

D2.1 Light materials assessment for rail freight bogie application

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EXECUTIVE SUMMARY

The focus of task 2.1 Light materials assessment for rail freight bogie application has been to assess the use of lighter materials than those normally used in freight locomotive bogie applications, but still maintaining the target that the material has to be used in a heavy freight rail environment.

With the overall aim of reducing mass and consequent reductions in energy consumption and carbon emissions, task 2.1 of the DYNAREIGHT project has looked at the possibilities of using innovative materials and manufacturing methods for the construction of railway locomotive bogies. Due to the distribution of mass in the bogie with the bogie frame making up 15% - 30% of the mass and the difficulty in changing the design of many of the other key components the work has focused specifically on the bogie frame itself.

This report summarises the findings of this work. It starts with a review of existing methods of construction of the bogie frame and the standards and assessment methods used by the railway industry. Previous work in this area was also reviewed as well as innovations in other transport modes and other industry sectors. The most promising options were considered including the use of high strength steels, novel construction methods including hydroforming and a brief look at the potential of more radical solutions such as the use of composite materials.

To support the study, computer aided design tools were set up to analyse the potential of the new designs and the effects that the changes would have on the locomotive performance. A vehicle dynamics model was set up in VAMPIRE and a finite element analysis developed in ANSYS Workbench. Some simple analysis was also carried out to establish rolling resistance, energy consumption and track damage.

The work has shown that there are potential gains but that these are modest for all except the most radical design changes. Although a 43% reduction in the mass of the bogie frame is achievable this is only likely to result in 5% reduction in energy consumption. Reductions in track damage could potentially be more significant with up to 12.5% reductions possible but this depends strongly on operating conditions. When translated into track access charges a reduction of only around 1% would be likely based on the current charging regimes.

More radical construction methods and the use of novel materials such as glass or carbon fibre composites have been briefly reviewed and pointers taken from other industries. Although these more radical solutions offer significant potential mass savings they also face significant barriers to implementation and acceptance.

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1. INTRODUCTION

1.1 OBJECTIVES

The main objectives of this task were to assess the use of lighter materials than those normally used in freight locomotive bogie applications, but still maintaining the target that the material has to be used in a heavy freight rail environment.

The original plan was to review potential for the application of novel materials based on the functional requirements of the key bogie components. In line with that an initial assessment was undertaken and it was decided that the main area for potential lightweighting lay with the bogie frame which includes 17% of the mass of the target bogie and is less constrained than the other major components such as the wheelsets and traction motors.

The potential for optimising the existing design was assessed as well as the potential for the use of high strength steels and novel materials and manufacturing methods, including new welding procedures. The review was carried out against the background of the existing standards and other design constraints.

1.2 INPUTS

The work was led by a team from the University of Huddersfield (HUD) with a range of expertise including design with materials, finite element analysis and vehicle dynamics analysis. Input on the existing design and current standards was provided by colleagues from Stadler Rail Valencia (STAV) who also reviewed the emerging findings of the work. A workshop was held between HUD and STAV to discuss the work. A presentation on the findings was made to the DYNAREIGHT steering group and the draft deliverable was circulated for comment.

1.3 MAIN RESULTS

The work has shown that optimisation of the specifications of the design including variations in material thickness, use of higher strength steel and improved weld performance can potentially result in a reduction of up to 43% of the bogie frame mass. The vehicle dynamics studies show that this would translate into a 12.5% reduction in track damage but only a 5% reduction in energy consumption and a 1% reduction in track access charges.

Although there is potential for significant mass reductions from more radical manufacturing methods such as the inclusion of cast nodes or hydroforming of sections or the use of novel materials such as glass or carbon fibre composites there are still considerable barriers to the use of these methods and they have not been considered further at this stage.

1.4 POSSIBLE LINKS OF RESULTS WITH OTHER DELIVERABLES

The modelling and analysis work carried out in this deliverable has been closely linked to the modelling being carried out in Task 2.3 'Passive and Mechatronic Steering Systems'. The 'baseline' vehicle set up for T2.3 has been used for this work and the results of T2.1 will be used to inform the team carrying out T2.3 of the potential reduced mass bogie frame.

2. REVIEW OF CURRENT DESIGN

2.1 INTRODUCTION

Traditionally locomotive bogies are constructed around a fabricated or partly fabricated stiff steel frame which links two or three wheelsets. Other components including traction motors and transmission elements, primary and secondary suspension elements, braking components and other sub-systems are fixed to this frame.

Most common construction methods are based around the use of steel plates which are welded together to form the main part of the bogie frame. Jigs are used and the welding can be automated or partly automated.

2.1.1 Current bogie weight distribution

Table 1 shows a typical distribution of mass within the main components of a 3-axle motor freight locomotive bogie.

Table 1 Mass distribution in a typical 3 axle locomotive bogie

	Material	Norm	Mass (percentage of total bogie)
Wheelset - transmission			66%
Frame	Hot rolled steel S355J2	EN 10025-3[1]– [6]	17%
Other non-structural components			11%
Axleboxes	Cast iron EN-GJS-400-18-LT	EN 1563[7]	4%
Rods	Steel castings G20Mn5	EN 10293[8]	1%
Steel attachments	Hot rolled steel S355J2	EN 10025-3[3]	1%

The bogie frame constitutes approximately 17% of the total bogie mass and increasing up to 32% in freight wagon bogies. In the following work, it is selected as the component to be weight-optimized by the selection of new materials, factribaciton methods and design concepts.

2.1.2 Current manufacturing methods of the bogie frame

A typical bogie frame is a steel structure manufactured from several subassemblies: two symmetrical longitudinal beams and three cross beams joining them, see Figure 1. To these subassemblies, the brackets to mount the equipment are attached.

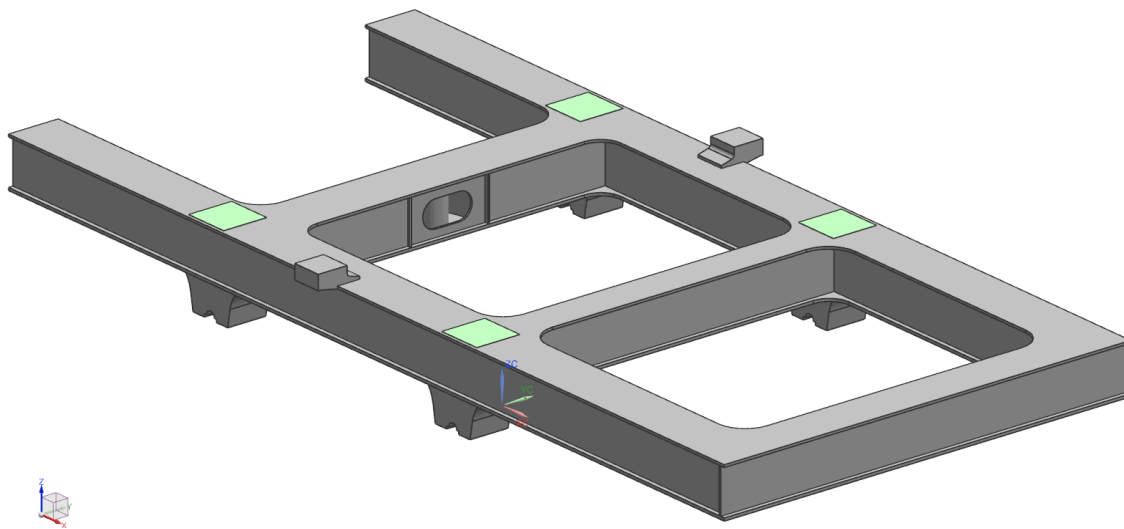


Figure 1 Typical locomotive bogie frame

Each longitudinal beam is typically realized as a closed structure with cross section consisting of an upper and lower plate and two webs as shown in Figure 2. Plate thickness fall in the range 10mm-25mm.

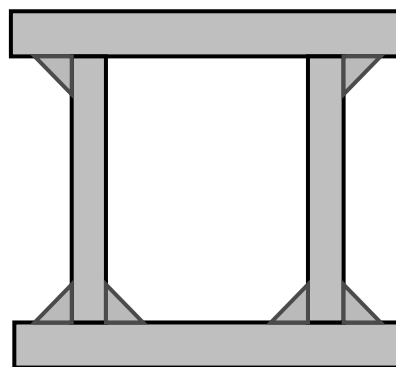


Figure 2 Typical fabricated beam construction

This kind of construction sets some limitations on the type of welding that can be done in each part of the structure, as the welding sequence plays an important role in the weld seam accessibility. Also, weld seams lead to stress notches that make a weaker structure than the base material itself.

After frame welding, stress relief annealing is performed on the frames in order to obtain a stabilized structure from a dimensional point of view and also to assure uniform frame strength over the serial production reducing the influence of the welding process on the final frame strength.

Then welded frame is shot blasted and equalized on a 3D measuring machine, reference points are fitted in order to ensure the correct distribution of material during the machining phase. Then the frame is protected against corrosion by painting, machined surfaces are also properly protected.

Typically the frame is mainly made of S355 steel hot rolled sheets according EN 10025 [1]–[6]; design may include cast brackets where required to optimize frame geometry. Cast steel parts are made of G20Mn5+QT according to EN 10293[8] or equivalent.

3. REVIEW OF WHAT HAS BEEN DONE ELSEWHERE

3.1 USE OF HIGH STRENGTH STEELS IN OTHER INDUSTRY SECTORS

The use of high strength steels offers a relatively straight forward way of reducing the weight of components through the use of thinner gauges with the resulting advantages of reduced energy consumption and lower carbon dioxide emissions over the life cycle of the component. The use of thinner gauge also leads to smaller welds or the replacement of welds by plate bending.

Weight-critical components can be found in a range of industry sectors, some examples being carrier frames, lifting and hoisting devices, building construction, many components associated with the offshore industry, and the automotive sector.

The current wide usage of thermomechanically processed high strength steel plate (yield strength = 460 MPa) has been shown to be more economical than Grade S355 for the deck structure of large container ships and aircraft carriers and that they are more economical than the quench & tempered (Q&T) grades [9]. Similarly, there appears to be a trend towards the use of higher strength steels in the construction industry.

Steels with yield strength (YS) in the range of 355-500 MPa are used in the jacket and topsides of offshore structures while Q&T grades with higher YS are used in jack ups, moorings, and the fabrication of legs, rack and pinions, and spud cans[9].

Some other examples of the use of very high YS steels are found in the manufacture of mobile lifting equipment (900-1100 MPa), beam lower flanges in bridges (700 MPa), and military deployable mobile bridges (1100 MPa). The move to higher strength steels is also evident in sectors using tubular sections as in the case of long distance gas transportation where steels with YS of 555 MPa is widely used and even higher strength steels have been evaluated in trials, although there are some concerns about their crack arrest characteristics. Light weighting in the aircraft and sporting equipment industry stands out as the use of high strength materials are not as restricted by cost considerations. However, detailed assessment of the use of high strength steels in other industry sectors is outside the scope of the current project and attention is drawn to detailed reviews available in the literature [9]–[12]. Nevertheless, there are a few noteworthy observations from the use of high strength steels in other industry sectors.

- In offshore structures, the use of high strength steel (>350MPa yield strength) increased from less than 10% to over 40% over in less than a decade[13]. This 1995 figure is likely increased further in recent years since the survey to meet the more demanding conditions on offshore platforms.
- Research has demonstrated the improved mechanical behaviour of high strength steel structures but the exploitation of their true potential requires the updating of existing design codes or specifications to take account of the attributes of high strength steels. Furthermore, the absence of design codes for steel structures utilising high strength steels emphasizes the need to develop the required expertise to assess the behaviour of components or structures made using high strength steels. Conflicts with design codes is very apparent in the case of pressure vessels/equipment for which the allowable design stresses (EN 13445) are limited to $YS/1.5$ or $TS/2.4$ and hence the use of high strength steels is impractical.
- Joints in structures are often regarded as the most demanding area of structures requiring special attention during design, fabrication, and in-service inspection. Despite being a minor part of structures, joints often dictate the dimensions and fabrication techniques of adjacent components and hence can influence the overall weight of structures.
- Designing with high strength steels raises the importance of structure shape which can be used to prevent buckling/distortion, control elastic displacements, and minimise the susceptibility to fatigue. Consequently, optimised exploitation of high strength steels is intrinsically linked to the design, fabrication, and even the in-service inspection of the components.

3.2 HALF COST TRAIN

In 2010, a study was conducted by Rail Safety Standards Board to quantify the benefits of reducing train mass. The influence of variations in train mass on energy and track costs were determined for a number of scenarios, covering a range of vehicle masses (+10%, -20%), routes and vehicle types. The proportion of the total cost saving, from a reduction in either energy and track costs, was shown to change with the route category (e.g. Intercity routes track cost savings were dominant, whilst for Metro lines energy cost savings were dominant). This resulted in a cost savings ranging from 1.1 to 1.9 €cent/km/tonne.

3.3 COMPOSITE BOGIES

Composites including Glass Reinforced Plastic (GRP) and Carbon Reinforced Plastic (CRP) have been used widely in other industries for more than 50 years. The aerospace industry for example is much further ahead of railways in the adoption of composite materials with 50% of the Boeing 787 Dreamliner and 53% of the Airbus A350XWB being composite material. This leads to a claimed reduction in fuel consumption of 25% for the Airbus and 20% for the Boeing [14]. Some of these composite components are quite large, for example the A350 XWB wing is made up of carbon fibre reinforced plastic components measuring 32 metres long by six metres wide.

Barriers to the adoption of new materials related to manufacturing and maintenance methods as well as standards have therefore been addressed in aerospace and lessons may be transferable to railway vehicles. In addition to composites modern airframes include other advanced materials including titanium and advanced aluminium alloys.

In the EU 'EUROBOGIE' project [15] a group of partners developed a glass fibre reinforced bogie structure. The proposed design which has been tested at 1/5 scale on track and at full size in laboratory tests incorporates much of the required stiffness and damping for the suspension into the composite bogie structure. Figure 3 shows the Eurobogie design. The project has successfully proved the durability of the composite bogie at small scale but this has not been trialed at full size yet and it has not been taken up by the railway industry.

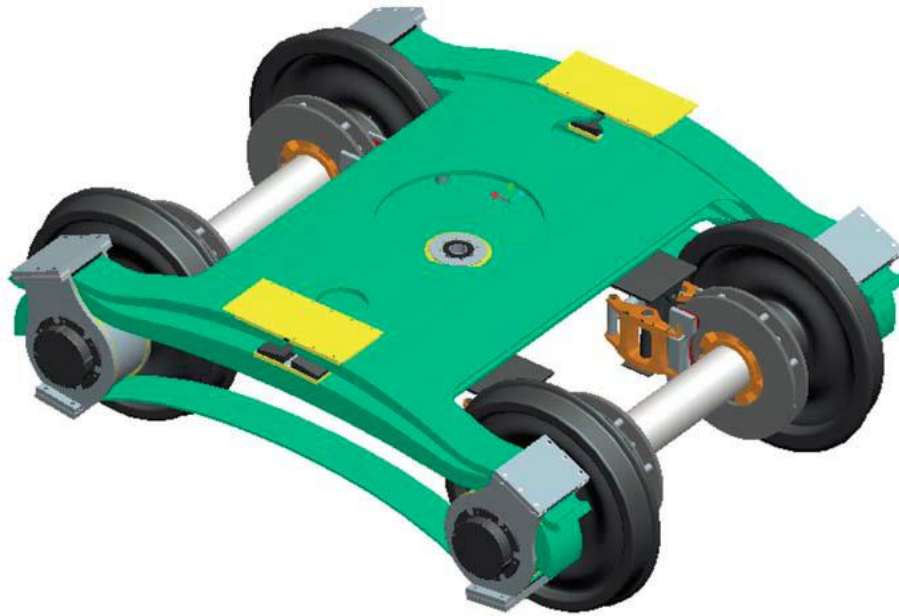


Figure 3 The Eurobog bogie [15]

The Kawasaki 'efWING' bogie (Figure 4) includes carbon fibre Reinforced Plastic leaf springs and claims a to bring weight savings of 40% compared with conventional bogies as well as other performance advantages, including increased safety and ride comfort, low energy requirements, environmental friendliness and reduced running costs[16].



Figure 4 The Kawasaki efWING bogie [16]

A glass fibre composite bogie frame has been developed by KRRI (Korea Railroad Research Institute). Several prototype bogie frames have been manufactured and tested and a 30% weight

saving compared with a conventional steel frame bogies is claimed which corresponds to a 635kg weight reduction per carriage.

4. STANDARDS AND DESIGN CRITERIA

4.1 INTRODUCTION & DESIGN CRITERIA

Any lightweight bogie frame structure, based on the current bogie design, is required to fulfill the following criteria:

- Deformation criteria. The structure deflection under vertical, lateral and longitudinal loads should be small enough to keep the rigid frame design assumption accurate enough. For this purpose, total deflections should not exceed 2 mm.
- Stiffness criteria. The structure natural frequency should not match dynamic modes of the vehicle in order to avoid resonance coupling. To allow simple evaluation against this criteria, natural frequencies of the frame should exceed 40Hz, the lowest natural frequency of the baseline bogie.
- Structural requirements for bogie frame both for static and fatigue assessment are specified in EN 13749[17]. This norm categorizes the bogie frame types into seven categories according to the bogie application and specifies the loading, assessment and test program that the frame will be able to withstand. BVII 'bogies for locomotive' is selected for the research of new materials in a 21 t/axle co'co' locomotive bogie frame. More detail is provided in Section 4.2.

For the assessment of new materials, only main load cases affecting the frame will be taken into account as particular loads in the frame supports don't lead to significant design changes in the main structure. Main dimensioning selected parameters are, according to EN 13749:

$$\begin{aligned}\alpha &= 0.2, \\ \beta &= 0.3, \\ \text{torsion} &= 0.5\%;\end{aligned}$$

where α is the roll coefficient and β is a bounce coefficient.

Material properties must be selected to suit chosen method of fabrication. For steel, the material properties cited in this document are available primarily in plate form and as they are widely used in offshore, shipbuilding, and construction industries, weldability is a key criteria for the design of their composition and hence the control of carbon equivalent. Consequently, weldable high strength steels are available. However, this claim could benefit from closer scrutiny in the context of the location of welds in the design of bogie frames and the influence of the heat affected zone (HAZ) properties on the fatigue life of the welded region. This is particularly important if heat treated plate grades are being considered for use in the manufacture of rail vehicle bogie frames.

4.2 ASSESSMENT METHOD

Assessment of the criteria (for specific outline designs based on changed plate thickness or section geometry) set out above is performed with the aid of a finite element model. Deflections for each load case may be checked to deflection criteria and modal analysis may be done for the free structure.

A static assessment using the resulting stress from the finite element are compared against calculated stress to determine the necessary yield strength for the particular design.

Fatigue strength assessment requires a more complex approach as the stress range between different load cases must be considered. Material limits in this case may depend, among many other factors, on the mean stress at each point of the structure. For typical rail vehicles, fatigue assessment is often done using codes such as DVS 1612 [18] or FKM Guideline[19].

DVS 1612 follows an endurance limit approach and is used in the current design. Stress are calculated using a nominal stress approach and 'notch cases' provided for common welded joints details. These allow the endurance limit for a range of stress amplitudes to be calculate. Only S355 and S235 steels are explicitly covered, but can be extended for the base, unwelded material to higher strength steels. For welds involving higher strength steels, the endurance limits for S355 are recommended.

4.3 STANDARDS

EN 15827 [20] and EN 13749 [17] set out design criteria for bogies and bogie frames, respectively. In this case of 'exceptional loads', assessment is based on the static strength of each component.

The bogie frame should be capable of withstanding 'exceptional loads' with a sufficiently low utilization and without unacceptable deformations.

The endurance limit or safe life of the bogie frame must exceed its anticipated fatigue loads or intended life. The fatigue can be accessed via either endurance limit or cumulative damage approaches. Fatigue loads will generally be lower than the exceptional loads used in the static assessment. Depending on the approach taken, each fatigue load case must have an attached frequency. EN 13749 Appendix B provides comprehensive guidance on the types of loads to be considered, for example track twist, lateral and vertical loads, and traction loads.

