The sustainable freight railway: Designing the freight vehicle – track system for higher delivered tonnage with improved availability at reduced cost

SUSTRAIL

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Executive Summary

In this report the track-train system is considered holistically, so the impact of changes to vehicles on the track and that of changes to the track on vehicles are both taken into account. The work was targeted to providing data to inform a prioritisation exercise at which representatives of infrastructure managers, freight operators, and researchers could together assess a number of duty requirements. The following process was used:

1. A route was chosen for which a full set of track and vehicle data was available (this was part of the SustRail UK route). Simulations of variations on the recorded route and traffic were undertaken to provide data on the forces, accelerations, and other parameters describing the loads experienced by both track and vehicle. The results were interrogated to provide indications of the effects of changes.
2. The simulation results were used in Network Rail's VTISM model (used to predict infrastructure maintenance and renewal costs) and in vehicle fatigue damage analyses. These enabled relatively detailed indications of cost implications of the changes.
3. A prioritisation workshop was held. This was attended by representatives of freight operators, infrastructure managers and researchers. The work described above and in the other tasks of WP2 "Duty Requirements" was outlined and feedback sought from attendees. This informed a prioritisation methodology that was developed to judge duty requirements against the objectives: availability; cost; service quality; environmental footprint; and technical viability.

At this stage in the project definitive impacts assessments are not available, but the preliminary findings are that the highest priorities for work in the remainder of SustRail are:

- Modest increase in freight speed (e.g. 120-140kph UK; 100-120kph ES,BG)
- Optimise axle load limits
- Reduction in energy used by rail vehicles + Vehicle Green Label
- Improve bogie design to reduce lateral forces

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1. INTRODUCTION

SustRail aims to contribute to the rail freight system to allow it to regain market share from road transport. The proposed solution is to be based on a combined improvement in both freight vehicle and track components. This holistic approach is aimed at achieving a higher reliability and increased performance of the rail freight system as a whole and profitability for all its stakeholders.

The description of work [1] states that Task 2.5 is to take a holistic approach to vehicle and track sustainability, recognising that freight sustainability cannot be improved by changes to track design and materials alone. In this work package the rail system (track and vehicles together) will be considered. It was intended that this deliverable would establish the base case for current vehicles and infrastructure, thereby supporting judgement of the performance of new vehicles (in WP3) and track systems (in WP4). However, it was considered that this aim should be extended to give a more robust basis to the prioritisation sub-task and assist in the definition of the principal areas for study in the later tasks of SustRail. Accordingly this task has the following objectives:

- Defining a base case for the current vehicle track system
- Support future decisions and judgements about new vehicle and track systems

Task 2.5 consists of four sub-tasks, with principal interrelations shown in Figure 1.1.

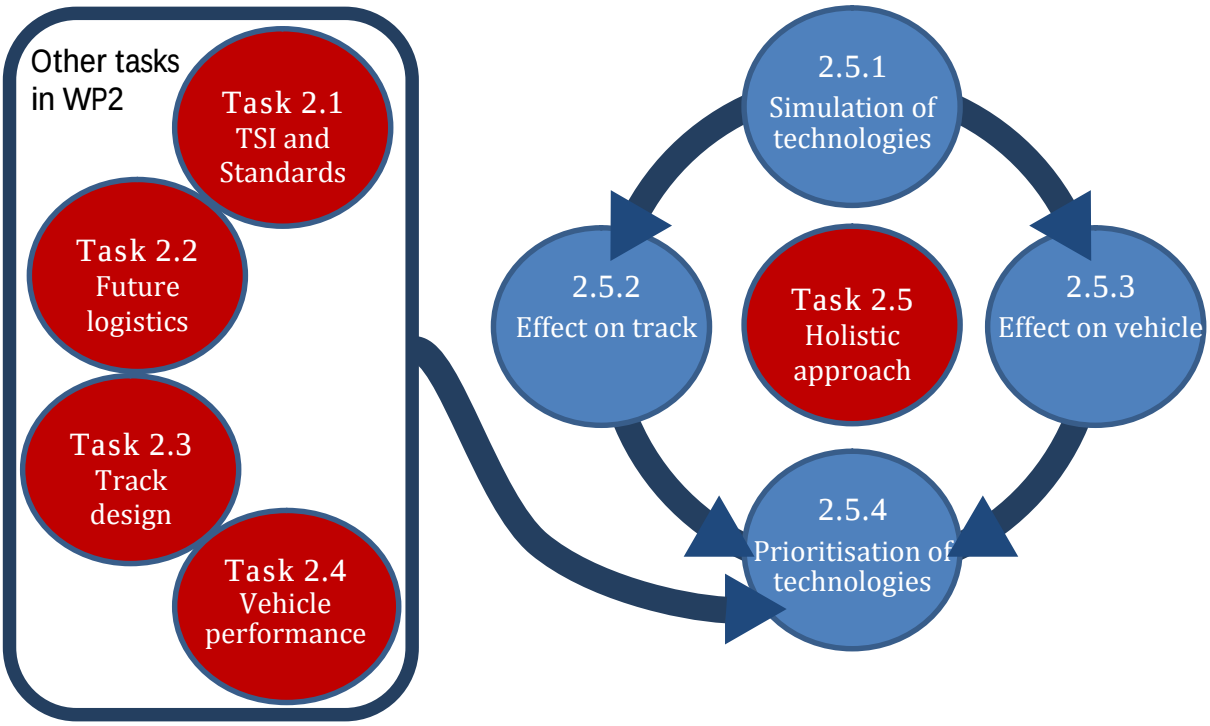


Figure 1.1: Structure of Task

1.1 Sub-Task 2.5.1: Track-train interaction

Dynamic simulations of a series of vehicles have been undertaken. These used the VAMPIRE® [2] software and modelled the vehicles as discrete masses/inertias connected by spring/damper systems. The properties of the vehicles and track were changed to enable force and acceleration data to be provided for a range of vehicle masses and speeds. The details of

the simulations and their outputs are given in Section 2. The results were analysed to determine the effect of the changes on various track and vehicle parameters.

1.2 Sub-Task 2.5.2: Rail infrastructure damage

The impact of the track forces calculated in Sub-Task 2.5.1 on the life-cycle of the rail infrastructure was determined using RSSB/Network Rail's Vehicle-Track Interface Strategic Model (VTISM) [3]. Details of the methodology and results are given in Section 3.

1.3 Sub-Task 2.5.3: The impact of track forces

The effect of track forces (Sub-Task 2.5.1) on vehicle system and component lives was assessed. The methodology and results are outlined in Section 4 where improvement or reduction in life is judged relative to the base case for current vehicles.

1.4 Sub-Task 2.5.4: Prioritising the technology requirements

It was expected that requirements of the operators and infrastructure managers could not all be satisfied, and not all changes would benefit track and vehicles equally. Based on technical viability and cost effectiveness, a decision process was developed to arrive at duty requirements which produced the greatest increase in sustainability, while meeting the most important needs of both operators and infrastructure managers. The methodology and results are presented in Section 5.

2. SUB-TASK 2.5.1: TRACK-TRAIN INTERACTION

The simulation and methodology employed for this exercise are explained in SustRail deliverable D2.4.1 [4]. Simulations were carried out using the Vampire® modelling software [2]. The input track data is from part of the SustRail UK route: 64.5km of the "DCL" 2100 track between Chester Line Junction (53miles 12chains) and Leamington Spa Junction (106miles 25chains) referred to below as the UK DCL track or route, or just DCL. Several freight vehicle models from a library of UK freight vehicles were used: Y-series flat bottom 60 foot containers vehicles with three different bogie configurations. A diesel multiple unit passenger vehicle was used for comparison. The three Y-series freight models are referred as v1, v2, and v3 in this document. In D2.4 the simulation results were presented according to damage type and their corresponding assessment models. In this deliverable, the same results are presented in more details and used to discuss several aspects of the vehicle-track system:

- Speed increase (from 120 to 140kph).
- Vehicle axle load ranging from 5t to 25.5t axle load:
  - Freight tare: v1=5t, v2=6.8t, and v3=5.7t
  - Freight part-laden: v1=11t (note: vehicle models v2 and v3 are not available in part-laden condition)
  - Freight laden: v1=20t, v2=25.5t, and v3=22.5t
  - Passenger multiple unit: 14t
- Track quality improvement (20% reduction in amplitude for vertical and lateral irregularities).
- Lower unsprung mass (20% reduction from 1202kg = 962kg).
- Behaviour of vehicle suspensions in curving (looking at 3 Y-series variations).
- Bogie spacing: 2m (freight v1 and v2), 1.8m (freight v3) and 2.6m (passenger).

2.1 Effect on vertical damage

2.1.1 Ride Force Coefficient and Constant (RFCC)

The RFCC are derived from vehicle dynamics simulations and characterise a vehicle's vertical dynamic ride properties as a function of the track quality it runs on. The method used to obtain these values is explained in D2.4.1.

Table 2.1 summarises the ride force coefficients (RF Coeff.) and constants (RF Cst.) for the runs on Vampire® track 160 at 120kph and 140kph (left hand columns), and on the UK DCL track at 120kph and 140kph (right hand columns). The Vampire® track 160 is provided with the software Vampire® in the track library and is representative of UK track quality for a line-speed of 160kph. Depending on the maximum operating speed of a vehicle, the practice is to use an appropriate Vampire® track (those representative of UK track quality for 120, 160 or 200kph) to determine the RFCC values. Here because we are interested in seeing the effect of running at a speed than higher 120kph, it was necessary to use a track of reasonable quality, i.e. Track 160. Note that the RFCC values obtained with Track 160 would be those provided for the VSTIM analysis. However, it is more relevant here (for SustRail) to look at results obtained for the UK DCL track.

For comparison, the RFCC for a generic passenger vehicle (14t axle load) is added. As expected both the RF coefficient and constant increase with vehicle load, as would the

associated damage. Figure 2.1 (left) plots the RF coefficients for the four cases simulated. It is interesting to see that the RF coefficients increase between 45 and 65% on the UK DCL track in comparison with the default Vampire test track. This is because a more representative range of track situations is covered in the case of the UK DCL track, particularly sections with lower track quality than those found on Vampire® Track 160. As speed increases from 120 to 140kph on Track 160 the RF coefficients also increase by 20% and 40% for laden and tare respectively. On DCL the increase is not so wide ranging but still significant with 32%, 26%, and 34% for laden, part-laden, and tare respectively.

	Speed	120kph (Track160)			140kph (Track160)			120kph (DCL)			140kph (DCL)		
		RF Cst.	RF Coeff.	$F/2_{mm}SD$	RF Cst.	RF Coeff.	$F/2_{mm}SD$	RF Cst.	RF Coeff.	$F/2_{mm}SD$	RF Cst.	RF Coeff.	$F/2_{mm}SD$
Passenger	Laden							1.21	0.926	3.1	1.75	1.218	4.2
Normal Un-Sprung Mass	Tare	3.29	0.474	4.2	3.52	0.666	4.9	2.00	0.785	3.6	2.06	1.049	4.2
	Part	5.58	1.315	8.2	5.60	1.752	9.1	3.23	1.964	7.2	4.18	2.475	9.1
	Laden	7.37	2.146	11.7	7.02	2.590	12.2	5.91	3.115	12.1	4.87	4.113	13.1
Low Un-Sprung Mass	Tare	2.92	0.448	3.8	3.03	0.640	4.3	1.84	0.732	3.3	1.85	0.985	3.8
	Part	5.46	1.301	8.1	5.49	1.726	8.9	3.16	1.937	7.0	4.15	2.430	9.0
	Laden	7.50	2.114	11.7	7.01	2.600	12.2	6.09	3.073	12.2	4.12	4.940	14.0
LUM % diff. wrt normal UM													
Low Un-Sprung Mass %	Tare	-11%	-5%	-10%	-14%	-4%	-11%	-8%	-7%	-8%	-10%	-6%	-8%
	Part	-2%	-1%	-2%	-2%	-1%	-2%	-2%	-1%	-2%	-1%	-2%	-1%
	Laden	2%	-2%	1%	0%	0%	0%	3%	-1%	1%	-15%	20%	7%

Table 2.1: Ride Force Constant and Coefficient (RFCC) calculated for VTSIM and on DCL, also includes the resulting dynamic forces for a track SD of 2mm

Figure 2.1 (right) gives a more direct measure of the dynamic force; that obtained on a track with a SD of 2mm, which is the largest representative track quality on the UK DCL route. Again the increase with tonnage is most obvious. The increase with speed ranges linearly between 5 and 15% (laden to tare) on Track 160 and non-linearly, 8%, 28% and 16% for laden, part-laden and tare respectively on DCL. In all cases the passenger vehicle shows much lower dynamic forces and by linear interpolation of the freight results, one is able to compare like-for-like a freight vehicle at 14t axle load with the laden passenger vehicle. This gives an increase of the dynamic forces for a track for which SD=2mm of 188% and 149% at 120kph and 140kph respectively. Note that the full % calculations are not reproduced here but are all derived from the values in Table 2.1.

The same cases were also run for the same vehicle with a reduction of 20% of its unsprung mass. The difference in results is added at the bottom of Table 2.1. It is seen that, considering the runs on the Vampire reference track, the benefit of lowering the unsprung mass is only realised for the case where the vehicle runs in the tare condition. However in the tare condition the vehicle has the lowest RF coefficient and constant. This means that this calculation does not show any apparent gain from lowering the vehicle unsprung mass.

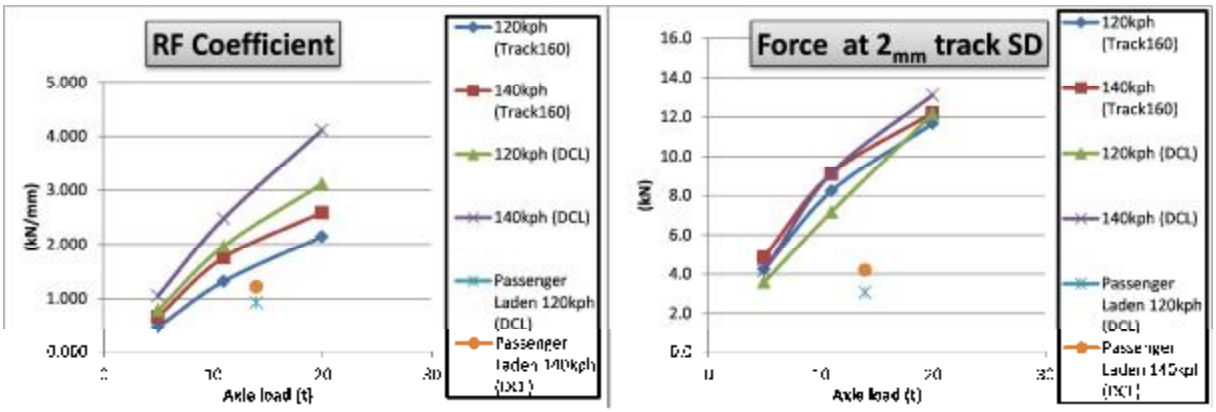


Figure 2.1: Comparison for different track and speed for RFC (left) and Force at 2mm track SD (right)

2.1.2 P2 force calculation at rail joint or insulator (or other wheel-rail anomalies)

The P2 force is a dynamic force occurring as the wheel passes a rail joint. It corresponds to the second dynamic peak force (P1 being the initial higher frequency peak force) of frequency around 90Hz, corresponding to the wheel bouncing together with the rail and involving the track support stiffness. In the UK a standard equation (details given in D2.4.1) is used and a limit given to control railway vehicle design, in particular the unsprung mass. Other influential parameters are the vehicle speed, the axle load, and the shape of the rail joint under deformation.

Table 2.2 shows the calculated P2 forces for various axle loads (tare, part-laden, and laden for freight models v1, v2, and v3) and, for reference, the non-powered axle of a generic passenger multiple unit (MU) at speeds of 120 and 140kph. Compared with the passenger vehicle, the P2 force for freight is reduced by about 9-24% for part-laden, and 28-39% for tare. The laden freight on the other hand shows an increased P2 force of between 0% (v1 at 20t axle load) and 22% (v2 at 25.5t axle load).

Of interest is the percentage increase with respect to speed: 8% to 13% from laden to tare (10% for passenger MU).

Also of interest is the decrease in P2 force associated with a 20% lower unsprung mass: 7-8% (laden), 9-10% (part-laden), and 12% (tare). An interesting conclusion here is that by lowering the unsprung mass by 20% and raising the speed from 120 to 140kph, one is able to obtain the same P2 force.

Vehicle		Axle load (t)	Speed (kph)	Unsprung mass /axle (kg)	P2 Force (kN)	% diff. Fre/MU	% diff. 140/120	% diff. LUSM
MU - crush - trailing axle		14	120	1800	185			
Freight v1	tare	5	120	1202	112	-39%		
	part-laden	11	120	1202	142	-24%		
	laden	20	120	1202	186	0%		
Freight v2	tare	6.8	120	1455	134	-28%		
	part-laden*	14	120	1455	169	-9%		
	laden	25.5	120	1455	226	22%		
Freigth v3	tare	5.7	120	1254	119	-36%		
	part-laden*	14	120	1254	159	-14%		
	laden	22.5	120	1254	201	8%		
MU - crush - trailing axle		14	140	1800	205	Fre/MU	10%	
Freight v1	tare	5	140	1202	127	-38%	13%	
	part-laden	11	140	1202	156	-24%	10%	
	laden	20	140	1202	201	-2%	8%	
Freight v2	tare	6.8	140	1455	151	-26%	13%	
	part-laden*	14	140	1455	186	-9%	10%	
	laden	25.5	140	1455	243	18%	7%	
Freigth v3	tare	5.7	140	1254	134	-35%	13%	
	part-laden*	14	140	1254	174	-15%	9%	
	laden	22.5	140	1254	216	5%	8%	
Freight v1 Low unsprung mass (-20%)	tare	5	120	962	99			-12%
	part-laden*	11	120	962	128			-9%
	laden	20	120	962	173			-7%
Freight v1 Low unsprung mass (-20%)	tare	5	140	962	111			-12%
	part-laden*	11	140	962	141			-10%
	laden	20	140	962	185			-8%

Note(*)for a direct comparison with the passenger vehicle, the freight part-laden v2 and v3 calculation is based on 14t axle load

Table 2.2: P2 force calculation with comparison of speed and lower unsprung mass

2.1.3 Track vertical settlement

Vertical track settlement is attributable to the total vertical force at the wheel-rail contact. Andersson et al. [5] proposed that this total force can be split into several components as per equation (2.1), in which Q_r is the static wheel load, Q_c the quasi static contribution (changing in curves with non-compensated accelerations), Q_{d20Hz}, dynamic contribution below 20Hz, and $Q_{d\,hf}$ dynamic contribution in the range 20-90Hz.

$$Q_{tot} = Q_r + |Q_c| + Q_{d20Hz} + Q_{d\,hf} \tag{2.1}$$

Vampire® simulations provide output for the total dynamic force either including or excluding the static wheel load (Q_r), so that the suspension effect can be isolated from the payload. Figure 2.2 shows the maximum dynamic load ($|Q_c|+Q_{d20Hz}$) variation at any wheel of the leading bogie along the UK DCL route. Note that the high frequency contribution ($Q_{d\,hf}$) is ignored here for the following reasons:

- EN14363/UIC518 requires a low-pass filtering of dynamics forces below 20Hz; during practical testing the high frequencies in the range 20-90Hz are therefore ignored.
- Vehicle dynamic simulations use measured input data for rail vertical and lateral displacement measured every 25cm, for a speed of 120kph this means that the input signal may extend slightly above 20Hz, but any higher frequency effect due to rail joint or surface defects are not considered.

- The forces predicted from the simulation are also low-pass filtered below 20Hz to replicate the condition of real vehicle testing.

The high frequency dynamic part of the force referenced above ($Q_{d\ hf}$) is normally predicted from analytical calculations based on the P2 force as presented in section 2.1.2.

Figure 2.2 shows the maximum dynamic force along the UK DCL route, taken as the 99.85th percentile of the dynamic force cumulative distribution (only 0.15% of forces exceed this value; these exceptional forces are likely to be associated with unusual effects that will not reflect normal service). A linear variation with the axle load of freight vehicles can clearly be seen. The effect of speed (120 to 140kph) is noticeable with an increase between 22 and 29% for the freight, depending on axle load and 34% for the passenger vehicle. The laden vehicles show between 64% and 103% higher dynamic loads than the passenger vehicle at 120kph, the part-laden around 14% higher, and the tare vehicles between 7% and 21% lower dynamic forces.

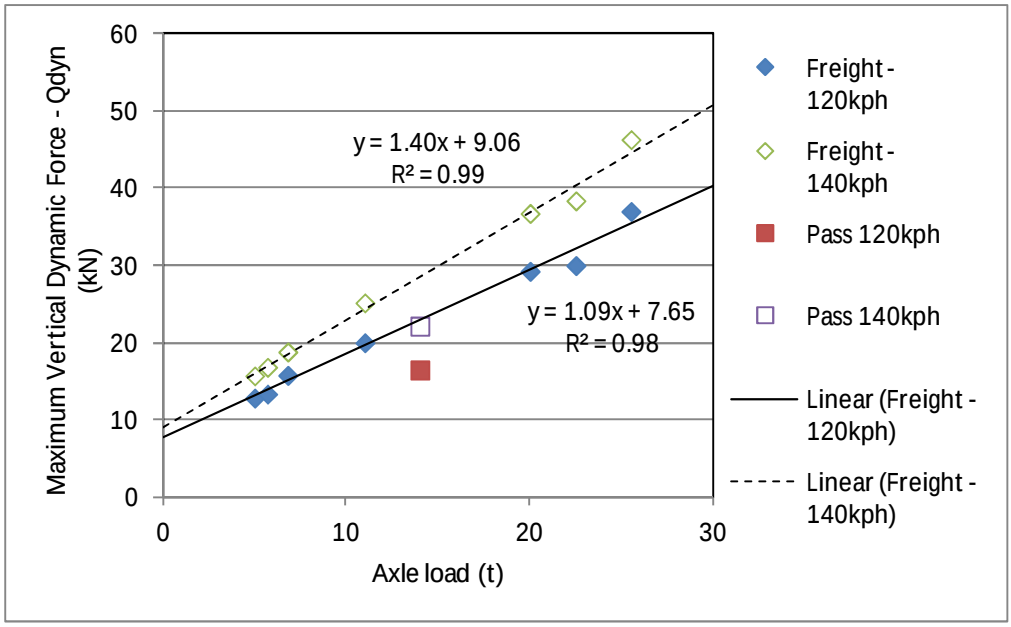


Figure 2.2: Maximum dynamic force against axle load on UK DCL route

The same plot can be produced for the total dynamic force (Q_r+|Q_c|+Q_{d20Hz}) including the wheel static load. Figure 2.3 shows the maximum value along the route taken from the 99.85th percentile of the total dynamic force cumulative distribution. In this case the linear relationship with load is far more obvious and the effect of speed is less noticeable (from 120 to 140kph): passenger +7%, laden freight +6%, part-laden freight +7%, and tare freight +4% (v1), +3% (v2) and +7% (v3).

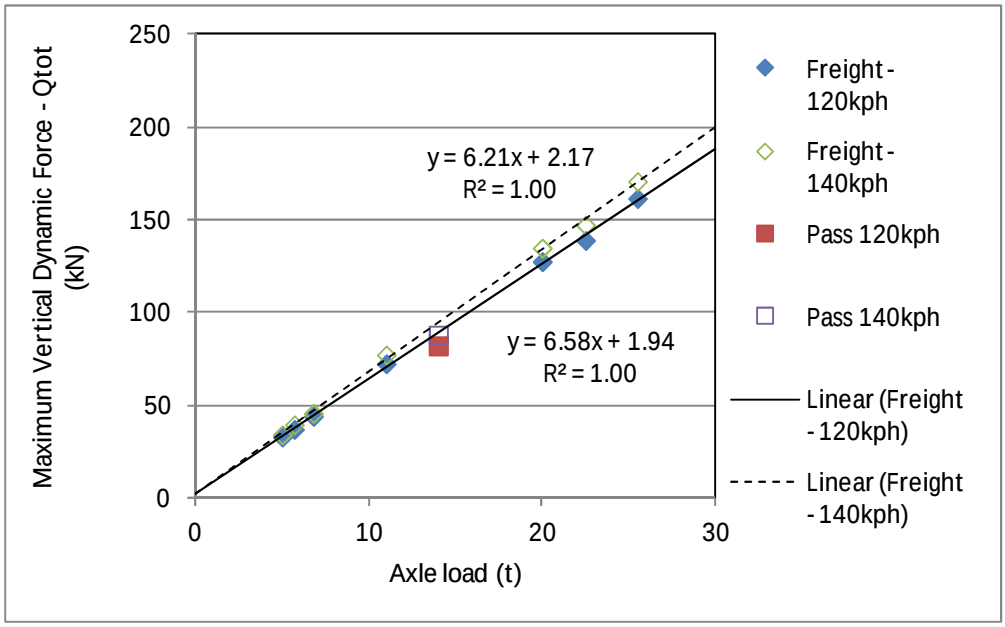


Figure 2.3: Maximum total dynamic force against axle load on UK DCL route

Running the freight vehicle v1 on improved track quality (20% lowered vertical/lateral irregularities), has resulted in the maximum dynamics force reducing by 4/8% (laden 140/120kph), and 15/17% (tare 120/140kph). The improvement is therefore mostly significant for low or nil payloads. If the quasi-static axleload is considered then the reduction of maximum total dynamic force is of the order of 3% at best (tare and part-laden).

Reducing the unsprung mass by 20% results in vertical dynamic forces that are around 5% lower (part-laden) and around 14% lower (tare). The total vertical maximum dynamic force is reduced by 2% (part-laden) and 5% (tare). There is no noticeable effect for the laden vehicle.

2.2 Effect on tangential damage

Tangential damage has been investigated in terms of RCF and wear generated along the UK DCL route.

2.2.1 Wear

Wear is calculated from the amount of work going through the wheel-rail contact patches ($T\gamma$[1]) A filtering function is applied so that mild wear slowly builds up for $T\gamma < 100N$, to reach a constant value for $100N \leq T\gamma < 200N$ and then severely increases beyond 200N. Severe damage occurs for high values of $T\gamma$ generally in curves and due to flange contact. The wear calculated on the rails for the UK DCL route is given in Figure 2.4, comparing the freight v1 vehicle (tare, part-laden, and laden) with the passenger vehicle.

As expected the wear damage on the low rail is very low compared to the damage on the high rail. The part-laden and laden freight vehicles are generally showing higher wear than the passenger, especially in large curves. In tight curves (distance 30km to 36km) the passenger vehicle's performance is approaching that of the part-laden freight; this is because flange contact is also occurring for the passenger vehicle in the tighter curves. Despite similar steering abilities for all payloads of the freight vehicle (poorer than that of the passenger vehicle), the tare vehicle shows less wear because of the lower axle load and reduced contact pressures and creep forces.

[1] $T\gamma$ is a measure of the energy generated in the contact patch from lateral forces and creepage

Reducing the track irregularities helps reduce the peak value of wear (99.85th percentile) mainly for the tare vehicle by up to 12%. The advantage is less obvious for more damaging laden and part-laden vehicles.

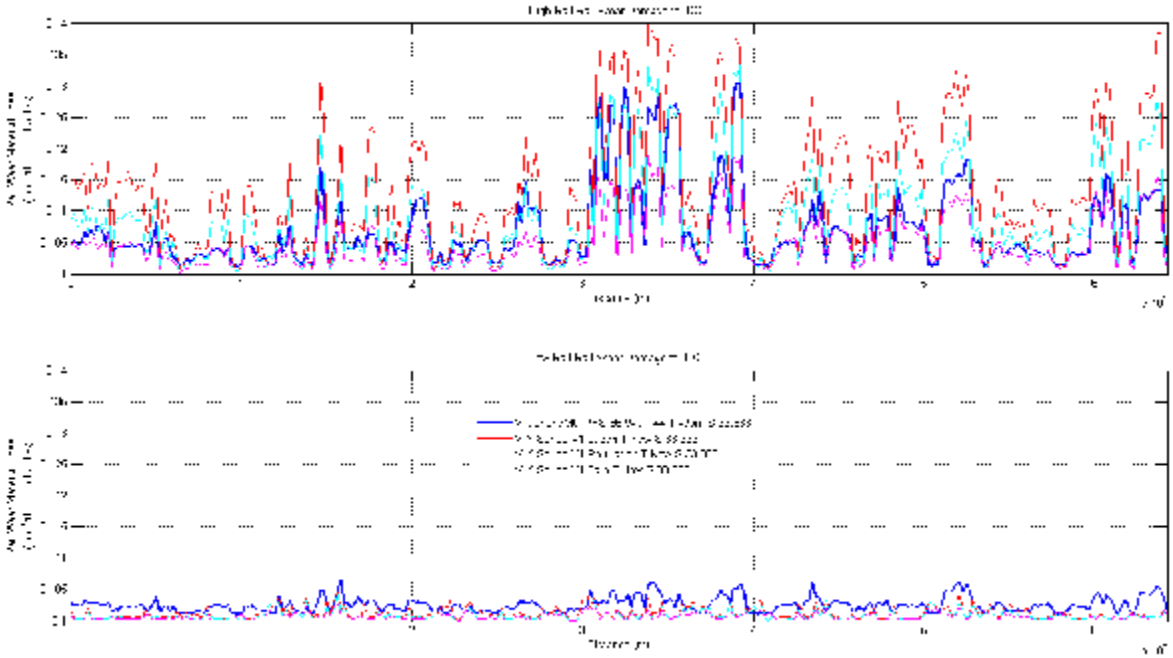


Figure 2.4: Rail wear on DCL, comparison of passenger MU, freight v1 part-laden on standard track, and freight v1 part-laden on reduced irregularity track: high rail (top) and low rail (bottom)

Increasing the speed from 120kph to 140kph has the effect of reducing the peak wear on rail due to the passenger vehicle by 25%. This is because of the redistribution of steering forces across the leading and trailing axle of the passenger bogie running at higher cant deficiency, leading to smaller angles of attack and smaller lateral axle displacement. The laden freight generally shows an increased peak Tγ in regions where values of Tγ are in the range 100 to 200N, therefore the wear damage remains about the same. However for one of the vehicles, freight v3, the increase pushes Tγ over the 200N limit into severe wear damage. For tare vehicles wear is increased by around 10%, although this is in a region where Tγ is below 100N (low wear).

