Furthermore, an additional constraint on fracture toughness is specified ($> 10 \, \text{MPa m}^{1/2}$). This is to screen out any very brittle materials that are clearly going to be unsuitable for the application.

4.4 Step four – material selection

Material selection charts were constructed using the CES software by plotting two properties against each other on logarithmic axes. For example, in Fig. 3 Young’s modulus is plotted against density. Each of the ‘bubbles’ on the chart represents a particular material; some of these have been labelled. Performance indices and attribute limits can then be superimposed on such charts to filter out unsuitable materials and identify potential candidates.

The straight diagonal line of gradient 1 shown in Fig. 3 represents the stiffness performance index, $M_1$, from equation (5). This line has been positioned to pass through the stainless-steel material that is currently used. All the materials that lie on the line perform equally well as a light, stiff beam. Those above the line perform better and are potential lightweighting candidates.
perform equally well as a light, stiff beam. Those above the line perform better. Those below the line perform worse. The further away from the line, the better (or worse) the performance.

Attribute limits are handled in a similar way, although they generally result in selection boxes rather than selection lines. Figure 4 shows those materials that satisfy both the fracture toughness constraint (>10 MPa m^{1/2}) and the price constraint (<7 €/kg).

Once the material selection charts for the various individual constraints have been constructed, it is then possible to produce an overall chart that shows only those materials that pass the requirements of all the constraints collectively (i.e. stiffness, vibration, fatigue, fire, cost, and fracture toughness combined). Such a chart for the grab rail is shown in Fig. 5. The final candidate materials consist of a number of steels, stainless steels, and other ferrous alloys, nickel alloys, aluminium alloys, magnesium alloys, chromium and its alloys, ‘Duralcan’ (a silicon carbide particulate reinforced aluminium matrix composite), and a zinc matrix composite.

Table 2 compares the key properties of some of the candidate materials. The values presented for Young’s modulus, E, density, ρ, fracture toughness, and price are mean values taken from CES. The performance index $M_1$ has been calculated using these mean values. The estimated mass saving compared to stainless steel is also shown.

### 4.5 Step five – interpretation of the results

Having identified the shortlist of candidate materials, the final step in the grab rail material selection process was to assess the viability of the proposed solutions. From Table 2 and Fig. 5, the three particularly promising looking options (i.e. those with the highest values of $M_1$) were the aluminium matrix composite, the chromium, and the zinc matrix composite. The study suggests that grab rails manufactured from these materials would be 30, 33, and 54 per cent lighter, respectively, than those manufactured from stainless steel. But can these savings be achieved in practice?

Chromium is normally used as an alloying element (e.g. in stainless steel) or as a plating material. It is not used as a structural material in its own right. The main reason for this is cost. It can be seen in Table 2 that chromium is 1.8 times more expensive per kilogram than stainless steel. Wider issues such as processability would also need to be considered.

The aluminium matrix composite is less costly per kilogram than chromium, but is still apparently 1.5 times more expensive per kilogram than stainless steel. Its fracture toughness is also much lower than stainless steel, so it is quite brittle. According to CES, it is already used in ‘transport components’ as well as ‘pistons, engine blocks, and heat sinks’, therefore it appears to be a viable engineering material. Overall, it is potentially interesting and worthy of further

![Fig. 4 CES material selection chart for the grab rail fracture toughness and cost constraints. According to the requirements of the application, the highlighted candidate materials are those with a fracture toughness above 10 MPa m^{1/2} and a price <7 €/kg](image)
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Fig. 5 Combined CES material selection chart for the grab rail showing only those materials that pass the collective requirements of the stiffness, vibration, fatigue, fire performance, cost, and fracture toughness constraints

Table 2 A selection of the grab rail candidate materials that pass the combined requirements of the stiffness, vibration, fatigue, fire performance, cost, and fracture toughness constraints