EN 13749 requires a test program to verify the static and fatigue capacity, split into three stages:

1. Stage 1: 6e6 cycles with design loads
2. Stage 2: 2e6 cycles with dynamic loads increased 20 %
3. Stage 3: 2e6 cycles with dynamic loads increased 40%

4.3.1 Fatigue

Due to the high number of load cycles during the design life, fatigue tends to dictate the sizing of members and welds in bogie frames. The weld fatigue is particularly significant in the context of lightweighting via material selection. This is because the endurance limit of the welds unlike the base material is not linked to yield strength of the base material and is more a reflection of the welding parameters and process control. In this respect, control of the HAZ (Heat Affected Zone) is essential. One of the ways of achieving high strength plates is the heat treatment that they go through after rolling which produces the desired material structure. However, the heat generated during welding can very significantly modify the properties in the HAZ and the specifications need to emphasize the need or even mandate the determination of properties relating to HAZ. Furthermore, research also needs to be focused into the welding of high strength steels.

EN 15085 [21]–[25] governs the design and manufacture of welds for railway vehicles. In particular, EN 15085-3 offers a general framework for the design of welds. However, the designer is free to choose from a number of assessment methods and codes. For example, DVS 1612 and the FKM guideline could be used to assess both static and fatigue performance. Of these, DVS 1612 is explicitly written to satisfy the requirements of EN 15085, significantly simplifying the design process. Fatigue is assessed via an endurance limit approach, taking into account the

weld geometry, inspection and safety class. The endurance limit of welds is capped for higher strength steels with no provision for post weld treatment. The FKM guideline allows for both endurance limit and cumulative damage approaches. Again, weld fatigue performance is unaffected by the yield strength of the base material. Unlike DVS 1612, it does include provision for post welding treatment such as shot preening but not ultrasonic preening.

5. METHODOLOGY

5.1 INTRODUCTION

In order to assist with the assessment of the potential benefits of reduction in bogie mass several analytical and simulation tools have been set up and used. A baseline six axle 'Co-Co' locomotive was established within the DYNAFREIGHT project, in Task 2.3 Passive and mechatronic steering systems and the parameters of this baseline locomotive were used in this work. Variations in design were assessed against this baseline.

5.2 VEHICLE DYNAMICS

Vehicle dynamics tools are now widely used in the railway industry and their results have been validated in a wide range of applications. In this task, the vehicle dynamics software Vampire is utilized to evaluate the improvement of the vehicle dynamic behaviour by using the lightweight material of the bogie frame. With the reference of the dynamics parameters of the baseline freight locomotive bogie, the corresponding vehicle dynamics model is established by using Vampire software (see Figure 5 & Figure 6).

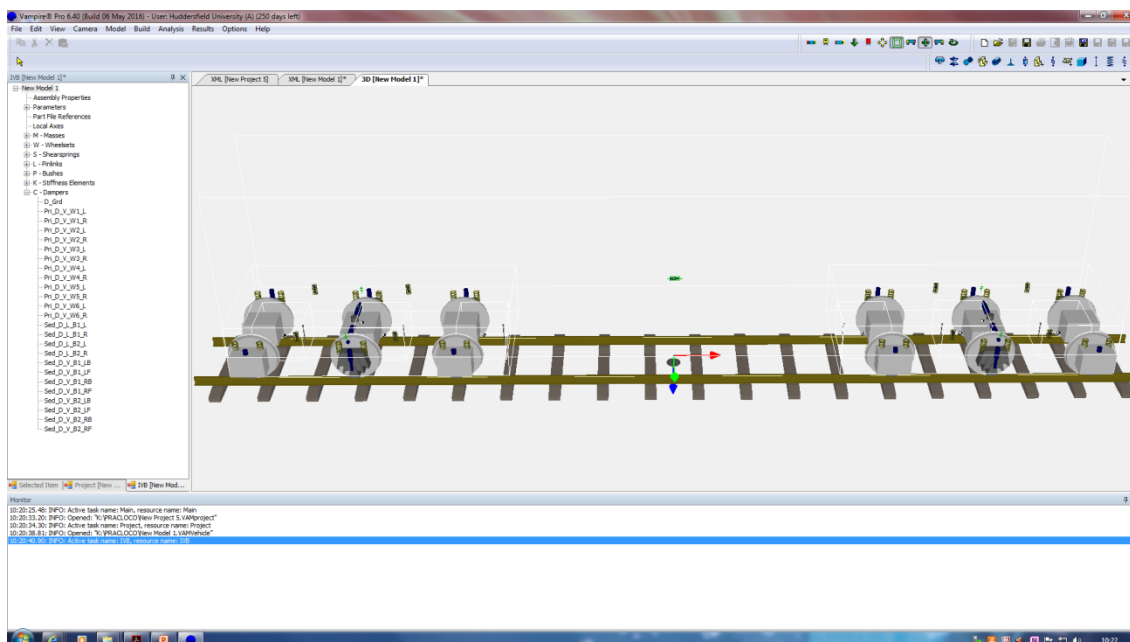


Figure 5 Vampire model of 6-axle baseline freight locomotive

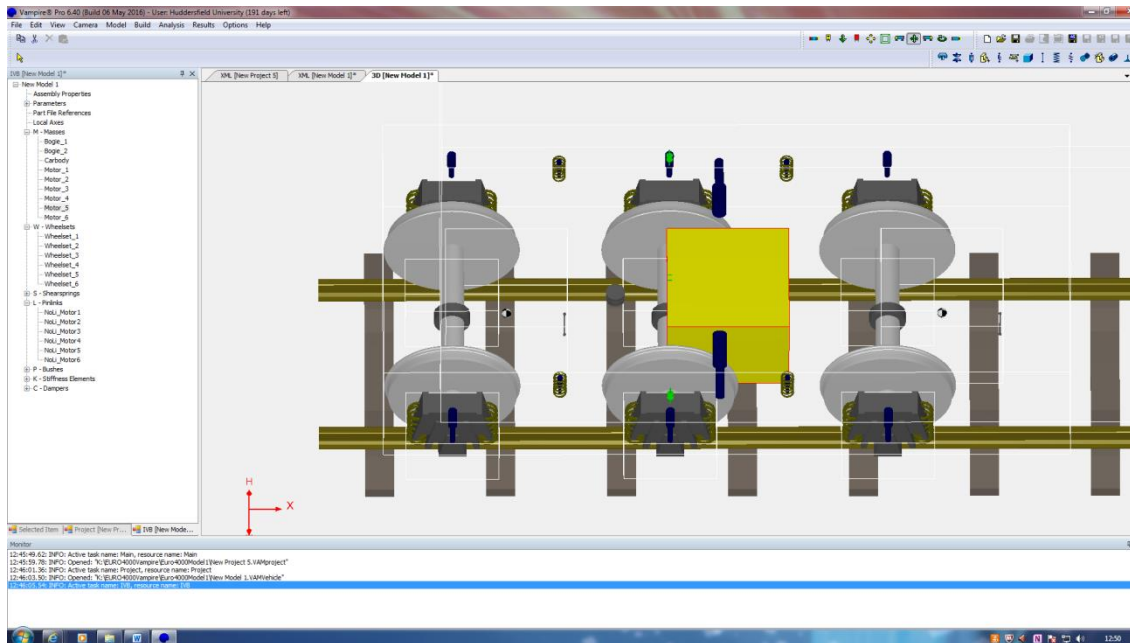


Figure 6 Vampire model of locomotive bogie

In this three dimensional simulation model, 6 Degree-of-freedoms (DOFs) are considered for each mass element, including one carbody, two bogie frames and 6 motors. In Vampire, 6 DOFs are considered for each wheelset elements with the pitch motion of the axle-box included. Therefore, 90 DOFs are utilized to describe the dynamic behaviour of the locomotive.

In the primary suspension, bush elements are used to model the axle guidance device, whose key parameters are the longitudinal stiffness and the lateral stiffness. The lateral stiffness for the centre wheelset is relatively low due to the required lateral motion of the wheelset during curve negotiation. Shear spring elements and damper elements are used to model the coil axle spring and the primary damper respectively. For the secondary suspension, the secondary spring is also modelled with the shear spring, which provides the stiffness on both vertical and horizontal directions. The bush element and the damper element are used to model the traction device and the secondary lateral damper in respect. The bump stops between the carbody and bogie frame in the lateral and vertical directions are also considered in the model. The lateral constraint of the centre wheelset is also modelled as a bumpstop element.

Three motors are included but only one is shown in the figure for clarity. As the motor mass and mounting configuration can have a significant effect on the dynamic behaviour of the bogie a

typical arrangement was assumed with one end of the motor supported by the frame and the other end supported by the axle. The connection to the axle end is modelled as a bush element with a large stiffness. The nose suspension on the bogie frame end is modelled as a pinlink element with a smaller stiffness, whose reaction force acts along the direction of the link.

5.3 FINITE ELEMENT MODELLING

A simplified finite element model has been developed to examine the effects of changing stiffness on deflection, natural frequency, buckling and moment/force distribution. From a materials perspective, finite element modelling was necessary to establish the areas of highest stresses and the potential consequences of using thinner plates. In this simplified model, only the bogie frame is modelled excluding suspension elements, traction links etc. Therefore, suitable constraints and load application points are needed, see Figure 7 for component names. The boundary conditions used in the finite element model are shown in Figure 8 -Figure 10. In the longitudinal direction, the frame is fixed at carbody traction link as shown in Figure 8. In the lateral direction, the frame is fixed at primary traction link mountings as shown in Figure 9. In the vertical, the frame is fixed at the primary suspension spring mountings as shown in Figure 10. The position of loads in

Table 2 are shown in Figure 11-Figure 13. Vertical loadings are applied to the secondary suspension mountings as shown in Figure 13. Longitudinal loads are applied to the mounting for the primary traction links mountings as shown in Figure 11. Lateral loads are applied to the lateral bumps stops as shown in Figure 12. In this last case, the lateral loads are assumed to be applied to the centerline of the side frame beam thus will underestimate the twist moment introduced in the longitudinal side beams by the lateral loads.

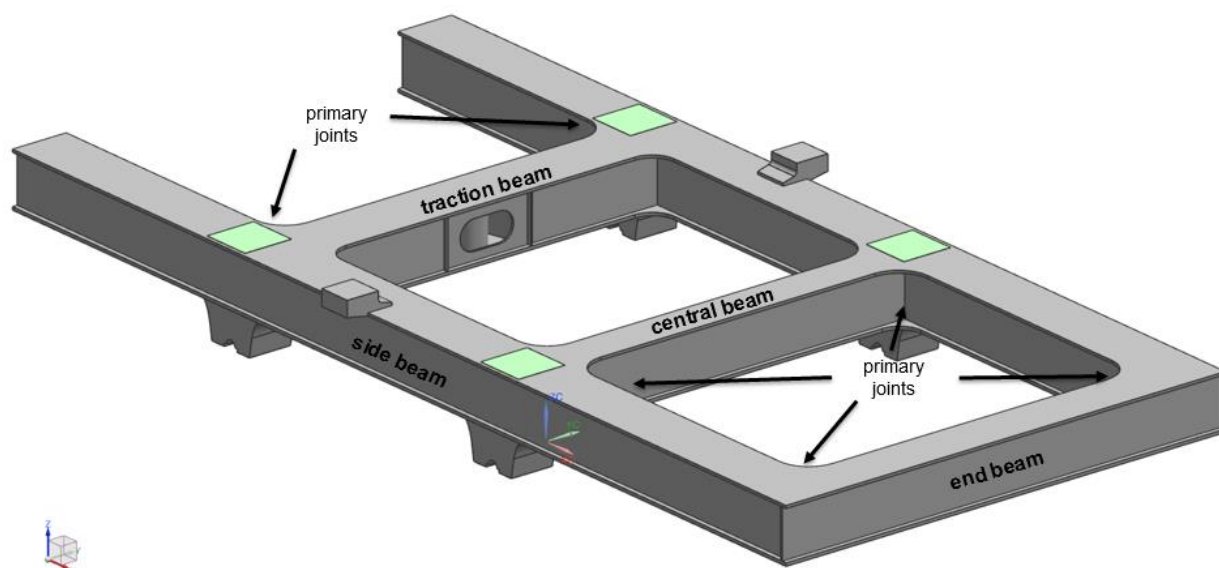
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Table 2 relates to track twist. In this case, it is impossible to apply this directly to the frame without incorporating primary suspension elements. However experience suggests a wheel loading/unloading pattern at frame level similar to that in Figure 14. For the original design, the simplified boundary conditions in Figure 15 produce results in line with Figure 14. In order to simplify analysis, this has been assume to produce accurate results for the range of stiffness considered within this study. However, a spot check was carried out promising to verify this assumption.

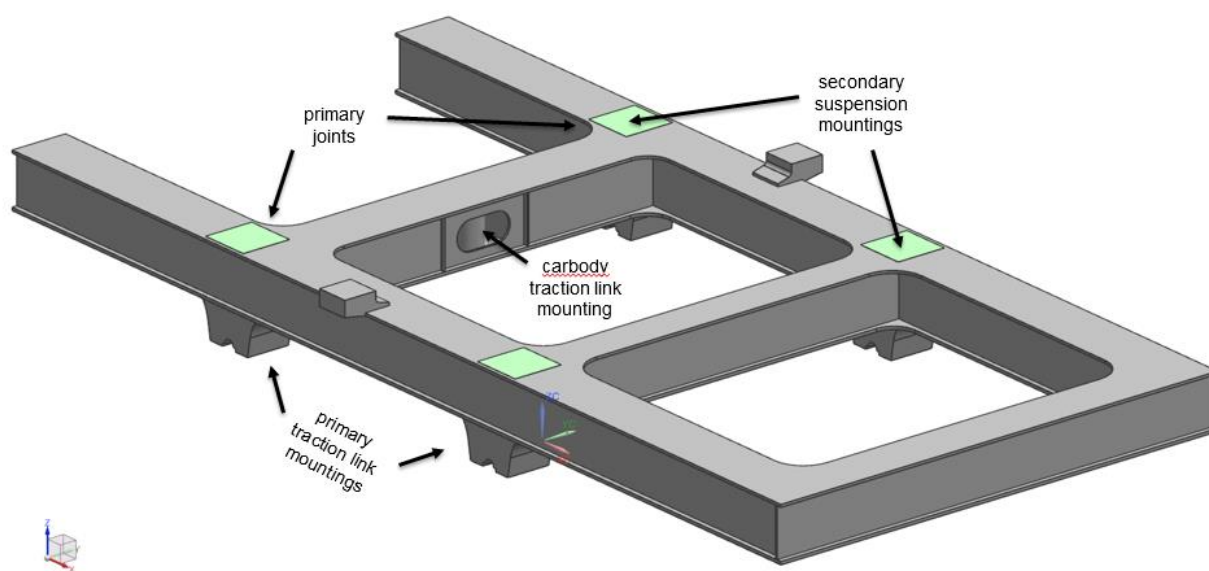
The simplified finite element model preserved the basic geometric outline and constraints described above. However, the side frames and connecting beams were replaced by beam elements. Thus allowing, a parametric study to be undertaken, varying the stiffness of the beams to find an acceptable range of beam properties for the frame. Load cases used in the original frame design were applied for all stiffness combinations, assuming the interaction between the load distribution and stiffness is limited. Note that modelling the frame as beam elements allows for consideration of a range of possible beam stiffnesses, but does not consider local stress concentration at the points of load application and fixity. To allow determination of normal stresses by linear superposition, rectangular hollow sections have been assumed. Several combinations of width, height and flange thickness have been considered and results compared to the criteria in Section 4.1, allowing an estimate of the realisable weight savings to be determined.

Additionally, a linear buckling check has been produced from each of the load cases; however only the minimum buckling factors are reported. This type of analysis is not conservative as it does not consider imperfections/ out of straightness in the beams, but is a valuable indication of a design's susceptibility to buckling. It should be noted that this check is a global buckling analysis and does not consider local buckling of beam flanges or webs. Finally, a modal analysis was undertaken using the same boundary conditions described above but with no loads imposed.

Sample results for the original design are reported in Figure 16 and Figure 17.



a) primary structural elements



b) ancillary mounting

Figure 7 Component names

Table 2 Finite element load cases

Load case	Fz1 [kN]	Fz2 [kN]	Fy1 [kN]	Fy2 [kN]	Fx1 [kN]	Fx2 [kN]	Torsion (%)
1	213.4	213.4	0.0	0.0	0.0	0.0	0
2	192.0	106.7	0.0	0.0	0.0	0.0	0
3	192.0	106.7	0.0	154.5	0.0	0.0	0
4	320.1	234.7	0.0	0.0	0.0	0.0	0
5	320.1	234.7	0.0	154.5	0.0	0.0	0
6	106.7	192.0	0.0	0.0	0.0	0.0	0
7	106.7	192.0	-154.5	0.0	0.0	0.0	0
8	234.7	320.1	0.0	0.0	0.0	0.0	0
9	234.7	320.1	-154.5	0.0	0.0	0.0	0
10	192.0	106.7	0.0	154.5	0.0	0.0	0.5%
11	320.1	234.7	0.0	154.5	0.0	0.0	0.5%
12	106.7	192.0	-154.5	0.0	0.0	0.0	0.5%
13	234.7	320.1	-154.5	0.0	0.0	0.0	0.5%
14	192.0	106.7	0.0	154.5	0.0	0.0	-0.5%
15	320.1	234.7	0.0	154.5	0.0	0.0	-0.5%
16	106.7	192.0	-154.5	0.0	0.0	0.0	-0.5%
17	234.7	320.1	-154.5	0.0	0.0	0.0	-0.5%
18	213.4	213.4	0.0	0.0	125.0	125.0	0
19	213.4	213.4	0.0	0.0	-125.0	-125.0	0
20	213.4	213.4	0.0	0.0	61.8	-61.8	0
21	213.4	213.4	0.0	0.0	-61.8	61.8	0