2.2.2 RCF

Figure 2.5 shows the distance plot for the RCF damage on the UK DCL route on the high and low rail for the freight v1 vehicle (tare, part-laden, and laden) compared with the passenger vehicle at 120kph. On this figure a value of $1x10^{-6}$ means there is RCF initiation after 1million axle passes; a value of $10x10^{-6}$ means initiation after 100,000 axles passes. The damage on the low rail is approximately zero. On the high rail the highest areas of damage appear in curves. The freight laden vehicle generally generates much higher damage than the passenger vehicle. The tare vehicle generally generates much less damage while the part-laden generates slightly less damage.

The same output can be presented against curve radius, to understand the damage intensity according to the track layout. Figure 2.6 shows how the mean damage depends on radius along DCL. Above 2500m-radius curves the passenger vehicle is the least damaging while the freight in tare condition is also showing little damage. For all vehicles, the RCF damage increases as the radius get smaller. Note that there are no small or very small radii on the UK DCL route, otherwise the trends would tend to come back down towards the left hand side of the graph. For radii below 1400m the passenger vehicle becomes as damaging as or more

damaging than the part-laden freight vehicle. In all cases the laden freight is the most damaging vehicle. Figure 2.7 shows the same output without averaging; this means that the damage is summed for all vehicles and for all curves within a certain radius range. This gives an overview of the damage produced along DCL as a function of the curves that represent the route. The damage increasing with tightening radius is also observable. The larger proportion of damage due to the laden freight is also obvious on this plot. Also appearing on this plot are several peaks of damage in curves around 1.3km, 1.6km, and 2.5km, which are well represented on DCL.

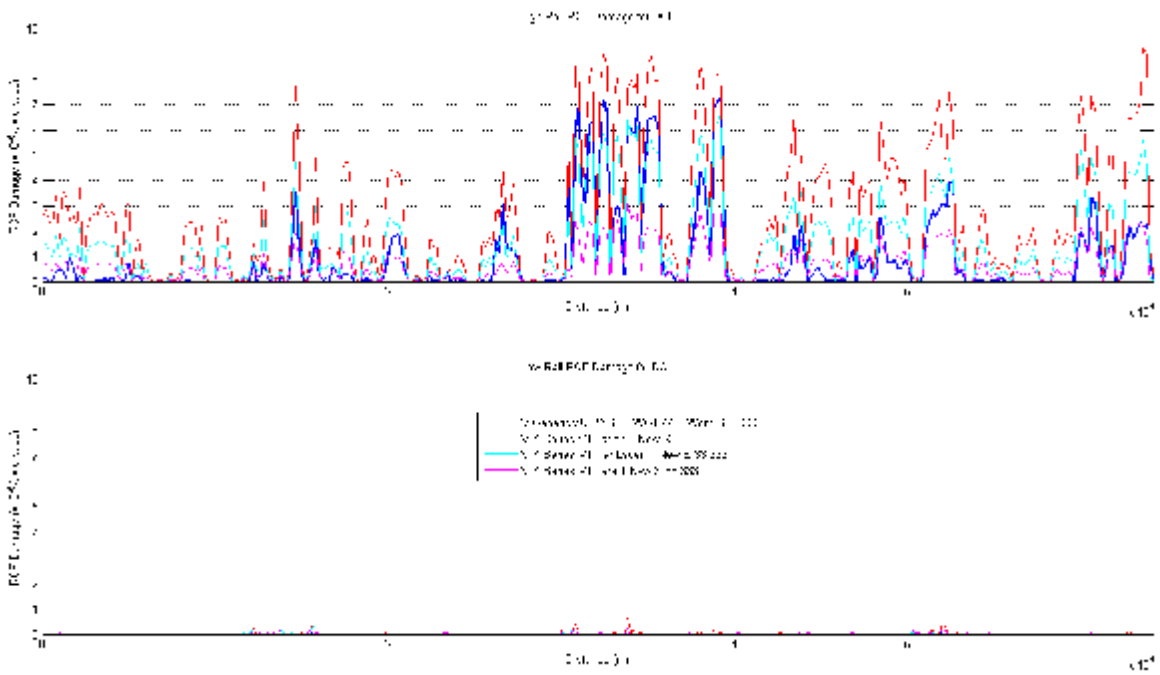


Figure 2.5: 200m mean RCF damage function on DCL, high (top) and low rail (bottom)

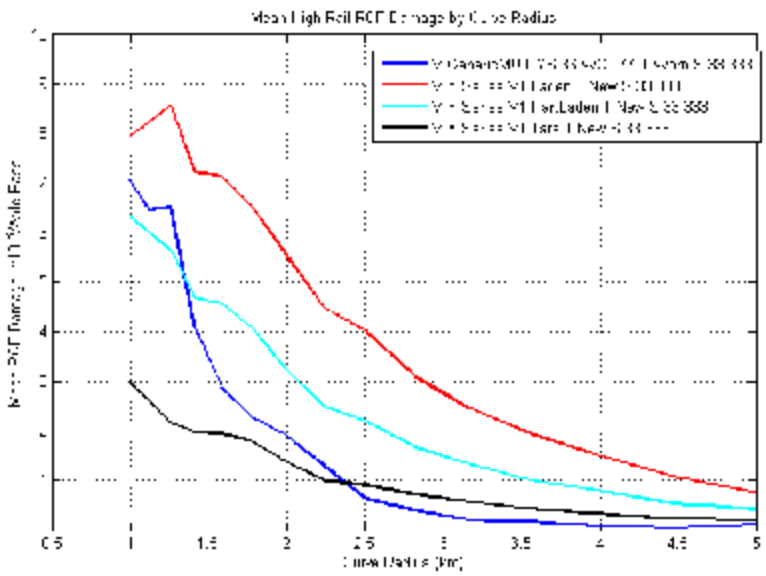


Figure 2.6: Variation of mean RCF damage with curve radius for DCL

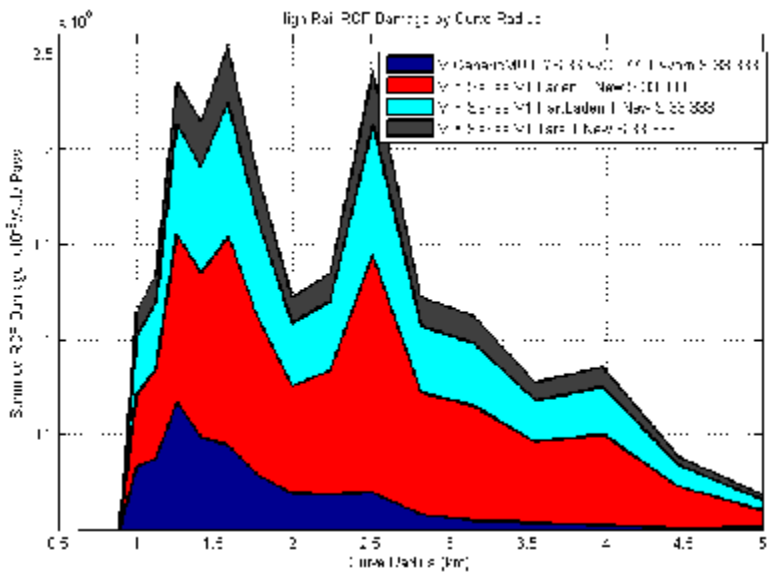


Figure 2.7: Variation of total RCF damage with curve radius for DCL

Figure 2.8 show the same results presented as a cumulative distribution. This graph clearly shows that the heavier the axle load on the freight vehicle, the more the curve shifts to the right towards higher damage values. It is also clear that the better steering abilities of the passenger vehicle makes it less damaging in most curves along the route with nearly 80% of the values fitting below a damage value of $1x10^{-6}$ (1 million axle passes before initiation), which is also close to the tare freight wagon case. On the other hand in the top 10% of cases (90 to 100%) the passenger vehicle gives rise to damage in the order of 3 to $7x10^{-6}$, compared to 2 to $3x10^{-6}$ (tare), 4.25 to $6.5x10^{-6}$ (part-laden), and 7 to $9x10^{-6}$ (laden).

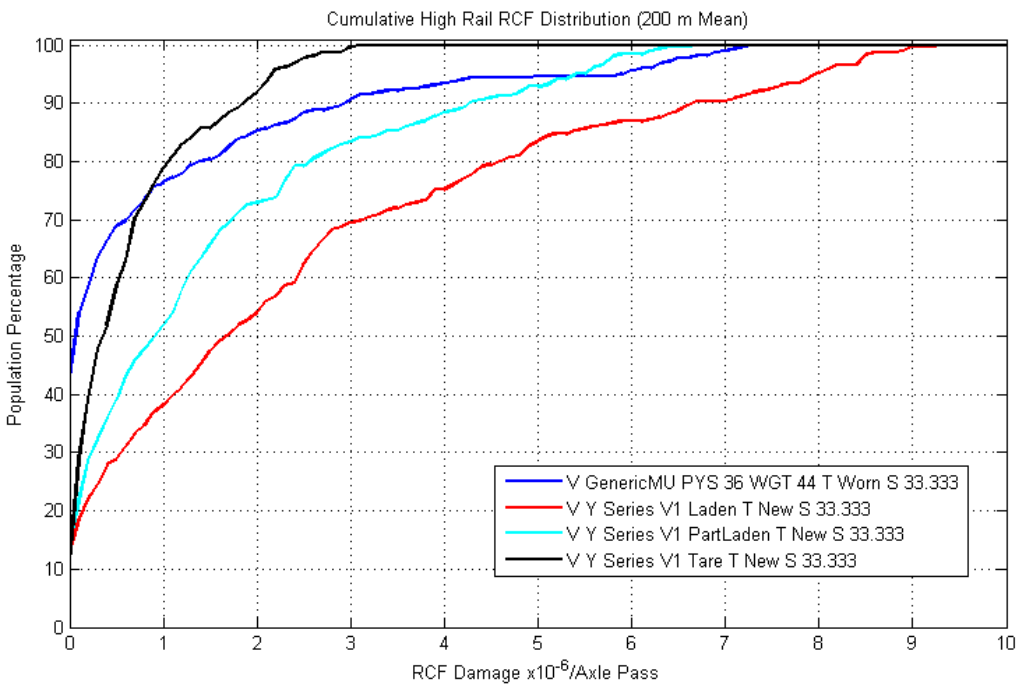


Figure 2.8: Cumulative distribution of 200m mean RCF damage function on DCL, high rail

Looking at the 200m averaged RCF value on the high rail and taking the 98th percentile of the distribution curve (the 99.85th percentile does not seem as representative in this case), for an increase of speed from 120kph to 140kph shows:

- A decrease of damage from the passenger vehicle of up to 40%
- A decrease of damage from the laden freight vehicle of up to 10%
- A decrease of damage from the tare freight vehicle of up to 6%

2.3 Effect on component damage and track lateral deterioration

It is proposed that combined vertical and lateral loading (parameters identified as 'B_{qst}' and 'B_{max}' in draft vehicle testing standards) will be used in later work packages to assess the effect of the various vehicles and their running conditions on track component damage and lateral deterioration. Results are not included here at this stage of the project.

2.4 Effect on Running Safety

The EN14363 [6] value H_{max} (sum of lateral axlebox forces) is used to assess the running safety of the various vehicles. Figure 2.9 shows the cumulative distribution of the absolute value of 'H force' (largest value of H_{max} for the two axles on the leading bogie) along the UK DCL route, comparing the freight vehicle v1 with the passenger vehicle. The passenger vehicle shows the highest lateral forces for most of the route, and the tare freight vehicle shows the lowest forces.

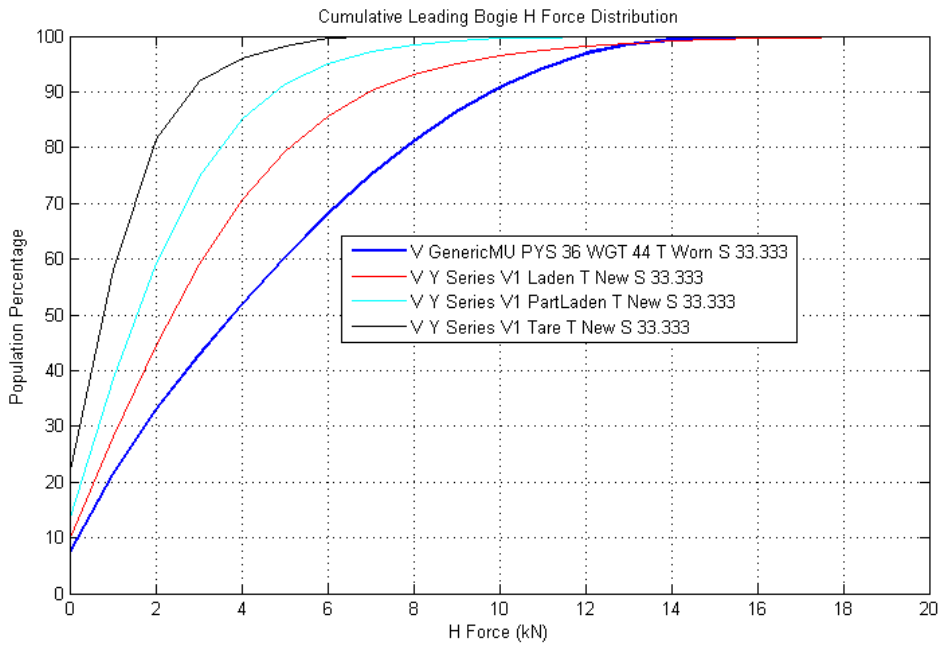


Figure 2.9: Cumulative distribution of H force along DCL

Figure 2.10 shows the absolute maximum (99.85th percentile) of the H_{max} force along the same route. The maximum force increases linearly with axle load with the passenger vehicle fitting nicely on the same linear trend as the freight vehicles.

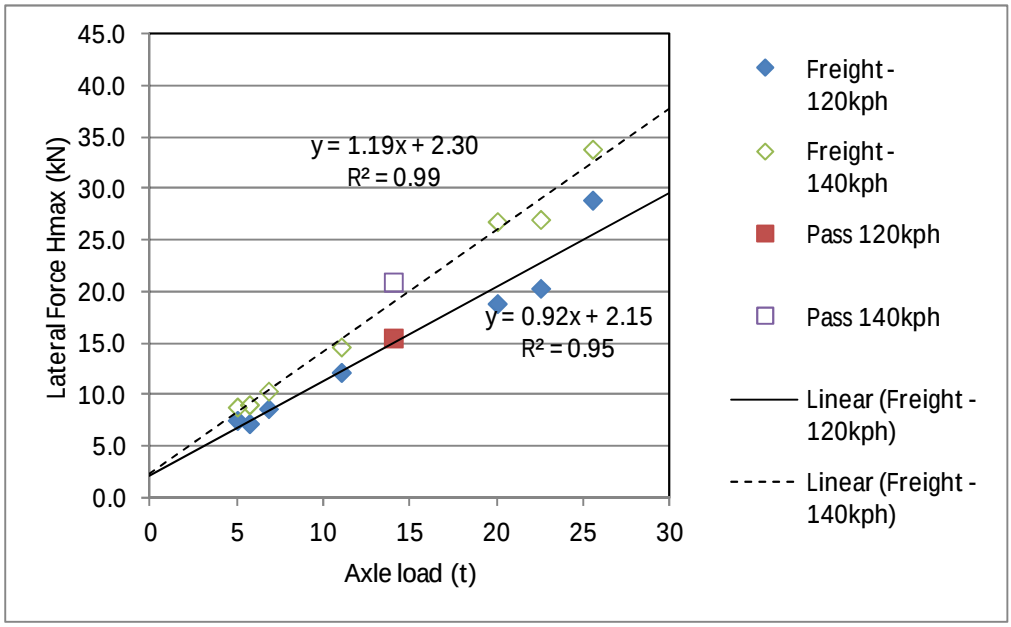


Figure 2.10: Maximum (99.85th percentile) lateral axlebox force for H_{max} on DCL

Increasing the speed from 120kph to 140kph leads to a 35% increase in lateral peak force for the passenger vehicle, between 17% and 25% increase for the tare freight vehicle, 20% for the part-laden freight, and between 17% and 42% for the laden freight vehicle.

Reducing the unsprung mass by 20% leads to the peak lateral axlebox force for the freight vehicles reducing by around 2% (laden), 3% (part-laden), and by 5-7% (tare). Here also the tare vehicle benefits the most from a reduced unsprung mass.

2.5 Effect on Ride Quality

Figure 2.11 shows the cumulative distribution for the vertical acceleration above the leading bogie along the UK DCL route for freight vehicle v1 compared with the passenger vehicle. It is obvious that the freight vehicle experiences far higher accelerations than the passenger vehicle (three to four times higher for the 90th percentile and above). It is also seen that the laden freight shows slightly higher accelerations than the part-laden and tare vehicles.

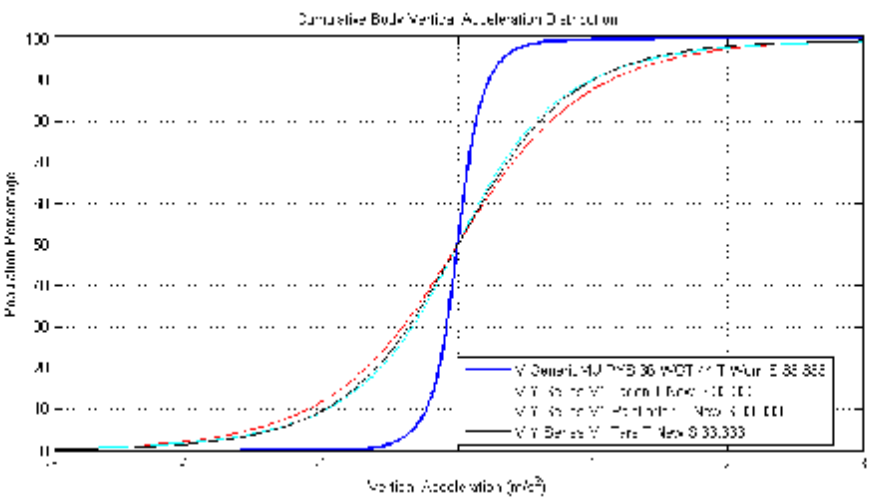


Figure 2.11: Cumulative distribution of body vertical acceleration along DCL

In the lateral direction the same performance difference is observed between the passenger vehicle and the freight vehicle (two to three and a half times higher for the 90th percentile and above), although the lighter the vehicle load, the higher the accelerations are. Figure 2.12

shows, for all vehicles, the variation of the maximum (99.85th percentile or absolute value of 0.15th percentile whichever is greatest) lateral acceleration with axle load. There is not a linear variation because of the non-linear characteristics of the bogie suspension and steering abilities.

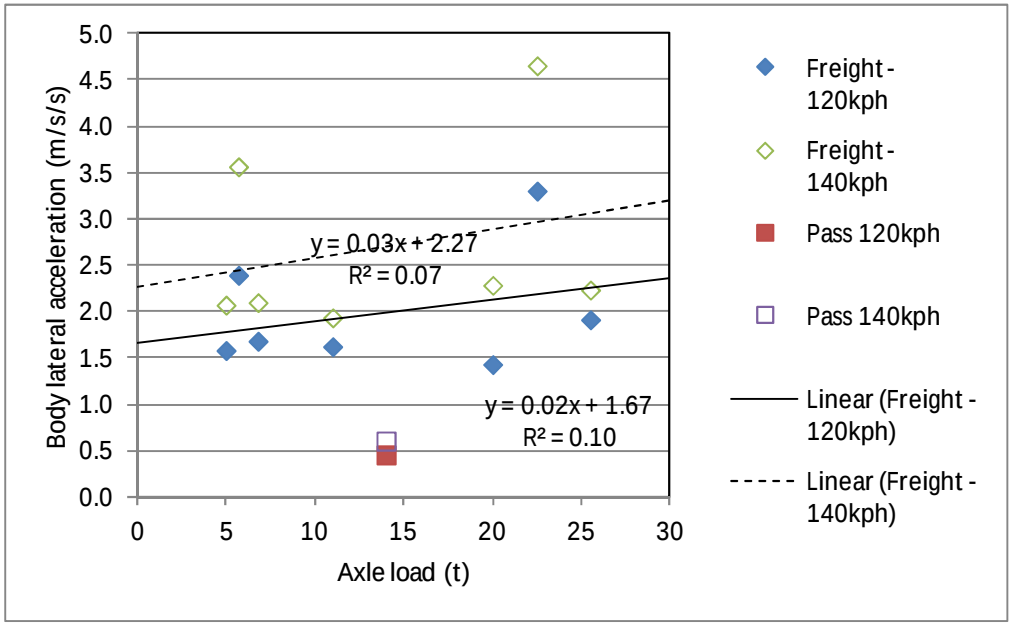


Figure 2.12: Maximum car body lateral acceleration as a function of axle load (passenger and freight vehicles at 120kph and 140kph)

The influence of speed (120 to 140kph) is to raise the level of lateral acceleration (peak value, 99.85th percentile) by about 30% for the passenger vehicle, between 25% and 50% for the tare freight vehicles (v1, v2, and v3), around 20% for the part laden freight vehicles (v1), and between 15% and 60% for the laden freight vehicles (v1, v2, and v3). In the vertical direction the increases are about 10% for the passenger vehicle, between 15% and 40% for the tare freight vehicles (v1, v2, and v3), around 35% for the part laden freight vehicles (v1), and between 0% and 30% for the laden freight vehicles (v1, v2, and v3).

Reducing the track irregularities by 20% leads to a reduction of the largest accelerations (those above the 90th percentile) of between 15 and 20% (vertical), and of between 1 and 14% (lateral).

Reducing the unsprung mass by 20% seems to help reduce the car-body peak lateral accelerations (those above the 90th percentile) by about 3 to 4% for the tare vehicle (v1) and 1 to 3% for the part-laden (v1). Vertical accelerations are practically unchanged.

Looking at the peak values of lateral acceleration it is interesting to note that the bogie wheelbase seems to be an influential factor, i.e. with a shorter wheelbase a stable ride of the bogie may be more difficult to achieve to the detriment of the lateral ride quality. Figure 2.13 shows the same output as Figure 2.12 against bogie wheelbase this time. A reasonable exponential trend line can be used to fit through the data highlighting the fact that the increased bogie wheelbase of the passenger vehicle, combined with better suspension design, can significantly improve the ride.

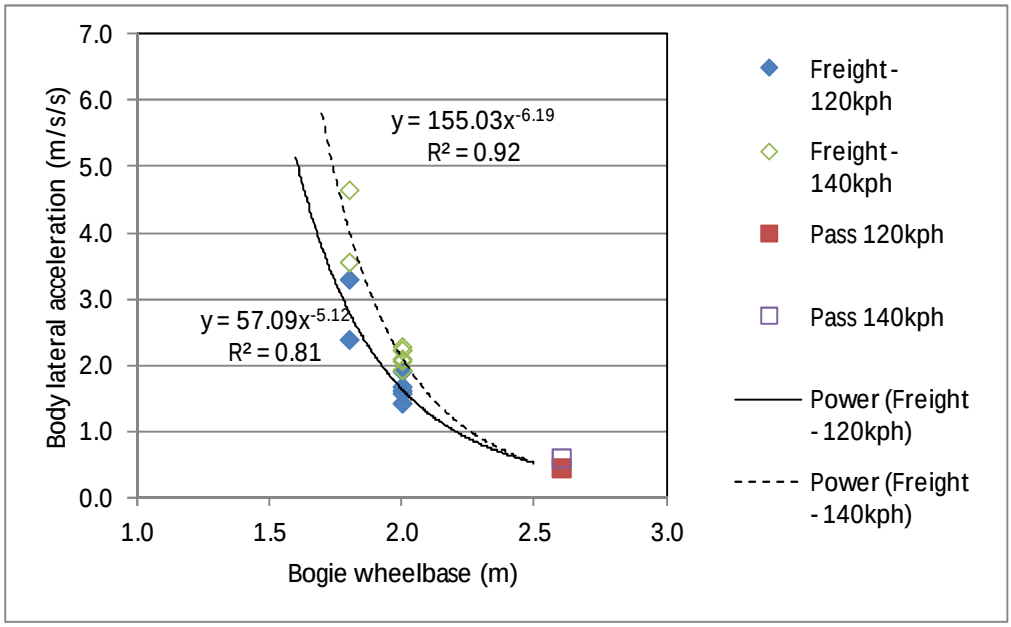


Figure 2.13: Maximum car body lateral acceleration as a function of bogie wheelbase (passenger and freight at 120kph and 140kph)

2.6 Summary

Various aspects of freight vehicle design and running conditions have been assessed and compared to a typical passenger multiple unit when running over 64.5km of the DCL part of the UK SustRail route. The effect of changing certain parameters on various types of damage, ride quality and safety has been analysed. Table 2.3 summarises the results.

	Vertical damage	Tangential damage (wear and RCF)	Ride quality	Ride safety
Vehicle parameters				
Increasing axle load	The most relevant parameter (positive correlation).	Highly relevant.	There is a slight increase of lateral accelerations. A trend is not obvious for the vertical accelerations.	Lateral forces increase, however once vertical load is considered, the trend is not obvious.
Reducing unsprung mass	Mostly beneficial for tare vehicle, however the tare vehicle is far less damaging than laden or part-laden.	Not specifically assessed in this report. Influence probably minimal.	No direct influence.	Helps reduce sum of lateral axlebox forces (H_{max}) by a few percent.
Increasing bogie wheelbase	No influence.	Not directly assessed in this report but in combination with suspension will be an influential factor.	There is a strong influence of bogie wheelbase on the lateral accelerations.	Not conclusive from this report.
Bogie type	Not assessed in this report.	Some small differences observed between the three Y-series vehicles. Passenger type suspension reduces significantly the RCF damage for a wide range of curve radii.	Strong influence.	Bogie type has a great influence especially for higher payloads.
Operating parameters				
Speed increase (120kph to 140kph)	Significant: 20-90Hz frequency forces up by ≈10%; <20Hz frequency forces up by up to 28% (part-laden).	Helps reduce the RCF and wear damage for passenger type suspension. RCF can also be reduced for freight to a lesser extent but effect on wear is generally worst.	Strong influence for the lateral and vertical ride (accelerations increase, probably lateral increase more).	Strong influence by increasing significantly the lateral forces.
Track parameters				
Geometrical quality improvement	Not assessed in this report, however track support stiffness highly influences track vertical degradation	There is a slight reduction, particularly for the tare vehicle peak damage (12% reduction). Track layout (radius and cant deficiency) is more influential.	Significant influence on the vertical ride. Some on the lateral ride.	Small counter-beneficial effects were observed. In-conclusive.

Table 2.3: Summary table of influential aspects of vehicle-track interaction

3. SUB-TASK 2.5.2: RAIL INFRASTRUCTURE DAMAGE COSTS

This section describes the assessment of track maintenance and renewal costs on the UK strategic freight routes using the Vehicle Track Interaction Strategic Model (VTISM) [3] which has been developed and refined in the UK by the Rail Safety and Standards Board (RSSB) and Network Rail (NR). This model has been used by the UK Department for Transport (DfT) to help in the assessment of the procurement of new trains, and also by Network Rail to inform track maintenance decisions, particularly when new fleets are introduced, and for predicting future budgets for track maintenance and renewals. It was also used in the EU FP6 Innotrack research project [7].

This analysis is focused on UK track and traffic but it is expected that quantitative conclusions would be generally relevant to most other freight railways in Europe. Some of the conclusions might not be quite so transferrable to freight running on new high speed track, as in the Spanish data provided, but there will probably still be many Spanish routes where the conclusions will apply.

3.1 The Vehicle Track Interaction Strategic Model (VTISM)

VTISM links inputs such as track and vehicle characteristics to outputs such as rail and wheel life and maintenance regimes. In this study only the track degradation side of VTISM is used, Figure 3.1.

VTISM was developed by integrating vehicle dynamics simulation outputs from VAMPIRE® [2], the Whole Life Rail Model (WLRM) [8], and Network Rail's Track Strategic Planning Application (T-SPA) [9][2] in the following manner:

- **A railway vehicle dynamics simulation package** such as VAMPIRE® is used to build a virtual model of a rail vehicle and its suspension, which is then simulated to run over track using track geometry data obtained from measurement trains running along the specified route section.
- **Whole Life Rail Model (WLRM**) uses the output from the VAMPIRE vehicle runs to predict the damage from lateral wheel/rail forces giving the rate of formation of Rolling Contact Fatigue (RCF) and wear on the rails. Damage factors are calculated across the railhead by aggregating the impact of each wheel-set passing over the rail.
- **T-SPA** is a software tool which predicts the impact of different options for track renewal and maintenance and train services on the future condition and performance of the track. It calculates track damage resulting from the vertical and lateral forces associated with the traffic running along the route, and, using a specified maintenance strategy, it calculates the maintenance costs over a specified period of time.