<table>
<thead>
<tr>
<th>Material</th>
<th>E (GPa)</th>
<th>ρ (kg/m³)</th>
<th>M₁ (MPa m³/kg)</th>
<th>Fracture toughness (MPa m¹/²)</th>
<th>Price (£/kg)</th>
<th>Mass saving (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel</td>
<td>198</td>
<td>7970</td>
<td>24.8</td>
<td>195</td>
<td>4.2</td>
<td>-</td>
</tr>
<tr>
<td>Aluminium alloy</td>
<td>74</td>
<td>2685</td>
<td>27.5</td>
<td>21</td>
<td>2.0</td>
<td>10</td>
</tr>
<tr>
<td>Chromium</td>
<td>265</td>
<td>7150</td>
<td>37.1</td>
<td>135</td>
<td>7.5</td>
<td>33</td>
</tr>
<tr>
<td>Duralcan aluminium matrix composite</td>
<td>98</td>
<td>2770</td>
<td>35.4</td>
<td>16</td>
<td>6.1</td>
<td>30</td>
</tr>
<tr>
<td>Magnesium alloy</td>
<td>45</td>
<td>1835</td>
<td>24.5</td>
<td>16</td>
<td>2.8</td>
<td>-1</td>
</tr>
<tr>
<td>Zinc matrix composite</td>
<td>221</td>
<td>4150</td>
<td>53.1</td>
<td>10</td>
<td>10.5</td>
<td>54</td>
</tr>
</tbody>
</table>

Investigation provided that the magnitude of the mass saving justifies a cost premium.

The zinc matrix composite is described by CES as ‘experimental’ and so is assumed to be commercially unavailable. Furthermore, it is also by far the most costly (presumably by virtue of its experimental nature). However, it does have the potential to more than halve the mass of the grab rails.

Looking at the materials that lie closer to the performance index line in Fig. 5, it can be seen that a number of more conventional materials would provide viable alternatives to stainless steel, although with little in the way of mass reductions. However, a number of aluminium alloys and steels might provide similar performance levels at reduced cost.

It is interesting to note that no fibre reinforced polymer composite materials passed the combined constraints, despite the fact that they often provide good solutions for lightweighting. A careful examination of the material selection results reveals that they mainly fail on the cost constraint. Although glass fibre reinforced polymers would provide no significant lightweighting benefit (i.e. their stiffness to weight ratio is similar to that of stainless steel), carbon fibre reinforced polymers (CFRPs) would provide a good solution if the cost barrier could be overcome, with estimated mass savings of up to 70 per cent. As discussed earlier, focussing on the overall cost of the grab rail might be a better approach than relying solely on CES’s material price attribute.
For example, suitable off-the-shelf, standardized, affordable pultruded sections might be a viable option.

4.6 Implementation

Satisfied with the findings of the grab rail lightweight material selection exercise, the MODURBAN partners decided to proceed to a prototyping stage. Two candidates were carried forward for consideration – silicon carbide reinforced aluminium matrix composites and CFRP matrix composites. Although the latter had ‘failed’ the selection process on the material price constraint, it was felt that the simple geometry of the grab rail might lend itself to the use of affordable standardized pultrusions. The two final candidate materials were therefore considered in more detail.

With respect to the aluminium matrix composites, further investigations into commercial products supported the suggestion that their specific stiffness properties were superior to those of stainless steels. However, the investigations also highlighted three problematic issues that would have to be resolved if the materials were to be employed. The first issue has already been mentioned: cost. According to CES, aluminium matrix composites are around 1.5 times more expensive per kilogram than stainless steel. Therefore, a decision would need to be taken as to whether the magnitude of the weight saving and its associated benefits justified the additional cost. The second issue is processing. The particulate reinforcements are very hard and the resulting material has low ductility. This makes machining, extrusion, and so on somewhat problematic, necessitating specialist expertise. The third, and perhaps the most critical, issue is availability. It would appear that particulate reinforced aluminium tube stock is not currently available ‘off-the-shelf’ and that some development effort would be required to realise a metal matrix composite grab rail. Again, a decision would need to be taken as to whether this effort was commensurate with the likely benefits.

In contrast, the CFRP grab rails were found to be more promising in practice than initially suggested by CES. Provided that the production volumes were sufficiently large (say, 1000 m or more, to keep tooling and set-up costs down), quotations received from suppliers of composite pultrusions suggested that the cost of such grab rails would be comparable to, or even slightly more affordable than, equivalent stainless-steel sections. Taking a 2 m long, 35 mm outside diameter, 3 mm wall thickness, and 4.8 kg stainless-steel grab rail as a benchmark, a CFRP grab rail of equivalent stiffness was designed and prototyped. The characteristics of the lightweight grab rail were as follows.