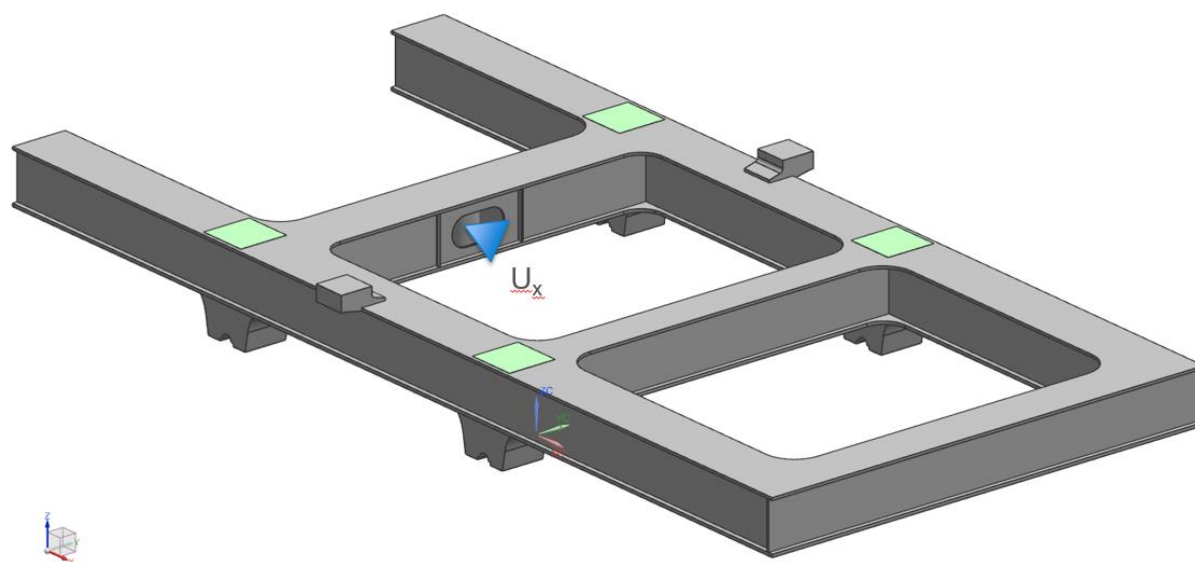


Figure 8 Longitudinal constraints used in finite element model

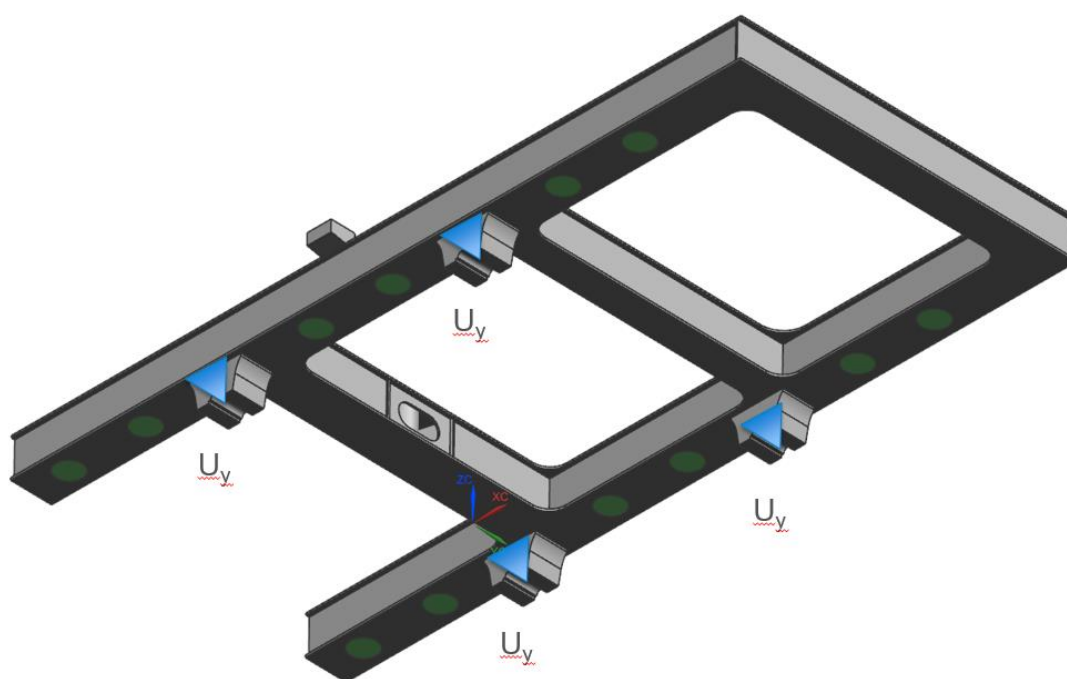


Figure 9 Lateral constraints used in finite element model

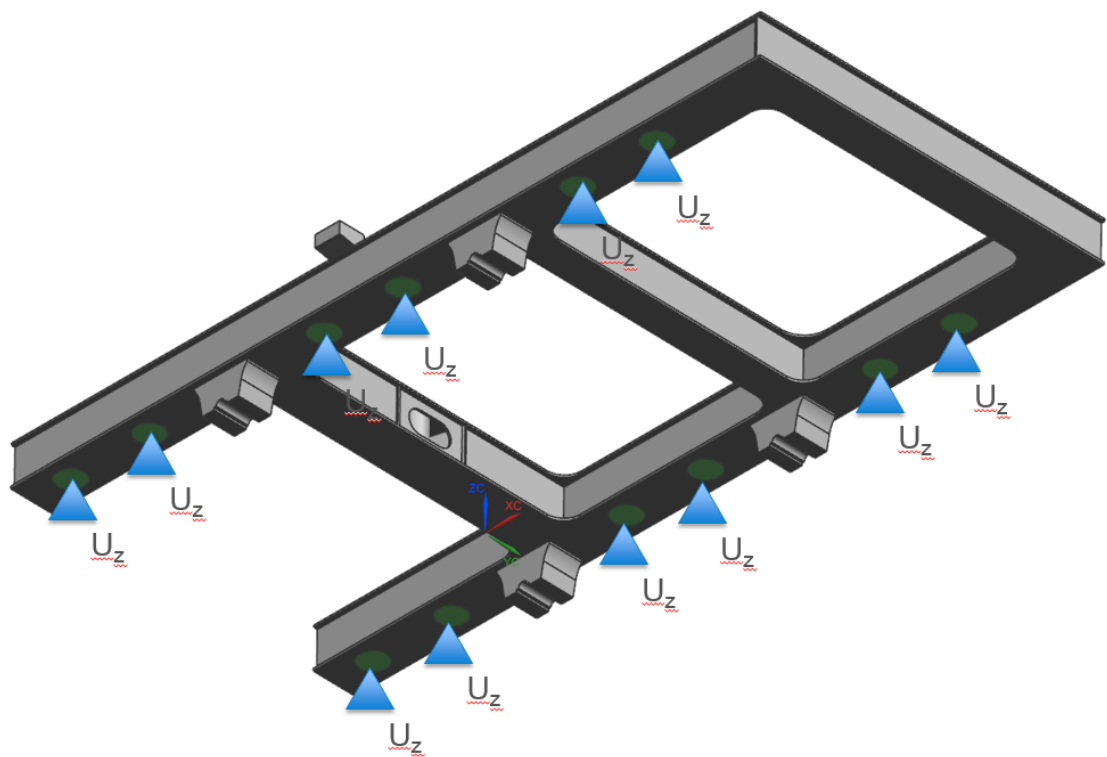


Figure 10 Vertical constraints used in finite element model

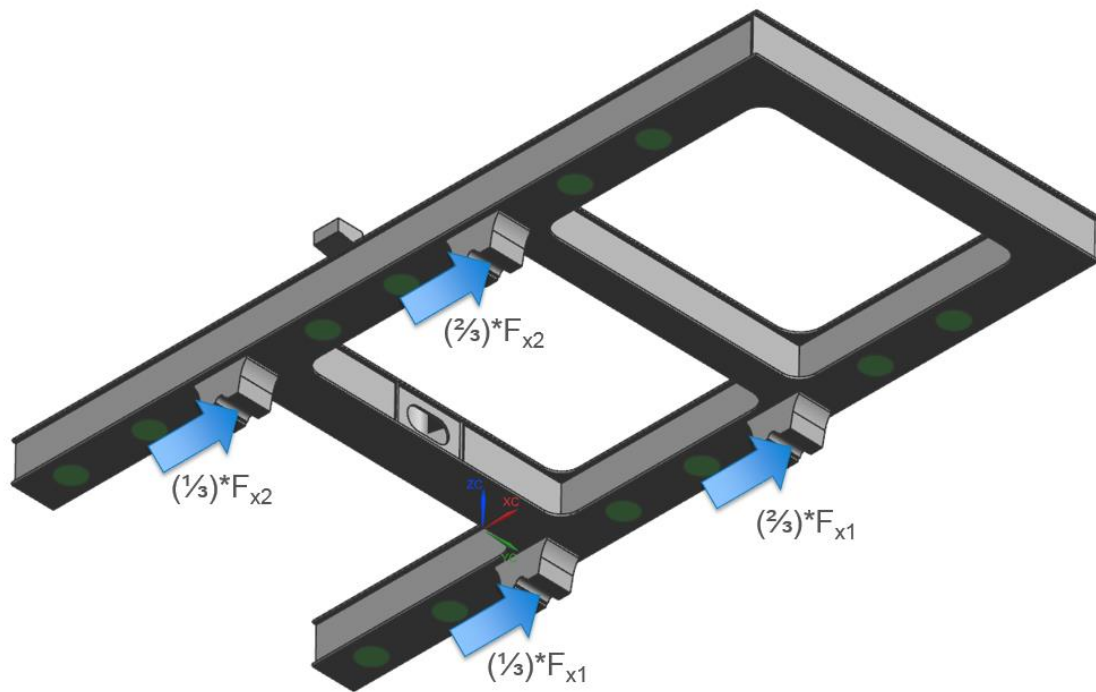


Figure 11 Position of longitudinal loads

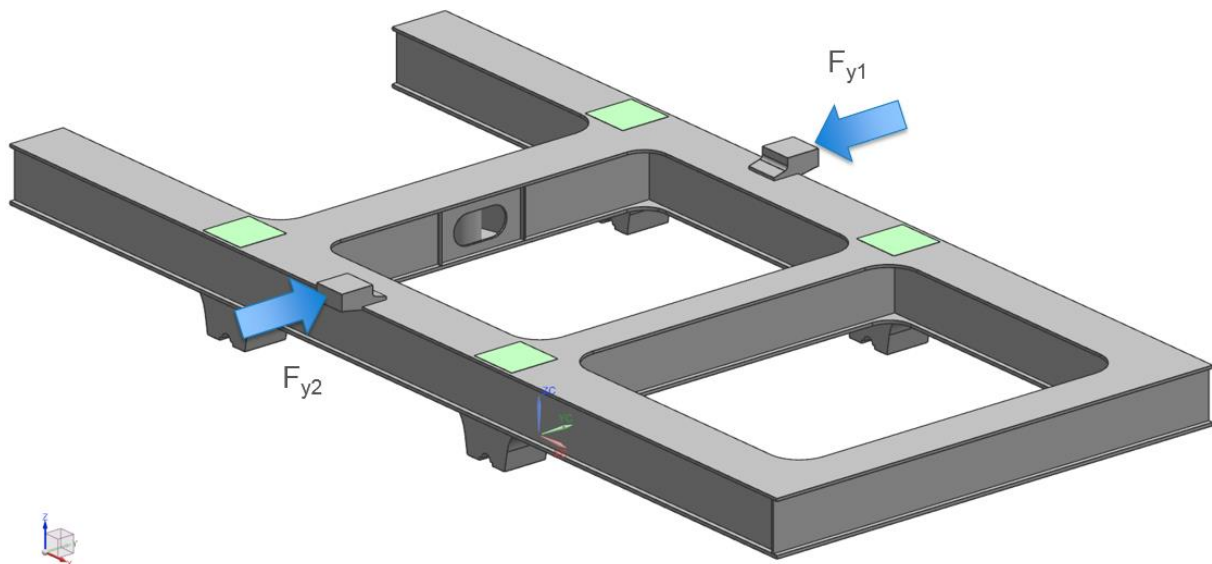


Figure 12 Position of lateral loads

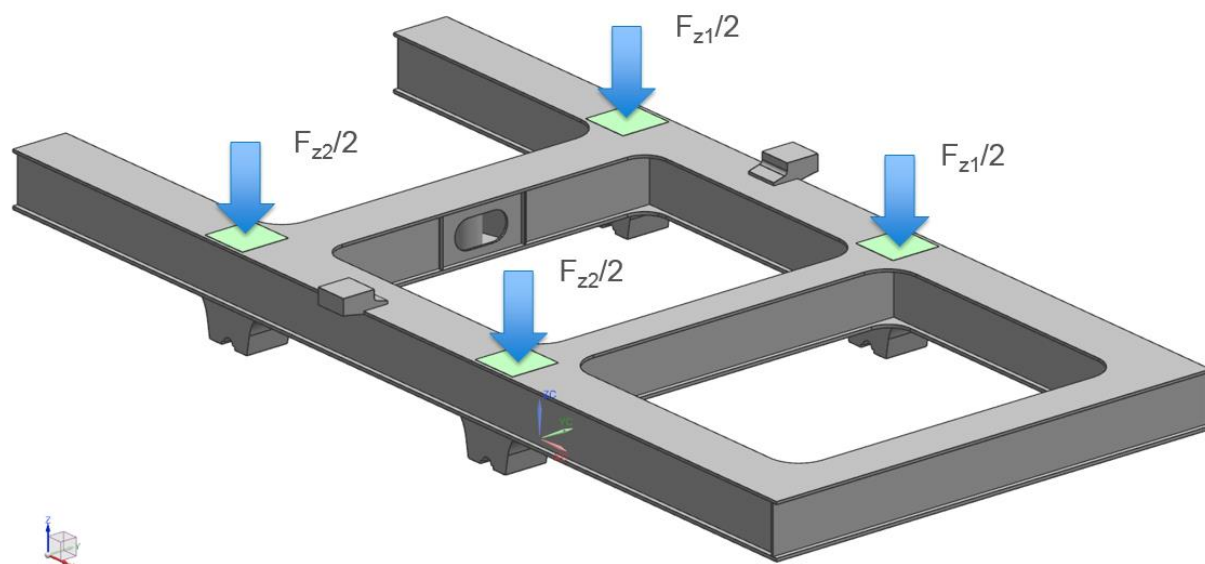


Figure 13 Position of vertical loads

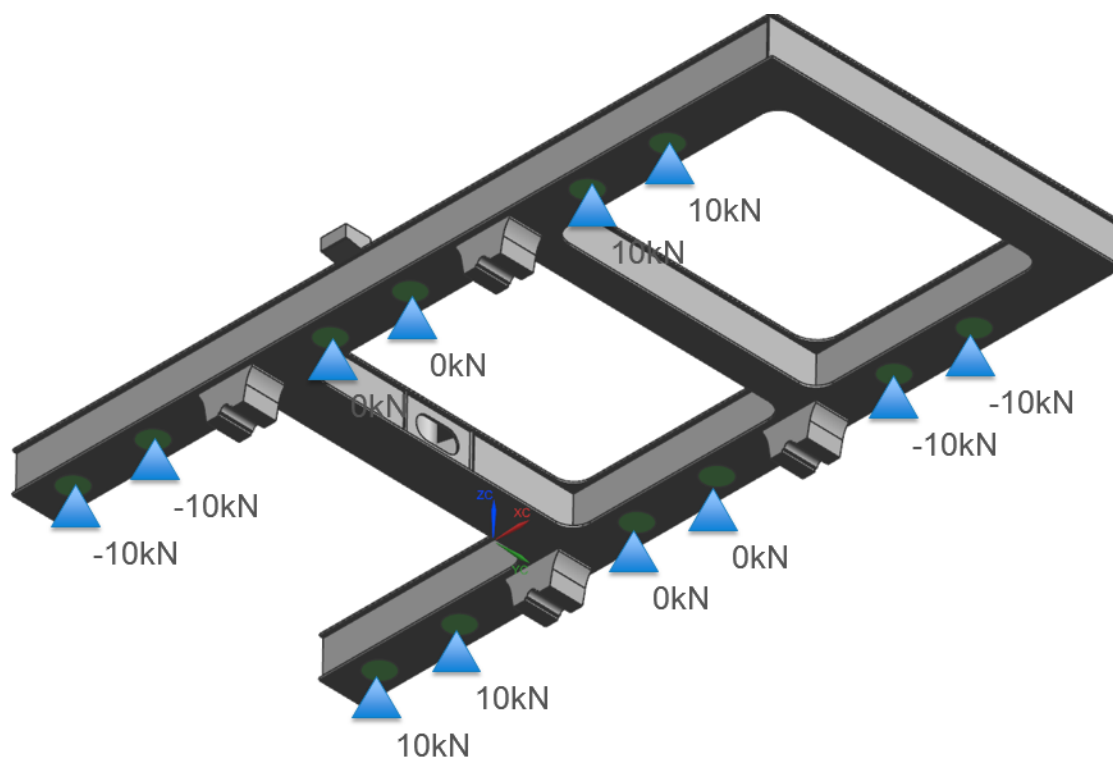


Figure 14 Typical wheel unloading for 0.5% twist

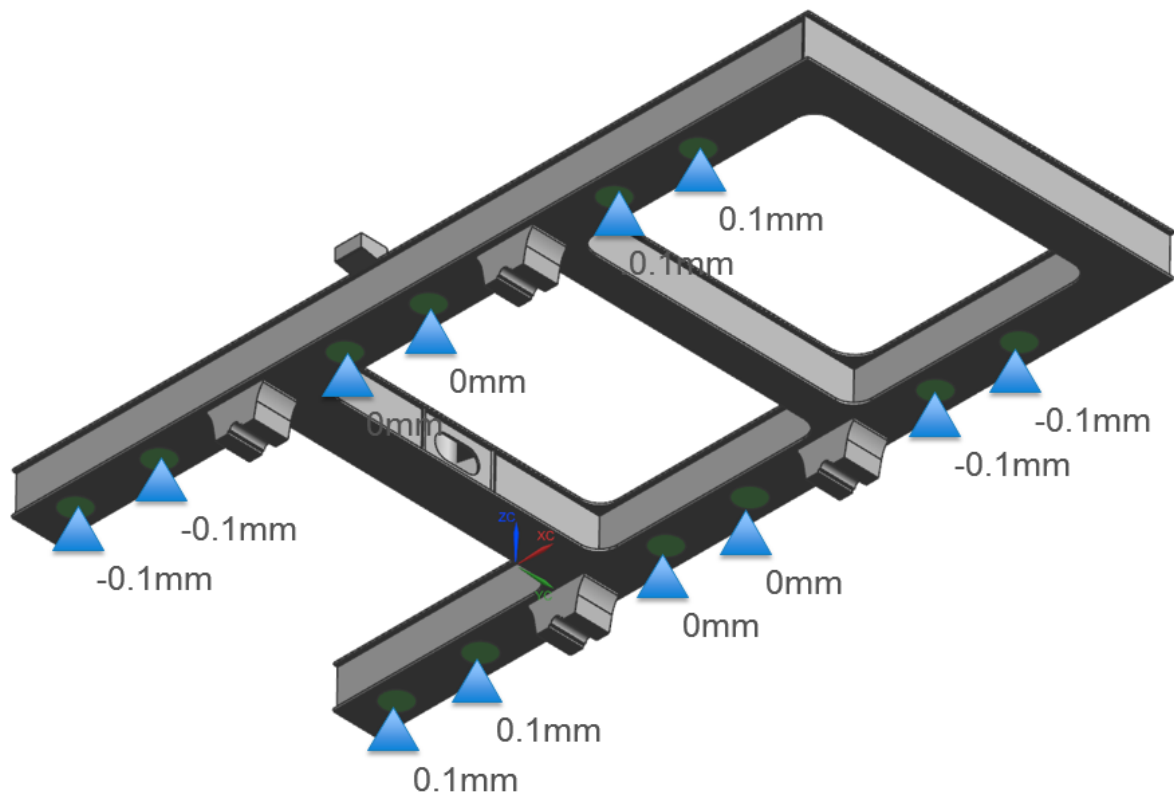


Figure 15 Application of finite element model constraints corresponding to track twist 0.5%

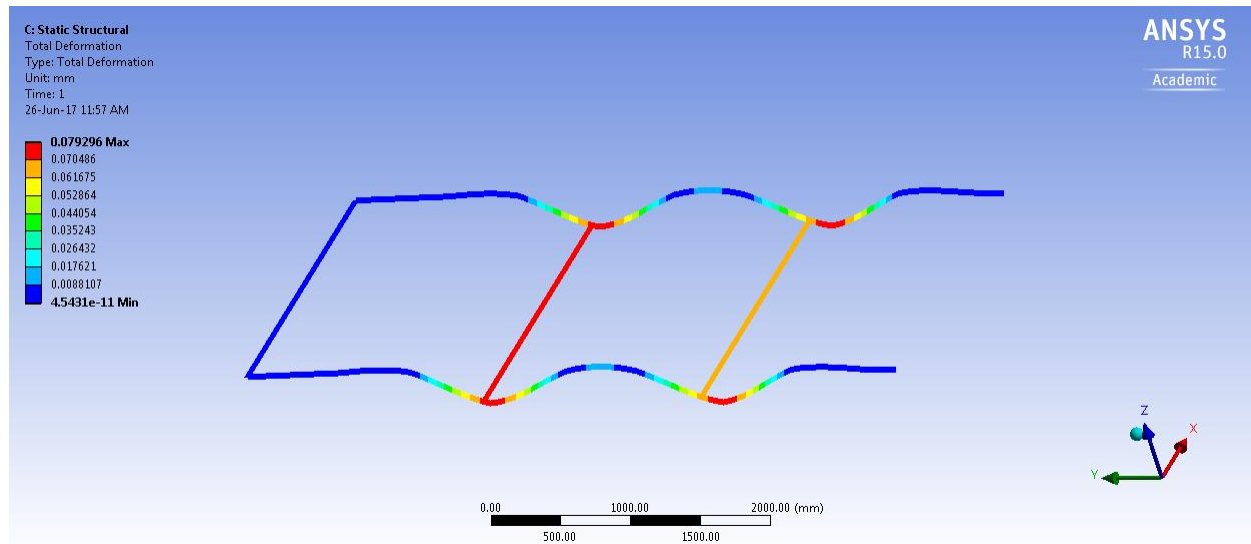


Figure 16 Sample finite element result – static structural for baseline design [load case 1]

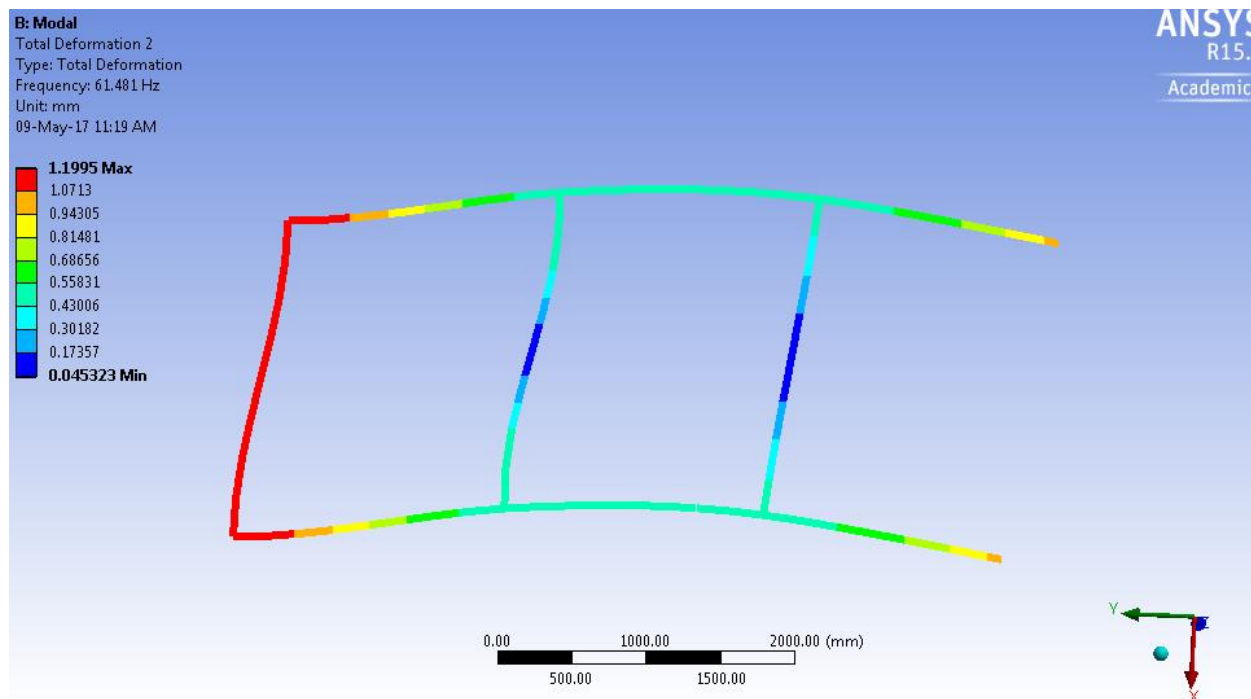


Figure 17 Sample finite element result – modal analysis for baseline design

6. POTENTIAL SAVINGS

6.1 INTRODUCTION

Reduction of the mass of a railway vehicle has the potential to improve the performance in a number of ways. The models described in section 5 have been used to evaluate this for the modifications being considered against the baseline vehicle.