[2] Referenced in [7]

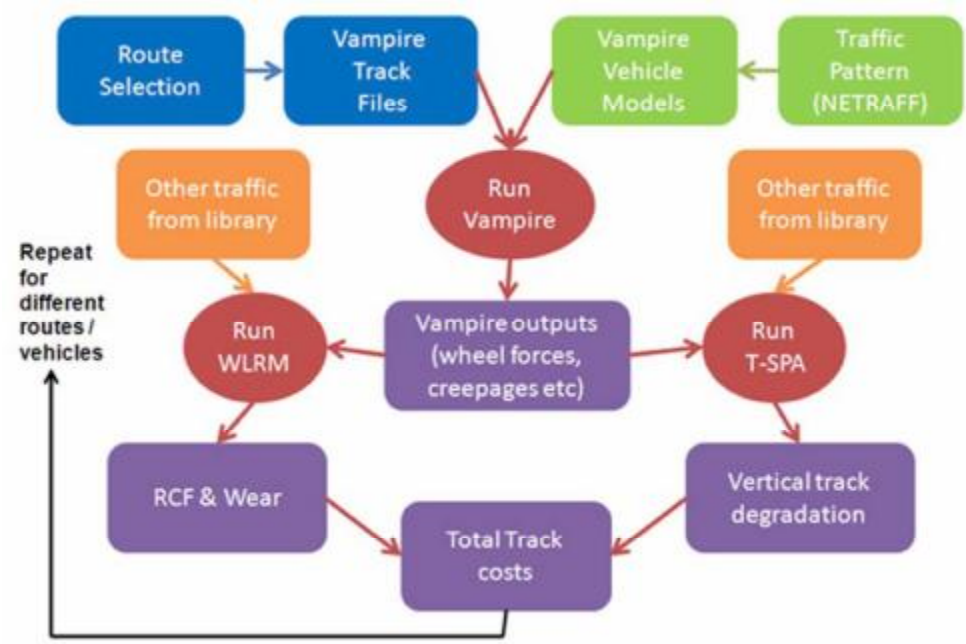


Figure 3.1: Diagram of the working of the track degradation modelling of VTISM

The main data inputs to VTISM include:

- Route track data – derived from
  - GEOGIS – this is a key NR database ("Geography and Infrastructure System", or "Geographical Information System") recording the history of maintenance and life of components over the whole railway network. It also includes a record of curvature along every route.
  - Track geometry measurement trains, which feed data into a Network Rail program that uses the DeltaRail TrackMaster algorithms to derive track degradation rates for every 200m along a route. The measurement trains also provide data on curvature and cant along a route. Curvatures and distances from the measurement trains have to be aligned with the GEOGIS data. Detailed track geometry files are also provided for vehicle dynamics modelling.
  - RDMS – the "Rail Defect Management System" database which records details of rail defects (types, locations, dates, how discovered, remedial actions required, etc.)
- Vehicle / axle and traffic data – usually derived from NETRAFF, a NR database of traffic flows over every 200m section of the rail network. NETRAFF has vehicle load data for each vehicle class currently operating in service in Great Britain. Sometimes researchers use data from another NR database, ACTRAFF, which is a record of every vehicle that has travelled over each 200m section. This ACTRAFF database tends to be more accurate for freight traffic than NETRAFF and was the main source for traffic data in these studies
- Permanent way engineering data comprising rules for renewal and maintenance actions, track engineering parameters and unit costs for every maintenance and renewal operation
- Vehicle models used in the vehicle dynamics modelling

- Wheel and rail profiles of new and worn wheels and rails for use in vehicle dynamics modelling

The VTISM software is supplied with the following generic VAMPIRE® vehicle models:

- Two-axle passenger railbus
- Bogie passenger coaches
- Bo-Bo locomotive
- Co-Co locomotive (with and without axle steering)
- Two-axle freight wagon
- Bogie freight wagons

Most of the models are supplied in different variants, such as tare and laden, and all of the models are designed so that certain key parameters can be easily modified by the user. However for the main VAMPIRE modelling work carried out in this SustRail study, more detailed models for 60ft intermodal wagons with Y33 bogies were developed and used (see Section 2 above).

VTISM was originally developed and calibrated using models of passenger rail vehicles operating on main passenger routes. Passenger vehicle suspensions tend to have more linear characteristics whereas the freight vehicle bogies, such as the Y25 and Y33 bogies, have rather more non-linear characteristics and have to be more carefully modelled. When calculating track degradation costs from passenger vehicles, generally about 10% of the maintenance and renewal costs are due to RCF and wear caused by the input from lateral forces. In these initial VTISM studies for SustRail, the track damage costs predicted were in line with other previous estimates for passenger vehicles. However, using freight vehicle models, a much higher proportion of the cost (at least 50% of the total) was predicted to be due to lateral forces. This is largely due to high wear caused by the poor steering of the freight bogies. This will be examined further in WP3.

The weights of passenger vehicles do not vary too greatly between tare and laden – a fully laden passenger vehicle might be 20% heavier than a tare vehicle, so one might predict an average passenger vehicle weight with reasonable accuracy. For freight vehicles, a tare weight might be 20t with a fully laden weight of 82 tonnes. For intermodal vehicles an average laden weight might be between 40t and 52t, especially as trains sometimes run with a number of empty containers and high value goods can be fairly light. Records of intermodal vehicle weights were inspected and this led to defining a typical laden vehicle weight for a 60ft intermodal vehicle (FE) as 44 tonne on the UK routes. For some tests fully laden (82t) freight vehicles were included to more accurately model the traffic loads on a particular route.

VTISM has been used by NR to predict average costs for track maintenance and renewals for the years 2014-2019 of £33,000/track km/year (£52,800/track mile/year), Table 3.1, as well as the track costs for each of the UK strategic freight routes. The Southampton route was predicted to have significantly larger costs due to the much higher traffic capacity.

Approximate investment to end of CP5 2014-2019	Felixstowe (F2N)	S'hampton (Route 3)	NR Average
Renewals (£/km/yr)	£24,000	£35,000	
Maintenance (£/km/yr)	£14,000	£18,000	
Total	**£38,000**	**£53,000**	**£33,000**
Renewals (£/mile/yr)	£38,400	£56,000	
Maintenance (£/mile/yr)	£22,400	£28,800	
Total	**£60,800**	**£84,800**	**£52,800**

Table 3.1: Network Rail predictions for track costs for the two strategic freight routes

The UK railways' Rail Safety and Standards Board used VTISM to carry out a study on the value of passenger vehicle mass for different types of services and reported the findings as report T712 in 2010 [10]. This study showed that the benefit of reducing vehicle mass on track damage costs was between 0.29 and 0.52p/tonne/vehicle mile, Table 3.2, depending on the type of service.

Average Results	Inner Suburban p/tonne/ mile	Outer Suburban p/tonne/ mile	Inter Urban p/tonne/ mile	Inter City p/tonne/ mile
Benefit of saving mass on track costs	0.29	0.32	0.43	0.52

Table 3.2: Predictions of the impact of vehicle mass on track costs for passenger vehicles (T712, RSSB, 2010 [10])

3.2 VTISM studies: DCL route from Didcot towards Leamington Spa – Vertical Forces Only

Most of the initial VTISM studies were carried out on the southern 64.5km of the DCL section of the Southampton route between Didcot and Leamington Spa (UK DCL route). These initial tests mainly included only the vertical impact forces and not the lateral inputs. Around 40% of the traffic is currently intermodal freight wagons (FE) with speeds up to 120kph, 40% passenger trains with speeds up to 140kph and 20% of other wagons and locomotives. VAMPIRE® modelling was carried out for 60ft intermodal freight wagons at 120kph and 140kph with weights tabulated here, Table 3.3.

Loading	Vehicle Mass (tonne)	Designations (using axleload and speed)
Tare	20	FE5W120 and FE5W140
Semi-laden (or 'part-laden')	44	FE11W120 and FE11W140
Fully laden (or 'laden')	81	FE20.5W120 and FE20.5W140

Table 3.3: Vehicle masses and designations

VAMPIRE® runs were also carried out for a representative passenger vehicle at 120kph and 140kph.

The VTISM results from the DCL route in Figure 3.2 feature tests with intermodal freight wagons travelling at 120kph but do not include any lateral damage for these intermodal wagons (FE). The "Current" traffic models the current total tonnage predicted on the route but replaces all the present intermodal wagons with the representative semi-laden or tare vehicles FE11W120 and FE5W120 depending on whether the wagons are reported by NETRAFF to be laden or tare.

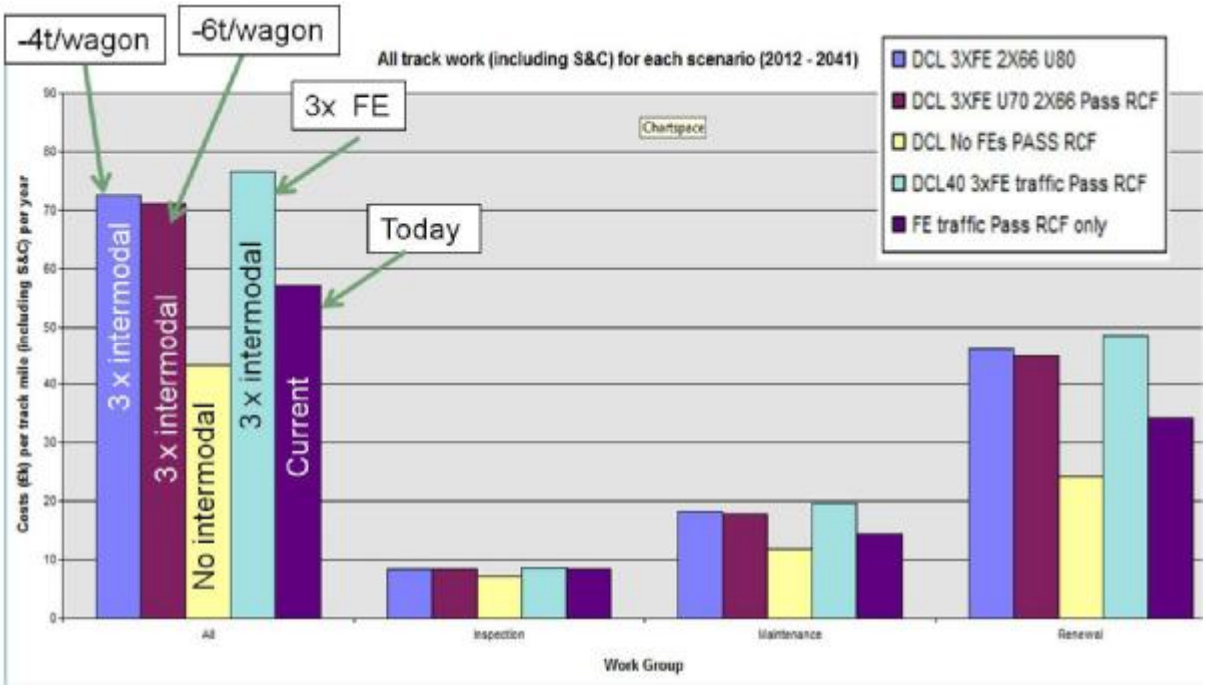


Figure 3.2: Track damage costs for DCL 2100 route averaged over 30 year period – Intermodal 120kph wagon fleet (FE) does not include lateral damage

Predictions of track costs in £k per track mile per year are shown in Figure 3.2 for:

- the "Current" traffic, labelled "Today"
- the "Current" traffic but with 3 times the amount of intermodal freight traffic (3x FE)
- "Current" traffic but with no intermodal wagons
- the "3xFE" traffic but reducing the intermodal vehicle masses by 4 tonnes, labelled "-4t/wagon" (designation FE11U80 in Table 3.4)
- the "3xFE" traffic but reducing the intermodal vehicle masses by 6 tonnes, labelled "-6t/wagon" (designation FE11U70 in Table 3.4)

Each prediction is broken down to show the costs of inspection, maintenance and renewals. The actual figures are shown in Table 3.4 below.

Where 'FE' is a 60ft Intermodal Wagon; Costs averaged 2012-2041							Costs (£k) per track mile per year	Costs from FE only
DCL40 over 40 miles		Vehicles /year	Annual tonnage (Mt)	% of total tonnage	Estimated Total route tonnage (Mt)	Graph description	Total	£k per track mile per year
FE11W120	44t semi-laden Intermodal 120km/h	110346	4.86	36.2%	13.4	FE wagons in "Current" traffic tonnage	57.2	13.8
FE5W120	20t tare Intermodal at 120km/h	24537	0.49	3.7%				
Cl 66 CoCo	126t Loco	8460	1.07	8.0%				
Total Passenger Vehicles		109370	5.30	39.5%				
No FE vehicles					8.1	No FE wagons - "No intermodal"	43.4	
FE11W120	44t semi-laden Intermodal 120km/h	331038	14.57	57.9%	25.2	"3x Intermodal" 3x FE traffic 2x66	76.7	33.3
FE5W120	20t tare Intermodal at 120km/h	76513	1.53	6.1%				p/t/veh mile from extra FE wagons
FE11W120	*44t semi-laden Intermodal 120km/h*	*331038*	*14.57*	*57.9%*	*25.2*	*3xFE traffic 1x66 - extra test run*	*73.1*	0.16
								p/t/veh mile from weight reduction
FE11U80	40t semi-laden Intermodal 120km/h	331038	14.57	57.9%	25.2	"3x Intermodal " (-4t/FE wagon)	72.6	0.25
FE11U70	38t semi-laden Intermodal 120km/h	331038	14.57	57.9%	25.2	"3x Intermodal" (-6t/FE wagon) U80-U70	71.2	0.17
						6t loss result - FE to U70		0.22

Table 3.4: DCL VTISM results – impact of traffic increases and weight reduction (Figure 3.2)

The cost of track damage for "Current" traffic, £57.2k/track mile/year, excluding intermodal wagon lateral damage impact costs, is lower than the £84.8k (Table 3.1) that NR had predicted for the total costs for the whole Southampton route between 2014 and 2019 which includes the high capacity BML1 and WCML sections. These lower values might be expected for tests that do not include the lateral force inputs.

The savings from reducing intermodal wagon masses by 4t and 6 t average out at 0.22p/tonne/vehicle mile which is at the lower end of the predictions from the RSSB T712 studies on passenger vehicles [10]. Later tests, reported below, which included lateral forces gave values in line with the T712 studies.

Figure 3.3 shows the impact on track costs from vertical forces only of increasing the operational speed of the freight intermodal wagons (FE) from 120kph to 140kph both for the current traffic flows and for the 3x intermodal traffic example. Table 3.4 shows that the increase in track costs for this speed increase for the "current traffic" case and the "3x Intermodal traffic" case averages to 10.5%.

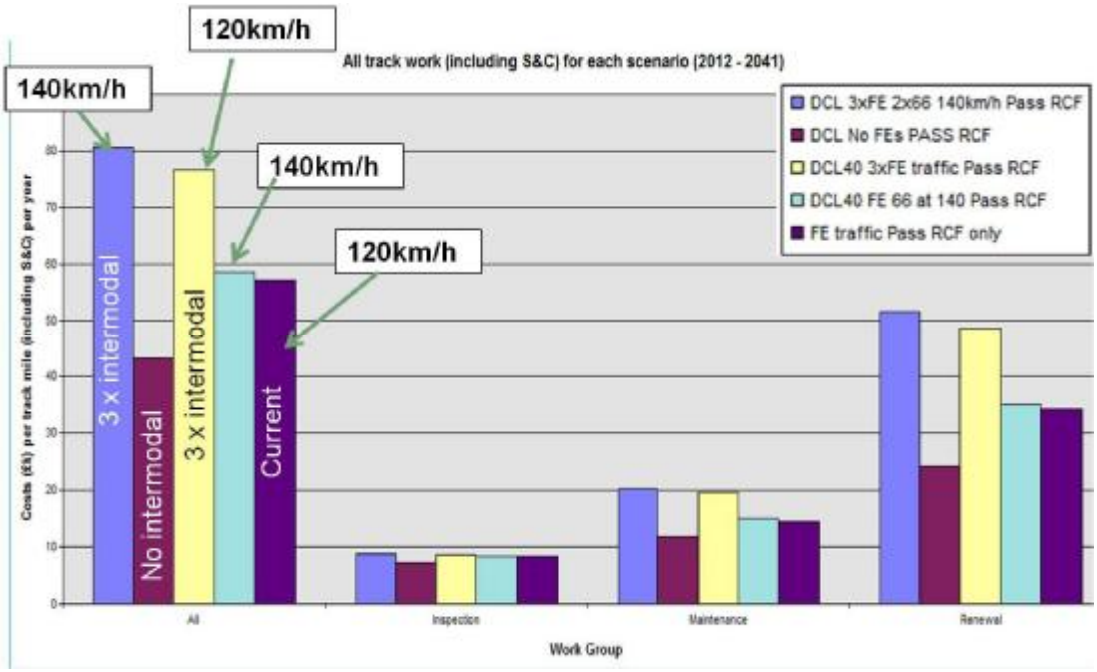


Figure 3.3: DCL route: Impact of increasing speed on track costs

Where 'FE' is a 60ft Intermodal Wagon; Costs averaged 2012-2041							Costs (£k) per track mile per year	
DCL40 over 40 miles		Vehicles /year	Annual tonnage (Mt)	% of total tonnage	Estimated Total tonnage (Mt)	Graph description	Total	
FE11W120	44t semi-laden Intermodal at 120km/h	110346	4.86	36.2%	13.4	"Current " FE traffic 120km/h	57.2	p/t/mile
FE11w140	44t semi-laden Intermodal at 140km/h	110346	4.86	36.2%	13.4	"Current" FE traffic 140km/h	58.5	from extra FE wagons
FE11W120	44t semi-laden Intermodal 120km/h	331038	14.57	57.9%	25.2	"3x Intermodal" 120km/h	76.7	0.16
FE11W140	44t semi-laden Intermodal 140km/h	331038	14.57	57.9%	25.2	"3x Intermodal" 140km/h	80.6	0.21
								from lower weight wagon
FE10W140	40t semi-laden Intermodal at 120km/h	331038	13.24	56.3%	23.5	"3x Intermodal" 140km/h (-4t/wagon)	75.5	0.31
								lower unsprung
FEA140 80% axle	44t semi-laden Intermodal 140km/h	331038	14.57	57.9%	25.2	"3x Intermodal" 140km/h -20% unsprung mass	79.0	0.26

Table 3.5: DCL route: Results for impact of increasing speed on track costs (Figure 3.3)

The reduction in vehicle mass from 44t to 40t at 140kph reduces costs by 0.31p/tonne/vehicle mile for the 3x FE traffic flow case. This compares with the 0.22p/tonne/vehicle mile at 120kph. One test was made reducing the unsprung mass by 20% but keeping the axleload the same. This gave a reduction in costs of 0.26p/tonne of unsprung mass/vehicle mile. This is dealt with in more detail in Section 3.4.

3.3 VTISM studies: Comparison of routes – Vertical Forces Only

VTISM predictions for track costs were carried out on 5 different route sections. For the CCH section East of Ely good traffic data was hard to find so the same traffic data was used as on the EMP route. The results quoted in Table 3.6 below are a comparison just using vertical forces and not including the VAMPIRE® modelling of the lateral forces.

	Total Mtonnes	% FE	Number of FE wagons per year	Track costs £k/mile/yr	Track costs £k/mile/yr No FEs	p/t/veh mile	3xFE Track costs £k/mile/yr	p/t/veh mile from 3x	3xFE (-4t) Track costs £k/mile/yr	p/t/veh mile from (-4t)
CCH	6.7	42.5%	55206	46.4	27.8	0.58	62.6	0.25		
EMP	6.7	41.6%	52483	59.8	42.4	0.56	75.3	0.25	73.3	0.32
DCL	13.4	39.9%	134883	57.2	43.4	0.24	76.7	0.17	72.6	0.25
ECML	9.2	48.6%	101233	52.9	45.2	0.17	68.8	0.18	65.6	0.26
BML1	21.1	36.5%	129652	104	58.6					

Table 3.6: Comparison of track damage costs for different route sections

The track costs for the CCH route (£46.4k) were significantly less than for the EMP section (£59.8k) although both had the same traffic loads. Three factors may have contributed to this:

- The much softer ground and poor embankments on the EMP route section
- Higher curvature on the EMP route
- The relative age and condition of track components and the number of S&C and level crossings on the EMP section

It is probable that the track cost values for freight bogies running on the very straight Spanish high speed lines which have solid substructures will be much lower than the values found on these UK routes.

3.4 VTISM studies: DCL route from Didcot towards Leamington Spa – Including lateral force inputs

At this stage the studies included the lateral force inputs and VAMPIRE modelling. The graph in Figure 3.4 shows the impact of lateral forces at 120kph service speed. Damage due to RCF and wear can be seen to account for half the track force costs caused by the intermodal wagons (FE). For the passenger vehicles, by comparing the “Current-no lateral” with “Current with Pass RCF” (and wear), it can be seen that the RCF and wear accounts for around 12% of the total track damage costs.

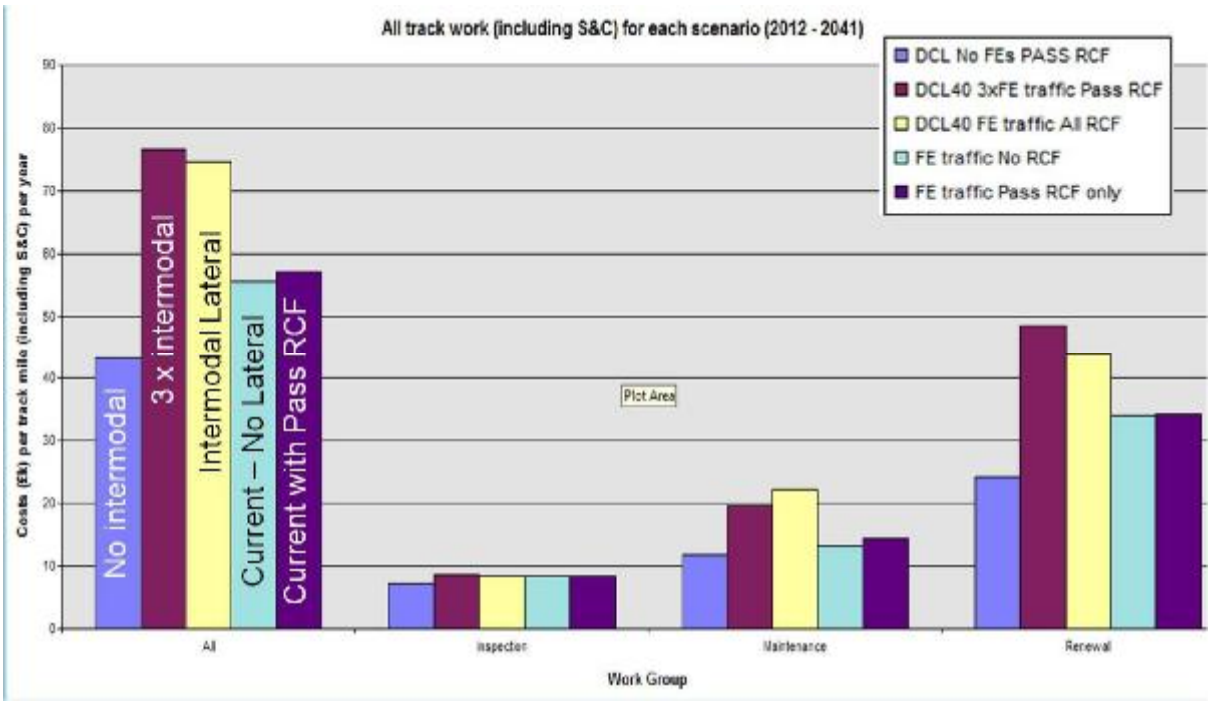


Figure 3.4: DCL route: Impact of lateral forces from intermodal wagons on track costs

The track damage costs including lateral forces for the current traffic levels are predicted to be £74k/track mile per year which is now quite close to NR's predictions, £84.8k, for the whole strategic freight route from Southampton between 2014-2019

Figure 3.5 shows the difference in breakdown of work required for the two variant cases of:

i. having 3 times the intermodal wagon traffic or
ii. including the lateral force costs for the current intermodal wagon traffic

Increasing the number of intermodal wagons 3 fold gives significant increases in the amount of complete renewals and grinding costs. The effect on grinding is not surprising as the algorithm for grinding just depends on annual tonnage. The inclusion of damage caused by lateral forces can be seen to increase the single rail repairs and general rail repairs due to wear and RCF.

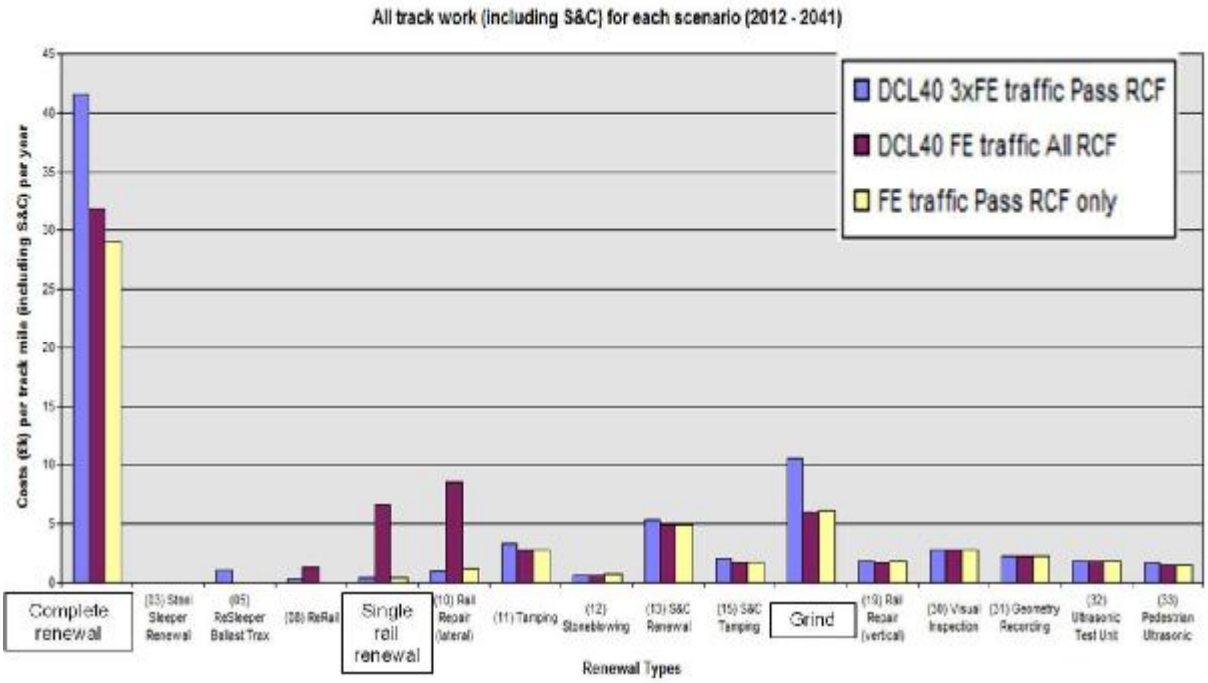


Figure 3.5: Impact of increasing intermodal traffic and inclusion of lateral forces on track costs

To help understand the large increases in costs from lateral forces with intermodal vehicles the outputs of RCF and rail wear in Figure 3.6 and Figure 3.7 from the Whole Life Rail Model (WLRM) were inspected.

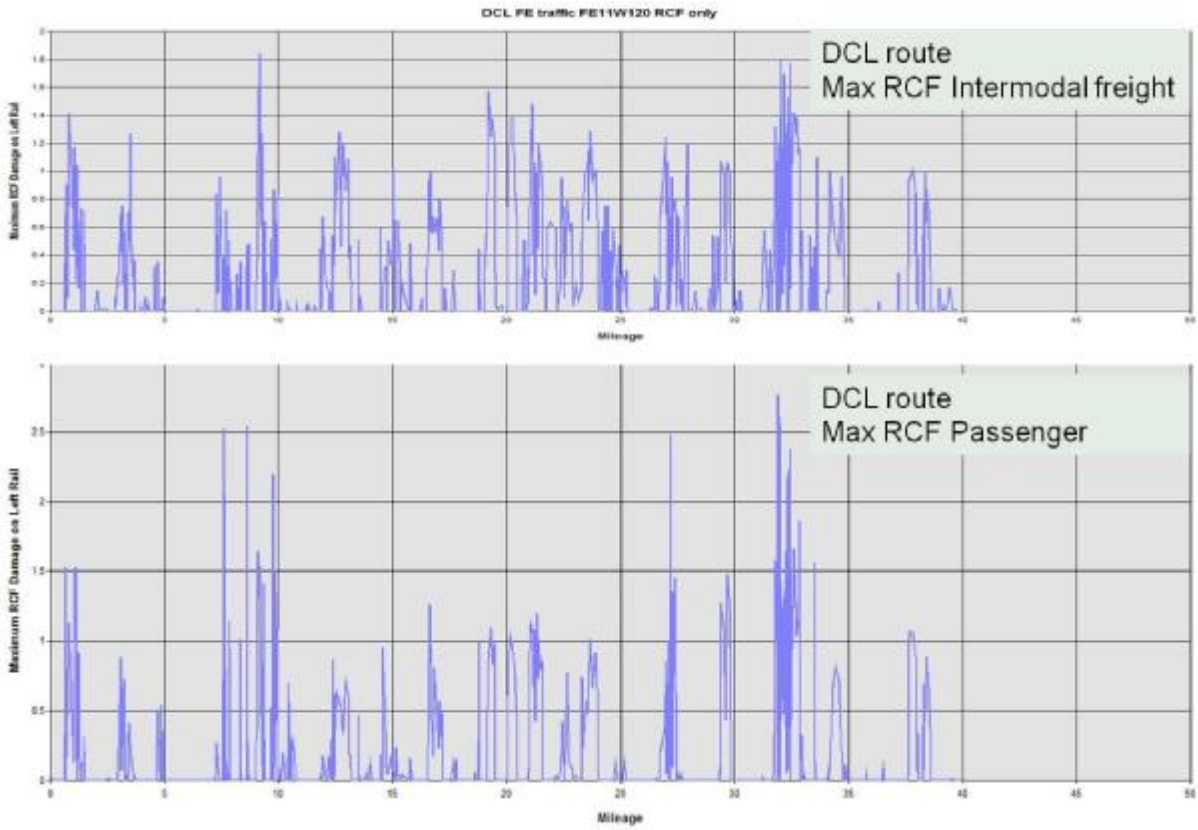


Figure 3.6: Maximum RCF damage - passenger and intermodal wagons on the DCL route

In Figure 3.6 the X-axes are distance in miles from 0 to 40 miles. The y-axes are maximum RCF damage on the left rail[3]. Note that the vertical scales are not the same. Although there seems to be more occurrence of RCF for the freight vehicles there are some higher RCF peaks for the passenger vehicles.