1. The material was a carbon fibre reinforced modified acrylic. The modified acrylic matrix resin was a proprietary fire retarded mix formulation.
2. The manufacturing process used was actually pull-winding rather than pultrusion. Pullwinding allows for the inclusion of angled fibre layers in the grab rail lay-up (for hoop strength), which is preferable to having all the fibres aligned along the length of the tube (as would be the case with pultrusion).
3. The length was 2 m (i.e. the same as the stainless-steel grab rail).
4. The outside diameter was 38.1 mm. The inside diameter was 25.4 mm. These dimensions were, to an extent, dictated by the availability of existing tooling (to avoid the cost of new tools). However, the dimensions also provide the same bending stiffness as the benchmark stainless steel grab rail.
5. Following manufacture, the grab rails were primed and painted using a proven system that has the required characteristics in terms of resistance to fire, scratching, impact, chipping, abrasion, and graffiti.
6. The measured mass per unit length of the CFRP grab rail following painting was 1.032 kg/m, a 57 per cent weight saving compared to the benchmark stainless-steel design.

As part of MODURBAN’s end-of-project dissemination activities, a metro vehicle fitted with a selection of the technologies developed within the project was demonstrated at a public event in Madrid on the night of 16/17 December 2008. The lightweight grab rail was one of the technologies showcased at this demonstration (Fig. 6).

Overall, the grab rail lightweighting exercise was considered a success. A viable material substitution was identified that more than halves the mass of typical existing grab rails at equivalent cost and performance levels. For a typical six car metro set, if all grab rails were replaced by the lightweight variant, the total weight saving could be as high as 400 kg. Furthermore, the MODURBAN partners now have sufficient information on the CFRP grab rails such that they can be added to their respective technical libraries for inclusion in future vehicle programmes.

5 QUANTIFICATION OF OPERATIONAL ENERGY SAVINGS AND ECONOMIC BENEFITS

In order to estimate the energy savings associated with metro vehicle mass reductions, an energy consumption model developed elsewhere within the MODURBAN project was employed. Some of the relevant parameters used by this model were as follows.

1. The simulated metro vehicle was a six car set with a total tare mass of 191 tonne.
2. The passenger loading was assumed to be 660 persons, each with a mass of 75 kg, for a total passenger mass of 49.5 tonne.
3. The simulations were performed over two straight, consecutive 1500 m track segments, the first with an uphill gradient of 1:25 and the second with a downhill gradient of 1:25. The train was brought to rest between the two segments, simulating a station stop. Figure 7 shows the vehicle velocity characteristics for the two segments.

Multiple runs of the model were performed with different vehicle mass reductions. The results are presented in Fig. 8. For example, if it was possible to save a total of 60 tonne (corresponding to an overall vehicle mass saving of ~30 per cent), then the resulting energy saving is estimated to be ~20 per cent. In fact, as a general rule for the scenario considered here, the percentage energy saving is ~0.7 times the percentage mass saving. Therefore, a mass saving of 10 per cent would yield an approximate energy saving of 7 per cent (for this particular scenario).

Using an energy cost of 0.1 \( \text{€/kWh} \), the following procedure was adopted to estimate the annual operational economic savings because of reductions in vehicle mass.

1. The total journey time for the simulated uphill and downhill segments presented in Fig. 7 was 173 s – 93 s for the first uphill segment and 80 s for the second downhill segment.
2. Assuming a vehicle runs 18 h a day, 365 days per year, there will be 136 717 such journeys annually (18 \times 60 \times 60 \times 365 \div 173).
3. Therefore

   Annual operational cost saving per vehicle due to mass reduction = Estimated operational energy saving due to mass reduction during one simulated 173 second journey (from MODURBAN energy model, as illustrated in Fig. 8) \times Number of journeys annually (= 136 717) \times Cost of energy \( (= 0.1 \text{ €/kWh}) \).

The results of this calculation are shown in Fig. 9. In ballpark terms, for the model considered here, each 1 per cent (~2 tonne) mass reduction is estimated to yield an annual cost saving due to reduced operational energy consumption of ~10 000 €/vehicle.

One should also consider that, in the future, the cost of energy is only likely to increase. Hence, the economic benefit of reducing the energy consumption of rail vehicles through lightweighting could well be significantly greater in, for example, 5, 10, or 20 years time.