6.2 VEHICLE-TRACK INTERACTION

Light weighting of the rolling stock is one of the effective ways to alleviate the vehicle-track interaction for the railway industry. Clearly, the mass reduction leads to a lower axle load which decreases the total passing tonnage for the railway infrastructure. In addition, the reduced mass and inertia of key components can contribute to the improved dynamic performance of the vehicle and enhance the reliability during operations. Other benefits of light weighting may be more evident in relation to the steering behaviour and curve negotiation. Light weighting of the rolling stock also contributes towards the desired lowering the carbon footprint of the industry.

In this work a typical curve negotiation case is considered: The curve radius is 600 m, the length of the constant radius curve is 100 m and the lengths of two connected transition curves are 60 m; the super elevation of the high rail is 90 mm, while cant deficiency is around 60 mm. The vehicle speed is 72 km/h for all the cases.

In this situation, when the locomotive negotiates this small radius curve, the leading wheelset normally exhibits the most critical dynamic behaviour. For the leading wheelset, the flange contact occurs on the outer wheel leading to high wheel/rail lateral force inside curve, while the wheel/rail lateral force on the inner wheel directs outside the curve due to the lateral creep. Under this circumstance, the inner and outer rails subject to the relatively large lateral loads on the opposite directions. This case may cause gauge spreading, which may constitute a derailment risk for the locomotive or other vehicles.

In Figure 18 and Figure 19, the influences of the bogie frame mass reduction on the dynamic behaviour of the curve negotiation with reductions in bogie frame mass of 25% and 50% are illustrated.

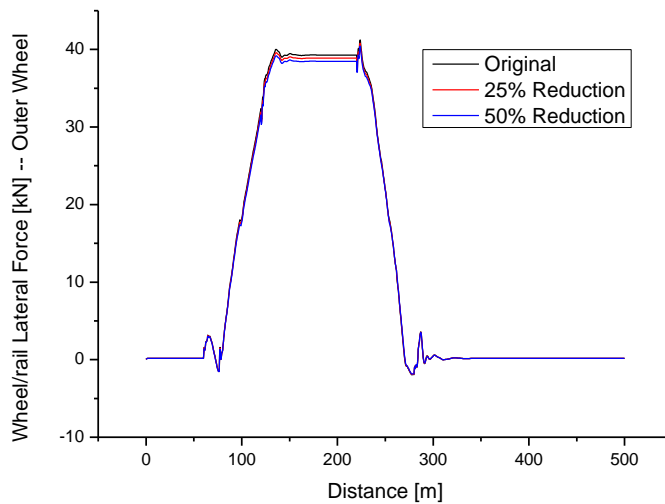


Figure 18 Comparison of wheel/rail lateral force of outer wheel (leading wheelset)

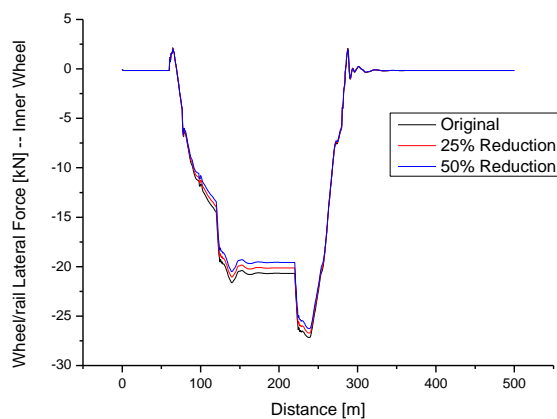


Figure 19 Comparison of wheel/rail lateral force of inner wheel (leading wheelset)

The wear index can be evaluated and this gives an indication of the rate of wear that is likely to occur in a curve. Changes in this rate of wear for reductions in bogie frame mass of 25% and 50% are again shown. Reductions at the outer wheel tread of up to 12.5% can be seen although at the

flange only 7.5% reduction is seen, see Figure 20 and Figure 21. Reductions at the inner wheels are not significant, see Figure 22.

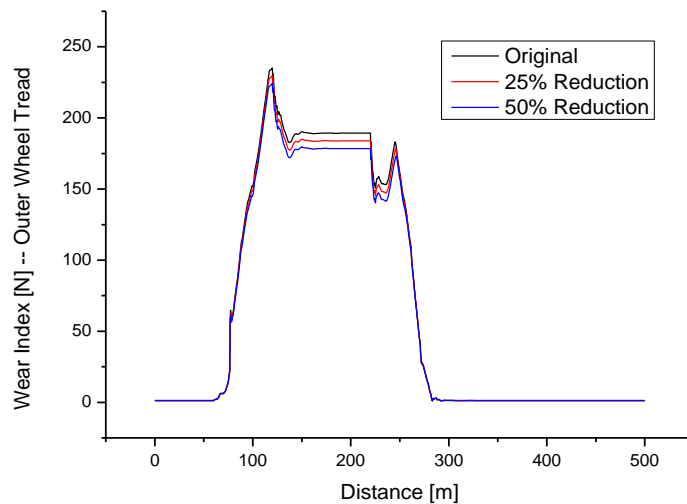


Figure 20 Comparison of wear index of outer wheel tread (leading wheelset)

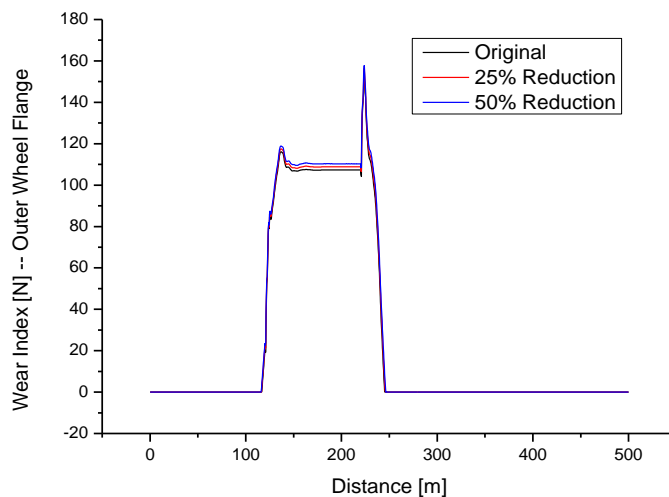


Figure 21 Comparison of wear index of outer wheel flange (leading wheelset)

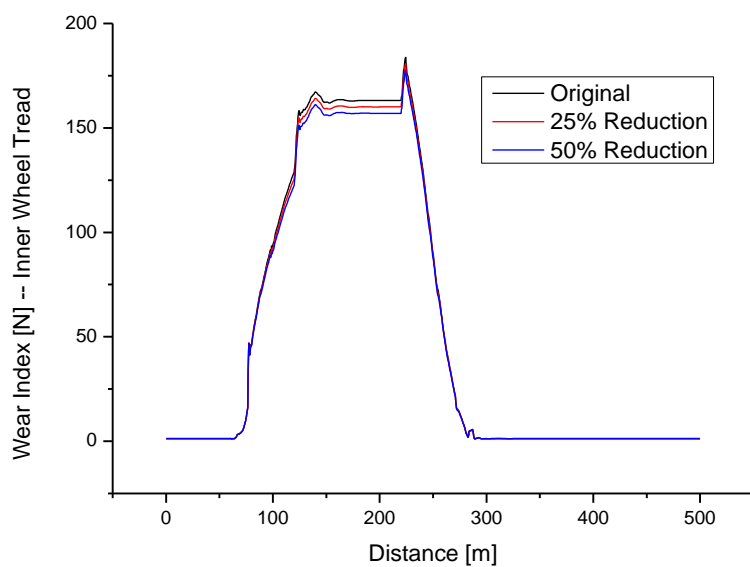


Figure 22 Comparison of wear index of inner wheel tread (leading wheelset)

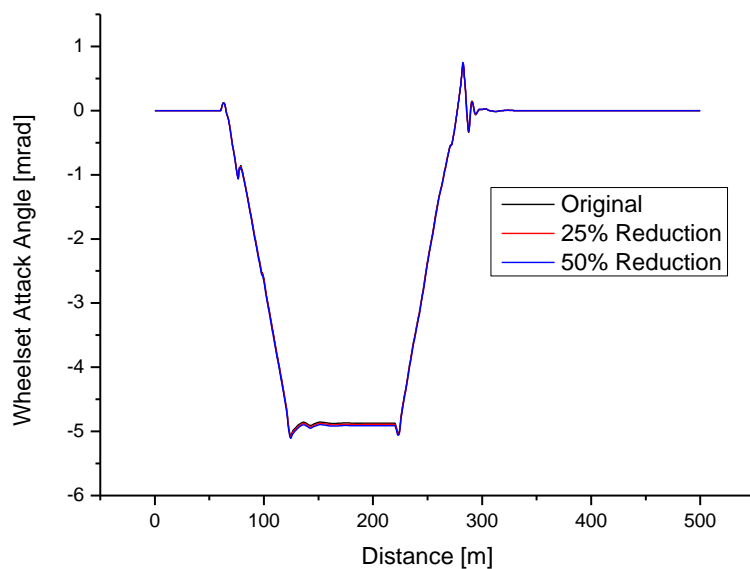


Figure 23 Comparison of wheelset attack angle (leading wheelset)

Derailment is often evaluated by the ratio of lateral force to vertical force (Y/Q) at any wheel. A limiting value of 1.0 (or lower) is taken to indicate high derailment risk.

In this case the Y/Q value was simulated and no significant change from the baseline vehicle was evident, see Figure 24 and Figure 25.

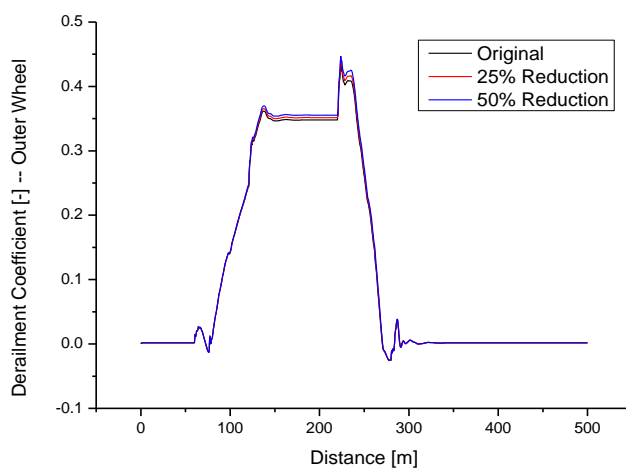


Figure 24 Derailment coefficient of outer wheel (leading wheelset)

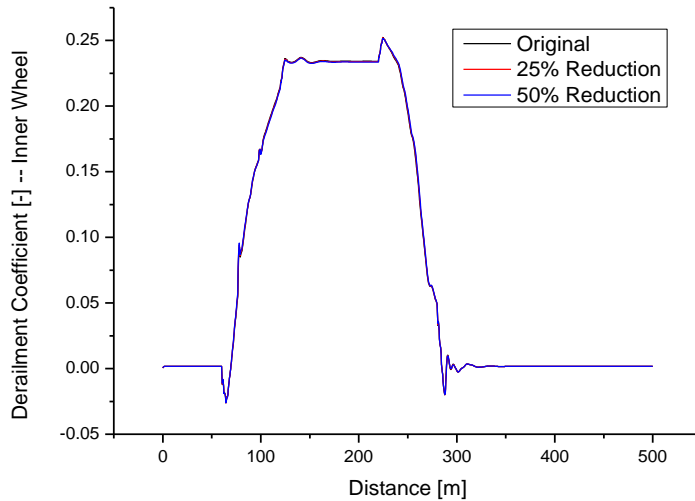


Figure 25 Derailment coefficient of inner wheel (leading wheelset)

In summary, it can be seen that the wheel/rail lateral forces can be reduced if a light-weight bogie frame is adopted. This is evident for a reduction of 25% in bogie frame mass. The effect is more obvious for the outer wheel. Furthermore, the bogie mass reduction can lead to less wear index of the wheel/rail interface. This is due to the reduced wheel/rail normal force and tangential force by mass reduction. However, the derailment coefficient and the wheelset attack angle (a high value of which can result in greater damage or risk of derailment) are not significantly affected by the bogie frame mass reduction, which still guarantees the safety issues. That is because the reduced lateral loads counteract the decreased vertical loads. Therefore, the bogie frame mass reduction contributes to the alleviation of the vehicle-track interaction, which could potentially decrease the detrimental damage to the track system.

6.3 RUNNING RESISTANCE AND ENERGY CONSUMPTION

Vehicle mass has a significant influence on the running resistance and fuel consumption. Various methods have been used to quantify these effects and SNCF proposed an empirical formula for running resistance of diesel and electric locomotives. The running resistance is calculated as (in N)

$$F_r = 9.81(0.65L + 13n + 0.01LV + 0.03V^2) \quad (1)$$

Where L is locomotive weight (in T), n is the number of axles, V is speed (in km/h).

From this equation, the term $0.65L + 13n$ is related to the rolling resistance between the wheel and rail; the term $0.01LV$ is a function of speed and related to the mechanical resistance, such as traction and braking; the term $0.01 V^2$ is the aerodynamic resistance. Definitely, the first two terms are affected by the locomotive weight.

Additionally, when the vehicle negotiates the curve, the resistance is generated from the creep and friction from the wheel/rail interface. The curving resistance is more obvious in the small radius curve. The curve resistance is also a function of locomotive weight and shown as,

$$F_c = 6116L / R \quad (2)$$

where R is the curve radius (in m).

The following figures exhibit the influence of bogie frame mass reduction on the running resistance and curving resistance.

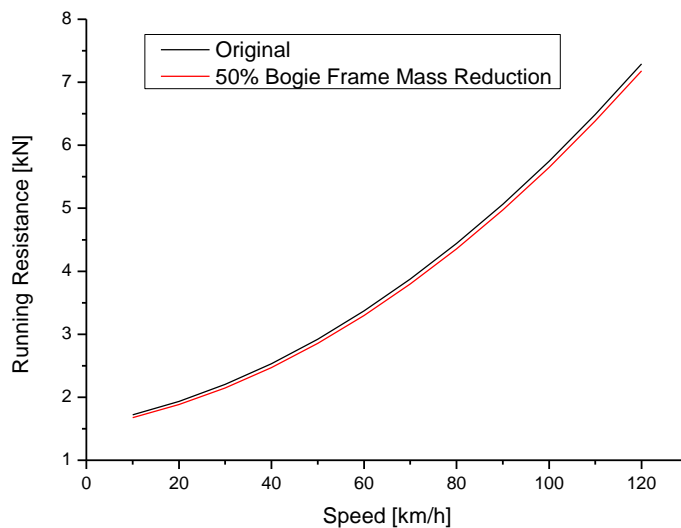


Figure 26 Comparison of running resistance

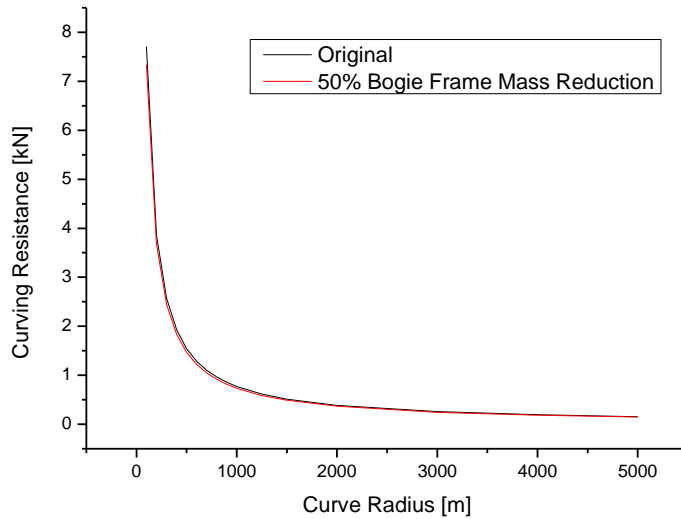


Figure 27 Comparison of curving resistance

Furthermore, the power loss by the running resistance can be calculated by (in kW)

$$P_{\text{loss}} = F_{\text{pr}} V / 3600 \quad (3)$$

The following figure exhibits the influence of bogie frame mass reduction on the power loss by running resistance.

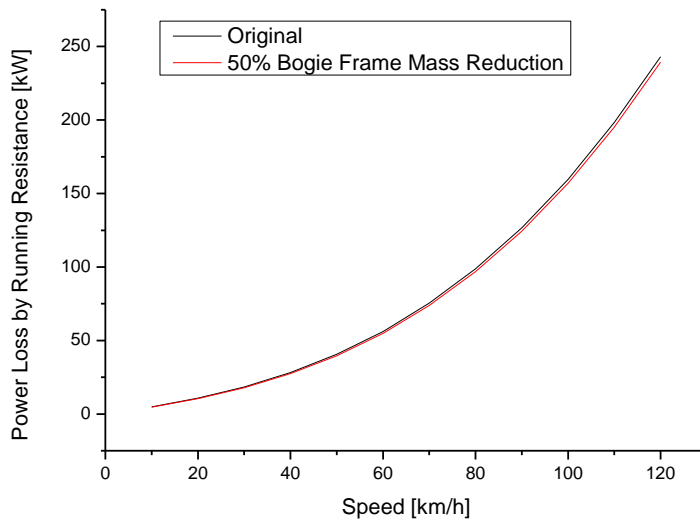


Figure 28 Comparison of power loss by running resistance

From the figures above it can be seen that even though the bogie mass reduction leads to very limited improvements of the operational resistance and energy consumption; considering the service span of decade for the locomotive, the mass reduction of the bogie frame is still contributing to the overall benefit of the fuel consumption cost.