Figure 3.7 shows the output of the wear predictions from the WLRM[4]. This clearly shows the freight vehicles giving much higher wear (perhaps on average by more than 4 times) than the passenger vehicles although the passenger vehicles do give some high wear values at particular points.

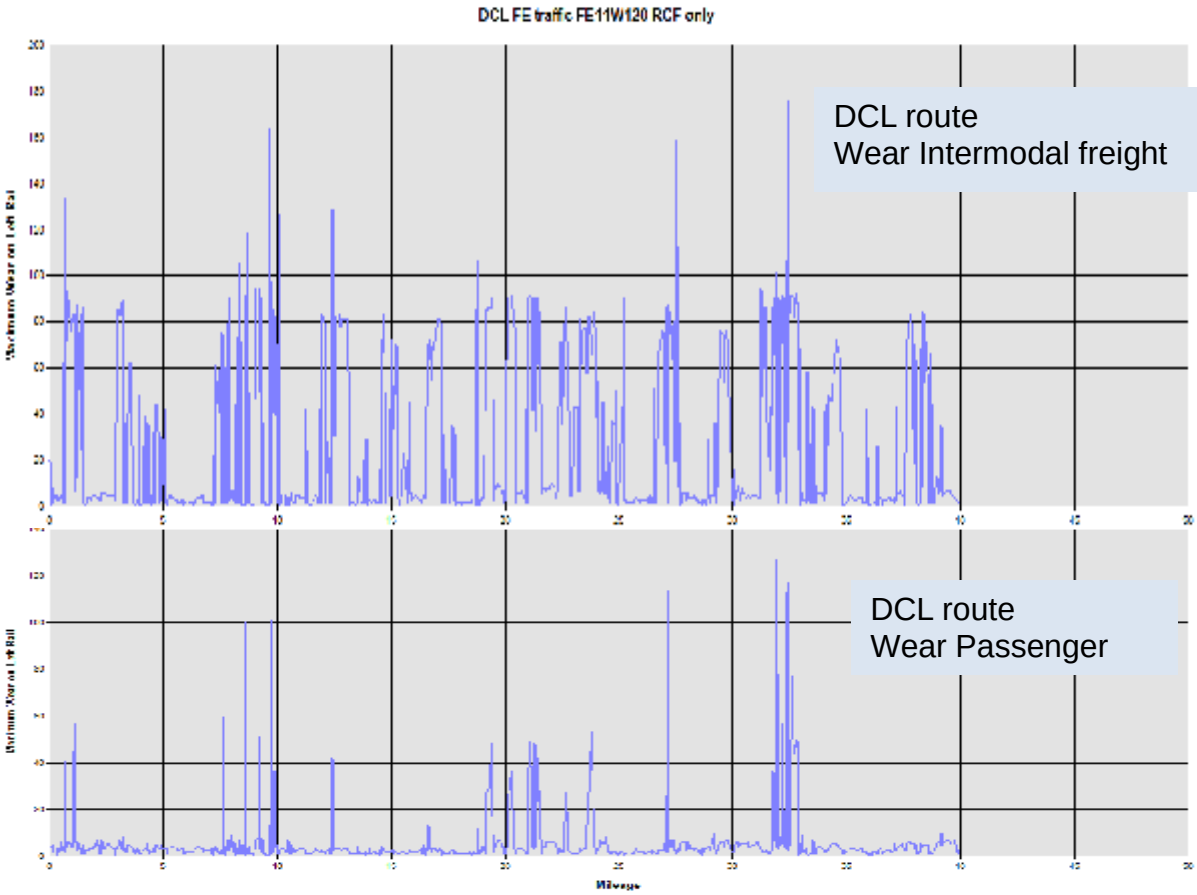


Figure 3.7: Maximum rail wear - passenger and intermodal wagons on the DCL route

These higher wear values produced by the freight bogies arise at higher Tγ values (recall that Tγ is a measure of the energy generated in the contact patch from lateral forces and creepage). An increase in wear rate removes material before RCF cracks can form. Further investigations would need to consider how these wear values could be reduced by optimising bogie characteristics but without causing any increase in predicted RCF.

Recent tests have been carried out on the UK DCL route including the lateral forces but modelling the intermodal wagons with an unsprung mass of 1202kg and then with an unsprung mass of 962kg whilst keeping the vertical forces in T-SPA constant for the 20tonne and 44tonne wagon cases. These tests were carried out for:

[3] Figure 2.5 shows mean RCF damage on high and low rails so cannot be compared directly with the RCF plotted in Figure 3.6

[4] Figure 2.4 uses a different scaling for wear so cannot be compared directly with the wear plotted in Figure 3.7

1. Current intermodal traffic tonnages at both 120kph and 140kph
2. Traffic with 3 times the number of intermodal wagons at both 120kph and 140kph

Results are summarised in the Table 3.7 below.

DCL 40 route over 40 miles; Where 'FE' is a 60ft Intermodal Wagon; Costs averaged 2012-2042						Costs (£k) per track mile per year	Value of unsprung mass
Intermodal Wagons	Graph description Traffic	Vehicles /year	Annual tonnage (Mt)	% of total tonnage	Estimated Total tonnage (Mt)	Total	p/t/mile
44t 120km/h 1200kg unsprung mass	"Current" H 120km/h All RCF	110566	4.87	36.3%	13.4	73.94	
44t 120km/h 960kg unsprung mass	"Current" H 120km/h All RCF	110566	4.87	36.3%	13.4	73.29	0.48
44t 120km/h 1200kg unsprung	"3x Intermodal" H 120km/h All RCF	331697	14.60	57.9%	25.2	125.3	
44t 120km/h 960kg unsprung mass	"3x Intermodal" HA 120km/h All RCF	331697	14.60	57.9%	25.2	123.4	0.47
44t 140km/h 1200kg unsprung mass	"Current" H 140km/h All RCF	110566	4.87	36.3%	13.4	75.8	
44t 140km/h 960kg unsprung mass	"Current" HA 140km/h All RCF	110566	4.87	36.3%	13.4	75.2	0.44
44t 140km/h 1200kg unsprung mass	"3x Intermodal" H 140km/h All RCF	331697	14.60	57.9%	25.2	127.4	
44t 140km/h 960kg unsprung mass	"3x Intermodal" HA 140km/h All RCF	331697	14.60	57.9%	25.2	125.7	0.42

Table 3.7: Analysis of impact of unsprung mass – UK DCL route

This shows that the cost benefit from just reducing unsprung mass averages 0.45p/tonne/vehicle mile. Very similar values are obtained from these tests by calculating the value of mass using the results from increasing the intermodal traffic threefold.

Table 3.8 shows that the percentage of track costs from the lateral forces of the intermodal wagons on these most recent analyses are nearer to 58% and 60%.

DCL 40 route over 40 miles; Where 'FE' is a 60ft Intermodal Wagon; Costs averaged 2012-2042						Costs (£k) per track mile per year	% costs from lateral forces
Intermodal Wagons	Graph description Traffic	Vehicles /year	Annual tonnage (Mt)	% of total tonnage	Estimated Total tonnage (Mt)	Total	%
44t 120km/h 1200kg unsprung mass	"Current" H 120km/h Pass RCF/Wear	110566	4.87	36.3%	13.4	73.94	58.0%
44t 120km/h 1200kg unsprung mass	"Current" H 120km/h All RCF	110566	4.87	36.3%	13.4	56.22	
No Intermodal (FE)	Pass and locos only with RCF/wear				8.1	43.4	
44t 120km/h 1200kg unsprung mass	"3x Intermodal" H 120km/h All RCF/wear	331697	14.60	57.9%	25.2	125.3	59.9%
44t 120km/h 1200kg unsprung mass	"3x Intermodal" H 120km/h Pass/loco RCF/wear	110566	4.87	36.3%	13.4	76.2	
No Intermodal (FE)	Pass and locos only with RCF/wear				8.1	43.4	

Table 3.8: Percentage of track damage costs from lateral forces on UK DCL route

This demonstrates that the cost savings from developing a freight bogie that can minimise track costs from lateral forces (£59.1k per track mile /year for the 120kph threefold increased intermodal traffic case) are significantly higher than the benefits solely derived from reducing unsprung mass (£1.9k/track mile/year). However, reducing unsprung mass could be a significant factor in developing a better, low wear, freight bogie.

3.5 VTISM studies: ECML route from Edinburgh to Newcastle

To validate the large increases in track costs found on DCL from the inclusion of the lateral force inputs from the intermodal freight bogies, studies were carried out on a section of the East Coast Main Line between Edinburgh and Newcastle which had a similar curvature spectrum to DCL. This section of route is three times longer than the section of the DCL route that was used. The VAMPIRE® models and runs included with VTISM were from a different source to those used for the DCL route. Intermodal freight traffic was introduced into the traffic to give the same overall tonnage as the present route tonnage. The VTISM results on this ECML section, Figure 3.8 and Table 3.9, gave similar results to those found on DCL with a 47% increase in track costs caused by including the lateral forces for the intermodal freight bogies. The increase in costs due to increasing the intermodal traffic threefold shows an impact of 0.35p/tonne/vehicle mile when both vertical and lateral forces are included.

Reducing the weight of a wagon at 120kph by 4t (vehicle designation FE10W120) gave a cost saving of 0.26p/tonne/vehicle mile which is similar to the DCL result for vertical forces only.

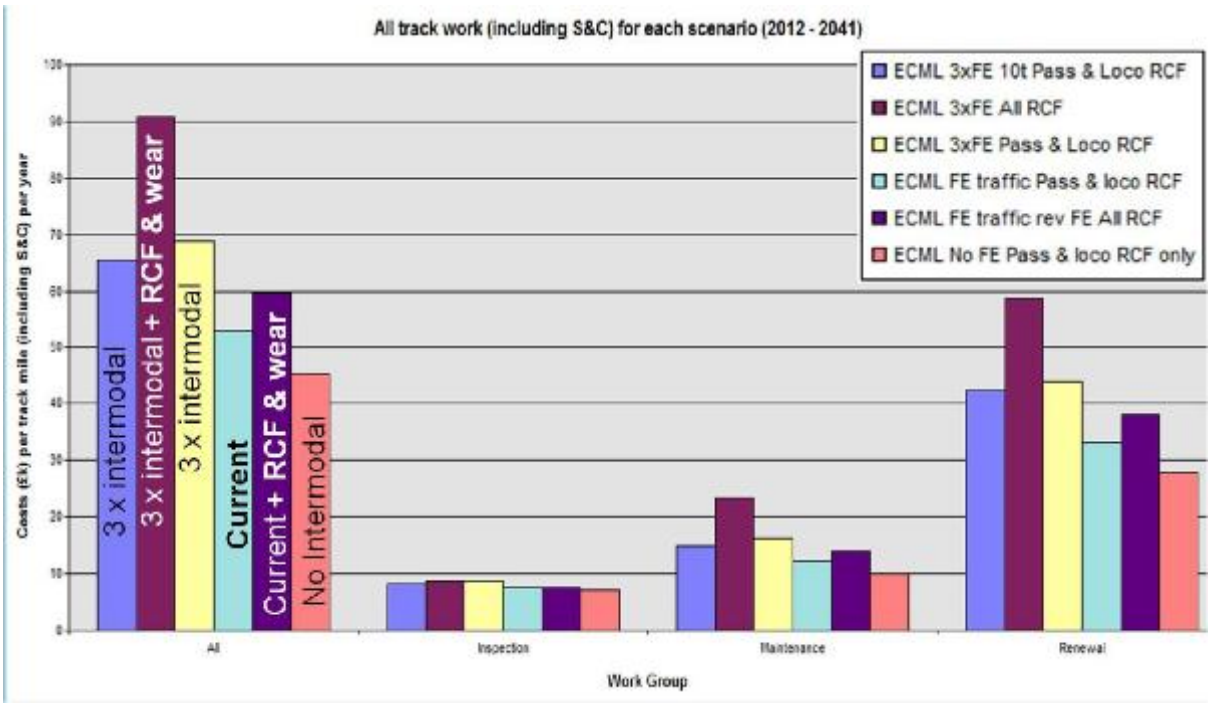


Figure 3.8: ECML route: VTISM results for increasing intermodal traffic and including lateral force inputs

ECML Traffic	Vehicle	Number / year	Mtonnes	%	Total Mtonnes	£k/track mile/yr	p/t/veh mile
							from total load of wagons
"Current" FE traffic Pass & loco RCF/wear	FE11W120	101233	4.5	48.6%	9.2	52.9	0.17
"No Intermodal" FE Pass & loco RCF/wear	Mk4L	61613	2.8	59.1%	4.7	45.2	
"Current" with FE RCF & wear	FE11W120	101233	4.5	48.6%	9.2	59.7	0.33
"3x Intermodal" with FE RCF & wear	FE11W120	303697	13.4	73.9%	18.1	90.8	0.35
"3x Intermodal" Pass & Loco RCF/wear	FE11W120	303697	13.4	73.9%	18.1	68.8	0.18
							from lower wagon mass
"3x Intermodal" (-4t/FE wagon) Pass & Loco RCF/wear	FE10W120	303697	12.1	72.1%	16.8	65.6	0.26

Table 3.9: ECML route: VTISM results for increasing intermodal traffic, including lateral force inputs, and for reducing vehicle mass (Figure 3.8)

3.6 VTISM studies: Main Findings from Initial Studies

The main findings from these VTISM studies on specific UK routes are

- Very high levels of lateral track damage costs are predicted for intermodal freight bogies, 50-59% of track damage costs, compared to those obtained for passenger bogies, 12%.
    - These large track damage costs from lateral inputs seem to be caused by rail wear.
    - Improving bogie designs could yield very large benefits if they reduce these large amounts of lateral wear. The risk of increasing RCF, as suspension parameters are optimized to reduce wear, needs to be considered
- Increasing speed from 120kph to 140kph is predicted to increase track damage costs by 6% (if lateral damage costs were ignored the increase would be 10.5%).
- The impact of vehicle mass on track damage costs on these UK routes is 0.35-0.44p/t/vehicle mile (only 0.20-0.3p/t/vehicle mile if lateral damage is ignored)
- VTISM predicts that, when vertical and lateral forces are included, the impact of reducing unsprung mass on track damage is 0.45p/tonne/vehicle mile.
- When track damage costs due to both vertical and lateral forces are included on the UK DCL route the overall values, £74k/track mile/year, are in line with NR's predictions for the CP5 budget period from 2014-2019

It is expected that these findings would be relevant to many European freight services operating over traditional routes.

4. SUB-TASK 2.5.3: THE IMPACT OF TRACK FORCES

The results of the simulations of freight vehicle 'v1' described in Section 2 included accelerations that would be experienced by equipment mounted on the vehicles. In this sub-task the effect that these accelerations would have on the fatigue life of equipment is assessed.

4.1 Methodology

An equivalent acceleration approach similar to that described in [11] was adopted. This involves initially calculating (for each direction: longitudinal, lateral, and vertical, and for equipment attached to wheelsets, bogies, and bodies) accelerations that would produce the same damage in 10million cycles ([12], [13]) as would be experienced over the design life of the base-case vehicle. It is assumed that this vehicle was designed for a life of 30years travelling about 60,000km per year [14] (so the acceleration histories calculated for the 40mile stretch of track are repeated about 28 thousand times in the vehicle's life) and the damage for all other vehicles was calculated using the allowable acceleration that is implied by this choice. Note that implicit in this procedure is that fatigue stresses in equipment mountings are proportional to the accelerations, which is reasonable as they would not survive if they experienced large strains. Also it is assumed that stresses resulting from the accelerations in each direction can be considered independently; items that are mounted obliquely or for other geometric reasons affected by more than one direction of acceleration will have lives related to combinations of the relevant stresses.

The damage was calculated by summing the fraction of the number of cycles to failure for each acceleration range in the acceleration histories of the equipment. These ranges were calculated using a Matlab [15] implementation [16] of the rainflow counting procedure [17]. The damage calculations that were used are described in the following subsections.

4.1.1 BS7608 Damage

This is the calculation that is specified in the British Standard for fatigue design and assessment of steel structures [18] referenced in the (British) Railway Group Standard [13]. The damage is calculated using a stress-life (SN) curve appropriate for a specific weld and stress direction. The standard curves are shown in Figure 4.1. It is seen that they are all of the same form so the equivalent acceleration is independent of the weld class that is chosen.

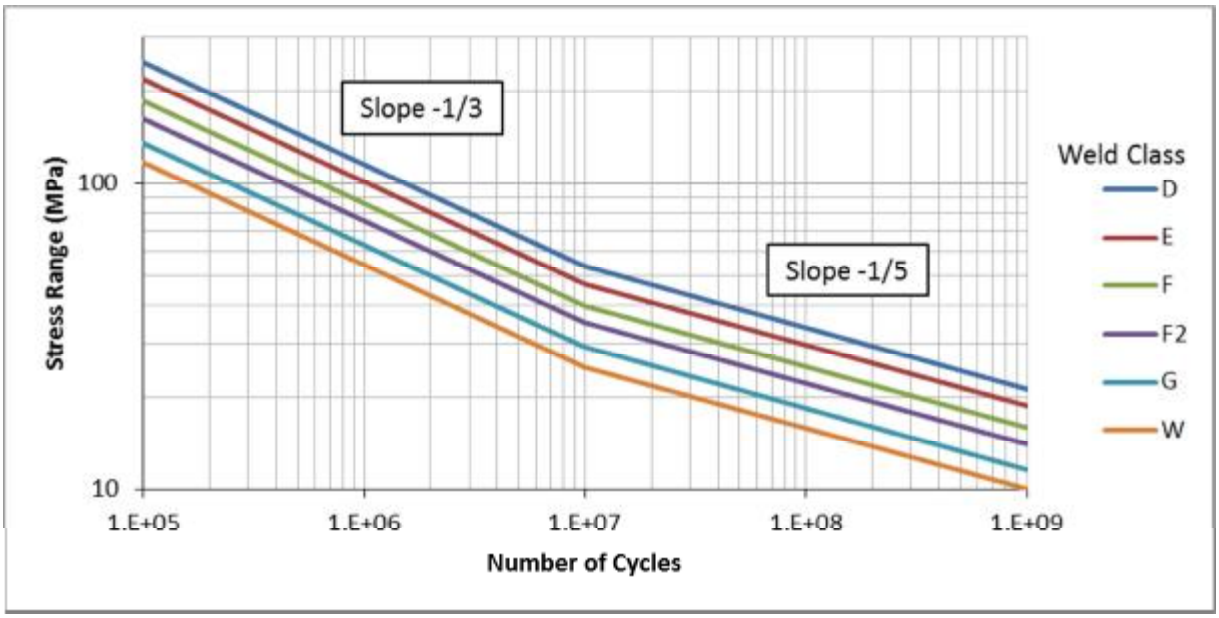


Figure 4.1: SN curves from BS7608

4.1.2 Eurocode Damage in Welds

The European structural standard for vehicle bodies [12] requires that stresses be assessed using "current European, International or national standards". Accordingly the method described in the Eurocode for structural steelwork [19] (Eurocode 3) was implemented. This is similar to the method of BS7608, but uses the SN curves shown in Figure 4.2. Once more the form of the curves means that the equivalent acceleration is independent of the specific detail category that is chosen (note that the detail category is the stress at 2 million cycles).

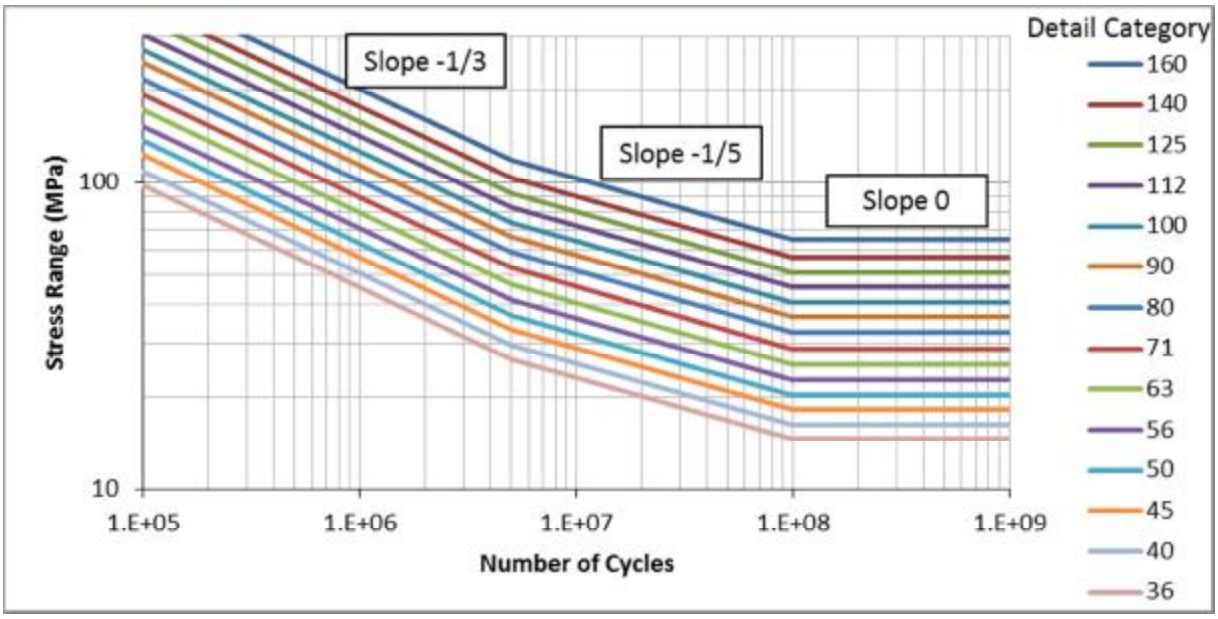


Figure 4.2: SN curves from BS EN 1993-1-9

4.1.3 Eurocode Damage in Plain Metal

The Eurocode for structural steelwork allows the mean stress to be taken into account for "non-welded details or stress-relieved welded details". The effective stress range is calculated by "adding the tensile portion of the stress range and 60% of the magnitude of the compressive portion of the stress range". Once this is done the damage calculation is the same as for welds, using the SN-curves shown in Figure 4.2.

4.2 Results

4.2.1 Acceleration amplitudes

The following plots show the amplitudes (note the range is double the amplitude) of the accelerations that were calculated using the rainflow counting procedure (each cycle also had an associated mean value but these are not indicated). In each plot the number of cycles is shown on a logarithmic scale and the twelve different vehicles are identified by the designations that include:

- N or L: unsprung mass: N for normal (1.8t); L for lower (1.4t)
- Loading: Laden for 21t axle load; PartLaden (or Part) for 11t axle load; Tare for 5t axle load
- Speed: in kph

For each of the three assemblies to which equipment could be attached (axlebox, bogie, and body) there are three plots, one for each acceleration direction (X: longitudinal, Y: lateral, Z: vertical).

Note that the scales on the abscissae are different on each plot; larger accelerations in any direction are experienced by equipment attached to axleboxes than by equipment attached to bogies with the lowest accelerations being experienced by equipment attached to vehicle bodies. Similarly, the vertical accelerations are larger than lateral ones and these are larger than the longitudinal ones.