Lightweighting would, of course, bring wider economic benefits in addition to those due to reduced operational energy consumption. For example, the following can be considered.
1. Lighter vehicles are likely to cause less damage to track, thereby resulting in reduced costs for infrastructure maintenance and renewal.

2. Similarly, lighter vehicles are likely to experience reduced wear of components such as wheels and brakes.

3. In some countries, lighter vehicles attract lower track access charges for operators.

4. For a given maximum axle load, reductions in the tare mass of a vehicle because of the application of lightweight materials and designs could allow for increased payloads (i.e. more passengers per train). The increased revenue from these additional passengers would be a direct economic benefit for an operator.

5. There could also be ‘secondary’ or ‘knock-on’ effects of lightweighting. For example, if certain weight-saving thresholds could be achieved, it may be possible to replace a standard bogie with a lighter variety. Or it may be possible to use fewer sets of brakes, and so on.

6. In the future there are likely to be environmental taxes linked to emissions.

6 WIDER CONSTRAINTS ON THE USE OF LIGHTWEIGHT MATERIALS

Besides the process of identifying and specifying lightweight materials to meet the technical requirements of a given application, consideration should also be given to some of the wider industry constraints that need to be addressed. For example it is not uncommon for materials to be specified in a very prescriptive fashion in customer requirements documents, an example being ‘the grab rail shall be made from satin-polished stainless steel or aluminium’. This means that without a modification to the customer requirements document or a concession, the use of alternative materials in such instances is essentially prohibited. Clearly, functional specifications would be preferable from the perspective of optimized design. Rather than rigidly stating what material(s) must be used, it would be beneficial to specify the required properties of the finished component, thereby allowing designers to have an input to the material selection process.

The cost of qualifying alternative materials for an application can be another barrier to their introduction. There is anecdotal evidence of occasions in the past in which both suppliers and operators have been unwilling to accept the commercial risk associated with the long and costly qualification of a new material. Such risk aversion, which is often due to less tangible ‘traditional’ or ‘psychological’ barriers as well as sound commercial reasoning, can be difficult to overcome. One solution might be to engage operators in restricted (e.g. one vehicle) in-service trial programmes to validate new materials technologies in advance of their more widespread introduction.

Life cycle assessment (LCA) is becoming an increasingly important aspect of the design process and is a useful tool. From a material selection perspective, it is able to provide a comparison between an existing material and any candidate replacement materials across a component’s production, operation, and end-of-life phases. Furthermore, apart from the expense of actually performing the LCA, it may not act as a barrier to the introduction of alternative lightweight materials. Indeed, the LCA might provide evidence to show that a lightweight material provides a net benefit.

7 CONCLUSIONS

Provided that one adopts a suitably systematic and rigorous approach, this article has demonstrated the feasibility of metro vehicle lightweighting through material substitutions. Although it has some limitations, the CES Selector software proved to be a useful tool for identifying lightweight candidate materials for a given application, thereby addressing some of the perceived issues surrounding the management and comparison of materials data.

Through the application of an energy model developed within the MODURBAN project, a quantified relationship between metro vehicle mass reduction and operational energy saving has been established. For the particular scenario described in this article, a 10 per cent reduction in vehicle mass was estimated to equate to a 7 per cent saving in energy consumption and a corresponding 100 000 € annual operational cost saving per vehicle. Such data can now be used to support decision making with respect to the benefits of lightweighting.
Finally, in order to further facilitate the implementation of lightweight materials the following can be considered.

1. It would be preferable for operators to replace prescriptive material specifications with functionally based component requirements.
2. The commercial risk and supplier/customer engagement associated with the introduction of alternative material technologies needs to be carefully managed, perhaps through limited pilot programmes.
3. LCAs may support the case for new materials.

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REFERENCES


APPENDIX

Notation

\begin{align*}
A & \text{ cross-sectional area} \\
E & \text{ Young's modulus} \\
I & \text{ second moment of area} \\
L & \text{ length} \\
m & \text{ mass} \\
M_1 & \text{ stiffness performance index} \\
r & \text{ radius} \\
S & \text{ beam stiffness} \\
t & \text{ wall thickness} \\
\rho & \text{ density}
\end{align*}