6.4 TRACK ACCESS CHARGES

When railway vehicles run on the track they exert forces which vary according to the vehicle speed and load and on other characteristics including suspension design and condition. The effect of these forces also varies according to the condition of the track itself and can drive several different damage mechanisms resulting in deterioration of the track. These mechanisms have been studied extensively over many years [26]–[28] and methods have been established for predicting the rates of damage. Some railway authorities are now using this understanding to allocate the costs of maintaining deteriorated track to the vehicles doing the damage.

The main damage mechanisms and corresponding maintenance methods are: Tamping to restore track geometry following uneven track settlement and Grinding to restore rail head due to wear and rolling contact fatigue. These are briefly described below:

In conventional track with rails supported on sleepers, which in turn sit on a layer of ballast, any misalignments which develop can be periodically corrected by tamping. Other support structures which use concrete slabs instead of ballast (slab track) are increasingly common on high speed lines and may provide more stable support over a longer period but do not allow corrective action as easily as ballasted track.

Wear on the head and/or gauge corner of the rail is a natural process when railway vehicles run but the rate of material removal can increase significantly if the forces and the contact conditions are not well controlled. This can cause particularly severe problems if the wear causes significant changes to the cross sectional profile, resulting in a change of the running surface as seen by the wheel. Irregular surface wear can result in roughness or corrugation and a consequent increase in rolling noise.

Rolling contact fatigue (RCF) occurs if the rail surface is subjected to repeated plastic deformation as is often caused by repeated wheel passages. If the forces generated are below what is known as the shakedown limit for the material it is possible for them to be accommodated through elastic deformation and RCF avoided. If rail wear levels are high then RCF is reduced or even prevented as the cracks are worn away faster than they grow.

The dividing line between these cases is not easy to establish but the factors influencing the generation of RCF are the normal and tangential forces at the wheel-rail contact and also the contact conditions (mainly the contact pressure and prevailing coefficient of friction). Some tools have been proving effective at predicting whether RCF cracks will appear for example the shakedown curve weighted TGamma curve currently being used by Network Rail [27].

Finally, higher frequency components in the forces (over about 20Hz) can cause fatigue damage to various components within the infrastructure such as rail pads clips etc. This is much more difficult to model and is probably less significant as a cost driver.

6.4.1 Top-Down + Bottom-Up method

Network Rail in the UK uses a combined 'Top-Down' and 'Bottom-Up' approach to track access charging. This is based on the following principles:

- c) The sum of money to be recovered is determined by a top down assessment of the variability of maintenance and renewals.
- d) This sum is allocated to the vehicle fleet using a bottom up model of marginal costs by vehicle type

The aim is to influence vehicle design (eg reduced axle load and unsprung mass) and traffic mix.

The top-down model calculates an Aggregate Variable Cost (AVC) by applying variability percentages to anticipated maintenance and renewal expenditure.

The distribution of the cost to the vehicles is made according to an Equivalent Gross Tonne Mileage (EGTM) which is a weighting of the actual Gross Tonne Mileage. There are two parts to this weighting, one for damage to track and one for damage to structures (bridges etc):

$$\text{EGTM} = K \text{ Ct } A^{0.49} S^{0.64} \text{ USM}^{0.19} \text{ GTM} \quad (\text{for track})$$

and
$$\text{EGTM} = L \text{ Ct } A^{3.83} S^{1.52} \text{ GTM} \quad (\text{for structures})$$

where:

- K is a constant;
- Ct is 0.89 for loco hauled passenger stock and multiple units and 1 for all other vehicles;
- S is the operating speed [mph];
- A is the axle load [tonnes];
- USM is the unsprung mass [kg/axle];
- GTM is gross tonne miles [Tonne.miles].

These values were derived by fitting regression relationships to a large amount of data from damage models

6.4.2 Inclusion of rail head damage

The additional contribution of the vehicle to the rail head damage are included by calculating the energy dissipated in the contact patch between the wheel and the rail. To do this the value of 'TGamma' ($T\gamma$) is calculated and used in a weighted form as a measure of potential rolling contact fatigue generation. In this way an additional term for Equivalent Vehicle Mileage (EVM) is added based on the value of $T\gamma$ calculated for all the wheels of a vehicle:

$$EVM = J \sum (f(T\gamma) VM)$$

where J is a constant; $f(T\gamma)$ is a function of the contact energy $T\gamma$ at each wheel [N]; T is the tangential force at the wheel [N]; γ is the traction coefficient at the wheel [-]; and VM is the miles travelled by the vehicle [miles].

6.4.3 Inclusion of higher frequency components

In Sweden Trafikverket have explored a model which includes the elements described above in the Top-Down + Bottom-Up model but additionally recognises the effect of higher frequency force components on the damage to track components [28].

The determining factors behind these mechanisms are said to be the vertical and lateral wheel-rail forces and the energy dissipation at this interface. The authors of the report state that they have used the best 'state of the art' knowledge to construct a numerical tool (DeCAyS) which includes all four mechanisms. The model is based on a 'mean value' approach where marginal cost and damage to the track are distributed across the whole network being considered. The model is calibrated to the Banverket system.

The DeCAyS tool takes in vehicle and track data and calculates wheel-rail forces. The vertical forces (leading to ballast settlement and component fatigue) is handled separately from the lateral forces (leading to rail wear and RCF).

The total vertical wheel load is evaluated as:

$$Q_{\text{tot}} = Q_{\text{st}} + Q_{\text{d20Hz}} + Q_{\text{dhf}}$$

where: Q_{st} = static vertical load at wheel; Q_{d20Hz} = dynamic vertical load at wheel (up to 20Hz); and Q_{dhf} = dynamic vertical load at wheel (over 20Hz). The static load includes quasi static forces from curving.

The dynamic vertical forces are calculated from

$$Q_{\text{d20Hz}} = 0.80 \cdot K_v \cdot K_s \cdot P \cdot (V+760)$$

$$Q_{\text{dhf}} = 1.32 K_s \cdot V \sqrt{m_{\text{uw}}}$$

where: $K_v = 0.4$ for locomotives and freight wagons and 0.2 for other vehicles; $K_s = 0.0036$ on high speed track and 0.0042 otherwise; P = static axle load (tonne); V = vehicle speed (km/hr); and $m_{\text{uw}} =$ unsprung mass per wheel (kg). K_v and K_s are calibrated from measurements of track forces from four vehicles (including a locomotive a high speed passenger vehicle and a loaded freight wagon).

Track settlement is then calculated using the following equation as proposed by ORE:

$$E(T_a) - E_0 = k \cdot T_a^\alpha \cdot (P_{\text{dyn}})^\beta$$

Where: $E(T_a)$ = track deterioration after passage of traffic T_a ; E_0 = initial state of track deterioration; T_a = tonnage carried by the track and $P_{\text{dyn}} =$ dynamic axle load (kN); and the values of the coefficients k, α and β have been tabulated by ORE.

Only the quasi static component of the wheel-rail forces is required by DeCAyS (Deterioration Cost Associated with the Railway Superstructure) for calculation of rail wear and RCF. These forces are calculated using the GENSYS vehicle dynamics simulation tool and a matrix of wear numbers is created for each vehicle being considered.

A limited number of discrete parameter values for curve radius, primary suspension stiffness, axle load, wheelbase (axle spacing), coefficient of friction and wheel-rail profile combination is included for each vehicle.

RCF and wear are then calculated using a modified version of the Rail Surface Damage model proposed in [27]. When the wear number is between 0 and 15Nm/m no wear or RCF is assumed to occur; between 15Nm/m and 175Nm/m, RCF dominates and above 175Nm/m wear dominates. The total damage for each wheel of a vehicle can then be evaluated from the sum of the three components.

The combined effect of the various components in the DeCAyS simulation tool predicted for a representative traffic volume and vehicle distribution has been calculated and calibrated based on the known costs for each deterioration mechanism for the year 2001. this is based on the methods used in a previous banverket tool for prediction of track deterioration cost, DeCoTrack. As a result of this, 3 weighting coefficients have been established:

$$\begin{array}{lll} K_1 & \text{(track settlement)} & = 7.74 \cdot 10^{-10} \\ K_2 & \text{(component fatigue)} & = 1.08 \cdot 10^{-9} \\ K_{34} & \text{(wear and RCF)} & = 3.98 \cdot 10^{-2} \end{array}$$

6.4.4 Conclusions regarding track access charges

Although it is difficult to be precise, as the charging methodologies used in different countries are based on different methods, it could be estimated that a reduction in mass should result in a significant reduction in track access charges. Although the greatest benefit would be attained if the unsprung mass could be reduced or the wheelset steering improved, (the later is being evaluated on Task 2.3), even taking the simple axle load component of the charging mechanism a reduction in bogie frame mass of 43% should result in a 1% reduction in track access charges for the same operating conditions (see appendix 1).

6.5 FINITE ELEMENT RESULTS

A parametric study has been undertaken using the methodology described in Section 5.3. This parametric study varied the width, height and wall thickness of assumed rectangular hollow section (see Figure 34) to ascertain the effect on deflection, natural frequency and stress. The results of this parametric study are summarized in Table 3. These results have been compared against the criteria in set out in Section 4.1 and highlight in red to indicate a failure or in blue for a pass.

Examination of Table 3 reveals that a 43% reduction (highlighted) in mass is achievable. Deflection criteria would appear to be the limiting factor, particularly for the lozenging load cases, see Figure 29. After this, natural frequency tends to limit the design, see Figure 30. Performance against both these criteria is primarily linked to stiffness. Consequently, weight must be reduced while maintaining stiffness. Assuming a steel frame and a fixed frame layout, this is only possible by increasing ratios of web to wall thickness and flange to wall thickness. However, designs with high web to wall and flange to wall ratio become increasingly prone to local buckling. Introducing local stiffening features to control this would result in increased manufacturing cost. Furthermore, the sections with higher web to wall and flange to wall ratios than those in Table 3 are less readily available. Note that global buckling is unlikely to be a limit factor in design based on the results in Figure 31 and Table 3; however, this should be confirmed by a detail nonlinear design check.

A maximum normal stress (longitudinal to the beam) of 112MPa was obtained via superposition for a 43% weight reduction. The greatest stress amplitude occurs in the middle of the traction beam at the carbody traction link mounting, see Figure 32 and Figure 33, and coincides with the point of maximum stress. The endurance limits from DVS 1612 [18] for fully reversing stress, compare Figure 32 and Figure 33, are 123MPa and 150MPa respectively for S235 and S355, suggesting weight savings may be possible using mild steels and only limited to negligible benefits in switching to higher strength steels. However, this does not account interaction with other stress components such as shear or consideration of local stress raisers. Additionally, joints and welds may further reduce the endurance limit further, although careful location of these would mitigate against this.

Load cases involving twist were not critical. However, a spot check was undertaken to confirm the twist was properly applied. The original relative displacement, see Figure 15, did not produce the right wheel loading/unloading pattern. However, doubling relative displacements resulted in the desired wheel loading/unloading pattern, but did not impact the results in Table 3.

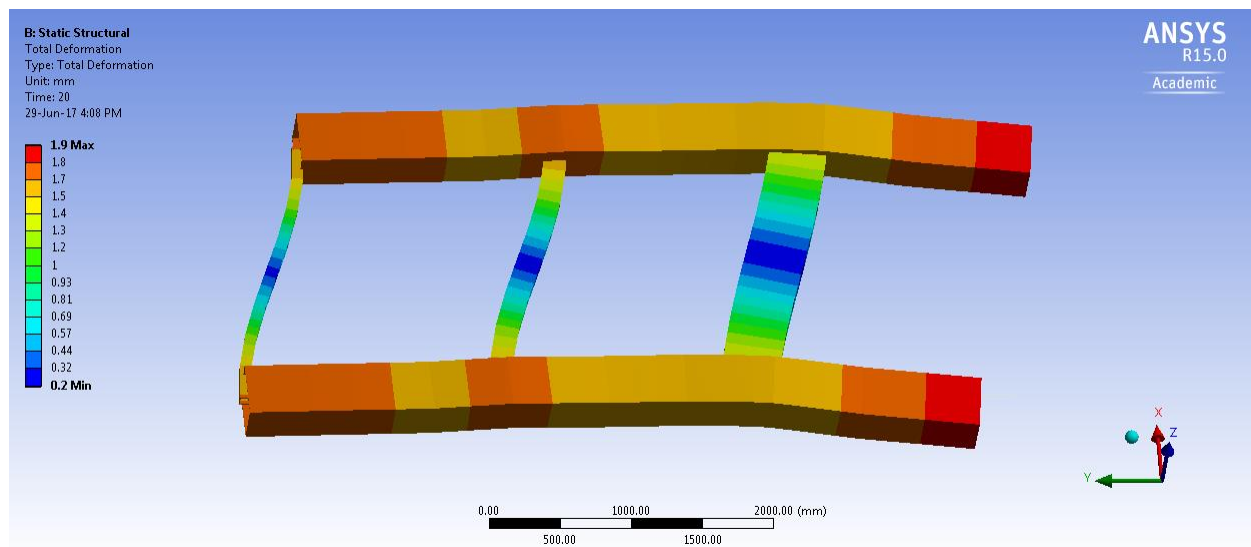


Figure 29 - Maximum Deflection [load case 21 & 43% weight reduction]

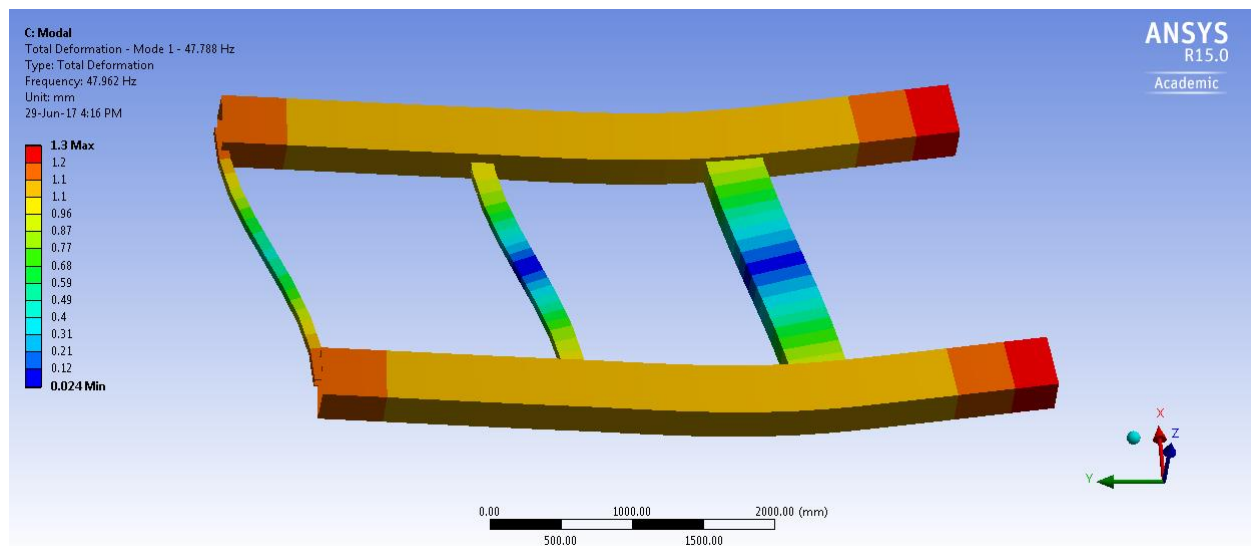


Figure 30 1st Mode- 48Hz Natural Frequency [43% weight reduction]

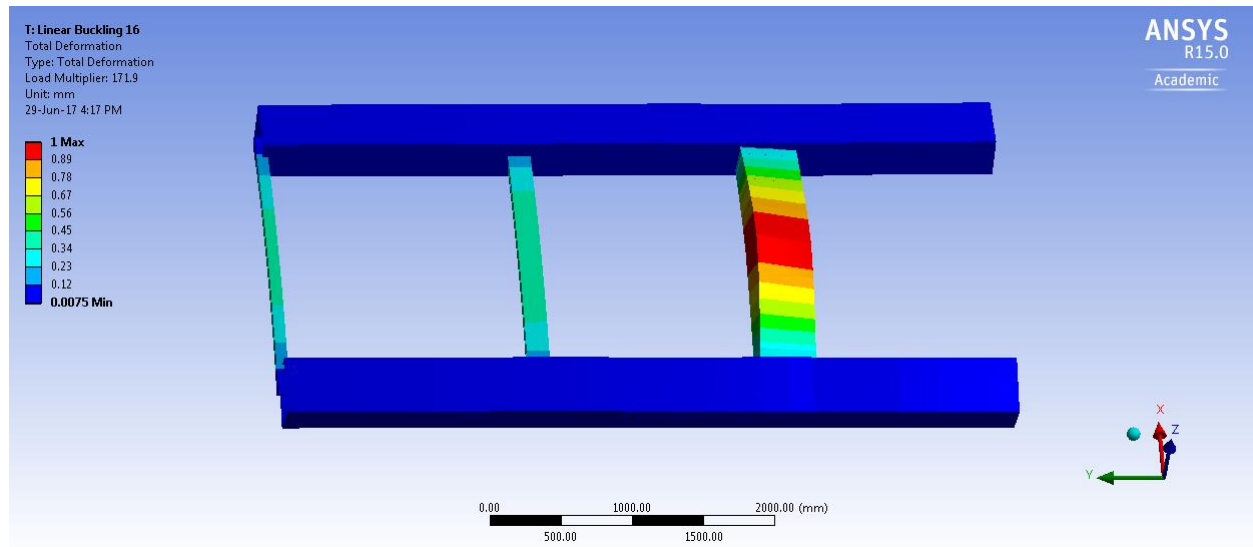


Figure 31 Buckling mode, 172 factor on loads [load case 16 & 43% weight reduction]

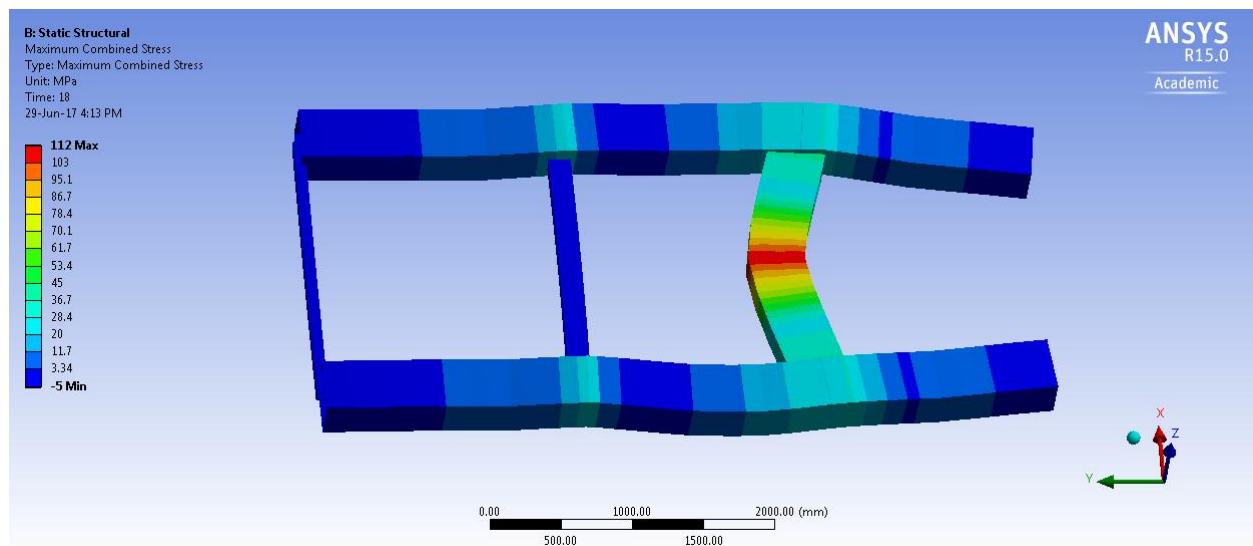


Figure 32 Maximum Normal Stress (Parallel to beams) [load case 18 & 43% weight reduction]