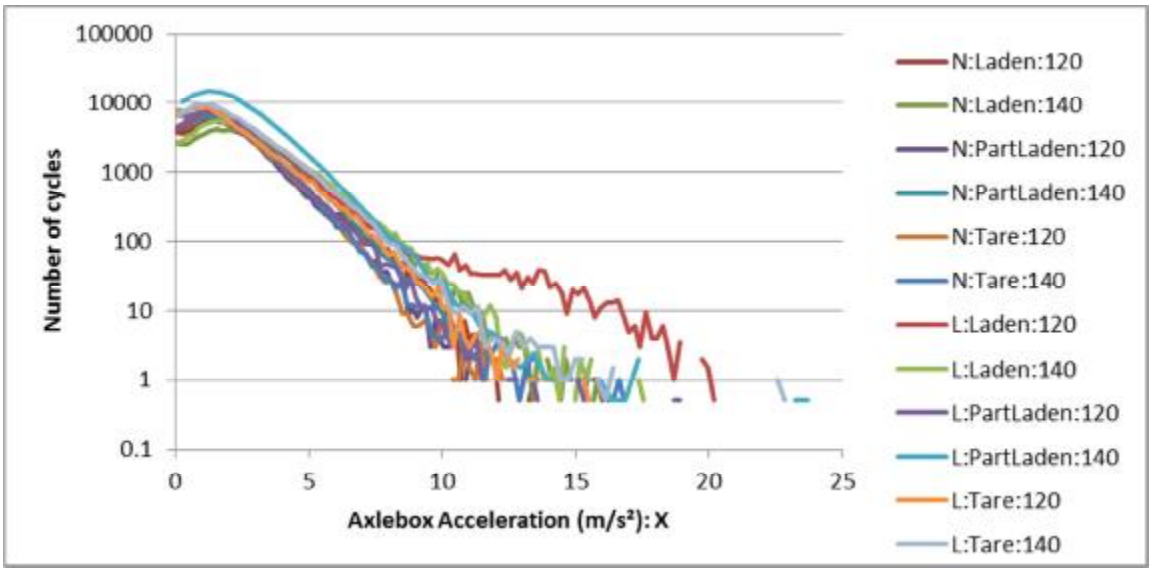


Figure 4.3: Axlebox longitudinal acceleration spectrum

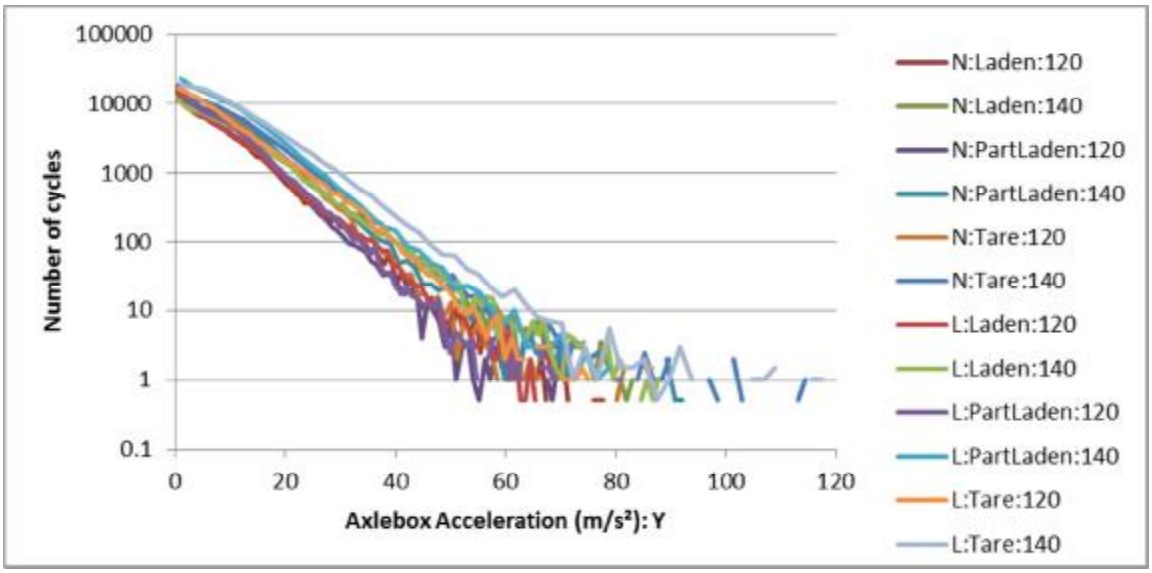


Figure 4.4: Axlebox lateral acceleration spectrum

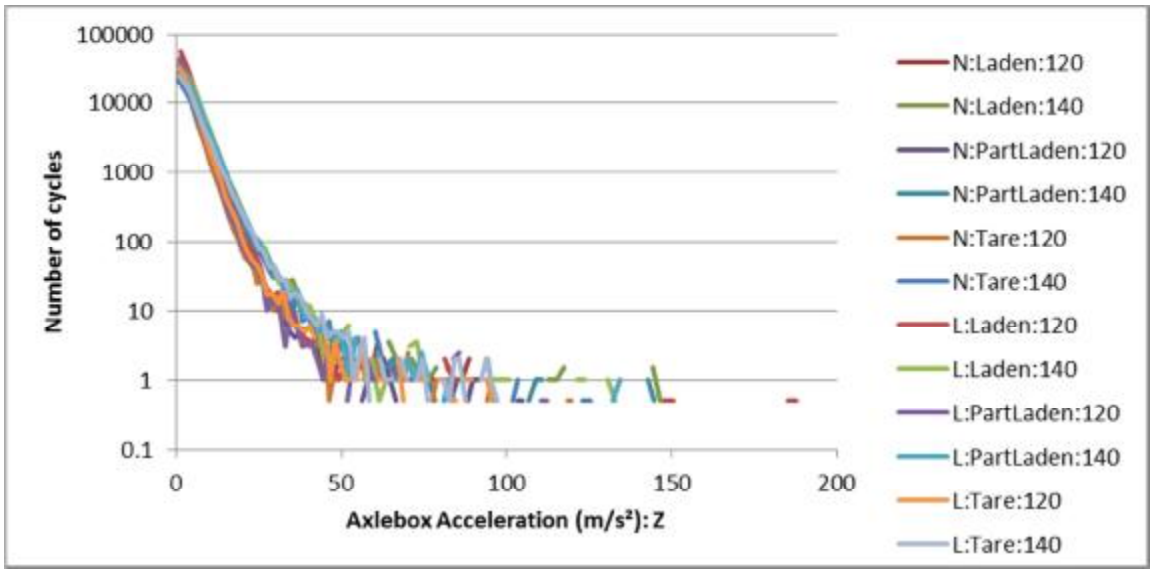


Figure 4.5: Axlebox vertical acceleration spectrum

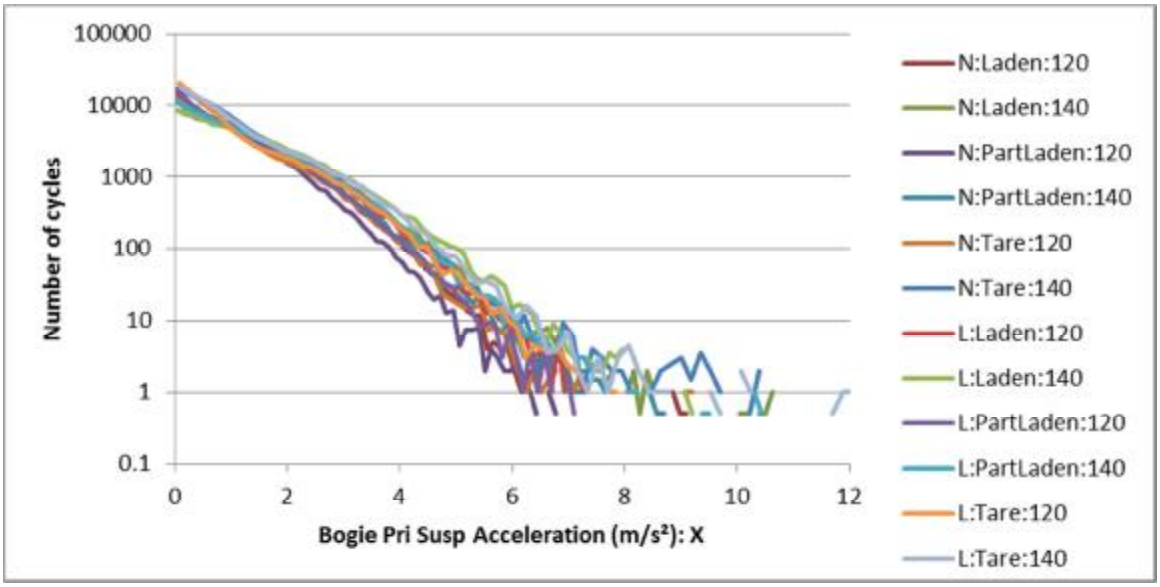


Figure 4.6: Bogie longitudinal acceleration spectrum

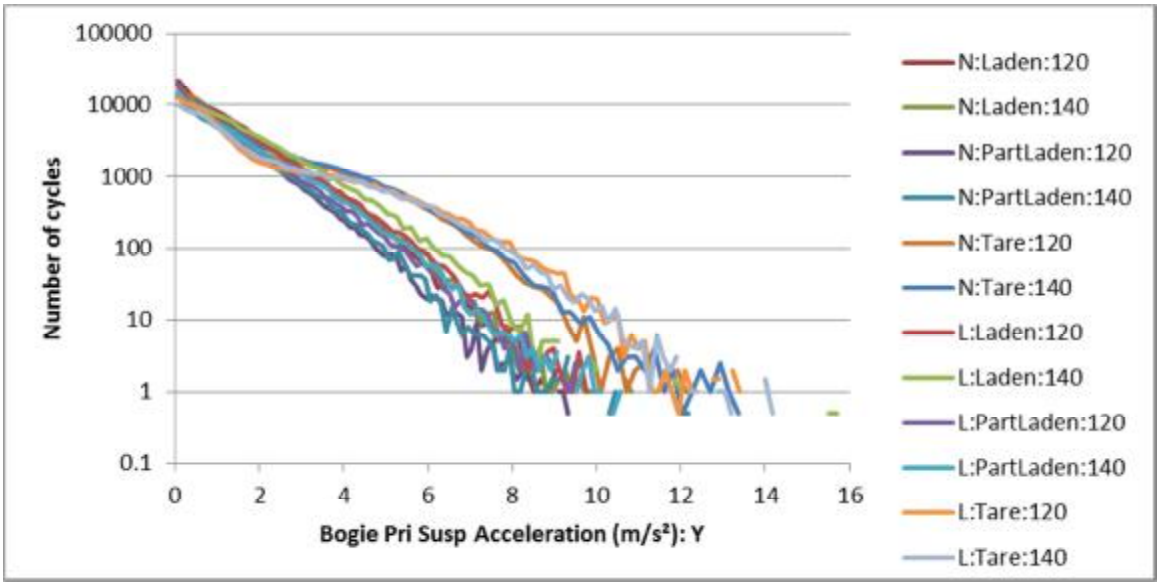


Figure 4.7: Bogie lateral acceleration spectrum

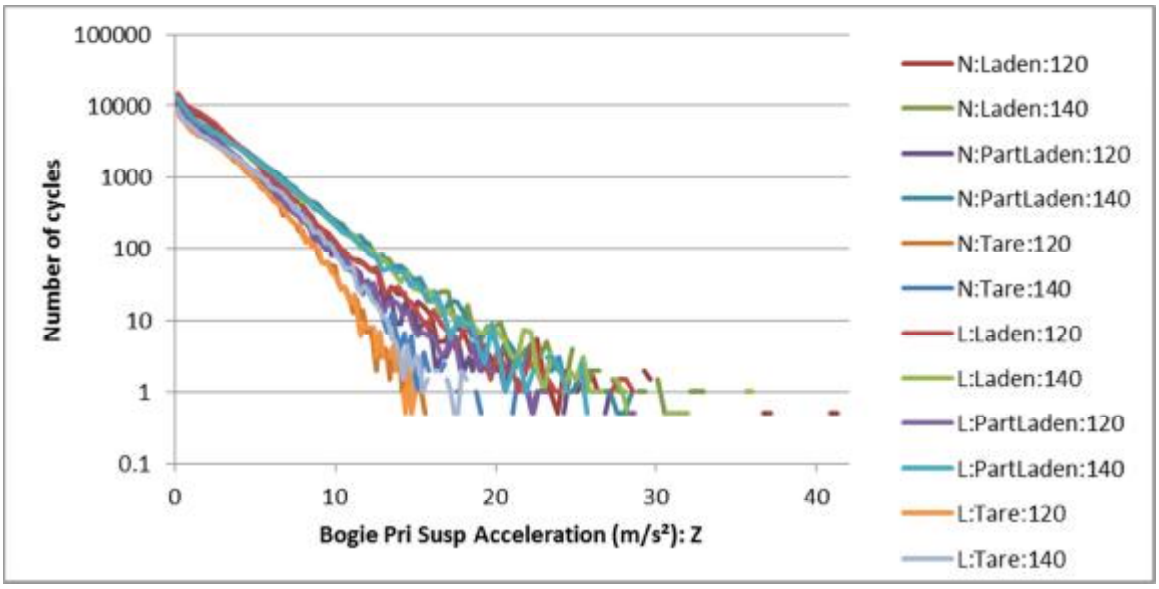


Figure 4.8: Bogie vertical acceleration spectrum

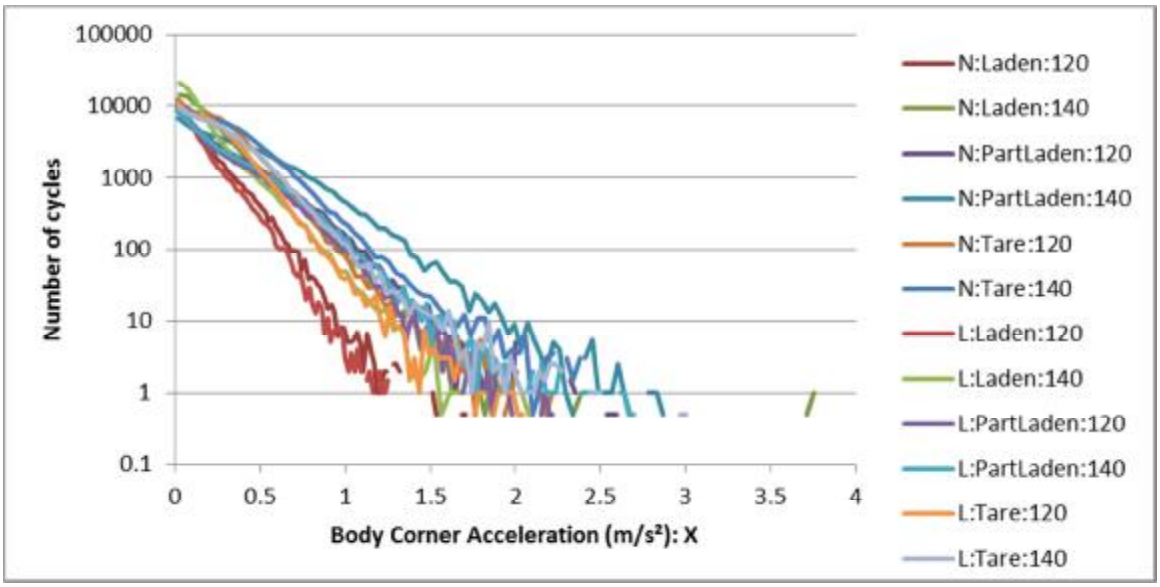


Figure 4.9: Body corner longitudinal acceleration spectrum

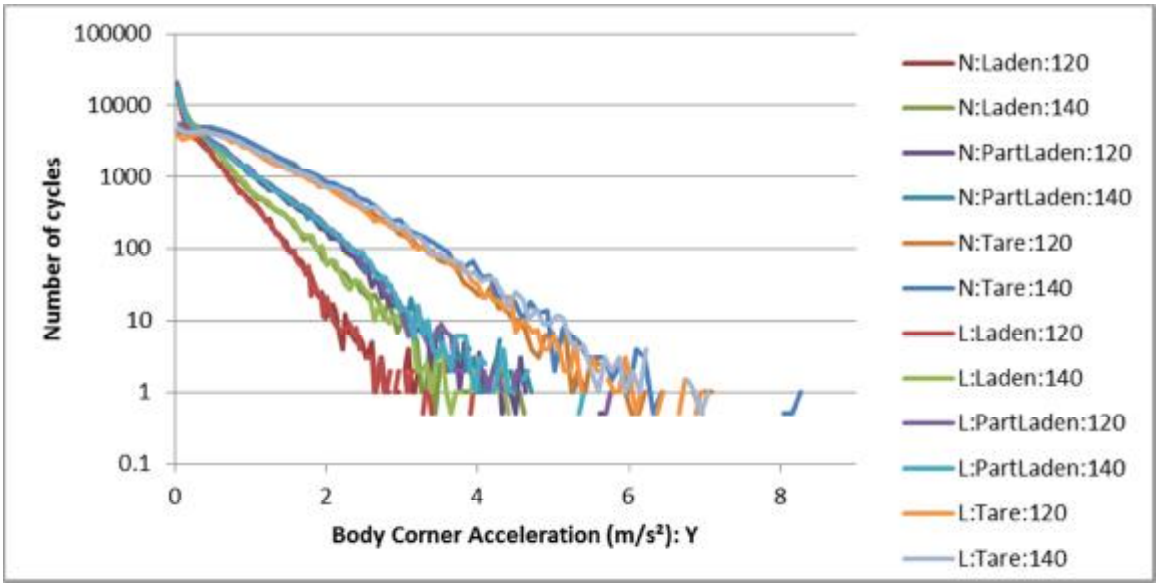


Figure 4.10: Body corner lateral acceleration spectrum

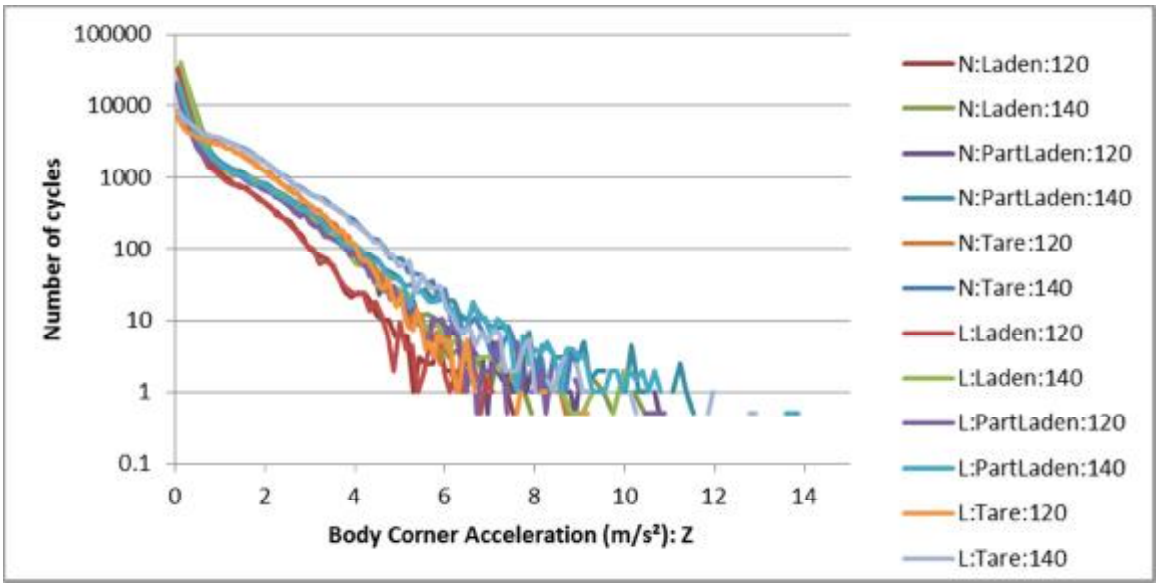


Figure 4.11: Body corner vertical acceleration spectrum

Interpreting these plots as damage on vehicle attachments requires the use of the methodology outlined above, but some preliminary observations can be made by comparing the curves:

- Axlebox accelerations
  - The largest values in each direction are associated with vehicles travelling at 140kph
  - There appears to be an anomaly in the numbers of longitudinal acceleration amplitudes larger than about 9m/s² counted for the laden vehicle with reduced unsprung mass travelling at 120kph (more than expected)
- Bogie accelerations
  - The tare vehicles travelling at 120kph are associated with the lowest vertical accelerations but the highest lateral
  - The part-laden vehicles travelling at 120kph are associated with the lowest longitudinal accelerations
- Body accelerations
  - The unsprung mass has little effect
  - The lowest values in each direction are associated with laden vehicles travelling at 120kph
  - The tare vehicles are associated with the largest lateral accelerations
  - The largest values in each direction are associated with vehicles travelling at 140kph

4.2.2 Equivalent Accelerations

The equivalent constant amplitude accelerations that would give the same damage in 30 years as the spectra shown in Section 4.2.1 are plotted below for the three damage calculations described in Section 4.1. It is clear that (apart from the anomalous longitudinal axlebox accelerations on the “L:Laden:120”, laden vehicles with reduced unsprung mass travelling at 120kph, and the lateral acceleration of the bogie for “L:Tare:…”, tare vehicles with lower unsprung mass) each of the equivalent accelerations is higher for vehicles travelling at 140kph than at 120kph.

Comparative values from appropriate standards (identified at the start of the subsections) are quoted for comparison; note that the values calculated here assume that the vehicle spends its whole life traversing the same 40mile section of track at the specified constant speed so the

values are not expected to be directly comparable but are quoted to illustrate the industry standards.

The consequence of these accelerations on the damage experienced by equipment attached to the vehicles is presented in Section 4.2.3.

4.2.2.1 Equivalent Accelerations for BS7608 Damage

These values can be compared to those specified in Railway Group Standards (RGS) [13]; these are listed under each plot.

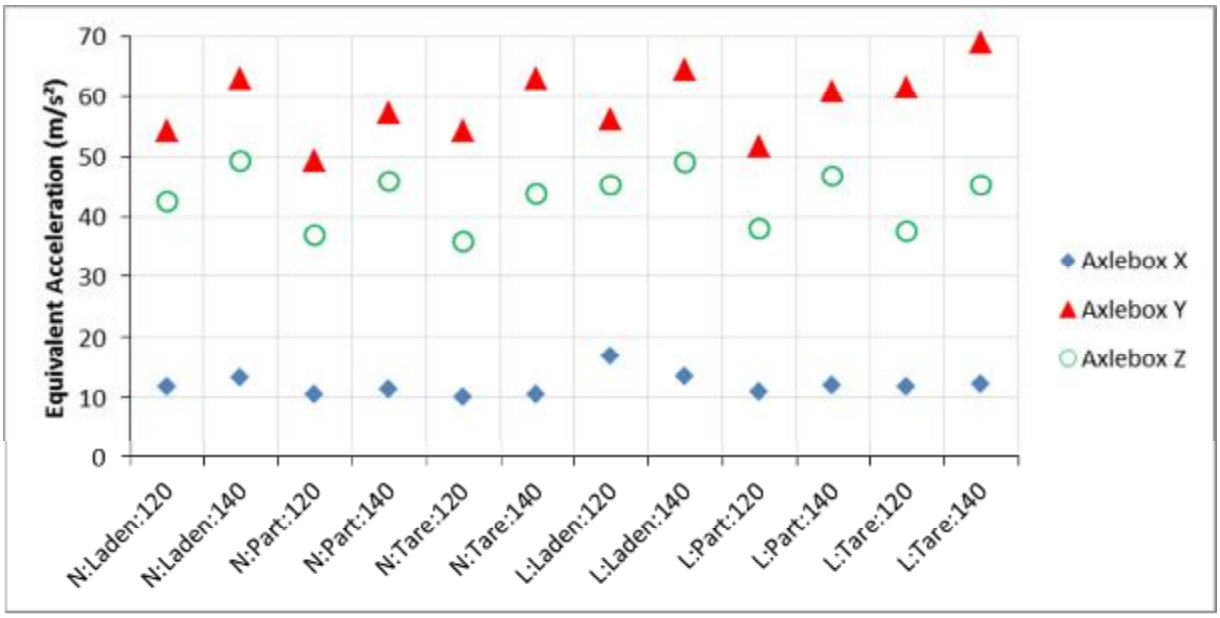


Figure 4.12: BS7608: Equivalent accelerations for equipment attached to axleboxes

Allowable axlebox accelerations from RGS: X n/a; Y 5g=49m/s²; Z 25g=245m/s².

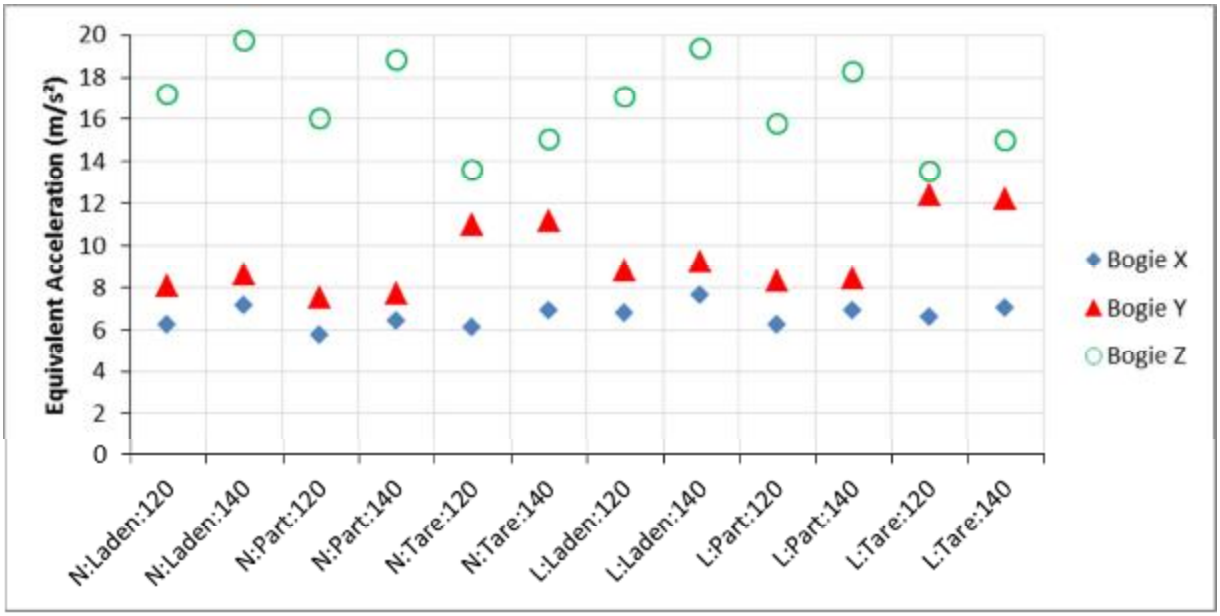


Figure 4.13: BS7608: Equivalent accelerations for equipment attached to bogies

Allowable bogie accelerations from RGS: X 2.5g=24.5m/s²; Y 5g=49m/s²; Z 6g=58.8m/s².

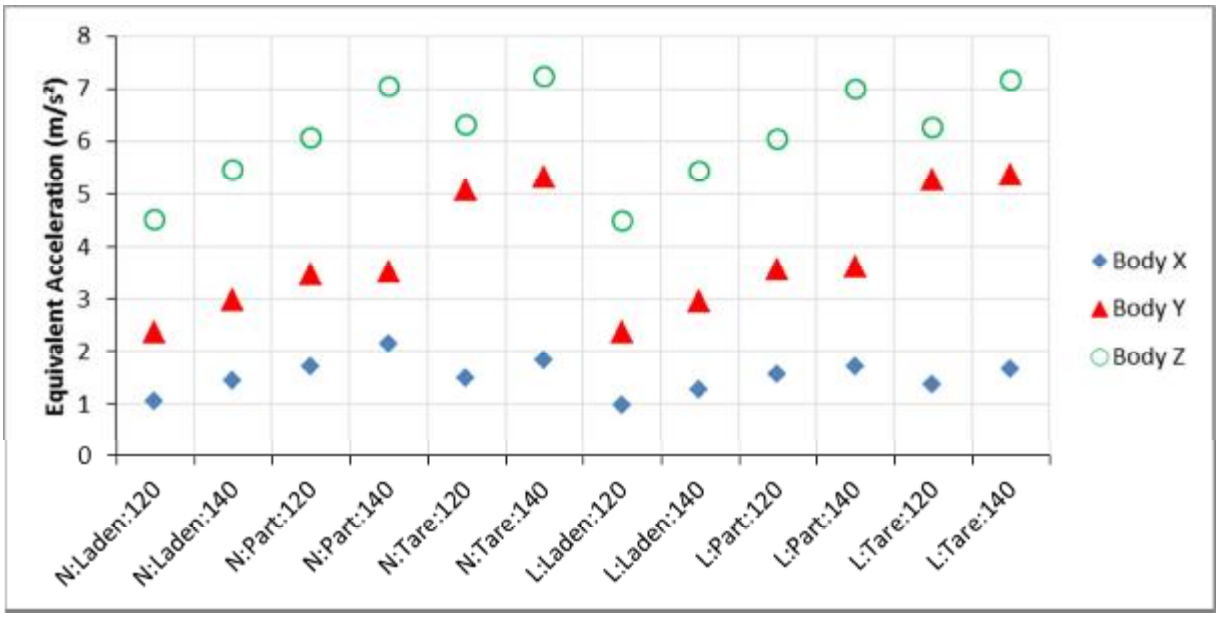


Figure 4.14: BS7608: Equivalent accelerations for equipment attached to vehicle bodies

Allowable body accelerations (RGS specifies using EN [12]): X 0.3g=2.9m/s²; Y 0.4g=3.9m/s²; Z 0.3g=2.9m/s².

4.2.2.2 Equivalent Accelerations for Eurocode Damage in Welds

These values can be compared with those specified in the European structural standard for vehicle bodies [12] or those specified in the European standard for bogies [20] (EN).

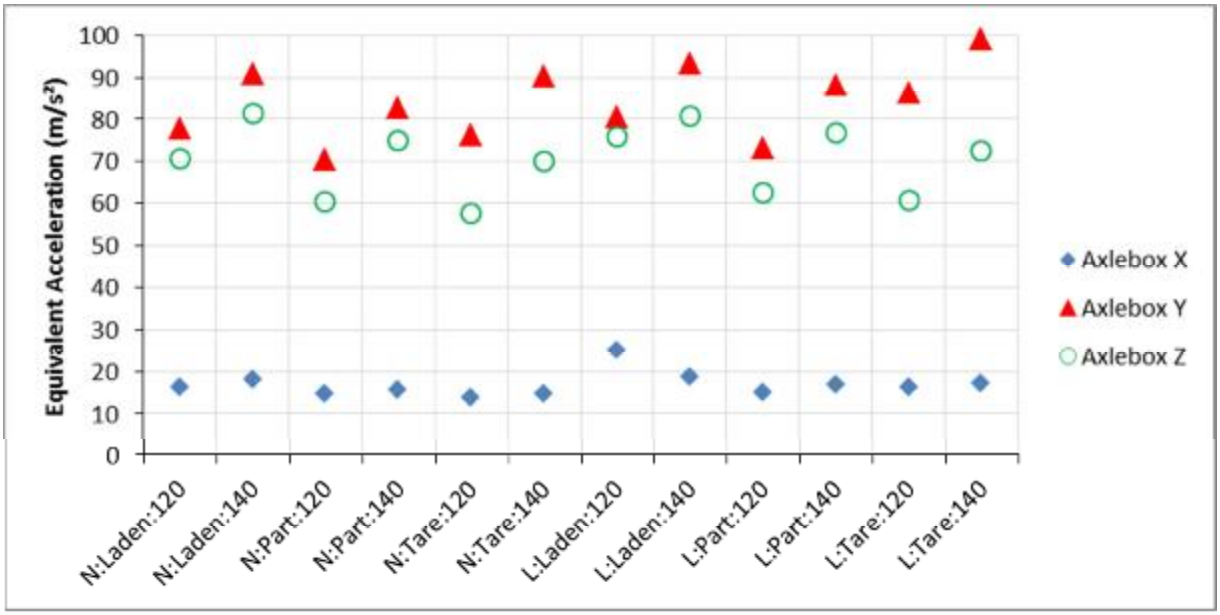


Figure 4.15: Eurocode: Equivalent accelerations for equipment attached to axleboxes (welded)

Allowable axlebox accelerations from EN: X 5g=49m/s²; Y 5g=49m/s²; Z 25g=245m/s².

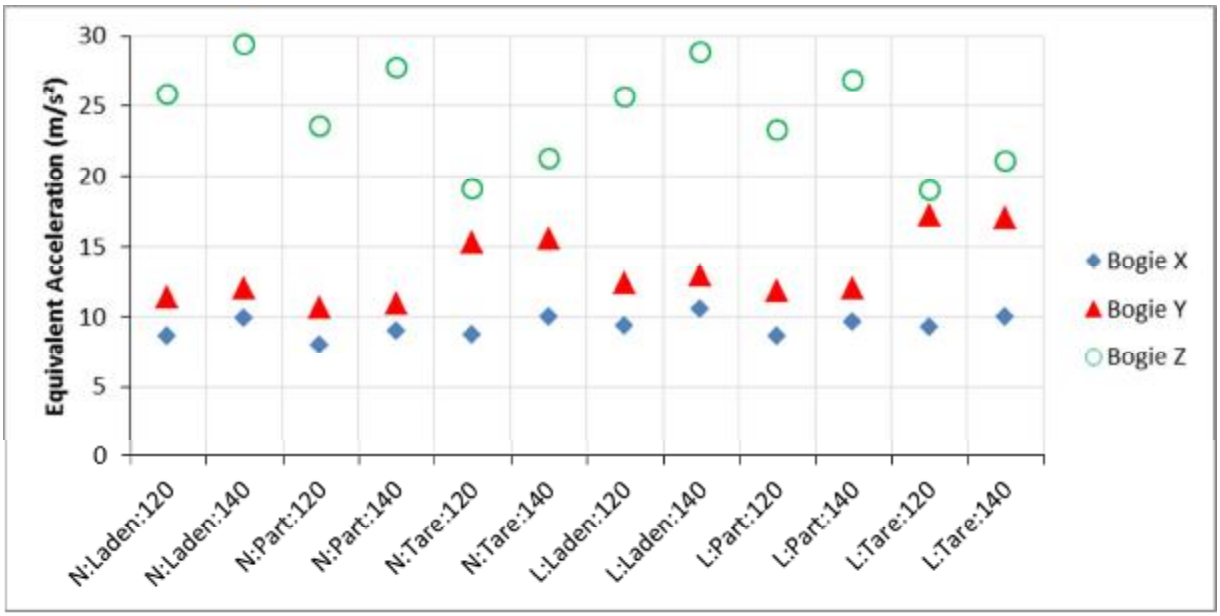


Figure 4.16: Eurocode: Equivalent accelerations for equipment attached to bogies (welded)

Allowable bogie accelerations from EN: X 2.5g=24.5m/s²; Y 5g=49m/s²; Z 6g=58.8m/s².

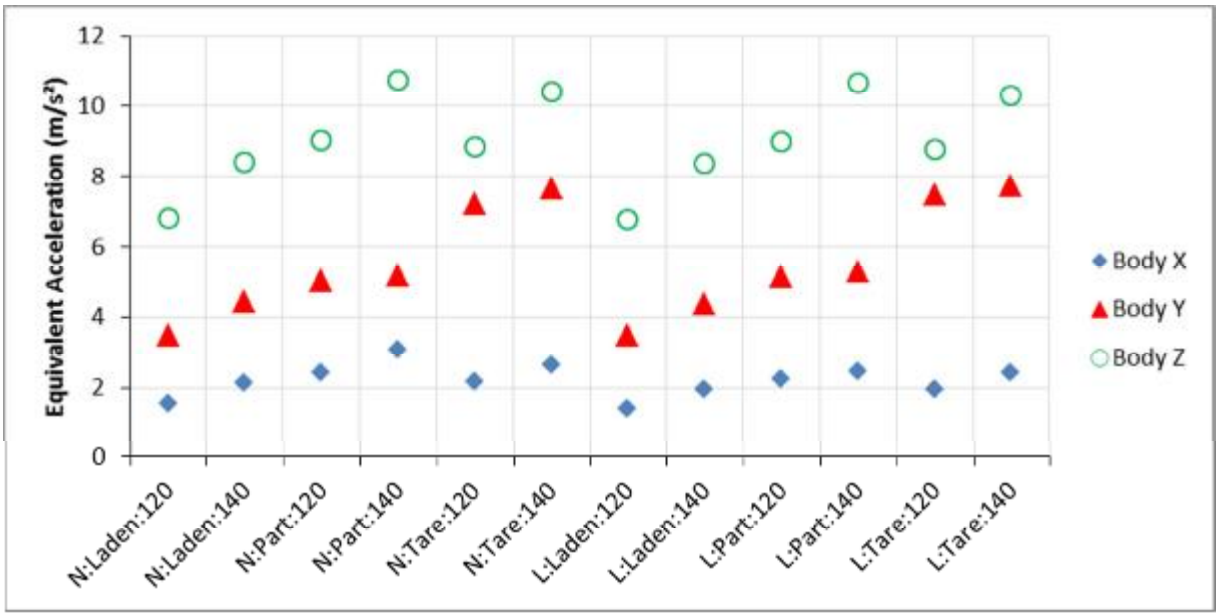


Figure 4.17: Eurocode: Equivalent accelerations for equipment attached to vehicle bodies (welded)

Allowable body accelerations from EN: X 0.3g=2.9m/s²; Y 0.4g=3.9m/s²; Z 0.3g=2.9m/s².

4.2.2.3 Equivalent Accelerations for Eurocode Damage in Plain Metal

The same allowable accelerations apply as for the welds of Section 4.2.2.2, but, instead of amplitudes, the acceleration ranges are used here (once there is a non-zero mean stress the loading is not symmetric).

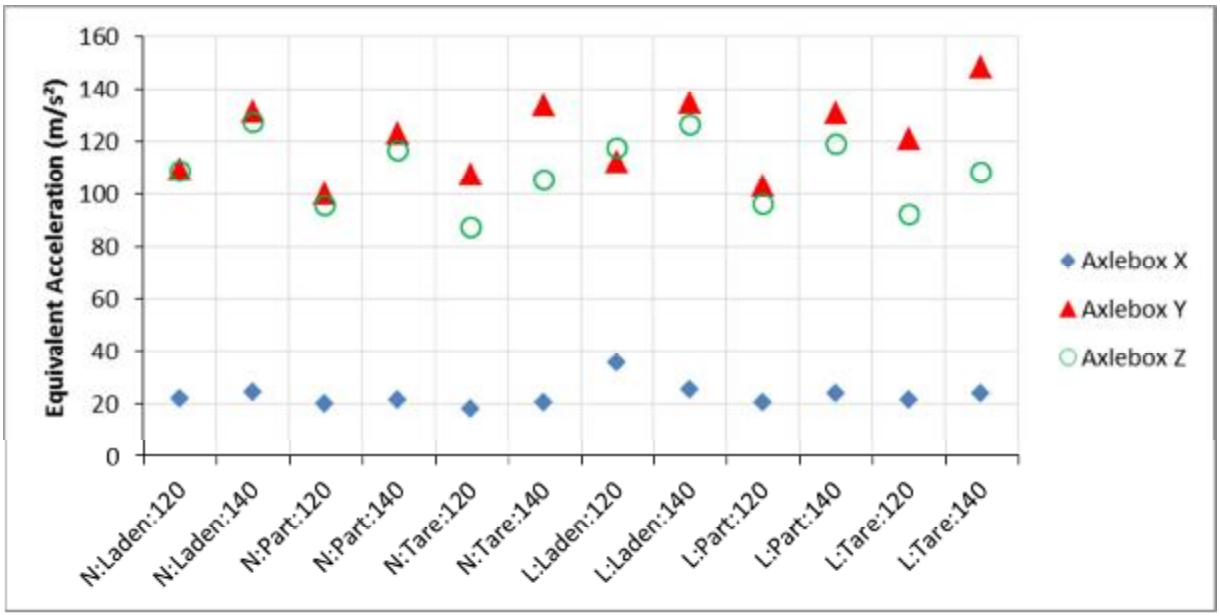


Figure 4.18: Eurocode: Equivalent accelerations for equipment attached to axleboxes (plain metal)

Allowable axlebox accelerations from EN: X 10g=98.1m/s²; Y 10g=98.1m/s²; Z 50g=490m/s².

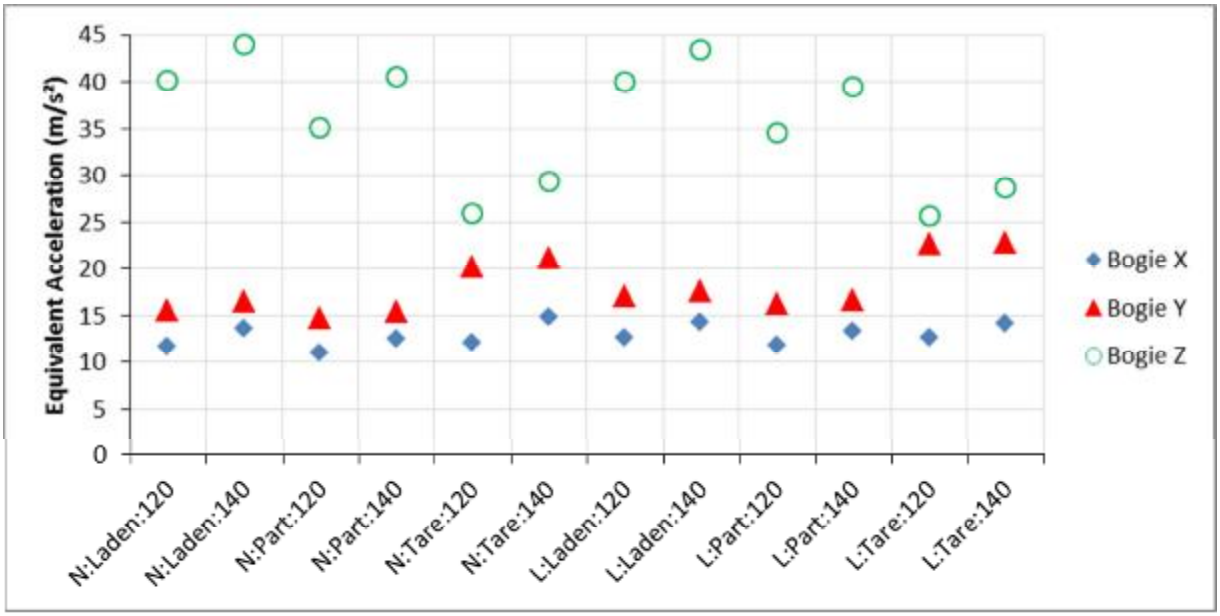


Figure 4.19: Eurocode: Equivalent accelerations for equipment attached to bogies (plain metal)

Allowable bogie accelerations from EN: X 5g=49m/s²; Y 10g=98.1m/s²; Z 12g=117.7m/s².

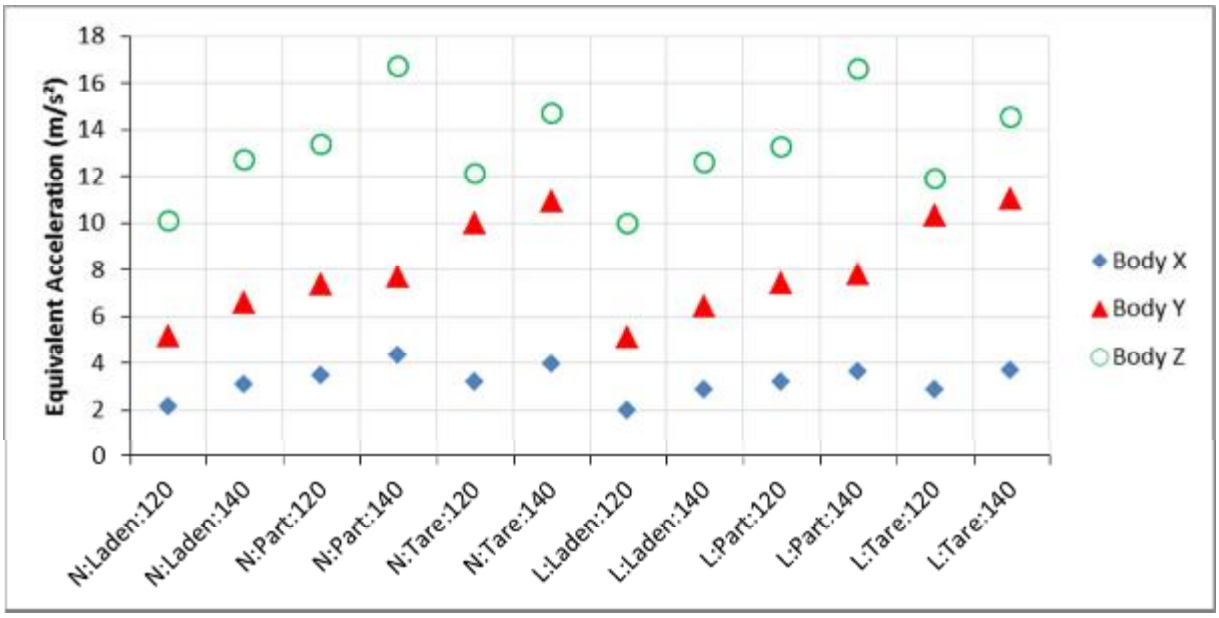


Figure 4.20: Eurocode: Equivalent accelerations for equipment attached to vehicle bodies (plain metal)

Allowable body accelerations from EN: X 0.6g=5.9m/s²; Y 0.8g=7.8m/s²; Z 0.6g=5.9m/s².

4.2.3 Equivalent Damage

The following subsections contain plots showing the damage that would be associated with the stresses produced by the acceleration spectra on a piece of equipment that was designed to be mounted on the indicated part of the vehicle. It is assumed that the design satisfied the requirements for a 30year life when attached to vehicle designed with a normal axle load to travel at 120kph (i.e. equivalent damage≤1 for "N:Laden:120", "N:Part:120", and "N:Tare:120").

4.2.3.1 Equivalent Damage using BS7608 Damage

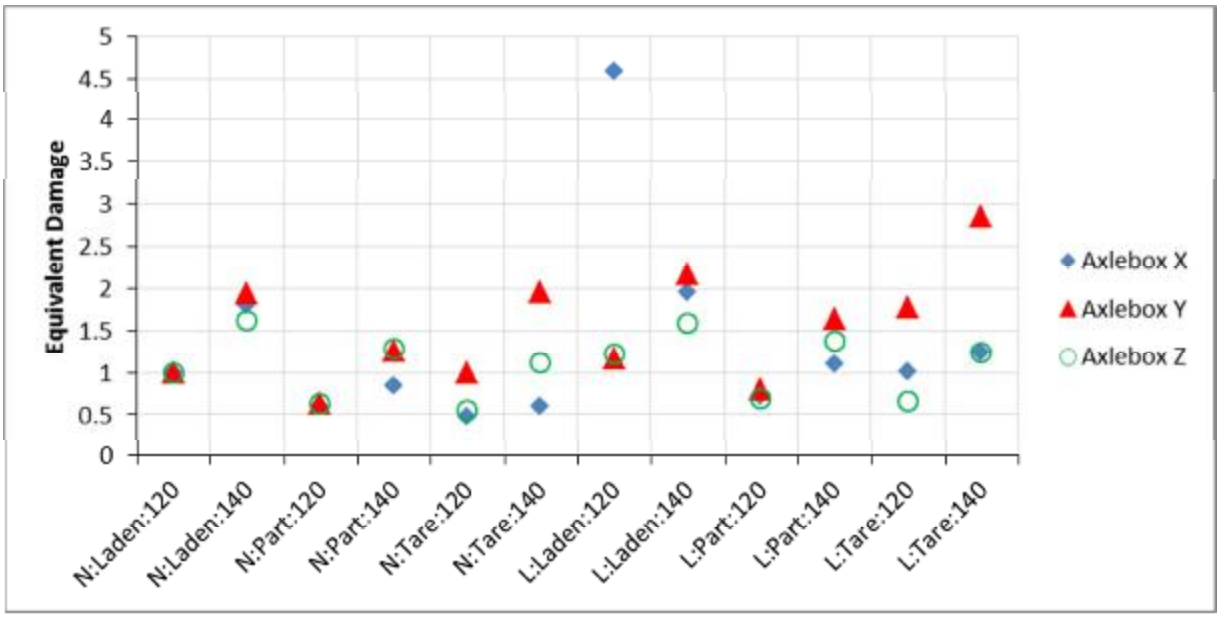


Figure 4.21: BS7608: Equivalent damage for equipment attached to axleboxes

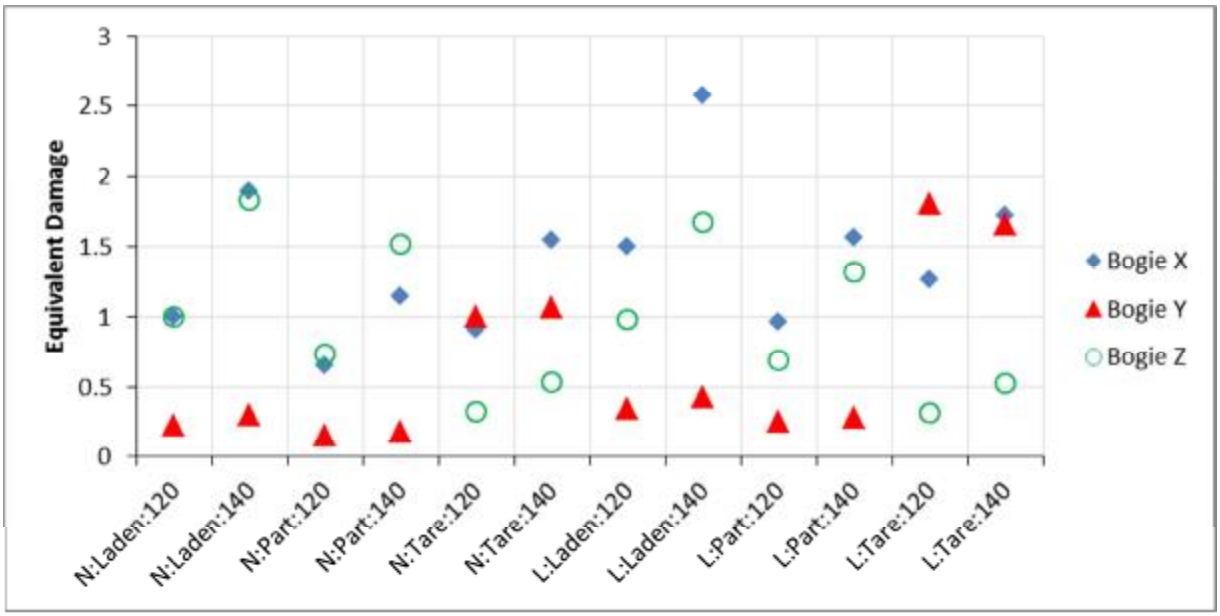


Figure 4.22: BS7608: Equivalent damage for equipment attached to bogies

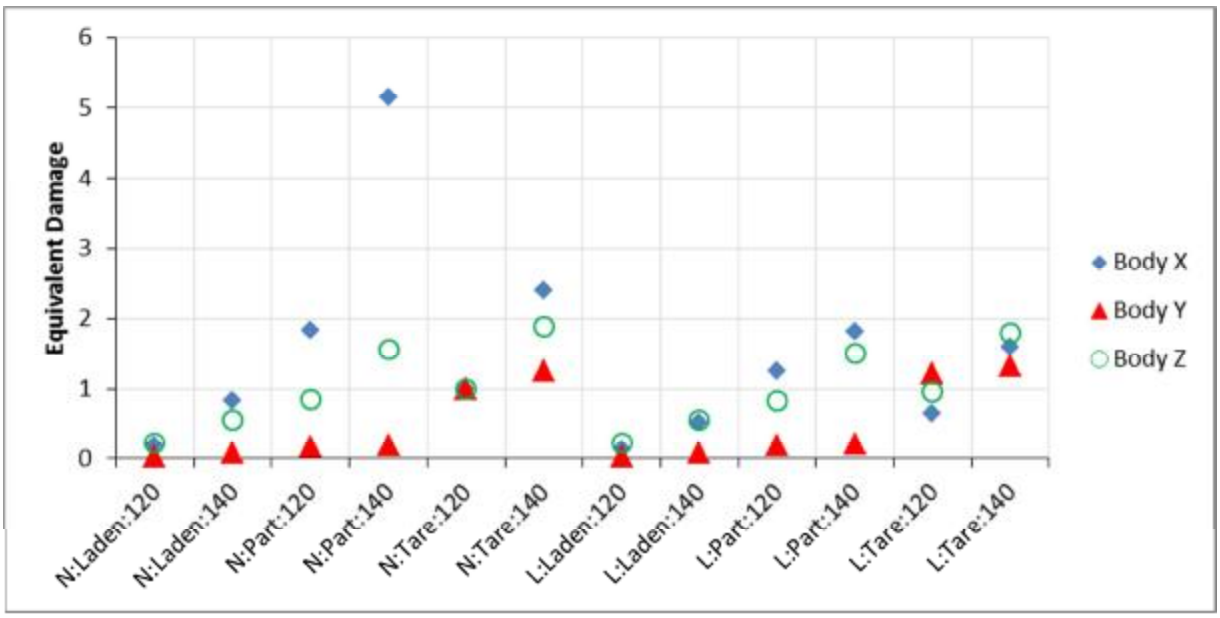


Figure 4.23: BS7608: Equivalent damage for equipment attached to vehicle bodies

4.2.3.2 Equivalent Damage using Eurocode Damage in Welds

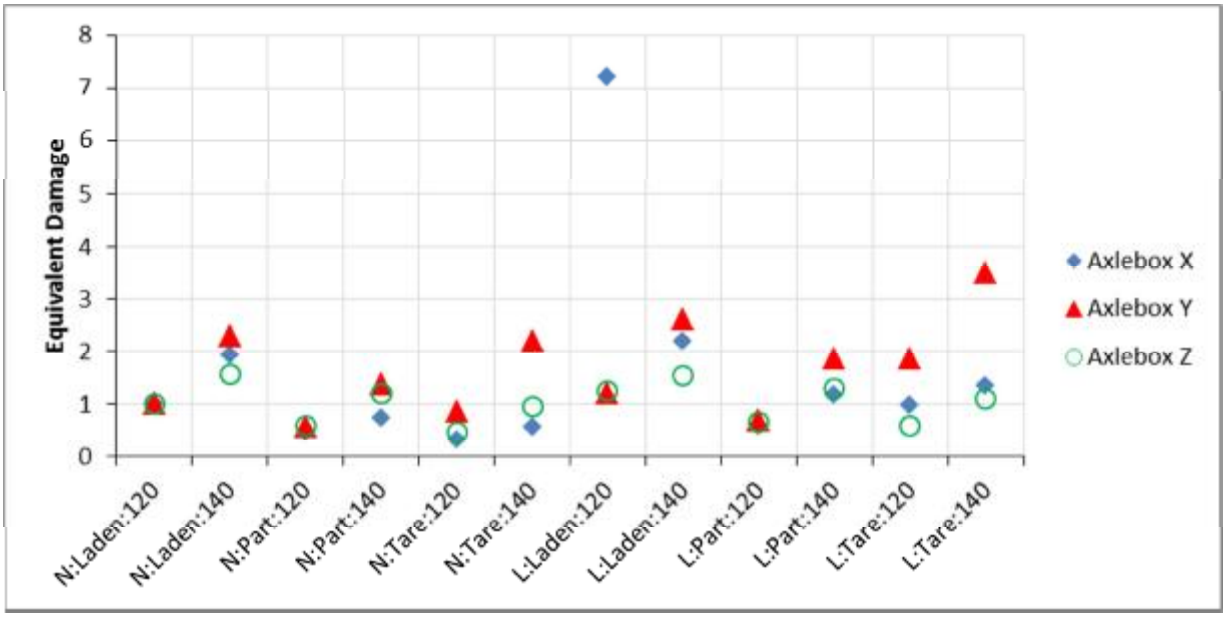


Figure 4.24: Eurocode: Equivalent damage for equipment attached to axleboxes (welded)

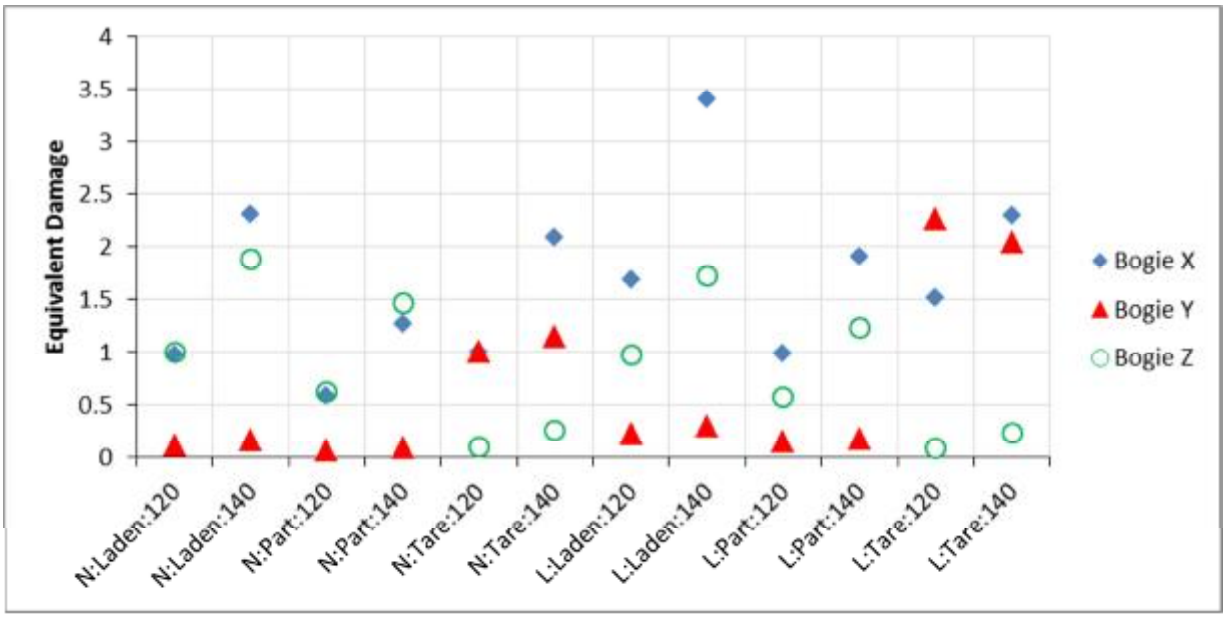


Figure 4.25: Eurocode: Equivalent damage for equipment attached to bogies (welded)

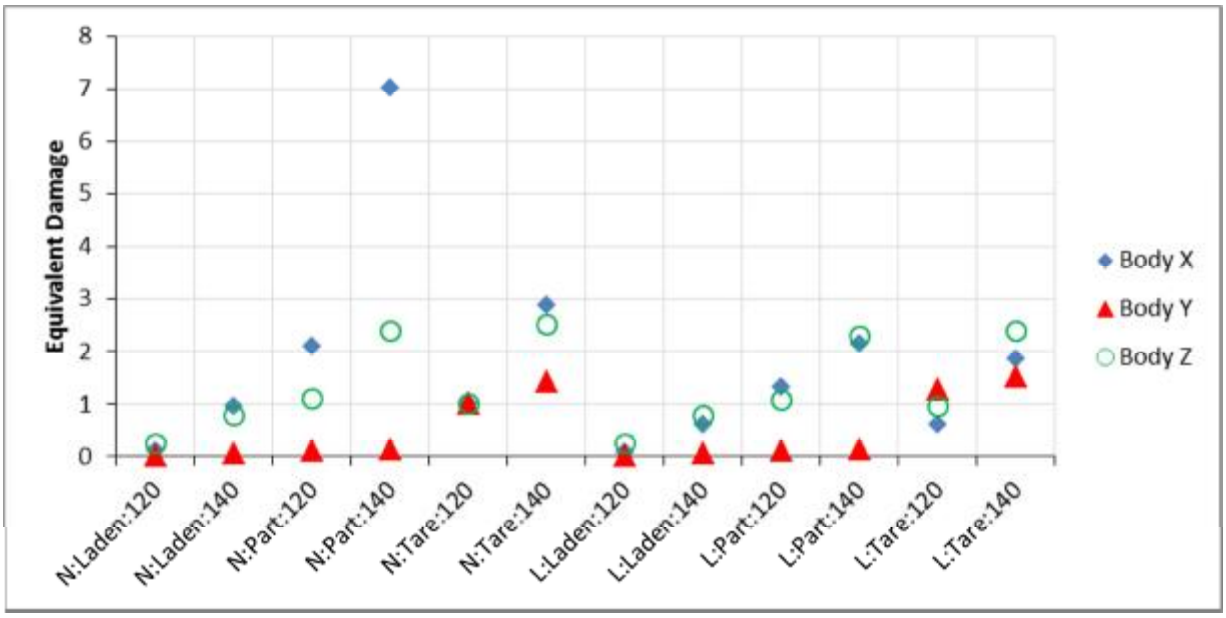


Figure 4.26: Eurocode: Equivalent damage for equipment attached to vehicle bodies (welded)

4.2.3.3 Equivalent Damage using Eurocode Damage in Plain Metal

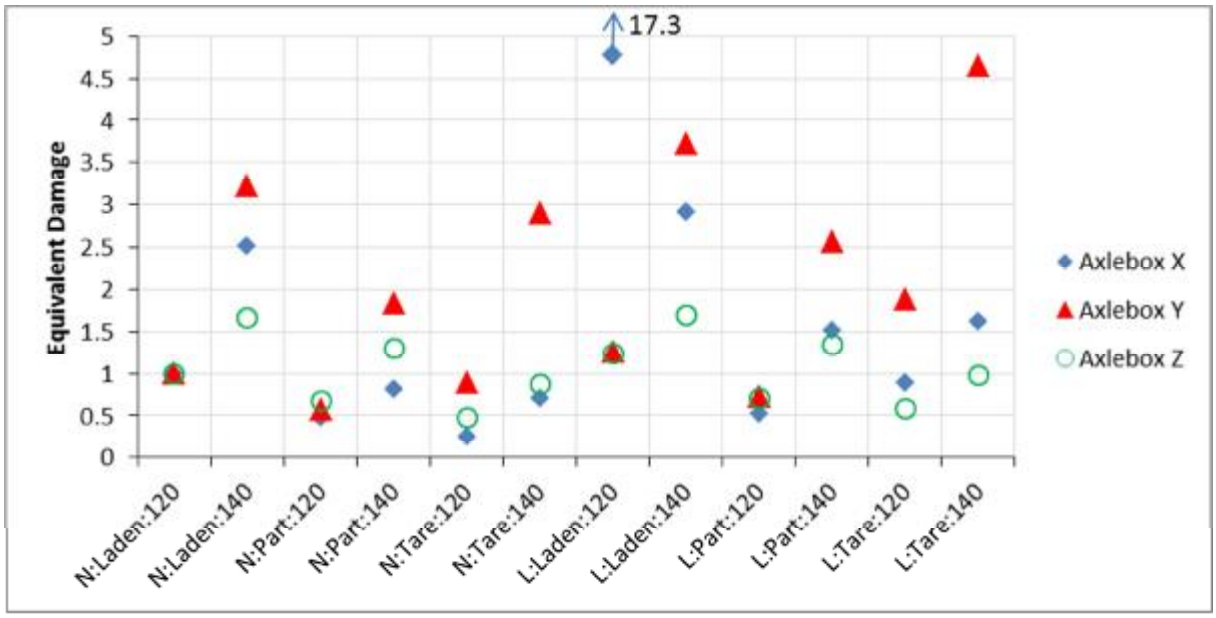


Figure 4.27: Eurocode: Equivalent damage for equipment attached to axleboxes (plain metal)