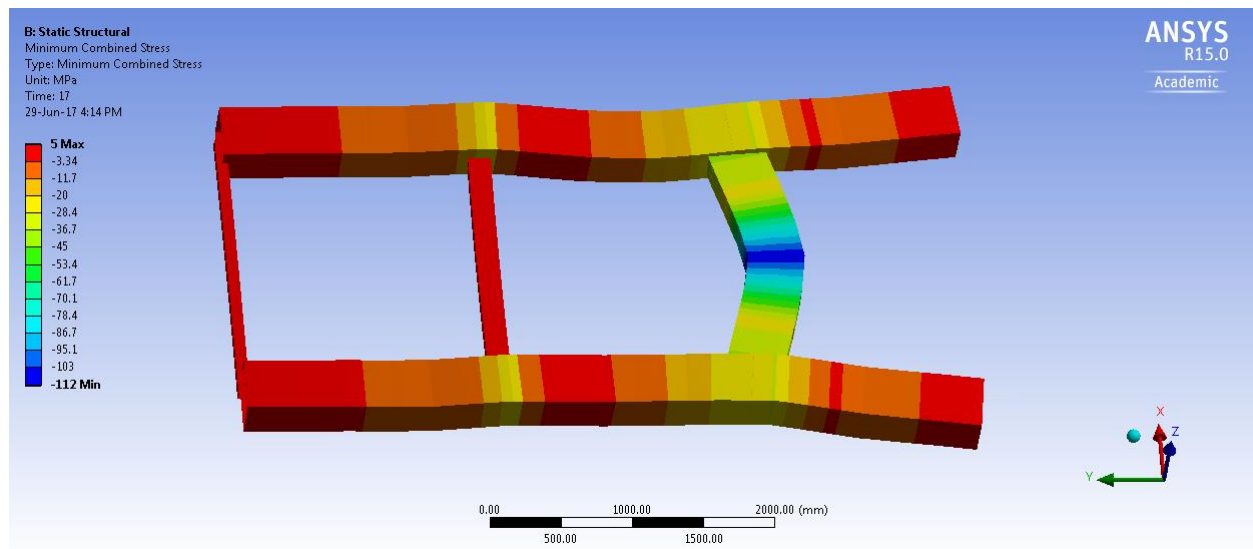


Figure 33 Minimum Normal Stress (Parallel to beams) [load case 17 & 43% weight reduction]

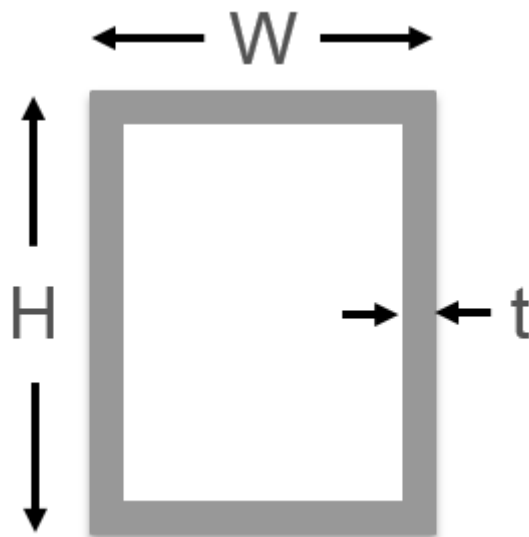


Figure 34 Rectangular beam section parameters

Table 3 Summary of finite element parametric study (see Figure 34 for beam parameters)

	End beam			Central beam			Traction beam			Side beam			Criteria			abs. normal stress
mass saving	W	H	t	W	H	t	W	H	t	W	H	t	max deformation	lowest natural freq.	Euler buckling x load	
	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[Hz]		[MPa]
5%	100	200	5	100	100	5	500	250	5	500	500	10	1.0	44	322	80
16%	160	160	5	160	160	7.5	500	400	7.5	500	500	7.5	0.7	59	871	46
17%	160	160	7.5	300	300	7.5	500	400	7.5	500	400	7.5	0.6	66	842	46
19%	160	160	5	300	300	7.5	500	300	7.5	500	400	7.5	0.6	66	556	55
24%	160	160	7.5	150	150	7.5	500	500	7.5	300	500	7.5	1.4	49	676	46
24%	160	160	7.5	300	300	7.5	500	400	7.5	400	350	7.5	0.7	60	739	51
29%	160	160	5	300	300	7.5	300	500	7.5	300	400	7.5	1.4	48	712	75
30%	100	200	7.5	100	100	7.5	500	250	7.5	250	500	7.5	2.3	41	323	73
31%	100	100	7.5	100	100	7.5	500	250	7.5	250	500	7.5	2.4	40	315	73
32%	160	160	7.5	160	100	7.5	400	300	7.5	400	300	7.5	1.3	53	398	76
35%	150	150	7.1	160	100	7.1	400	300	7.1	400	300	7.1	1.4	53	378	80
35%	150	150	6.3	160	100	7.1	400	300	7.1	400	300	7.1	1.4	53	377	80
36%	150	150	6.3	150	100	7.1	400	300	7.1	400	300	7.1	1.4	52	377	80
36%	150	120	6.3	150	100	7.1	400	300	7.1	400	300	7.1	1.4	52	375	80
36%	120	120	6.3	150	100	7.1	400	300	7.1	400	300	7.1	1.5	51	375	80
36%	120	120	6.3	160	80	7.1	400	300	7.1	400	300	7.1	1.5	51	374	80
36%	120	120	6.3	120	100	7.1	400	300	7.1	400	300	7.1	1.6	50	374	80
37%	120	120	6.3	160	80	7.1	350	300	7.1	400	300	7.1	1.6	49	348	91
37%	120	120	6.3	160	80	7.1	350	250	7.1	400	300	7.1	1.7	48	261	102
39%	100	100	5	100	80	7.1	300	200	7.1	400	300	7.1	2.4	40	163	137
40%	160	160	7.1	160	100	7.1	300	250	7.1	300	300	7.5	2.2	43	211	129
41%	100	100	7.1	160	100	7.1	300	250	7.1	300	300	7.5	2.4	42	208	129
41%	100	100	7.1	160	100	7.1	250	250	7.1	300	300	7.5	2.7	39	185	155
42%	120	120	5	160	80	6.3	350	250	6.3	400	300	6.3	1.8	48	233	114

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42%	120	100	5	160	80	6.3	350	250	6.3	400	300	6.3	2.0	47	161	129
43%	100	100	5	160	80	5	350	250	6.3	400	300	6.3	2.0	46	161	129
43%	80	80	5	160	80	5	400	200	6.3	400	300	6.3	1.9	48	172	112
43%	100	100	5	160	80	5	350	200	6.3	400	300	6.3	2.1	46	161	129
44%	50	50	5	160	80	5	400	200	6.3	400	300	6.3	2.1	46	125	114
44%	100	100	5	150	80	5	350	250	5	400	300	6.3	2.1	45	197	138
45%	100	100	5	160	80	5	350	250	6.3	350	300	6.3	2.3	46	216	119
45%	100	100	5	160	80	5	350	250	6.3	400	250	6.3	2.1	47	220	116
45%	100	100	5	150	80	5	350	200	6.3	350	300	6.3	2.4	45	149	135
49%	100	100	5	160	80	5	350	250	6.3	400	300	5	2.2	49	218	117

7. POTENTIAL TECHNOLOGIES AND OPTIONS

7.1 INTRODUCTION

The following sections introduce and evaluate some promising materials and fabrication techniques for reducing bogie frame mass. These have been introduced earlier in the context of different industries and/or rail projects. A set of potential design options making use of these materials and fabrication technologies will then be set out. Design optimization needs to extract potential synergies from the three key contributing factors: material properties, fabrication techniques, and the influence of these two on the design of the component. The optimisation of these three factors also requires consideration of degradation/failure mechanisms, the associated rates of degradation experienced by the incumbent system and the property parameters that are considered critical for the intended application. For applications governed largely by the yield strength (YS) of the material, the lightest solution is provided by the material with the highest value of σ_y^m/ρ , where σ_y is the yield strength, ρ is the material density and the exponent 'm' equals 1 for simple tension, 2/3 for a beam under bending, and 1/2 for a plate under bending load [29]. A cost parameter can also be included to arrive at low cost solutions and the above relationship becomes

$$\sigma_y^m / (C \cdot \rho)$$

where C is the cost per unit mass of the material [9].

7.2 HIGH STRENGTH STEELS

The relatively low cost of steel compared to other materials makes it an attractive choice although the cost of High Strength steels is greater than the mild steel grades commonly used in many applications. Although confirmation through more recent data is necessary, earlier data[9] indicates that the price of structural steel is roughly proportional to the square root of its strength in MPa as shown in the relationship below:

$$C(\sigma_y)/C(235) = (\sigma_y/235)^{0.5}$$

where $C(\sigma_y)$ is the cost of steel with a yield strength of σ_y MPa; and $C(235)$ is the cost of steel with a yield strength of 235 MPa. This suggests that provided the above cost increase relationship is validated for current prices and the value of the exponent 'm' is >0.5 , lighter solutions based on

higher strength steels may not just give better performance and weight reduction but are also likely to be cost beneficial. The view is also reflected in the development of structural steels over the past few decades to support the drive for lighter structures.

Steel has proven its diversity and its capability to provide increasingly attractive properties over many decades and there is a belief that a vast majority of steels in use today were developed in the last couple of decades. Steel offers a very wide range of tensile strengths from <200 MPa for ultra-low carbon interstitial-free steels to 2800 MPa for Maraging steels and more than 5000 MPa for fine cold drawn wire. However, the tensile strength range for the plate steel grades that could be considered for substitution in the current fabrication process for the manufacture of bogie frames is between 400 and 1150 MPa with a corresponding range for yield strength of between 355 and 960 MPa.

The chemical composition and key properties of all structural steels included in EN10025-2004-1 to EN10025-2004-6 [1]-[6] are summarised in Table 4 and Figure 35.

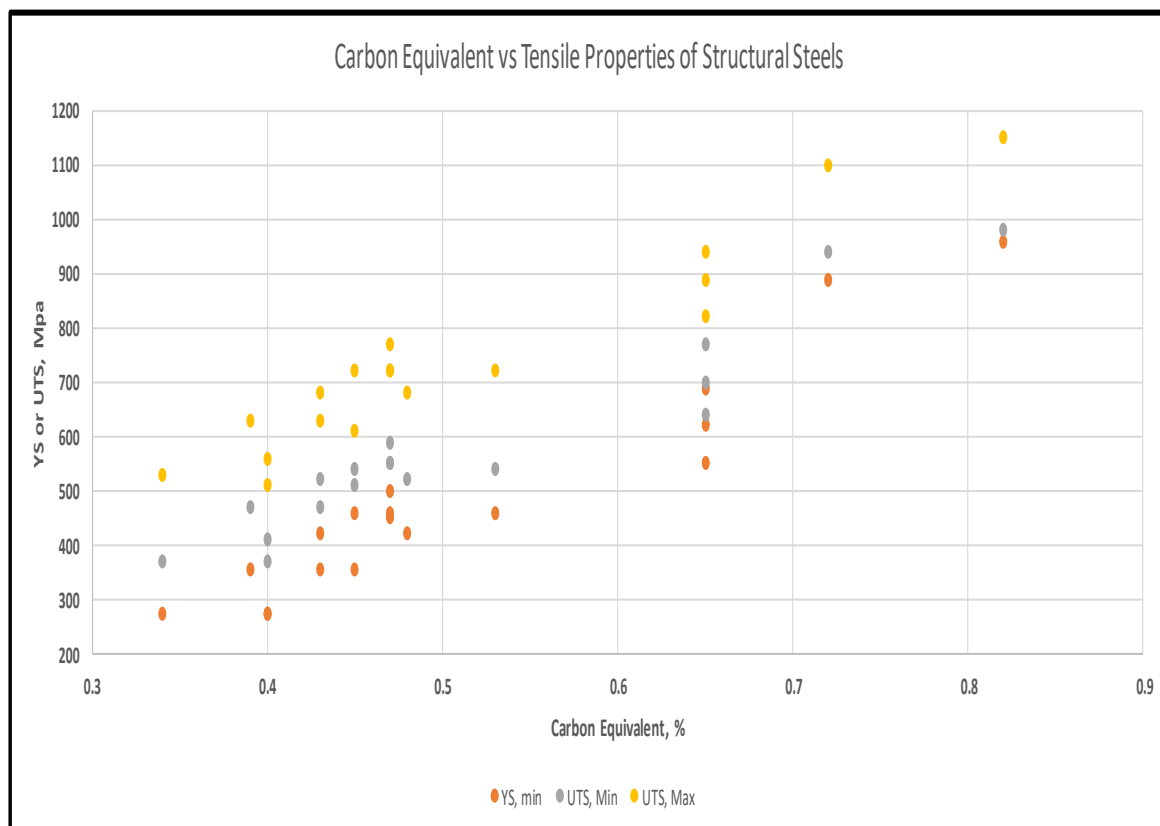


Figure 35 Carbon Equivalent and Strength of Structural Steels (EN10025 – 2004)

However, as the properties achieved are from a combination of steel composition and processing conditions, it is necessary to understand the implications of the manufacturing process route employed. The manufacturing process for plate steel grades can be categorised in four groups:

1. **As- rolled (AR):** Plates rolled without being subjected to any special rolling and/or heat treatment condition.
2. **Normalising Rolling (NR):** Plates rolled employing a process in which the final deformation is carried out in a certain temperature range leading to a material condition equivalent to that obtained after normalizing
3. **Thermomechanical Control Process (TMCP):** Plates rolled employing a process in which the final deformation is carried out in a certain temperature range leading to material properties which cannot be achieved by heat treatment alone.
4. **Quenched & Tempered (Q&T):** Plates that are either directly quenched and tempered following rolling or are subsequently reheated, quenched, and tempered to achieve a tough tempered martensitic microstructure with higher strength than those achieved by other processes.

As apparent from Table 4, maximum levels of the alloying elements are specified while minimum levels or a range is specified for the key properties. Thus, the flexibility of steel composition and the non-objective nature of the process specifications suggests that a wide range of properties that satisfy the requirements of EN10025-2004 could be available from different manufacturers [11], [30], [31]. Relatively small changes in composition and/or variations in processing route can significantly affect the resulting mechanical properties[11]. In general, standards specify the maximum, minimum or a range for the concentration of any particular alloying element but this can often overlook the synergy brought about by the interaction between two elements. 'Old' and 'new' versions of steels within 3 standard steel grades, i.e. 355, 450 and 690MPa yield strength were shown to satisfy the grade requirements (primarily with respect to specified minimum yield strength) but the 'newer' versions show much improved overall properties by combining the required yield strength with improved toughness (improved Charpy impact performance), and improved weldability (lower carbon equivalent values)[11]. An example of high tensile plates is the WEL-TEN series of plate grades from Nippon Steel covering minimum yield strength range between 450MPa and 885MPa. These steel grades are available in plate thickness of a minimum

of 6mm. However, the company brochure did not clarify whether these grades were thermomechanically processed or quenched and tempered. Furthermore, since the thickness of plates currently used for the manufacture of freight wagon bogies is $\leq 12\text{mm}$, they offer greater scope for thermomechanical processing. Consequently, an optimum combination of steel composition and thermomechanical treatment could be designed to give the desired properties in thinner plate sizes to facilitate a significant reduction in the weight of freight wagon bogies.

Table 4 Range of steel specifications in EN10025 – 2004

Ceq	Yield Strength, min [MPa]	Ultimate tensile strength, min [MPa]	Ultimate tensile strength, max [MPa]	Elongation, min
0.40%	275	410	560	23
0.40%	275	370	510	24
0.34%	275	370	530	24
0.45%	355	510	610	22
0.43%	355	470	630	22
0.39%	355	470	630	22
0.47%	450	550	720	17
0.48%	420	520	680	19
0.43%	420	520	680	19
0.53%	460	540	720	17
0.45%	460	540	720	16
0.47%	460	550	720	17
0.47%	500	590	770	17
0.65%	550	640	820	16
0.65%	620	700	890	15
0.65%	690	770	940	14
0.72%	890	940	1100	11
0.82%	960	980	1150	10

7.3 DESIGN AND FABRICATION USING HIGH STRENGTH STEELS

The selection of materials and the processes of design and fabrication are closely linked and although availability of a wide range of high strength steels has been established, the selection

of the optimum grade is dependent on the design and fabrication techniques to be employed. Design options might take one of two approaches:

1. Substitution of thinner gauges of high strength steels in the current design with permissible modifications to the fabrication technique to minimise number of components and welding. This option requires knowledge of the critical stresses in various parts of the frame design and this aspect is discussed further later in the report. However, modifications to the fabrication technique requires a more detailed assessment of the current process route followed by iterative optimisation of the fabrication steps to minimise welding at critical locations.
2. Modified design to enable the adoption of available high strength steels coupled with new fabrication techniques to reduce weight and cost of manufacture while improving longevity in service.

New designs and fabrication techniques used in manufacture are within the scope of the current report, so the three types of technologies are briefly discussed below.

7.3.1 Hydroforming

Hydroforming is a specialised metal fabricating technique which permits the shaping of metals using highly pressurised fluid as the shaping force. A distinctive feature of the process is the uniform distribution of the pressure exerted on the work piece that results in uniformity of deformation. There are two sub-sets of the hydroforming process: sheet hydroforming and tube hydroforming.

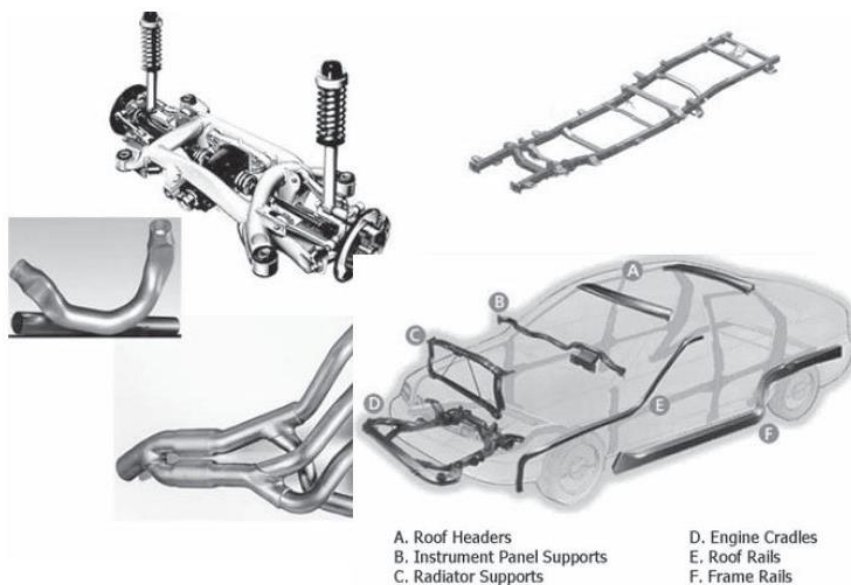
- Sheet hydroforming involves the deformation of a blank sheet into a die using high pressure water to arrive at the desired shape.
- Tube hydroforming is a process that uses tubular blanks and pre-forms that are expanded from the inside out by means of a liquid working medium in a closed die. This method makes it possible to manufacture hollow components with a complex external shape.

Effectively, hydroforming replaces the conventional stamping of two part halves that are subsequently welded together. Although the development of hydroforming goes back to the

1930s, it has developed very significantly since the 1990s and now serves a wide range of industry sectors including automotive where this process has made very significant contributions into the industry's drive for light weighting.

When compared to traditional metal stamped and welded parts, hydroformed parts are lightweight, have a lower cost per unit, and are made with a higher stiffness to weight ratio. The process has been shown to be more efficient in creating complex shapes without the need for welding. The process enables a reduction in component parts and could be utilised for single stage production of components saving on costs of tools, materials and labour.

Further details of the process are available in the literature [32] and through the manufacturers of hydroforming equipment [33]. Some examples [32], [33] of hydroformed components are shown in Figure 36**Error! Reference source not found..**



a) Examples of Hydroformed Components for Automotive Industry [32]



b) Hydroformed Engine Cradles and A Pillar [33]



c) Exhaust Parts [33]

Figure 36 Examples of Hydroformed Parts

However, the key question regarding the applicability of the process to the manufacture of freight wagon bogie frames is its limitation of the gauge and the yield strength of the plate that can be practically and economically deformed using currently available equipment.

The process of hydroforming has a number of constraints including the minimum radii that could be achieved at bends / corners, how formable the feedstock sheet or tube is, and whether the fluid pressure that will need to be applied is a practical proposition with the available equipment. Consequently, it will be necessary to qualify any conceptual designs that are suggested.

7.3.2 Ultrasonic Impact Treatment

Ultrasonic impact treatment (UIT) is a processing technique, similar to work hardening, in which ultrasonic energy is imparted into a metal object to develop compressive residual stress. Ultrasonic waves are produced by an electromechanical ultrasonic transducer, and applied to a workpiece. An acoustically tuned resonator bar is caused to vibrate by energizing it with a magnetostrictive or Piezoelectric ultrasonic transducer. The energy generated from these high frequency impulses is imparted to the treated surface through the contact of specially designed steel pins. When the tool, made up of the ultrasonic transducer, and pins comes into contact with the work piece it acoustically couples with the work piece, creating harmonic resonance. This harmonic resonance is performed at a carefully calibrated frequency, to which metals respond very favourably, resulting in stress relief and compressive residual stresses. A combination of different frequencies and displacement amplitude can be applied to achieve the desired results. In general, these frequencies range between 15 and 55 kHz, with the displacement amplitude of the resonant body of between 20 and 80 μm .

The process is highly controllable and yet flexible. Incorporating a programmable logic controller (PLC) or a Digital Ultrasonic Generator, the frequency and amplitude of UIT are easily set and maintained, thus removing a significant portion of operator dependency. UIT can also be mechanically controlled to provide repeatability of results through CNC milling machines, lathes, robotic control, and welding tractors. The delivery of the process can also be manual thereby providing the flexibility to access difficult to reach parts of any assembly. Further details of the technique and the process are available in the literature [34]–[36].

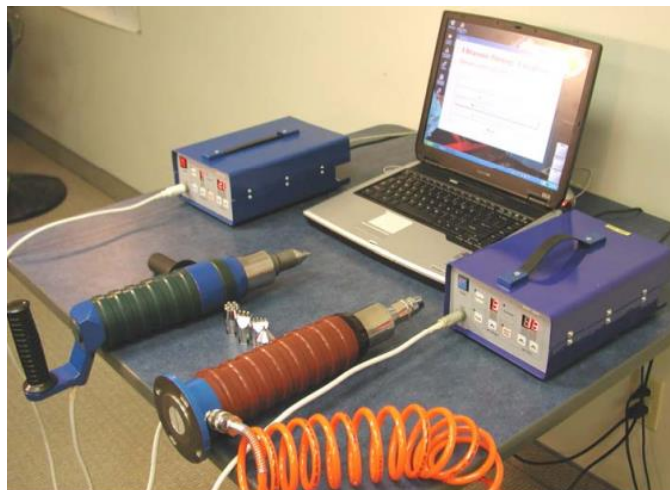


Figure 37 Basic UP systems for manual (left) and robotic (right) applications [36]

The key benefit of the treatment stems from the resultant compressive residual stresses that provide very significant enhancement of both low and high cycle fatigue lives of components [36].

Error! Reference source not found. shows the equipmented used in UIT treatment.

The welded locations and the methodology employed appear to have served the industry well as is evident from the low failure rates, long intervals between inspections, and the generally subjective nature of some inspections. Consequently, the introduction of beneficial compressive stresses in the weld bead/region is unlikely to produce justifiable benefits and cost savings. However, move to thinner plates with the incumbent fabrication techniques are likely to increase the magnitude of stresses around the weld detail and UIT can be deployed to counteract the expected increase in stresses by imparting compressive stresses. However, the consequences for ease of inspection needs to be considered as UIT produces a dimpled surface indentations.

7.3.3 Alternative joining technologies

Welds have been identified as weak points in the current design particularly regarding fatigue failure. Consequently, a cost effective lightweight design might minimize welds and optimize fatigue strength of the remaining welds. However for hollow sections, weld treatments such as UIT may have little discernable benefits[37]. For example in end to end joints, cracks often initiate at the weld root within the interior of the section, which is therefore likely to be inaccessible. Therefore, alternatively joining technologies that eliminate welds completely are attractive. Other industries, notably the automotive industry, have explored alternative joining techniques to replace welds with similar motivations.

Mechanical joining techniques are particularly attractive, allowing dissimilar material such as metals and composite material to be joined. In such techniques, material weldability is no longer a consideration allowing a wider range of materials to be used. Of particular interest are crimping technologies which use plastic deformation to fix parts together, for example by pressing thin walled tubes or sheets in specially designed grooves on mating components. Crimped joints capable of sustaining both axial and torque loads have been investigated[38]. Several methods of achieving crimp joints are available including electromagnetic forming. In electromagnetic forming, a high current pulse is passed through a coil to produce magnetic fields which in turn force the mating pieces together at high speed. Such high speed forming allows plastic deformations in excess of those achievable at lower velocities. Additionally, electromagnetic forming can be used to form welds by increasing the forming speeds even further [39]. However, current applications appear to use wall thickness considerably smaller than anticipated in the current project. Therefore, there is a need to establish the capability of this technique in terms of the maximum thickness that it can process.

Alternatively, interference fits could appear to be a more immediately promising alternative. In this case, traditional interference fits could be supplemented via the addition of adhesives [40]. Research shows that adhesives can significantly enhance the static and fatigue strength of joints.

7.4 SUMMARY AND OPTIONS

A review of some promising technologies and materials has been undertaken. In particular, a review of the available structural steel grades has been undertaken with a view to identifying steel

grades with strengths (YS & UTS) higher than those currently used in the manufacture of railway freight wagons.

The review has revealed a wide range of higher strength steels the use of which could provide the opportunity to reduce the weight of locomotive (or wagon) bogie frames. The different grades can be classified according to the metallurgical processing adopted to deliver the microstructure and properties. The selection of the optimum grade needs to consider its weldability and formability.

As the strengths of the various grades are a combined effect of steel composition and the manufacturing process, detailed discussions with manufacturers is recommended to tailor the composition and processing to deliver the optimum properties for the bogie frame.

The review has also revealed increasing usage of high strength steels in other industry sectors with examples of the grades used in other sectors.

Assessment of hydroforming as a fabrication technique for the manufacture of bogie frames has been suggested giving the growing usage of this technique in the automotive sector. However, there is a need to establish the capability of this technique in terms of the maximum thickness and yield strengths that it can process.

The use of Ultrasonic impact treatment (UIT) to enhance the fatigue life of welds has been highlighted, particularly since the reduction in the weight of bogie frames is likely to utilise thinner gauges of plates and hence smaller weld beads.

Additionally, alternative joining techniques have been explored to find alternatives to eliminate or reduce need for welding. Within joining using crimping, there is a need to establish the capability of this technique in terms of the maximum thickness that it can process. Joining technologies using interference and adhesive are likely to be more readily adaptable for the current application although further work to establish suitability for the range of section sizes and loads involved.

Composite materials offer significant potential especially if the design can be changed to fully adapt to the beneficial properties of the new materials. For example if the stiffness properties of the composite materials in different directions can be appropriately distributed throughout the bogie frame. One of the main barriers to the adoption of composite materials by the railway industry other than in relatively non-structural components is the lack of understanding of the

implications of the different failure mechanisms in a railway application. There is also currently a gap in many standards regarding the acceptable use of composite or other novel materials. This has been examined in previous EU projects for example REFRESCO but the lack of standards and the unwillingness of the railway industry to trial solutions including novel materials is still a major barrier.

A number of options examining how these technologies or combinations of these technologies might be used in the context of bogie frame design are set out below and summarized in Table 5. The descriptions in sections 7.3- 7.4.4 and Table 5 make use of the component names defined in Figure 7.

7.4.1 Option A

Option A is most similar to the current design. It maintains the welded beam sections created from plate steel. As in the current design, extensive welding is required to fix suspension elements, axles, and motors. The current S355 steel is however replaced by high strength steel. In option A, welds remain very significant weak points particularly in fatigue failure. Therefore, considerable attention will be required to ensure good weld finishes and properties.

A number of approaches could be used to achieve this:

- Change the fatigue design approach from an endurance limit approach to safe life design approach. Effectively reducing the margin of safety/ increasing utilization.
- Improve predicability of weld quality by maximizing use of automatic welding and non-destructive testing.
- Use of weld treatment techniques such as ultrasonic impact treatment to improve weld properties
- Combination of the above.

In the light of the above, the potential for economical weight reduction is considered small and benefits of switching to higher yield material limited. Substantial weight reduction are therefore likely to be prohibitively expensive.

7.4.2 Option B

Options B replaces the welded beam sections in the current design with commercial available sections, substantially reducing welding requirements. Hollow sections are preferred due to their good torsional stiffness and resistance to local buckling effects. Sections are available as either cold formed or hot formed sections in a large range of sizes. Hollow sections are available as rectangular, circular and elliptical shapes. Rectangular or elliptical shape allow more flexibility as stiffness and strength can be directional 'tuned'. Elliptical shapes can further 'tuned' by rotating the major semi-axis to coincide with the maximum applied moment.

Joining hollow sections to create a ladder shape is challenging. Direct joining via welded T-joints locates welds within regions of relative high stress, due to stress concentrations. Alternatively, cast joints or 'nodes' allow welds (or an alternative joining technique) to be moved away from the highest stressed regions, see application for offshore structures [10] and onshore bridges [41]–[43]. A conceptual sketch achieving a 32% weight reduction is shown in Figure 38. The location of butt welds joining the cast nodes and hollow sections in Figure 38 are also shown. This shows that the welds are located away from regions of highest stress; therefore, allowing improved fatigue performance.

These welds are likely to be single sided butt welds unless suitable access points (i.e. to inside of hollow section) are included within the design of the casting. Inclusion of suitable access points would also be beneficial in allowing access for post weld treatments. Typically, weld classifications [18], [19] consider single sided butt welds to have inferior properties to stressed regions, see application for offshore structures [10] and onshore bridges [41]–[43]. It is likely that these butt welds could be critical in determining the beam section sizes. Therefore, weld treatment such as ultrasonic impact treatment, could potentially provide significant savings; however, this is likely to depend on access to the interior of the sections.

Alternative joining techniques could also be worth considering. For example, a spigot could be provided on the cast node thus allowing mechanically based joining techniques: shrink-fit or expansion interference fits, and/or crimping to pre-cast grooves on the spigot. A spigot would allow components to be lined up thus potentially offering advantages in the manufacturing process. Adhesive can be used to improve the static and fatigue strength of interference fit joints. Mechanical joining techniques would allow use of less weldable materials particular for

cast nodes, where attachment of secondary elements by welding is less likely. Finally, a mechanical joint could be combined with a welded joint. However, the possibility of introducing a stress singularity at the weld root may make this option unattractive; an analogy in this case might be single side butt welds with backing. However, initial studies have found that good fatigue performance, due to a lower stress concentration, can be achieved for building design using a similar setup [44] .

Welding could be further reduced by incorporating primary traction link mounting and secondary suspensions mountings, including welded internal reinforcing ribs, into the cast nodes. Do so would result in only minor changes or no change to current suspension are layout (both are currently located close to the joints). Optimization of the cast nodes for both weight and manufacturability is likely to be a key component of any design broadly following Option B. Cast nodes could also allow increased section heights to be used without changing the vertical position of suspension elements. This could be achieved by varying top level of the frame through the cast nodes. Finally, cast nodes would allow section sizes to be varied for each individual beam selection with the cast nodes tailored to include suitable welding points.

At other locations, such as mounting positions for primary suspension reinforcement to prevent bearing type failures is likely to be required. The current design achieve this by welded internal reinforcing ribs. However, this option off-the-shelf hollow sections prohibit access for welding such internal ribs. Therefore, an attractive alternative is to cut circular holes through the hollow sections and weld in reinforcing elements as shown in Figure 39. The reinforcing elements could be either off-the-shelf hollow sections or specially cast elements. A carbody traction link mounting is likely to most challenging to attached due its complex geometry and moving parts. In fact, Figure 41 shows this to be one of the highest stresses regions in the conceptual design. For tubular or elliptical sections, hydroforming could be used provide flat fixing surfaces thus allowing standard sections to be used rather than bespoke castings.

Option B has the potential for significant weight saving and possibly even cost saving. In fact, significant savings are possible while maintaining the current S355 steel and there is likely to be only limited benefit to switching to higher strength steels, see Section 6.5.

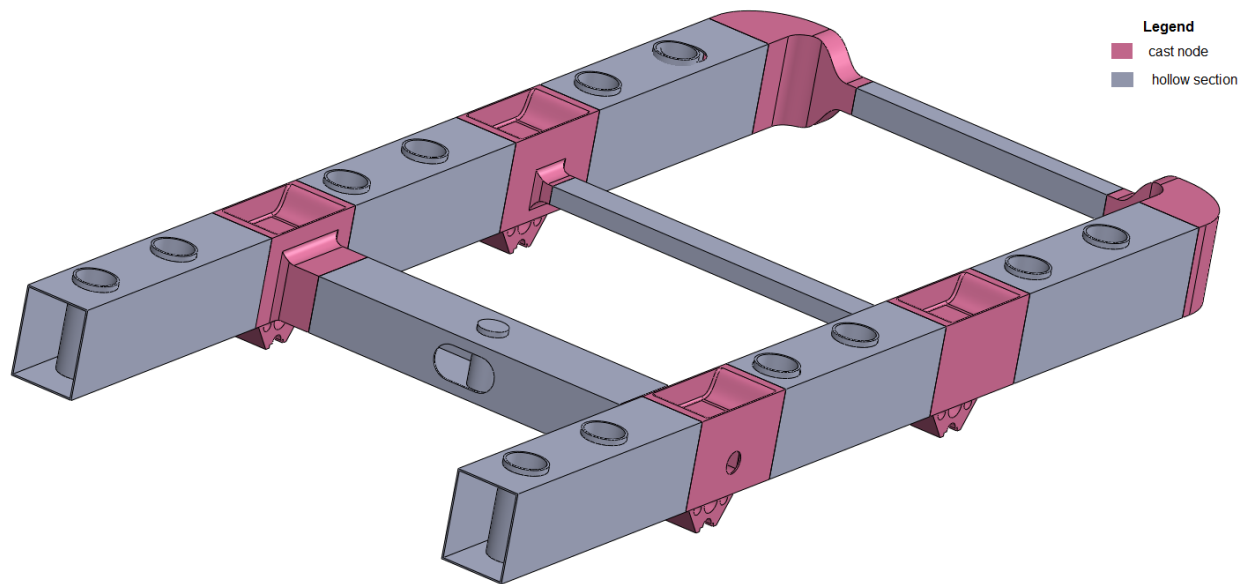
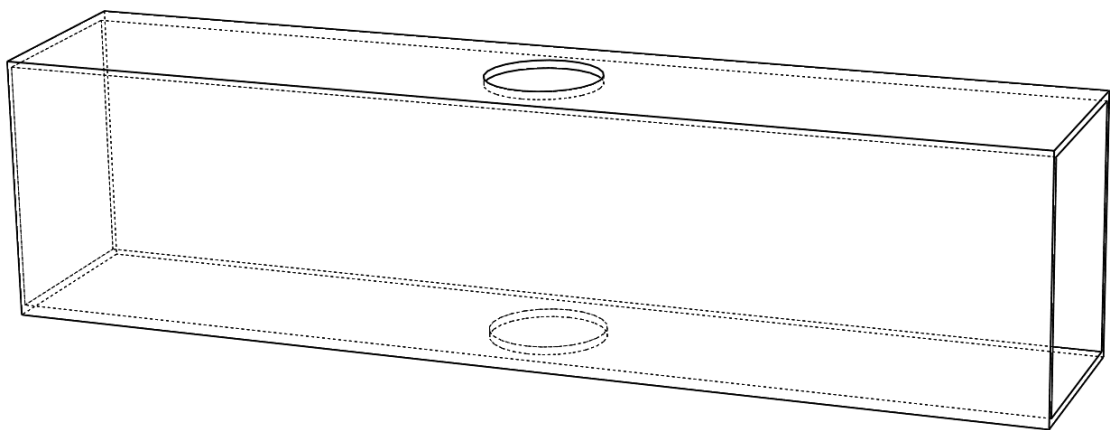
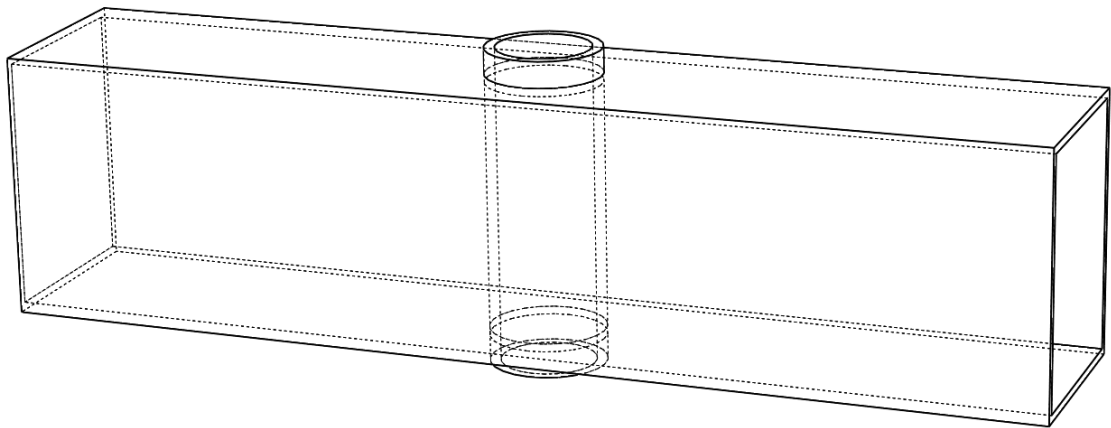


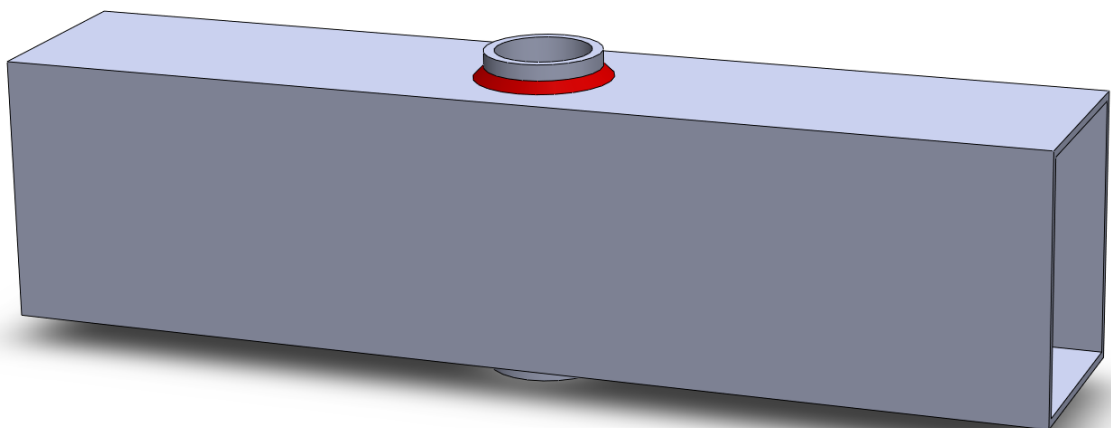
Figure 38 Sketch of Option B [for a 32% weight reduction]



a) cut holes through section



b) insert cylindrical reinforcing section



c) weld (weld in red)