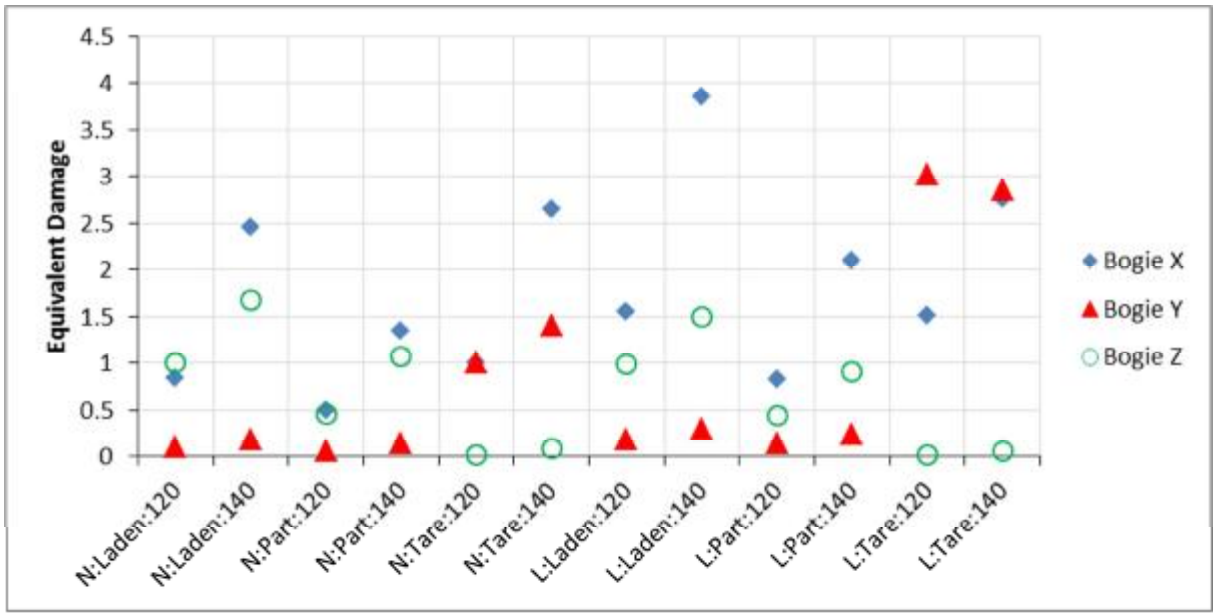


Figure 4.28: Eurocode: Equivalent damage for equipment attached to bogies (plain metal)

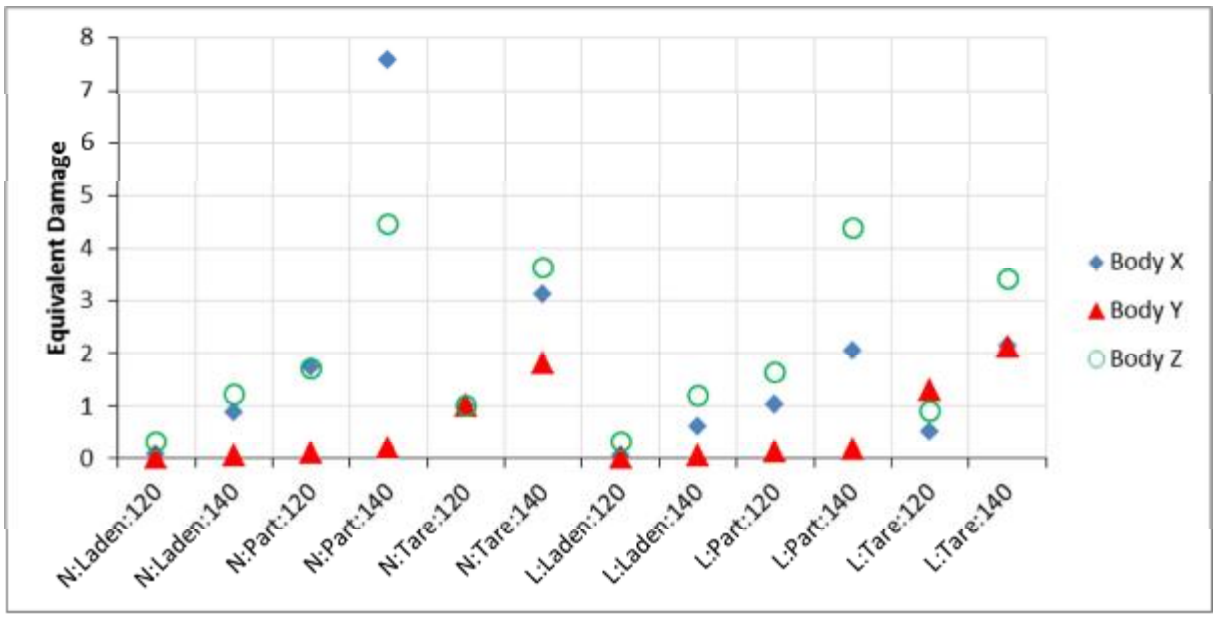


Figure 4.29: Eurocode: Equivalent damage for equipment attached to vehicle bodies (plain metal)

4.3 Discussion

The equivalent accelerations calculated using the BS7608 equations are lower than those calculated using Eurocode 3. This is because the Eurocode omits the damage caused by the large numbers of cycles with very small damage per cycle. The equivalent acceleration ranges for plain metal are a multiple of between 1 and 1/0.6=1.67 those for welds depending how much of the range would be in compression.

The differences in the damages reflect the differences in the equivalent accelerations, but have larger magnitudes resulting from the exponent (3 or 5) in the damage equation.

Comparing the plots in Sections 4.2.2 and 4.2.3 it can be seen that, although the magnitudes of the equivalent accelerations and damage differ, the trends are independent of the equations used to calculate damage (BS7608, or Eurocode 3 for weld or plain metal). The conclusions about relative effects are thus fairly robust, unlikely to be affected by the details of the design features being considered. For clarity the damage calculated using Eurocode 3, weld metal, is used in the comparisons presented below.

The simulations all considered constant speed running; the magnitudes of the accelerations of components associated with traction and braking of freight vehicles are considered to be relatively small for vehicles in normal service, so the associated damage can be ignored.

There are three factors considered in this project: speed, unsprung mass, and axleload; these are considered here. The tables below show the effect of changing these on the damage accumulating in equipment mounted on various parts of the vehicle. In each case the averages are over all relevant vehicles (for example the average effect of speed is found by averaging the effect of speed for the six pairs: N:Laden:120-140, N:Part:120-140, N:Tare:120-140, L:Laden:120-140, L:Part:120-140, L:Tare:120-140). The values can be read as the percentage increase in distance between inspections that would be achieved by not changing the factor (if the distance between inspections is proportional to rate of increase of damage).

4.3.1 Speed

It has been already been noted that the damage experienced by equipment mounted on a vehicle increases with increasing speed. The values in Table 4.1 quantify the increases. It can be seen that for body and bogie mounted equipment the effect on the lateral damage is least whereas laterally mounted equipment on the axlebox is most affected by this speed increase.

Equipment location	Axlebox mounted			Bogie mounted			Body mounted		
Acceleration direction	X	Y	Z	X	Y	Z	X	Y	Z
Increase in damage (%)	55	133	78	108	24	130	372	166	157

Table 4.1: Average effect of speed on damage (percentage increases at 140kph compared to 120kph)

4.3.2 Unsprung Mass

The effect of reducing the unsprung mass is more complicated, as can be seen in Table 4.2. The lighter axle (lower unsprung mass) produces larger accelerations in the axlebox and (apart from vertically) bogie, particularly in the less restrained lateral and longitudinal directions. There is a small effect on the vertical (Z) damage for any location and a significant reduction in damage associated with longitudinal accelerations for body-mounted equipment.

Equipment location	Axlebox mounted			Bogie mounted			Body mounted		
Acceleration direction	X	Y	Z	X	Y	Z	X	Y	Z
Increase in damage (%)	171	44	13	50	97	-9	-43	3	-3

Table 4.2: Average effect of unsprung mass on damage (percentage increases for 20% lighter)

4.3.3 Axleload

The effect of increasing the axleload is far more complicated, as can be seen in Table 4.3. An increase in axleload can be beneficial or detrimental depending on where and with what orientation equipment is mounted. It appears that as axleload increases body-mounted equipment experiences less damage due to lateral (Y) and vertical (Z) accelerations; this is expected since the heavier body has lower accelerations for a given input force.

Equipment location		Axlebox mounted			Bogie mounted			Body mounted		
Acceleration direction		X	Y	Z	X	Y	Z	X	Y	Z
Increase in damage (%)	Part to Laden	141	65	51	69	70	41	-86	-77	-71
	Tare to Part	17	-45	20	-39	-93	498	85	-91	-4

Table 4.3: Average effect of axleload on damage (percentage increases for changes in axleload)

4.4 Conclusions

The effect of changes to freight vehicles on equipment mounted on them has been determined by using the damage calculated from acceleration histories predicted by simulations of the vehicles travelling over 40miles (64.4km) of a UK SustRail route. Considering the damage experienced by equipment mounted at different locations and orientations it was found that:

- Increasing speed from 120to 140kph
  - There is a significant increase in damage (at least 24%) for all equipment
- Reducing unsprung mass (by 20%)
  - Increases damage for equipment mounted on axleboxes and bogies (apart from equipment mounted on the bogie and only affected by vertical accelerations)
  - Reduces damage for body-mounted equipment affected by longitudinal accelerations
- Increasing axleload
  - It is not clear whether this is beneficial or detrimental for most equipment
  - Axlebox-mounted equipment affected by longitudinal accelerations and bogie-mounted equipment affected by vertical accelerations will probably suffer increased damage
  - Body-mounted equipment affected by lateral or vertical accelerations will probably experience less damage

More work is needed to understand the effects revealed in this analysis.

5. SUB-TASK 2.5.4: PRIORITISING THE TECHNOLOGY REQUIREMENTS

This section of the deliverable describes the prioritisation of duty requirements emerging from the work in the five SustRail tasks 2.1-2.5. Participants in the prioritisation were Task 2.5 partners USFD, UNILEEDS, UPM (also representing ADIF), NR, NRIC, BDZ Cargo and MMU, plus coordinator TRAIN and Task 2.1 leader UNEW. VTU provided additional input, alongside Bulgarian partners BDZ Cargo and NRIC. LTU also participated for continuity with Work Package 5. Therefore the participants included freight operator representatives (BDZ Cargo) and IM representatives (NR and NRIC) as well as members of the research team.

Work by other WP2 partners was taken into account through written materials: KTH, KES, MERMEC, MARLO and TATA STEEL.

5.1 Duty requirements and technological solutions

The aim of the exercise was to prioritise duty requirements for the SUSTRAIL innovations in the context of future European rail freight in general and the three case study corridors in particular. The decision process followed was in five steps:

1. The project set out *objectives* which should guide the prioritisation. The objectives were circulated to partners first in October 2011, with the workplan for the prioritisation.
2. *Prior decisions* – certain decisions already taken in the project, e.g. on wagon type, helped to focus the prioritisation exercise.
3. Tasks 2.1-2.5 developed their *analysis of duty requirements*, including: scoping; literature reviews; model development; and results.
4. A *prioritisation workshop* considered the results in light of the objectives. The workshop took input from freight operators & IMs, and led to a list of duty requirements.
5. The research team carried out a final check. Duty requirements were allocated a priority indicator High/Medium/Low. Combinations of duty requirements were considered. This was used to produce a *final list* to take forward.

It is worth noting that duty requirements differ from technological solutions. Duty requirements do not generally specify how the need is to be achieved (i.e. the means) but specify which variable or parameter is to be changed, and where possible in which direction and by how much. Thus an increase in maximum freight operating speed to 140kph is an example of a duty requirement, whilst a new suspension design to allow 140kph running is a specific technological solution.

In some cases, it is possible to identify a key parameter although the magnitude and direction of change will require optimisation within the project (in WP3-5). The detailed modelling of costs and benefits, as well as the engineering-led research, will help guide this optimisation.

5.2 Duty requirements to improve the sustainability of European rail freight

5.2.1 Objectives for the prioritisation

The stated goal is "the greatest increase in sustainability, while meeting the most important operator and IM needs" (DoW Annex 1, SubTask 2.5.4, p15). This increase in sustainability is to be achieved through both:

- *attracting freight market share towards rail* from less sustainable modes (road in particular) by "designing the freight vehicle-track system for higher delivered tonnage with improved availability at reduced cost" (DoW, Annex 1, p1)
- *increasing the sustainability of rail freight* itself

Figure 5.1 gives an outline of the main impact pathways by which these are expected to be achieved. SUSTRAIL will propose changes to the vehicle-track system which have an impact on rail market share by:

- *increasing availability* – providing more disruption-free access to the network for rail freight and passenger traffic, with more optimal network flow
- *reducing costs* – i.e. whole life costs of vehicles, track, and the vehicle-track system as a whole, enhancing the cost competitiveness of rail versus other modes
- *increasing quality* from the end user's perspective, e.g. improved reliability, speed, security or other valued service quality characteristics, leading to a positive demand response from the freight market

SUSTRAIL will also propose changes that will have an impact on the environmental footprint of rail freight, for example reducing CO_2 emissions or noise.

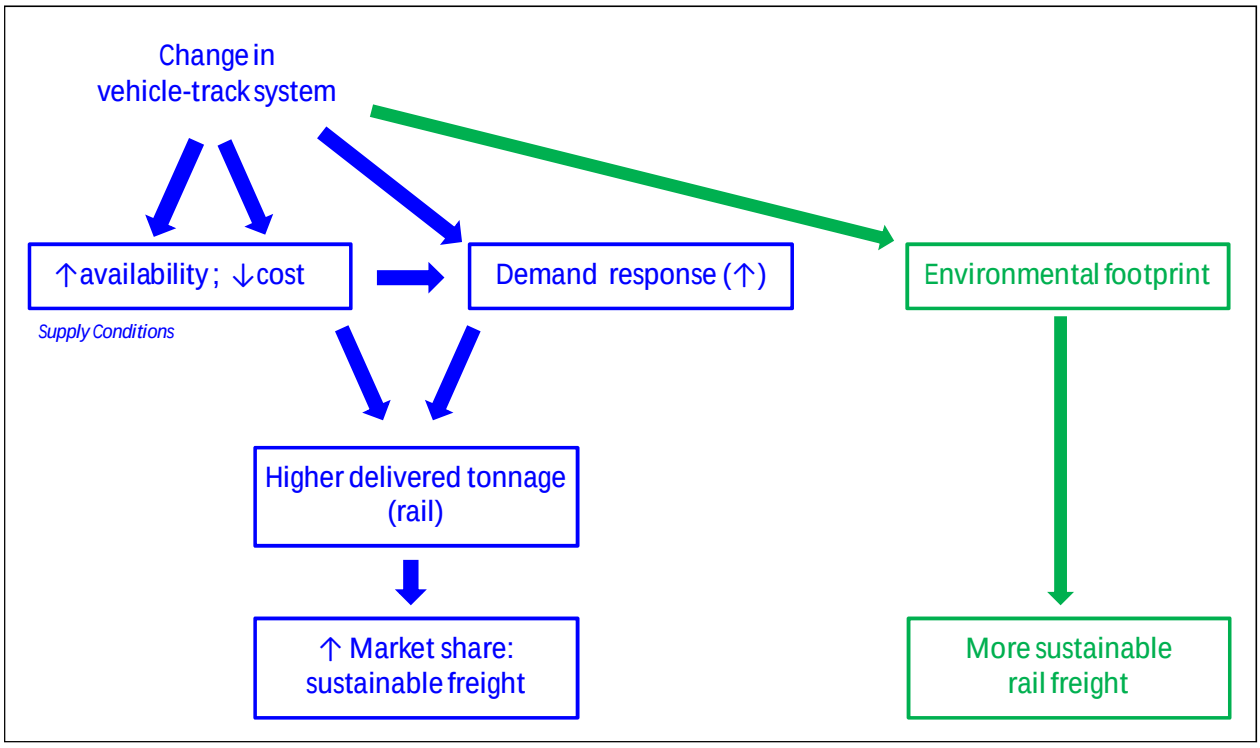


Figure 5.1: Sustainability impacts of SUSTRAIL innovations

At this stage in the SUSTRAIL project, the approach taken is to focus on a set of *intermediate objectives* and to rely on the operators' and IMs' input, as well as the evidence from the SustRail research (Tasks 2.1 to 2.5.3), to carry out a prioritisation. The intermediate objectives are (as above): availability; cost; service quality; and environmental footprint; plus technical viability. Technical viability refers to the operators', IM's and research team's judgement about whether the duty requirements are:

- capable of being addressed by the project with 3 years' intensive research
- implementable by the industry

5.2.2 Prior decisions

Previously in SUSTRAIL, decisions have been taken which help to focus the research and set the scope for the duty requirements. Firstly, it was decided in WP3 to focus on flat container wagons (UIC Class R, S) for intermodal traffic. That decision was informed by the assessment of future logistics requirements in Task 2.2, which found that intermodal traffic is both fast-growing and high-value. Whilst other traffic types have market potential in various countries, intermodal traffic offers the most universal and potentially valuable future market. This was affirmed by the operator and IM representatives at the prioritisation workshop.

Secondly, the Y series bogie, which is widely used on UIC Class R, S vehicles, was chosen by WP3 as the baseline. Bogies of this type are found across other wagon classes as well (e.g. UIC Class E high-sided box wagons), so development work should be of benefit to a wide range of commodity flows.

Thirdly, the Case Study routes will be three mixed traffic routes: in Bulgaria, Spain and the UK. This reflects the prevalence of freight traffic on mixed traffic routes in Europe, and that interactions between freight and passenger traffic will be an important issue for this study. The inclusion of passenger capacity in the 'availability' objective above supports this, as will the analysis to be carried out in Subtask 5.2.3 into 'infrastructure path capacity benefits'.

5.2.3 Analysis of duty requirements: Tasks 2.1-2.5

The duty requirements were developed and analysed in the five Tasks that made up Work Package 2:

Task 2.1 'TSI and standards'

Task 2.2 'Future logistics requirements'

Task 2.3 'Track design requirements'

Task 2.4 'Vehicle performance requirements'

Task 2.5 'Track-train interaction'

Two types of duty requirements emerge from this work:

- *essential duty requirements* – the expectation is that these will remain fixed for the foreseeable future, and form an important part of the background for the SUSTRAIL research – there are a very large number of these
- *duty requirements for improvement* – these are the duty requirements above and beyond current duty requirements which will allow rail freight to become more sustainable and gain market share

5.2.3.1 Task 2.1 'TSI and standards'

Task 2.1 'TSI and standards' is primarily a source of *essential duty requirements*. It provides an extensive set of references to external restrictions and definitions of duty, including:

- European Standards applicable to railways
- UIC Leaflets
- Technical Specifications for Interoperability (TSI)
- National Standards applicable to individual countries

There are a very large number of these standards and TSIs – D2.1 lists 1,238 in total, of which more than 100 are judged to be 'highly relevant' to SUSTRAIL (Franklin et al, 2011). A wide range of performance and safety issues are covered (see Table 5.1), with implications for most

aspects of design. It is implicit that in order to achieve the 'duty requirements', vehicles and infrastructure must comply with standards mandated in TSIs and by individual countries (where applicable).

Authority	Area	Number	Number High Relevance to SUSTRAIL
European Standards	Railway engineering in general	28	11
	Materials and components for railway engineering	27	22
	Railway rolling stock	210	60
	Rails and rail components	65	35
	Equipment for construction and maintenance	6	0
UIC leaflets		664	
TSIs	CR Control – command and signalling	18	
	CR Operation	1	
	CR Rolling Stock – freight wagons	96	
	Noise aspects	20	
	Safety in railway tunnels	11	
National Standards	GB Railway Group and NR	21	
	BS Section 45 Railway Engineering Non-EN	49	10
	Spanish Standards Railway Engineering Non-EN	22	

Table 5.1: Numbers and categories of TSIs and Standards related to SUSTRAIL

The SUSTRAIL innovations will be expected to comply with these standards and TSIs, unless there are exceptional circumstances in which a change in standards might be justified. A case would need to be made for any such change, including an economic and technical case (RSSB, 2010, p21), and it is recognised that the process of securing new or revised standards is "complex" and "challenging" (RSSB, 2012).

5.2.3.2 Task 2.2 'Future logistics requirements'

Task 2.2 'Future logistics requirements' addressed:

- the European freight market – its development and characteristics
- physical requirements of current and future freight flows

Regarding the European freight market, partners carried out an assessment of current flows, market trends and opportunities, held a Workshop at which IM and freight operator representatives input their experience and forward-looking perspectives, and prepared a synthesis of the findings. The main findings arising from this work were the following:

- The intermodal market is both fast-growing and high-value, and has a strong cross-border dimension. Table 5.2 illustrates the gap in value between traditional dry/liquid bulk freight and the growing flows of consumer goods and other (mostly containerised) commodities.

Commodities	Value, €/tonne
Coal	55
Metals (steel)	385
Construction materials (aggregates)	22
Oil and petroleum	320
Consumer goods and other traffic	1870

Table 5.2: Value of rail freight by commodity (Sources: Network Rail/Rail Freight Operations' Association, 2010)

In countries with maritime ports, and in countries with high levels of transit traffic (e.g. the Bulgarian case study, where already 50% of rail freight is transit traffic and the fastest-growing flows are with trading partners outside the EU to the east and south), intermodal services are key to capturing a greater modal share of international traffic from less sustainable modes. There is also rapid growth in domestic intermodal services, e.g. in the UK by 87% in the 10 years from 2002/3 to 2011/12 (3.38-6.31billion tonne km) (ORR, 2012), where rail is seen by end users as a strategic opportunity to reduce fuel costs and environmental footprint.

- Other specific market segments with growth potential for rail freight include: automotive (vehicles and components); urban construction materials; biomass; and recyclates. These, however, are secondary in value to the intermodal market.
- Nevertheless there are potential economies of scope because (i) there is widespread use of Y25 and derivative bogies across not only intermodal wagons (UIC Classes R,S) but also other types such as traditional high sided wagons for dry bulk freight (UIC Class E); and (ii) intermodal vehicles have the potential to serve multiple markets (including e.g. automotive component flows).

Considering the findings on current freight flows, the general and route-specific trends, as well as the future market opportunities for rail freight, Task 2.2 found that future rail vehicles should be designed to accommodate:

- cargo with a lower physical density and higher value
- smaller consignments in general
- various types of intermodal loading units (containers, swap-bodies, semi-trailers)
- items to be carried in reverse logistics processes (including returns, returned empties, packing material, and other waste)

Sustainable future rail vehicles should:

- be interoperable in use on different national railway networks
- be 'intelligent' (enabling supply chain visibility and vehicle condition monitoring as well as emergency response)
- be reliable in operation
- have design features to suit cargo to be carried under current and future market conditions (e.g. refrigeration for perishable foodstuffs through hotter climates)
- have a lower tare weight and an improved aerodynamic performance
- cause less noise
- have track friendly bogies
- be able to run at a higher speed

Regarding speeds, there is a general need across the case study routes to increase average freight operating **speeds**, although the specific requirements vary by route. The primary motivation is to maximise track capacity and service reliability by better integrating freight trains with passenger services. Increasing freight train maximum operating speeds is key to increasing average speeds towards line speed.

On the Mediterranean Corridor (Spain), 120kph capability is seen as an appropriate target, and is being achieved by some containerised freight on parts of the route. Barriers to be overcome include the speed limitations for some wagon types, signalling systems, and the interaction with short-distance passenger trains on the network around urban areas. On the UK route, raising the speed of all freight trains to 120kph would be valuable, and to 130 or 145kph more so. There are plans to upgrade the Bulgarian route, which would allow a target speed similar to the Mediterranean Corridor.

There is also an economic interest in optimising **axle load limits** for typical EU mixed freight/passenger routes such as the three SustRail case studies, where the axle load limits are approximately 22.5t. Whether the optimum is an increased axle load limit (e.g. to 25 or 25.4t), or not, is an empirical question that should be subject for further investigation in WP3-5. For bulk freight, greater vehicle payloads offer cost efficiencies for the operator, which might be partially/wholly offset by the cost increment in track maintenance. For containerised/intermodal freight, payloads tend to be volume-limited rather than weight-limited (D2.2, Platz et al 2012, contains calculations), therefore containerised freight adds little to the case for raising the axle load capability of the track. Conversely there may be a case for setting a specific and *lower* axle load limit for intermodal trains, where a lower axle loading capability is traded for higher speed limit specific to these trains. Again, WP3-5 should examine these trade-offs with the aim of identifying the combination(s) offering the best business case, in terms of efficiency, profitability and acceptability to the key parties (IM, operators, and end users).

5.2.3.3 Task 2.3 'Track design requirements for reduced maintenance'

Task 2.3 focused on the track duty requirements and definition of the IMs' needs.

Monitoring and inspection requirements were gathered for the three case study networks - BG, ES, and UK. These include inspection frequencies, levels of inspection, techniques and equipment used. Table 5.3 shows the current inspection frequencies for the UK (Loiero et al, 2012) – track category 1A is the most and 6 is the least intensively used.

	Track Category						
Activity	1A	1	2	3	4	5	6
Basic visual inspection of plain line jointed track	N/A	Twice per week	Twice per week	Once per week	Once per week	Once per 2 weeks	Once per 2 weeks
Basic visual inspection of plain line CWR	Once per week	Once per week	Once per week	Once per 2 weeks	Once per 2 weeks	Once per 4 weeks	Once per 4 weeks
Basic visual inspection of strengthened S&C	Once per week	Once per week	Once per week	Once per week	Once per week	Once per week	Once per 2 weeks
Basic visual inspection of non-strengthened S&C	N/A	Twice per week	Twice per week	Once per week	Once per week	Once per week	Once per 2 weeks
Supervisor visual inspection of S&C and jointed track	8 weekly	8 weekly	8 weekly	13 weekly	13 weekly	13 weekly	13 weekly
Supervisor visual inspection of CWR plain line	16 weekly	16 weekly	16 weekly	16 weekly	16 weekly	16 weekly	16 weekly
Engineer visual inspection	104 weekly	104 weekly	104 weekly	104 weekly	104 weekly	104 weekly	104 weekly
Supervisor cab riding	8 weekly	8 weekly	13 weekly	26 weekly	26 weekly	26 weekly	26 weekly
Engineer cab riding	13 weekly	13 weekly	26 weekly	52 weekly	52 weekly	52 weekly	52 weekly
Ultrasonic rail inspection of jointed track	8 weekly	13 weekly	26 weekly	52 weekly	52 weekly	52 weekly	52 weekly
Ultrasonic rail inspection of CWR track	13 weekly	26 weekly	52 weekly	104 weekly	104 weekly	104 weekly	104 weekly
Reportable track geometry recording	4 weekly	8 weekly	12 weekly	16 weekly	24 weekly	24 weekly	24 weekly

Table 5.3: Inspection frequencies (Network Rail)

In general, higher line speed and increased traffic level (Equivalent Million Gross Tonnes per annum, EMGTPA) will increase the required frequency of inspections. Since inspection costs are significant in IMs' total maintenance costs (UK: 19%; Sweden 12%), innovations which reduce inspection frequency or costs are potentially valuable for improving the IMs' efficiency (costs per track km).

Mobile inspections by track measurement vehicle are already used on all three networks, gathering a wide range of parameters including track geometry, rail profile and condition, crack detection using ultrasound, accelerations measured at the axle, and catenary performance. In addition, ground penetrating radar (GPR) can be used to identify trackbed condition and help to achieve better targeted trackbed maintenance.

Fixed lineside vehicle monitoring is another potentially important tool. Data on static and dynamic axle loads can be used to detect wheel faults, vehicle imbalances and axle load exceedances – which is potentially valuable information for both the freight operator and the IM.

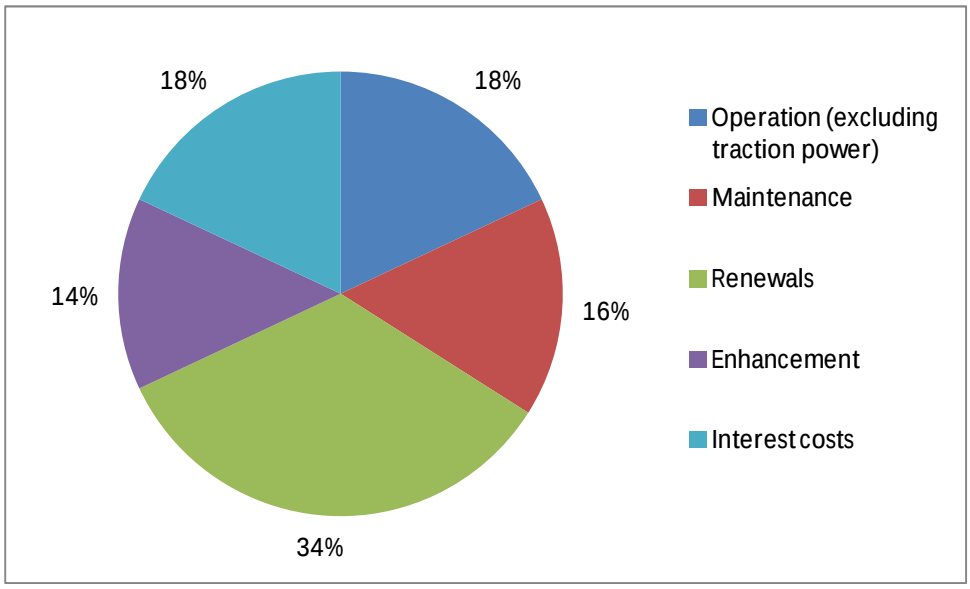
Maintenance strategies, schedules and costs: The maintenance strategies on the three case study routes exhibit a combination of regular/cyclical maintenance and "maintenance by state". Thus for example rail grinding is carried out every 45 EMGT on Network Rail (except on curves with radius <2500m, 15 EMGT), whilst corrective action for cross levelling is triggered by an inspection finding a point defect greater than ±5mm on the Mediterranean Corridor.