Figure 39 Installation of local reinforcement to hollow section

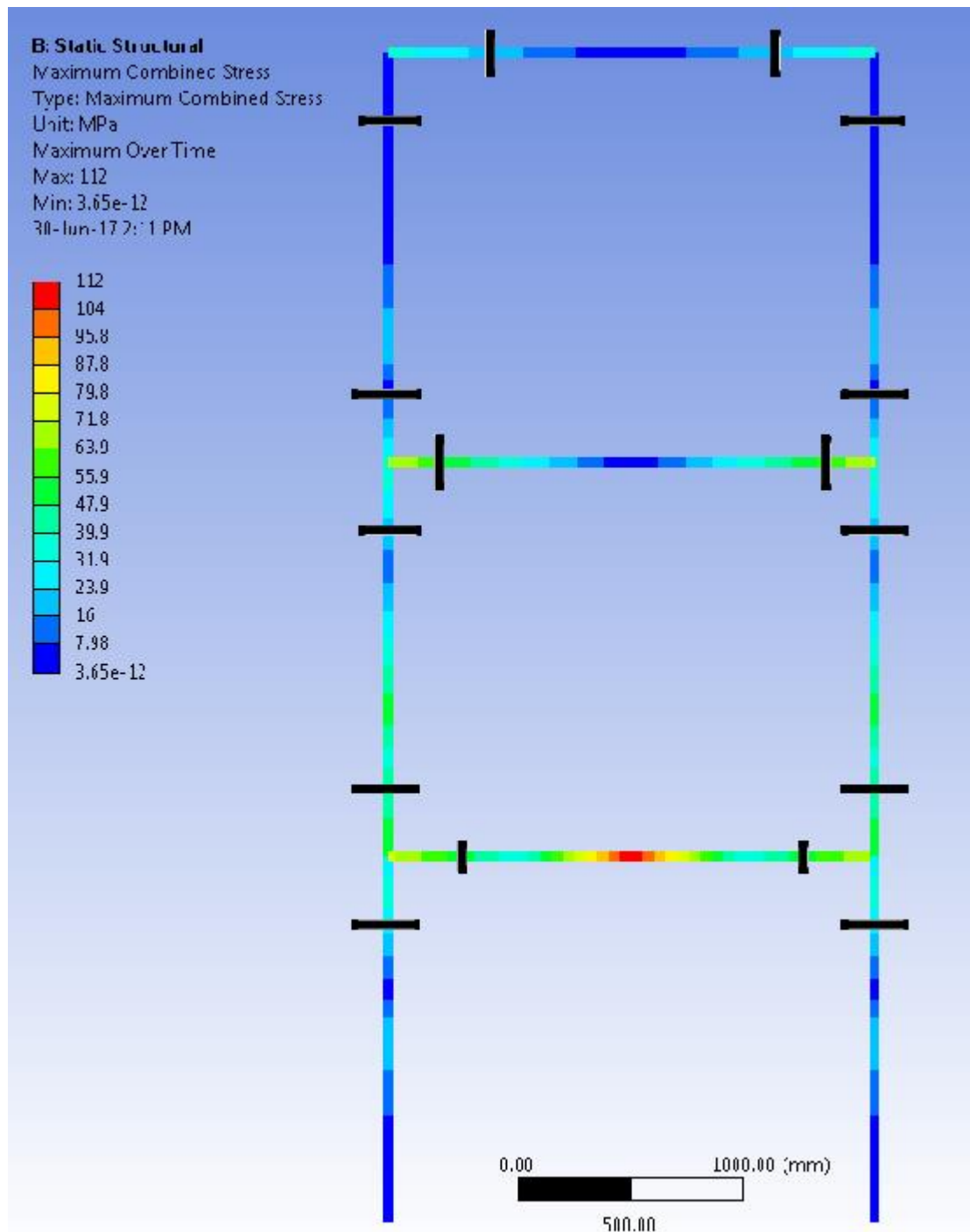


Figure 40 Maximum normal stress (all load cases) for optimum solution [43% reduction] in Table 3 [weld positions in Figure 38 shown by black lines]

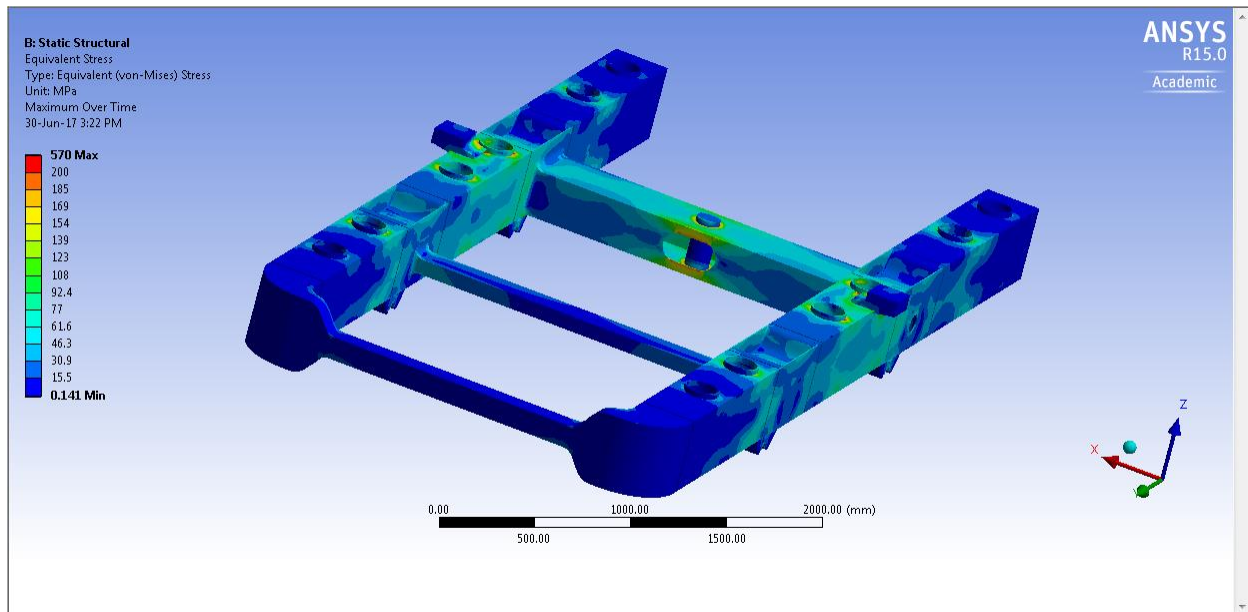


Figure 41 Maximum equivalent stresses for Option B [32% weight reduction]

7.4.3 Option C

Option C is similar to option B except the entire traction beam and attached joints/nodes, see Figure 42, are replaced by cast nodes thus incorporating the traction link mounting to the locomotive body within the cast. As with option B, significant weight savings (in the range 30-40%) are possible and much of the discussion for option B is still applicable. However, welds are no longer necessary in the highly stressed and complex region around the carbody traction link.

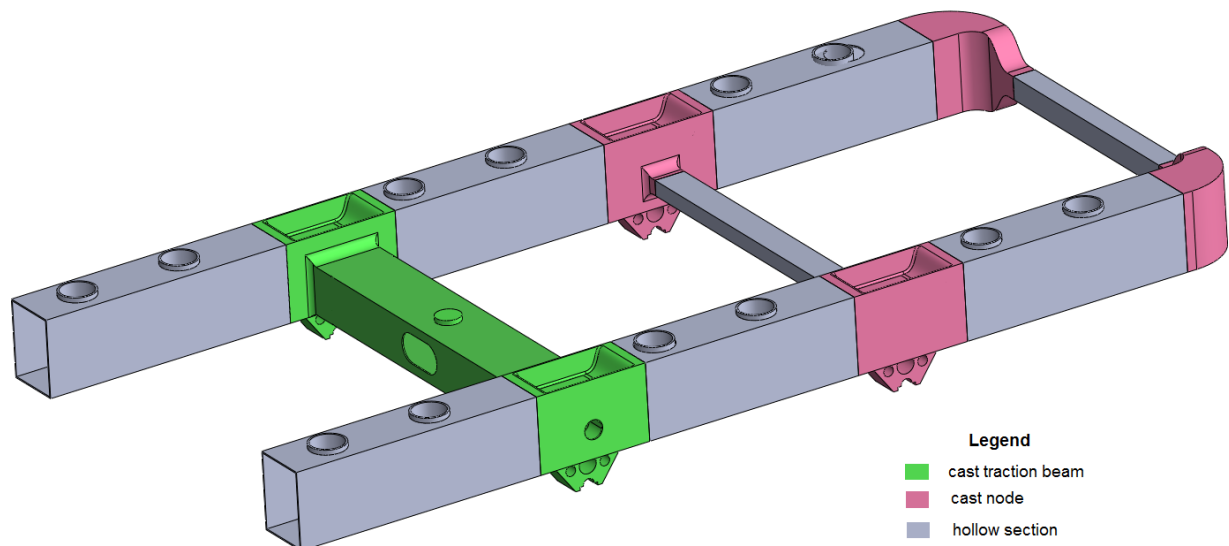


Figure 42 Sketch of Option C

7.4.4 Option D

Option D makes use of extensive cold-forming techniques such as hydroforming, electromagnetic forming and crimping. The main beam will be formed from tubular sections which are formed via hydroforming to create beams with continually varying cross-section profiles to provide directional optimal beam stiffness and strength. Additionally, appropriate mounting surfaces can be provided for mounting suspension and other components via welding or crimping. In the case of suspension and bump stop mountings experiencing significant loads, reinforcement using welded or crimped secondary elements inserted into cuttings are likely to be needed to avoid bearing type failures. However, the cuttings could potentially be formed during hydroforming and might include a suitable end joint for crimping secondary reinforcing elements, see Figure 44.

Primary joints could be formed using hydroformed T-junctions formed say in the side beams, see Figure 43. Beams could then be welded or mechanically fixed to T-junctions. The end beam or adjacent side beam could be curved to avoid the right angle junction better than the two. This option

might allow for significant weight reductions. However, little information is available for heavily load structures and significant research and development is necessary.

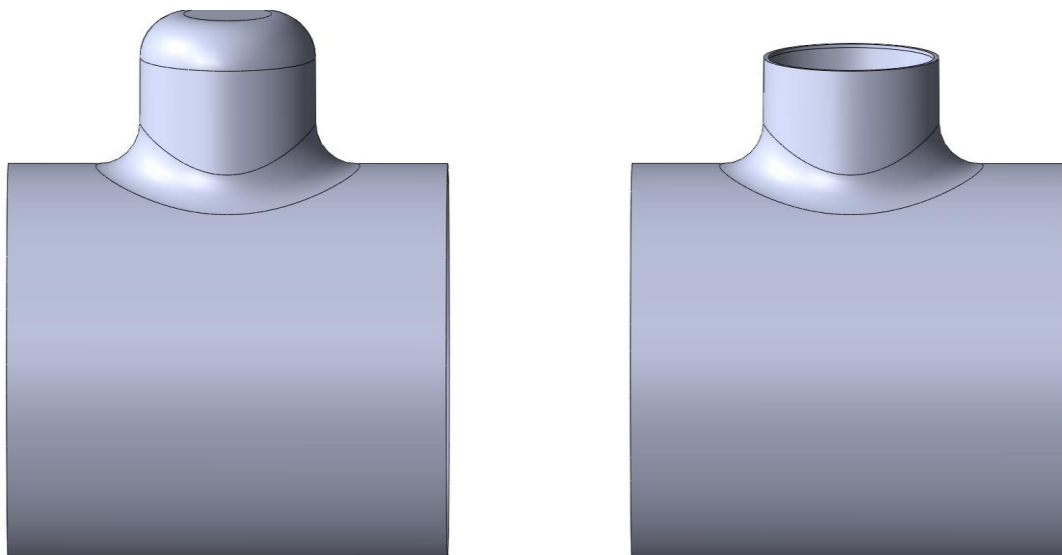
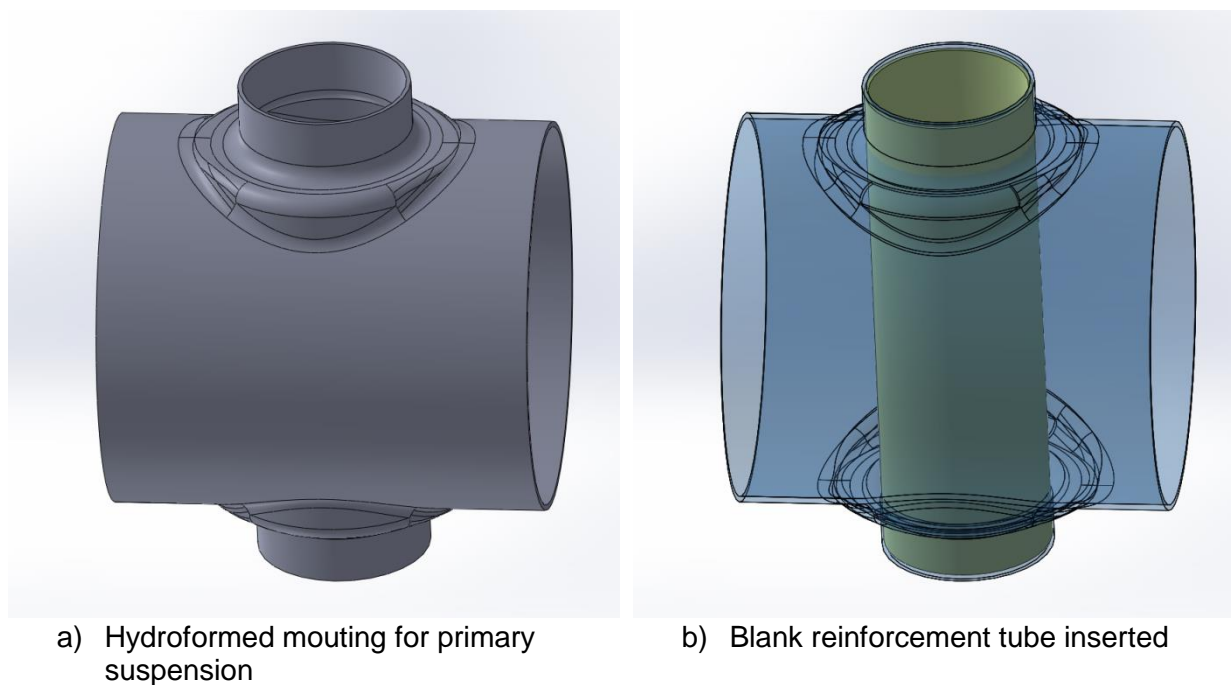
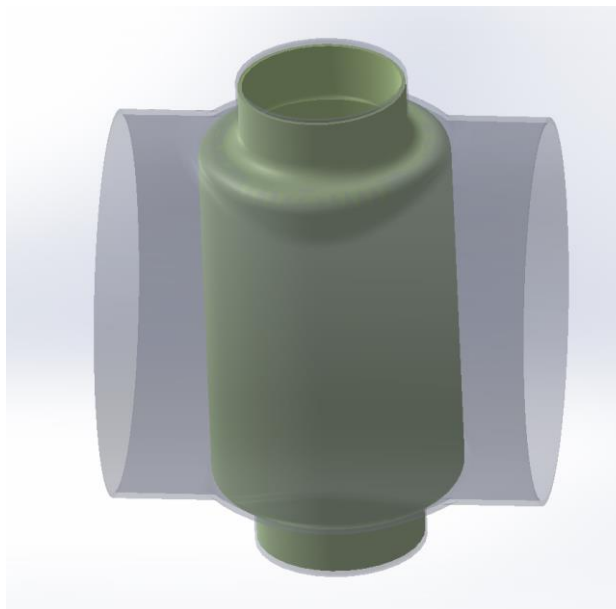


Figure 43 Hydroformed T-junction: a) immediately after hydroforming b) after removing excess material





- c) Reinforcing tube expanded to via
'moldless' hydroforming to create a
mechanical lock

Figure 44 Hydroformed local reinforcement

7.4.5 Combination

Options B-D are not mutually exclusive but aspects of each might be incorporated into the other. For example, the curved end beam in Option D might be incorporated into Options B and D. However, there is less potential for incorporating these into Option A.

Table 5 Summary of proposed options

Options	Beam sections	Primary joints	Load bearing ancillaries connections	Non-load bearing ancillaries connections	Welds	Forming	Material	Weight reduction	Cost
Current	Manufactured using steel plates and fillet welds	Butt welds between flanges & fillet weld between webs. Butt welds moved away from position of highest stress by cutting top and bottom plates.	manual welding inc. internal reinforcing ribs	Extensive use of manual welding	Extensive use of welds, no use of weld treatment and non-destructive inspection.	Limited use of plate bending, plates cut to shape prior to welding	S355 Steel	NA	NA
A	Same as current	Same as current	Same as current	Same as current	Extensive use of welds. Weld treatment used improve properties	Same as current	S355 Steel, very limited benefits to high strength steels	Limited especially without weld treatment	Cost high relative to weight reduction
B	Off-the-shelf hollow sections	Cast nodes allows node-beam join to away from high stress. Beam-node joint either: <ul style="list-style-type: none"> • Single side butt weld with treatment • Intefence fit with spigot on node potentially supplemented by adhesive bond • Crippling to spigot on node • Combination of above 	Incorporate secondary suspension and primary traction link mountings into cast nodes. Remaining connections and mountings provided by welding in bespoke casts or off-the-shelf sections to holes cut hollow section Potential use of hydroforming to provide flat mounting surfaces	Welding and/or use of hydroforming to provide flat mounting surfaces hydroforming	Reduced welding. Weld treatment (e.g. UTI) and NDT likely to be required for butt welds to cast nodes	Potential use of crippling for beam-node joints Hydroforming for ancillaries	S355 Steel, limited benefits to high strength steels	Potential for significant reductions (30-40%)	Potentially cost effective. Depending on number of individual cast needed and joining technology
C	Traction beam: cast incorporating joint nodes Remaining beams: off-the-shelf hollow sections	Same as Option B Reduced number of beam-node joints	Same as Option B but with carbody traction link mounting incorporated into traction beam casting	Same as Option B	Same as Option B	Same as Option B	Same as Option B	Same as Option B	Same as Option B

D	Off-the-shelf hollow sections hydroformed, locally optimizing strength and stiffness End beam replaced by curved formed member	Butt welds or other joining technology used. Hydroformed T-junction used to move joint away from region of highest stressed regions	Similar to Option B and C but hydroforming more likely to be used	Welding, crimping and hydroforming	Reduced welding. Weld treatment (e.g. UTI) and NDT likely to be required for butt welds to hydroformed T-junctions	Extensive use of hydroforming, crippling and other forming technolgies	S355 Steel, limited benefits to high strength steels	Potential for significant reductions. Reductions possible even with mild steel.	Potentially cost effective, but likely to be more expensive than Option B.
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8. CONCLUSIONS

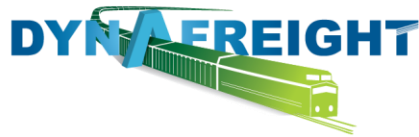
Taking a typical three axle locomotive bogie this study has looked at the potential for reduction in weight using conventional and more radical manufacturing methods. The study focused on the bogie frame as this was the component with the greatest mass (17% of the bogie mass in the target bogie) apart from the wheelsets and traction motors which are much more difficult to change without completely re-homologating the locomotive.

To assist the review vehicle dynamics and finite element tools were used and models of the target bogie were developed. The parameters for these models were linked to the work being carried out in Task 2.3 looking at novel running gear steering systems.

For more conventional construction methods the work has shown that optimisation of the specifications of the existing design including variations in material thickness and the use of higher strength steel can potentially result in a reduction by 43% of the bogie frame mass. The vehicle dynamics studies show that this would translate into a 12.5% reduction in track damage but only a 5% reduction in energy consumption and a 1% reduction in track access charges.

The mass reduction for the conventional design is limited by deflection and dynamic performance and might be possible with even with mild steels, but careful selection and placement of joints and joining technology is required. Maintaining system stiffness is key to adequate performance thus only limited benefits to switching to higher strengths steel are likely. Cast nodes with hollow sections appear to be the most promising and the technology is already tested in offshore and bridge. A more traditional approach might use butt welds from beams to cast nodes, but a more 'blue sky' option might considered alternative joining methods. Alternative methods for joining the 'end beam' to the side beam might be attractive.

The use of more radical materials such as glass and carbon fibre was considered and has potential to provide further mass reductions and also benefits related to non uniform stiffness distribution but the barriers to acceptance of these materials are still very high



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and it was not considered appropriate to assess this in more detail here. This has been considered in many previous projects including REFRESCO[45] and is being taken forward in Run2Rail[46] and other activities.

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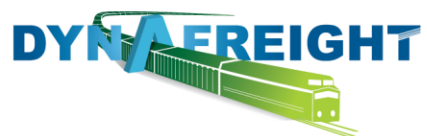
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[46] Run2Rail: Innovative running gear. New project selected under the Shift2Rail 2017 call for proposals.

APPENDIX 1 ESTIMATED REDUCTION IN TRACK ACCESS CHARGES

Using the UK track access charging set out in section 6.4.1

For a bogie frame mass reduction of 43%

As the bogie frame mass is 17% of the bogie mass in the target locomotive the 43% mass reduction corresponds to a 7.31% reduction in bogie mass.

Assuming that the bogies make up 30% of the mass of the locomotive, as approximation, this corresponds to a 2.2% reduction in the locomotive mass.

Using the following equation:

$$EGTM = K C_t A^{0.49} S^{0.64} USM^{0.19} GTM \quad (\text{for track})$$

$$\text{giving } (1 - 0.0292)^{0.49} \cong 1\%$$

So a 2.92% mass reduction corresponds to a reduction in EGTM of 1%