In general, intervention criteria depend on:

- mean,
- standard deviation, or
- extreme values

for each track parameter, and differ somewhat across the three case study routes – e.g. the values triggering intervention for track-gauge defects are ±4mm on a 160kph line in Bulgaria, vs. ±7mm for a point defect or 1.5mm over a control section on a 160kph line in Spain[5]. These country and route-specific 'essential' maintenance requirements are set out in Loiero et al (2012).

Looking forward, SUSTRAIL is focused on improvements to the vehicle-track system which reduce whole system cost, and even go "towards zero maintenance". There is a clear rationale for this: maintenance and renewals make up >50% of IMs' costs (Figure 5.2). At the same time, it needs to be remembered that the other cost categories exist, and any impact on those will need to be taken into account in SUSTRAIL. The example of slab track (below) illustrates this.



Source: Network Rail expenditure 2009/10 in England & Wales, other countries will vary

Figure 5.1: IMs' cost composition

One technology that could be pursued is a radical shift of track type, towards slab track. Loiero et al (2012) found that this offers a reduction of track maintenance unit costs from approx. €9-15/m/year for ballasted track, to approx. €5-7/m/year for slab track. However, Stalder (2001) also finds that the investment costs are €1300/m for slab track versus £500/m for ballasted track. In terms of life cycle costs, the same author estimates slab track to be 8% more expensive.

Furthermore, maintenance requirements – and costs – are driven in part by factors such as

- axle load
- maximum speed
- curve radius
- train frequency
- gross tonnage (EMGT)

If the other SUSTRAIL duty requirements impact on any of these factors, there may be unintended changes in maintenance cost. For example the proposed increase in freight operating speeds to 120 or 140kph is likely to increase track maintenance costs if other variables are kept constant.

[5] for a 3-25m wavelength (Spain)

Task 2.3 also addressed the r*equirements to meet the impact of climate change and environmental legislation*. The key aspects of this for SUSTRAIL are:

- targeting a 20% reduction in the energy used by rail vehicles to be achieved by 2020 versus 2010 (European Parliament, 2010)
- fitting ERTMS-compatible train control systems to all new rolling stock and to new/rehabilitated rail lines from 2011, for interoperability (European Parliament, 2010)
- increased electrification and potential fitting of regenerative braking to freight trains, to reduce freight transport's overall carbon footprint
- design for resilience to climate change effects, e.g. higher operating temperatures and track flooding risk
- reducing noise emissions – particularly noise generated by wheel-rail contact, e.g. by reducing track roughness (maintenance/renewal), and using rail dampers /pads /lubricants /noise barriers
- minimising the carbon footprint of rail infrastructure by designing track systems for longer service life with less frequent maintenance interventions and the maximum ease of recycling – examples are:
    - combining components that have a similar service life
    - using concrete sleepers rather than timber or steel
    - multiple-headed rails
    - more durable rolled premium steel or heat-treated steel rails

Track component requirements were investigated and are recorded in Loiero et al (2012, Chapter 4), covering:

- Ballast and/or sub-ballast
- Sleepers
- Rail fastening
- Rails
- Electrification equipment, catenary and the contact wire
- Track equipment (switch gears, etc.)
- Track Geometry quality

In each case, the relevant (essential) standards and maintenance requirements are given. Table 5.4 summarises the findings on current service lives of these track components, and also of railway *structures* which are part of the context for the SUSTRAIL research. These service lives are of key interest given the desire to reduce inspection frequency, maintenance operations and renewals – from both a cost and an availability perspective.

Component	Service life (years)	Notes
Ballast/sub-ballast	10-35	10-20 years on high traffic lines
Sleepers	15 (timber) 50 (concrete)	usually replaced simultaneously with rails
Rails	20-25 typical	varies with traffic – e.g. UK WCML~17; UK EMP~29; BG 36 years
Joints (insulated)	4-5 typical	large statistical variability
Fastenings	-	usually replaced simultaneously with rails
Pads	-	usually replaced simultaneously with rails
Electrification equipment	5-30 (contact wires) 30-50 (catenary)	
Structures	50-100	

Table 5.4: Service lives of railway infrastructure components

There has been a general shift towards preventative maintenance of these components, based on increasing automated inspection methods, in place of cyclical maintenance over their planned service life. The increase in monitoring activity is outweighed by a reduction in unnecessary maintenance work and the efficiency gains of automated monitoring over traditional methods. The detection of defects has therefore become critical in the overall management of the asset.

5.2.3.4 Task 2.4 'Future vehicle performance requirements'

Task 2.4 focused on the duty requirements for vehicles. Guided by the previous tasks (see 5.2.1 Prior decisions), Task 2.4 concentrated on intermodal vehicles, potentially travelling at modestly increased maximum speeds – 120kph instead of 100kph, or 140kph instead of 120kph on the faster sections of the Network Rail route – to meet IMs and operators' needs.

The aim of the first part of this task was to establish the limits for acceptable *ride quality and dynamic performance*, and to establish a design specification for *improved body/suspension characteristics*, considering total vehicle mass, unsprung mass and fatigue life. This work was carried out using Vampire® simulations assuming an FEA container flat wagon with Y33 series bogies as a representative vehicle. Cost analysis was then carried out using VTISM. The key findings were that:

- lowering the unsprung mass of the vehicle by 20% would allow the targeted speed increase to be achieved while maintaining an equivalent level of vertical damage (P2 calculation)
- without any change to the vehicle's unsprung mass, track damage costs would increase by 6% (including vertical and lateral damage) due to the speed increase
- improving bogie designs could yield very large benefits if they reduce the large amounts of lateral wear found to be caused by Y-series bogies (59% of track damage costs vs. 12% for passenger bogies) – whilst managing the risk of rolling contact fatigue (RCF) as suspension parameters are optimized to reduce wear
- to obtain an idea of the maximum cost savings available for European railways, the maintenance costs of a passenger-only line are in the region of 15-20% lower compared with a mixed traffic line (Task 2.3.1). The reduction in the Ride Force

Constant and Coefficient ($RFCC_{2mmSD}$) is of the order of 60% to obtain the same dynamic vertical forces as passenger vehicle (at 14t axle load)

Another part of this task focused on *aerodynamics*. The key findings at this stage are that: up to a 30% energy saving is achievable for intermodal trains (at 100kph) by carrying empty containers rather than having gaps (i.e. an operational change); whilst vehicle design changes offer a range of smaller potential savings (Table 5.5).

Design change	**Potential energy saving**
Streamline vehicle sides and tops	~23%
Bogie fairings	~10%
Smooth underframe (bogie skirts)	~7.5%
Covering hoppers	~3%
Streamline containers	~10%
Lengthen vehicle (80' instead of 60')	~14%
Reduce inter-vehicle gaps	~10%

Table 5.5: Potential energy savings from vehicle design changes

Other work within this Task focused on brakes, speed and acceleration, and noise. Emerging from that work was a proposal for a Vehicle Green Label for sustainability performance, recognising a vehicle's achievement – or degree of achievement – of the energy and noise reduction targets, i.e. 20% energy saving (European Parliament, 2010) and adherence to noise goals such as the WHO Community Noise Guideline Values (WHO, 1999).

5.2.3.5 Task 2.5 'Holistic approach to the vehicle-track system'

Task 2.5 focused on the duty requirements for track-train interaction, and the results are reported in Chapters 2-4 of this deliverable.

5.2.4 Duty requirements for improvement

The prioritisation workshop considered the analysis of duty requirements in Tasks 2.1-2.5. In the light of the prioritisation objectives (5.2.1 above), and taking into account the impact on IMs and freight operators, the environmental footprint, and technical feasibility of making improvements, the following shortlist was produced.

Duty Requirements (for improvement)	
1	Modest increase in freight speed (e.g. 120-140km/h UK; 100-120km/h ES,BG)
2	Uniform vertical stiffness (track) - optimise between 50-100 kN/mm
3	Optimise (increase/reduce) axle load limits (22.5t / 25t / 17-20t)
4	More reliable insulated rail joints (life*5)
5	Reduce vertical ride force to match passenger vehicle at equivalent axle load
6	Reduced rate of tolerable defects
7	(20%) reduction in energy used by rail vehicles + Requirement for Vehicle Green Label for sustainability performance
8	(20%) reduction in unsprung mass of freight vehicle
9	Optimise (/potentially double) service life of track components
10	Combine components that have a similar service life (harmonise MTBF)
11	Independent power supply (wagon or train based) - for braking or refrigeration
12	Improve bogie design to reduce lateral forces (by 50%)
13	Increased loading space per vehicle

Table 5.6: Shortlist of duty requirements for improvement in SUSTRAIL

5.2.5 Duty requirements' impact on the objectives

We now consider the impact of these 13 duty requirements on the prioritisation objectives, before drawing interim conclusions – at this stage of the project – about the priorities for SUSTRAIL. Table 5.7 summarises these impacts, giving a broad-brush assessment with some very preliminary, indicative estimates of their magnitude, where feasible. The assumptions underlying the cost estimates are explained below the table. In order to compare the different duty requirements in terms of their overall cost impact on freight end users, the Freight Operating Company (FOC) Costs column assumes that any infrastructure cost changes are passed through from the IM to the FOC. Obviously this will be subject to track access charging arrangements. Also, note that the cost changes in the IM and FOC columns should not be added, for this same reason.

Of course, in practice these potential benefits will be reduced due to the likely phased introduction of most of the proposed duty requirements. This however will also affect the costs of implementation, so the value for money or rate of return are not necessarily altered. We will need to have the LCC and RAMS, and other interim models available to predict how these changes in duty requirements would feed through to quantified impacts on the IMs, FOCs, end users and other parties[6].

[6] expected by Month 24

Duty requirement		Availability ↑	Costs ↓		Service Quality ↑	Environmental Footprint ↓	Technical Viability
			IM's costs, *passed through to ------>*	Freight operator's (FOC's) costs[1]			
1	Modest increase in freight speed (e.g. 120-140kph UK; 100-120kph ES,BG)	**ü ü** (on highly utilised lines) More homogeneous running speeds will increase path capacity of congested lines for freight and passenger services – particularly during daytime. Likely to be most relevant to UK Case Study.	**û** +1.0% estimated (note: cost increase) D2.5 indicates speed increase from 120-140kph leads to track maintenance and renewal cost increase of 6%.	**û/ü** equivalent to +0.12% if passed through Upward pressure on FOCs' costs from track access charges. Potential increase in fuel consumption, vehicle-mounted equipment, running gear and brake costs, at higher speeds. However, better integration with other traffic, i.e. better pathing, could lead to a substantial reduction in acceleration / deceleration and associated energy and maintenance costs. Net impact to be modelled.	**ü** Reduced pathing delays.	**û/ü** CO_2: depends on net impact on fuel consumption. Noise: expect both an increase from higher maximum speed, and a change in either direction from braking and acceleration changes with higher max speed but potentially improved pathing.	In Research **ü** In Implementation **ü** Technical challenge appears manageable in 3 years. For FOCs, poor pathing is still a key issue; better integration with passenger traffic will relieve the problem (e.g. GB Railfreight, 2012).
2	Uniform vertical stiffness (track) - optimise between 50-100 kN/mm	0/**ü** Reduced maintenance possessions could have a positive impact on rail freight availability on certain lines (e.g. low capacity or intensively used lines).	**ü** up to -0.7% estimated Aim would be to reduce whole system costs. Lopez-Pita et al's estimates (2004) suggest that the IM and FOC could share a saving equivalent to 4.2% of track maintenance costs (for high speed traffic on high speed lines). Impact likely to be smaller on conventional lines.	**û/ü** up to -0.08% estimated However, if the stiffness is *reduced* from the status quo, the IM will gain and the FOC will lose through increased fuel costs. If the stiffness is increased from the status quo the situation is reversed. Track access charges may be needed to reallocate the total benefits.	0/**ü** Reduced maintenance possessions could improve reliability.	**û/ü** CO_2: could go in either direction depending upon whether the track is more/less stiff (less/more CO_2). Noise: expect no impact.	In Research **ü** In Implementation ? Acceptability to both the FOC and the IM is an issue. Given differences in subsoil along a route, achieving uniform stiffness may be difficult in practice (Berggren, 2009). Transition sections may be required.

Duty requirement		Availability ↑	Costs ↓		Service Quality ↑	Environmental Footprint ↓	Technical Viability
			IM's costs, *passed through to ------>*	Freight operator's (FOC's) costs[1]			
3	Optimise axle load limits (22.5t / 25t / 17-20t)	**ü/û** Increased axle load limit effectively increases freight capacity for a given track capacity, and vice versa	**û/ü** Increased axle load limit increases IM's costs and vice versa.	**û/ü** Increased axle load limit allows more efficient use of wagons (↑ payload). Reduced axle load limit allows speed increase. Complex trade-offs. Modelling required.	0 Harmonisation would avoid wasteful differences in standard for cross-border traffic	**û/ü** Depends on net impact on fuel consumption, number and weight of trains.	In Research **ü** In Implementation **ü** FOCs and IMs both have an interest – particularly if differential speed limits and axle load limits can be used for intermodal versus heavy bulk trains. The optimisation will need to consider the increase in ride quality that could be associated with a reduction in axle load.
4	More reliable insulated rail joints (life*5)	**ü** Reduced maintenance possessions could have a positive impact on rail freight availability on certain lines (e.g. low capacity or intensively used lines).	**ü** -0.1% estimated Only 1% of IMs' maintenance costs relate to insulated joints. Also there may be a small offset against any increased purchase cost for the improved joint.	**ü** -0.02% estimated	**ü** Reduced track faults and maintenance possessions would improve service reliability.	0	In Research ? In Implementation ? The research challenge of increasing joint durability by 400% within 3 years is onerous / high risk. A lower target could be set, although the cost savings obtainable are small.
5	Reduce vertical ride force to match passenger vehicle at equivalent axle load (by suspension improvements)	**ü** Reduced maintenance possessions could have a positive impact on rail freight availability on certain lines (e.g. low capacity or intensively used lines).	**ü ü** -2.5% estimated Track maintenance costs reduced by 15%.	**ü** -0.29% estimated Any increase in vehicle ownership cost needs to be offset against this benefit.	**ü** Reduced track faults and maintenance possessions would improve service reliability.	0	In Research ? In Implementation ? Reduction of track damage from intermodal freight trains to passenger train levels would be a high risk research challenge in 3 years.

Duty requirement		Availability ↑	Costs ↓		Service Quality ↑	Environmental Footprint ↓	Technical Viability
			IM's costs, *passed through to ------>*	Freight operator's (FOC's) costs[1]			
6	Reduced rate of tolerable defects	ü Positive impact on availability of freight service, particularly for low capacity or intensively used lines.	? Unknown – cost implications not clear at this stage.	?	ü Reduced permanent and emergency speed restrictions (PSRs and ESRs) for more reliable operation.	ü Noise saving in particular, from reduced rail roughness and point defects.	In Research ? In Implementation ? Insufficiently defined to draw conclusions.
7	(20%) reduction in energy used by rail vehicles +Requirement for Vehicle Green Label for sustainability performance (2.4.3)	0	?	ü ü up to -5.7% estimated Up to 18% reduction in energy costs to the FOC (20% for wagons only). Net of any cost increases elsewhere, e.g. ↑ wagon ownership costs due to advanced materials.	0	ü Potentially an 18% reduction in CO_2 emissions.	In Research ? In Implementation ? Identifying wagon and track technologies that would save 18% energy use is a high risk research challenge in a 3 year period, although a lower target could be set. Aerodynamics offers savings up to 23%; vehicle weight reduction more challenging. Assume that the labelling scheme is focused on energy efficiency, and will support implementation of the target.
8	(20%) reduction in unsprung mass of freight vehicle	ü Reduction of track forces, defects and maintenance requirements would have a positive impact on rail freight availability, particularly on certain lines (e.g. low capacity or intensively used lines).	ü -0.3% estimated Lower unsprung mass reduces track maintenance costs by 2% if all vehicles upgraded.	ü -0.43% estimated Assuming lower track access charges and 1.2% saving in energy costs.	ü Potential reduced track faults and maintenance possessions would improve service reliability.	ü Potentially a 1.2% reduction in CO_2 emissions, and a reduction in noise.	In Research ü In Implementation ? Identifying vehicle technologies that would reduce unsprung mass by 20% is a moderate research challenge in a 3 year period. Vehicle performance and track damage differs between the laden and unladen (tare) conditions – a much lighter vehicle may face greater challenges when unladen.

Duty requirement		Availability ↑	Costs ↓		Service Quality ↑	Environmental Footprint ↓	Technical Viability
			IM's costs, *passed through to ------>*	Freight operator's (FOC's) costs[1]			
9	Optimise (/potentially double) service life of track components	ü Maintenance possessions are a significant component of capacity consumption (UIC406). Reduced maintenance possessions could have a positive impact on rail freight availability.	ü ü -8.5% estimated Assuming double service life for all track components and maintenance & renewal intervals.	ü -1.0% estimated	ü Reduced track faults and maintenance possessions would improve service reliability.	ü Noise saving in particular, from reduced rail roughness and point defects.	In Research ? In Implementation ? A high risk research challenge in 3 years for *all* track components.
10	Combine components that have a similar service life (harmonise MTBF)	ü Maintenance intervals would be increased to equal those of the rails (20-25 years). Potential positive impact on rail freight availability on certain lines (e.g. low capacity or intensively used lines).	ü -0.2% estimated Assuming that the life of insulated rail joints is extended *5 (as above) and in addition timber sleepers (life 15 years) are replaced by concrete (life 50 years) on the remaining ~20% of the track (UK data).	ü -0.02% estimated	ü Reduced track faults and maintenance possessions would improve service reliability – although to a lesser extent than under the more general requirement #9 above.	ü Noise saving in particular, from reduced rail roughness and point defects – again less than under #9.	In Research ? In Implementation ?/ ü The research challenge of increasing joint durability by 400% within 3 years is onerous / high risk. A lower target could be set, although the cost savings obtainable are small. The change of sleepers is risk-free, but does not produce a step change in maintenance costs and may anyway be part of the do-minimum scenario.
11	Independent power supply (wagon or train based) - for braking & refrigeration	0	û Heavier wagons likely to increase IM's costs.	û Likely to increase vehicle costs because freight trains generally lack powered bogies. Hence any power generator will add complexity and weight.	ü Refrigeration opens markets for foodstuffs in particular, e.g. Spain to Northern European markets, and from beyond Spain (by maritime) to Northern Europe.	ü Main source of environmental benefit is from mode shift: rail has lower CO_2 emissions per tonne-km vs. road, maritime or air freight.	In Research ? In Implementation û Viability of regenerative braking on freight trains is still in doubt. The freight operator representative considered that most EU countries do not require refrigeration, although we note there may still be specific markets which do.

Duty requirement		Availability ↑	Costs ↓		Service Quality ↑	Environmental Footprint ↓	Technical Viability
			IM's costs, *passed through to ------>*	Freight operator's (FOC's) costs[1]			
12	Improve bogie design to reduce lateral forces (by 50%)	ü Reduced maintenance possessions could have a positive impact on rail freight availability on certain lines (e.g. low capacity or intensively used lines).	ü ü -4.2% estimated Track maintenance costs reduced by 25%.	ü -0.48% estimated	ü Reduced track damage and maintenance possessions	ü Potential noise saving from reduced rail roughness and defects. Reduced CO_2 emissions from rail maintenance and renewal.	In Research ü In Implementation ü Whilst there is some risk over the 50% target, it should be feasible to improve the design for a significant reduction in lateral forces.
13	Increased loading space per vehicle	ü Increased freight capacity per vehicle/train – valuable on path-capacity restricted and train-length limited routes.	û Costs of establishing an increased gauge depends very much on the amount of tunnels and the available gauge on the lines used. Longer vehicles and longer trains results in higher wear on curved lines. Low floor wagons may require smaller wheels with higher wear on tracks.	û/ü Investment costs for new vehicles, but cost savings with more payload per vehicle and/or train. Low floor wagons may require smaller wheels with higher LCCs.	? Undetermined how larger capacity vehicles or trains will affect loading/ unloading times or reliability.	ü Increased loading space enable more cargo per vehicle or train, so resulting in less environmental impact per shipment transported.	In Research ü In Implementation ? Technical challenge of enhanced low floor vehicles appears manageable in 3 years. Reliability and cost issues of smaller wheels would need to be addressed to gain acceptance. Cost of gauge changes likely to be a serious issue.

Key: ü impact in the same direction as the objective; û impact counter to the direction of the objective; 0 no significant impact predicted; û/ü direction of impact uncertain; ü ü or ûû expected strong impact in either direction; ? unknown/insufficient data

Note: [1] the FOC's cost column always shows the costs to the FOC *including* any additional infrastructure costs assumed to be passed through from the IM as part of the track access charge

Table 5.7: Impacts of the shortlisted duty requirements on SUSTRAIL objectives

Assumptions which underlie the cost calculations include the following:

- that 16% of an IM's costs are for maintenance, and of those 40% are for track, while 34% are for renewals and 31% of those are for track (based on NR reported in D2.3)
- that 11.4% of a FOC's costs are for track access (excluding traction power) – this proportion is derived from MDSTransmodal (2012) for a freight trip from Felixstowe to Manchester
- that the unsprung mass of a UIC Class R/S container flat wagon is approximately 25% of the tare (unladen) weight, based on 5.3t vs. 21.5t for an FEA wagon in the UK, and typically 9% of laden weight (assuming on average 1.5 containers at 25t each) (FEA data: Johnson, 2012).

Duty	Requirements (for improvement)	Impact: on cost category	amount	% of IM costs	% of FOC costs	Research Feasibility?
1	Modest increase in freight speed (e.g. 120-140km/h UK; 100-120km/h ES,BG)	track maintenance	6%	1.0%	0.12%	
2	Uniform vertical stiffness (track) - optimise between 50-100 kN/mm	track maintenance+	-4.2%	-0.7%	-0.08%	
3	Optimise (increase/reduce) axle load limits (22.5t / 25t / 17-20t)	-	-	-	-	
4	More reliable insulated rail joints (life*5)	track maintenance	-0.8%	-0.1%	-0.02%	
5	Reduce vertical ride force to match passenger vehicle at equivalent axle load	track maintenance	-15%	-2.5%	-0.29%	
6	Reduced rate of tolerable defects	-	-	-	-	-
7	(20%) reduction in energy used by rail vehicles	energy cost	-18%		-5.7%	
	+Requirement for Vehicle Green Label for sustainability performance					
8	(20%) reduction in unsprung mass of freight vehicle	track maintenance	-2%	-0.3%	-0.04%	
		energy cost	-1.2%		-0.4%	
9	Optimise (/potentially double) service life of track components	track maintenance	-50%	-8.5%	-1.0%	
10	Combine components that have a similar service life (harmonise MTBF)	track maintenance	-1.2%	-0.2%	-0.02%	
11	Independent power supply (wagon or train based) - for braking or refrigeration	(service benefit)	-	-	-	
12	Improve bogie design to reduce lateral forces (by 50%)	track maintenance	-25%	-4.2%	-0.48%	
13	Increased loading space per vehicle	(service benefit)	-	-	-	

Key:		
	Size of Potential Cost Saving	≥5%
		~1-2%
		~0.1-0.5%
	Technical Viability within 3 Years of Research	Low Risk
		Medium
		High Risk*
	(*though with scope to set a more achievable target)	
	- indicates 'Unknown / Insufficient data'	

Table 5.8: First estimates of cost impacts, and a rating of technical viability in 3 years of research

5.3 Priorities for SUSTRAIL

This chapter has described the duty requirements emerging from SUSTRAIL and the results of a prioritisation exercise, which made use of the available information at this project stage and took input from a workshop arranged to consider the findings of Tasks 2.1-2.5, which was held on 12 July 2012 in Sofia, Bulgaria.

All proposed SUSTRAIL innovations must meet the *essential duty requirements* unless a strong case emerges for a change in standards. In addition, SUSTRAIL innovations are being designed to improve conditions for rail freight in the EU, so the main focus of this part of the deliverable has been on determining what those *improvements* should be, in terms of the parameters targeted, the direction of change, and in some cases where previous research evidence exists, the magnitude of the target. At the next stage of SUSTRAIL (in WP3, 4, and 5) models will be developed to refine these requirements for improvement and to carry out interim assessments of proposed technologies and engineering solutions.

Emerging from the prioritisation is a set of duty requirements which:

- Together address the full set of SUSTRAIL objectives. Individually the duty requirements cannot achieve this, as Table 5.7 shows – some even have small/moderate contrary impacts. Packaging the improvements together is important to achieve the desired outcome on each objective.
- Are judged to offer the best prospect of success within three years' research, and subsequent implementation. There is mix of lower- and higher-risk research topics here (Table 5.8), however the potential reward also varies. High priority will be given to a set of improvements which attempt to balance these considerations.

Table 5.9 rates these High/Medium/Low priority, with the implication that: High priority items will be pursued most urgently, using the majority of the resources, at the next stage of the research; Medium and Low items will be given less priority, however even the Low items have potential – their Low priority reflects greater risks and/or smaller apparent rewards.

Priority Level	Duty Requirements for Improvement	System
High	1. Modest increase in freight speed (e.g. 120-140kph UK; 100-120kph ES,BG)	whole
	3. Optimise axle load limits (22.5t / 25t / 17-20t)	whole
	7. (20%) reduction in energy used by rail vehicles + Vehicle Green Label	vehicle
	12. Improve bogie design to reduce lateral forces (by 50%)	vehicle
Medium	5. Reduce vertical ride force to match passenger vehicle at equivalent axle load (by suspension improvements)	vehicle
	8. (20%) reduction in unsprung mass of freight vehicle	vehicle
	2. Uniform vertical stiffness (track) - optimise between 50-100 kN/mm	track
	9. Optimise (potentially double) service life of track components	track
	10. Combine components that have a similar service life (harmonise MTBF)	track
	6. Reduced rate of tolerable defects	track
	4. More reliable insulated rail joints (life*5)	track
Low	11. Independent power supply (wagon or train based) - for braking & refrigeration	vehicle
	13. Increased loading space	vehicle

Table 5.9: Duty requirements for improvement, by priority level

5.3.1 High Priorities

In the High priority group, 1. and 3. are areas where there is a high level of confidence in successful outcomes, the requirements are clearly driven by market needs, and these are highly interrelated in engineering and cost-benefit terms. The rail industry would be key beneficiaries and this would contribute to growth in freight market share.

Meanwhile 7. targets the environmental footprint and energy costs for FOCs. 7. is high-risk although that is a consequence of the target level (20% energy use reduction); 7. is also potentially high-reward in terms of the cost advantage gained by rail freight. The Vehicle Green Label serves to reinforce and incentivise the achievement of the target.

12. is judged medium risk but also medium-to-high reward, in terms of the potential cost savings and positive impacts on all objectives.

5.3.2 Medium Priorities

In the Medium priority group, 4. is grouped here rather than high because only 1% of maintenance cost is attributable to rail joints, even if 80% of that can be saved. This could potentially be moved to a Low priority, depending on the scale of the Service quality and Availability benefits: the project needs to apply an initial RAMS model to this issue to establish if benefits are substantial enough to be worth pursuing.

5. may be instrumental to achieving 1. and 3. although the targeted reduction in vertical force is ambitious. This could move to the High priority group if further simulations can identify a suitable target level.

2. is in the Medium priority group because the cost savings appear modest, although this fits very well as part of a joined-up effort to optimise the vehicle-track system as a whole.

8. is moderately challenging but progress is expected to be achievable within three years, and could play a central role in achieving 7. Research to date suggested that better speed management, pathing, and train loading (for aerodynamics) could also make substantial contributions to 7. although those are not as close to the technical scope of the SUSTRAIL project. Rewards in terms of cost savings to operators are also potentially substantial.

9. clearly has a very wide range of potential benefits, and large potential cost savings for the IM, from which FOCs and end users could expect to benefit. If achievable, this would certainly be a High priority requirement. Doubling the service life of all track components could however be very challenging for research within three years. It is recommended that WP4 focus on the feasibility of extending the lives of specific components with a higher replacement/failure frequency (i.e. joints), as in 10., and through better monitoring, for example, work to reduce the rate of defects (requirement 6.).

5.3.3 Low Priorities

11. is currently rated Low priority mainly because of some technical viability issues, and differences in the assessment of market demand by Freight operators – i.e. this is not required for most European container traffic, but would be potentially valuable for some specific routes and flows. With additional quantitative evidence a business case can still potentially be built for this requirement.

Similarly, 13. is currently rated Low priority because although there are clearly some flows where a larger container would be valuable (see D2.2), however the extent of this needs to be quantified. There are very substantial costs associated with gauge enhancement. As with 11., additional evidence could potentially lead to a viable business case.

6. CONCLUSIONS

This report has considered the vehicle-track system as a whole and reviewed all of the work undertaken in WP2 to arrive at a prioritisation of the changes to the system that could be addressed by SustRail.

The first three subtasks applied modelling and simulation (the Vampire® multi-body dynamics software) techniques to determine theoretically what the effect of changes to vehicles and track would be on the system. In Section 2 the effect on vertical damage, tangential damage (wear and RCF), ride quality, and ride safety of changing axle load, unsprung mass, bogie wheelbase, bogie type, speed (120kph to 140kph), and the geometrical quality of the track were considered. In Section 3 the cost implications of reducing unsprung mass and axle load were addressed using the VTISM software and results of simulations. In

Section 4 the effect on equipment attached to freight vehicles was considered, again using results of simulations.

The final subtask reported on a prioritisation workshop at which the work for WP2 was presented and the implications for infrastructure managers and freight operators was discussed. A methodology was developed to take account of both qualitative and quantitative effects of changes to the track-train system and hence suggest a set of priorities for subsequent work. At this stage of the research the cost implications have not been fully explored and many analyses are yet to be undertaken. However, this work is valuable in providing a basis for the more detailed work in WP5 and confirming the priorities for WP3 and WP4.

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