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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Prepared by:	Roberto Loiero, UPM Juan Andrés Brunel Vázquez, UPM Juan de Dios Sanz Bobi, UPM Andrew Jablonski, NR María García Santiago, ADIF Enrique Mario García Moreno, ADIF Ed McGee, Tata Steel Ross Walker, Tata Steel Nick Coleman, Tata Steel Adam Beagles, USFD David Fletcher, USFD Per-Anders Jönsson, KTH Sebastian Stichel, KTH
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1. INTRODUCTION

The objective of Work Package 2 is to define duty requirements for vehicles and track to achieve potentially double the life of track components when combined with low impact vehicles.

In order to achieve the purpose of this work package, the activities have been oriented to three main requirements:

- To define duty requirements for current and future freight traffic flow;
- To define track design requirements, maintenance time and whole life cost based on optimised vehicle characteristics;
- To prioritize the combination of technologies for a freight vehicle-track system for higher delivered tonnage.

This deliverable D2.3 is mainly oriented to the specification of track performance required, and infrastructure managers' (IMs) needs; it includes the work of the task 2.3: Track design requirements for reduced maintenance.

This deliverable has been spit in five chapters:

- Chapter 2: Infrastructure Managers' track duty requirements;
- Chapter 3: Track design and duty requirements to meet climate change impacts and environmental legislation;
- Chapter 4: Track component duty requirements;
- Chapter 5: Track forces and energy dissipation.
- Chapter 6: Current Performance for Track Components

Inputs from freight operators and infrastructure managers have been used to achieve holistic whole system assessment of the duty requirements to be fulfilled to improve freight sustainability and competiveness during the Sustrail project.

2. IMs' TRACK DUTY REQUIREMENTS

This section is based on the subtask **2.3.1. IMs track duty requirements.** The main objective of the subtask is gathering input from the IMs in order to define the track duty requirements: maintenance intervals and intervention levels, requirement for and availability of personnel (including consideration of the impacts of an ageing population), requirement for plant, extension of existing track life and options for designs of replacement track (conventional and novel options).

The objectives of this section can be summarized in two main points:

- To define the requirements of track maintenance and replacement.
- To support sustainable achievements of the requirement to "potentially double the life of track components when combined with low impact vehicles"

For the first objective, a questionnaire was developed and distributed to the infrastructure managers (NR, ADIF, NRIC) in order to gather input from them to define track duty requirements, the intervals, the intervention levels, etc.

The questionnaire can be found in Appendix A – Maintenance Questionnaire

The most important features are:

1. Standards or routines, the examination / maintenance / operation / renovation of which the railway administrator has to perform:
2. Type, availability and amount of equipment and depot or base that are available to perform examination / maintenance / renovation operations.
3. Index of availability of the track section in the selected line in the last 5 years (2006-2010).
4. Track quality index of the section, in percentage over the total length of it, in the last 5 years (2006-2010).
5. Number of examinations and monitoring or prevention operations done over the past 5 years (2006-2010).
6. Number of maintenance operations done over the past 5 years (2006-2010).
7. Number of track renovation operations done over the past 5 years (2006-2010).
8. General information of annual maintenance performed in the last 5 years (2006-2010) in the selected line.
9. Annual maintenance cost, and replacement expenses, relative to the selected line in the last 5 years (2006-2010). The resources and the subcontract works should be taken into account.
10. Future Project Plan of maintenance and renovation. Take into account the current and the next year planning.

From the gathered data, a study was carried out to show the actual situation in the selected routes and to try to define the track maintenance and replacement requirements.

Some of the data regarding the selected routes has been collected in tasks 1.2: "Route Characteristics" and 1.4. "Infrastructure", and was used for extending this section and for drawing the conclusions.

2.1 IMs maintenance, intervals and intervention levels

The main track problems reported at Innotrack workshops by the Infrastructure Maintenance Engineers were based on frequency, and they are listed in order of importance in Figure 2.1:

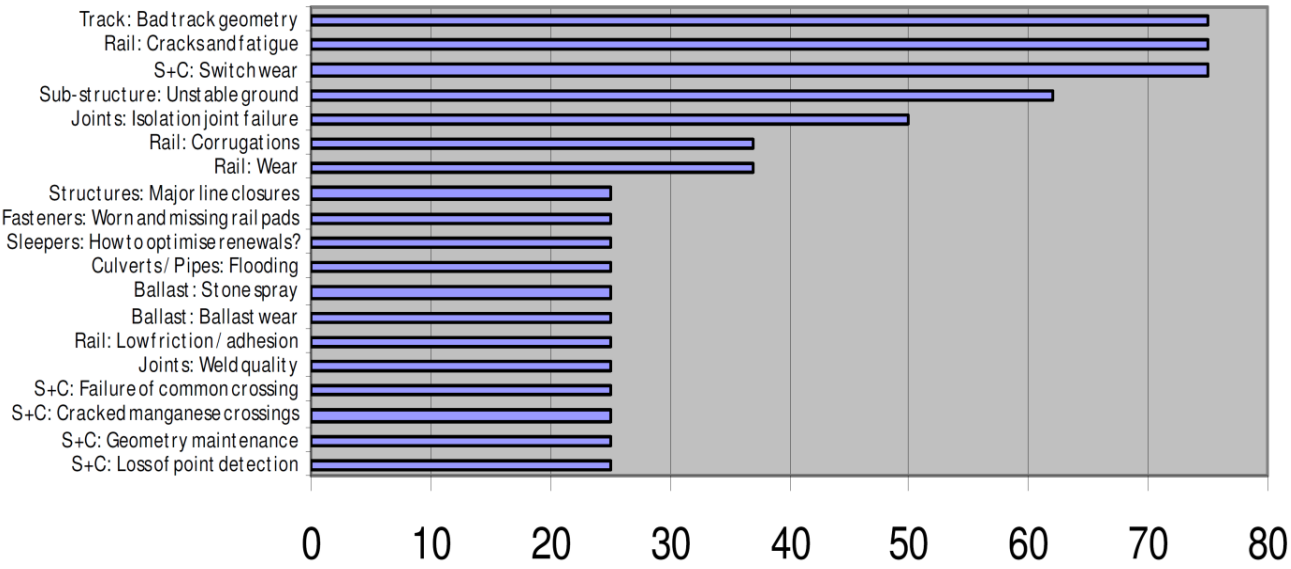


Figure 2.1: Percentage of Infrastructure Managers reporting a main track problem.

The top ten problems and their causes are described in Table 2.1.

Table 2.1: Track problems and causes.

Track problems	Causes
Rail: cracks and fatigue	creep forces
Rail: cracks and fatigue	bad wheel/ rail interface
Track: bad track geometry	soft sub-structure/ bad drainage
S+C: wear in switches	sub-structure
Rail: corrugations	vehicle/track interaction
S+C: cracked manganese crossings	weld quality
S*C: geometry maintenance	optimal maintenance regime
Sub-structure: unstable	soft sub-structure/wet bed
Track:bad track geometry	sub-optimal maintenance
Track:bad track geometry	wrong/unknown stress free temperature

According to these main track problems, each Infrastructure Manager plans their inspection, maintenance and renewal operations, and the intervals or intervention levels for each case.

2.1.1 Examinations and monitoring or prevention operations

There are two main auscultation techniques: geometric auscultation methods and dynamic auscultation methods. Geometric auscultation methods are based on direct measurement of the track geometry. Dynamic auscultation methods are based on the measurement of accelerations in the interior of the vehicle or in a specific part thereof.

Items to be inspected include:

- Track:- generally: obstructions of the line, including infringement of clearances; missing, inappropriate, defective or damaged components; condition of conductor rail equipment; permanent way materials interfering with signalling or other track mounted equipment; vegetation, particularly where this obstructs signals, sighting distances or positions of safety; buffer stops.
- Rails and rail joints:- visible rail defects, including rolling contact fatigue and other cracks, breaks, rail head damage and significant corrosion; excessive sidewear; check rails, for security, wear and flangeway obstruction; broken, cracked or defective fishplates; loose or missing fishbolts or multiple-groove locking pins; dipped joints; expansion gaps: joints in jointed track and adjustment switch settings in welded track; damaged end-posts and defective insulation at insulated rail joints, and lipping of rail ends; security of temporary rail clamping systems; loose or ineffective rail anchors; effectiveness of lubricators (is grease being applied correctly to the rails?); detached signalling or electrical bonds.
- Sleepers, bearers and fastenings:- broken, cracked or ineffective, vertical or lateral movement of chairs or baseplates; loose or missing fastenings, keys, pads or insulators; loose or damaged gauge tie bars.
- Switches and crossings:- broken, cracked, defective or worn switch rails and crossings; obstructions in switches and flangeways; evidence of wheels striking the back of the open switch; longitudinal position of check rails, to confirm that crossing noses are covered; wide flangeways to, and security of, check rails; evidence of irregular running contact band on the switch, stock rails and crossing; wheel strikes at crossing noses; damaged or loose stretcher bars; loose or missing bolts or multiple groove locking pins or studs; security of points clipped out of use.
- Track geometry:- vertical and horizontal misalignments, and twist; cyclic top; gauge widening.
- Track support:- areas liable to subsidence or other earth movement, including by burrowing animals; collapsed catch pits; signs of ballast voiding, slurring or effects of inadequate drainage on ballast conditions; deficiencies in ballast provision or excessive ballast, track drainage (signs of flooding, damaged catchpit covers.) longitudinal rail-carrying bridge timbers and associated transoms, ties and packing.
- Lineside and lineside security:- Level crossings and road–rail access points.
- Bridges and other structures:- new cracks or growth of existing cracks; signs of loose, displaced or fallen material; vandalism or accidental damage; signs of subsidence or ground movement; flooding and signs of obstructions against upstream faces; signs of misuse or significant change in the nature or extent of use in cold weather; signs of impact with platforms and structures by rolling stock; missing or damaged fixed track position data or datum plates.

- Cutting and embankment slopes:- signs of loose, displaced or fallen material (particularly after severe frost, heavy rainfall or thaw); signs of cracking (particularly in clay slopes during very dry weather); signs of movement where large trees are present that may fall onto the track.

Once the tracks have been auscultated, the quantification of the defects is obtained by the difference between the measured actual geometry and specified track geometry. The intervention criteria (or the decision of performing maintenance work) mainly depend on three types of statistical quantifiers:

- the mean,
- the standard deviation and
- The extreme values.

Both the mean and the standard deviation values (of parameters such as alignment, longitudinal level, etc.) allow the assessment of the overall track quality. In contrast, the extreme values contribute to the detection of point defects.

2.1.2 Maintenance operations

Since all the selected sections (except for a small section of the Mediterranean Corridor) are ballasted track, the study has been focused on this kind of track, as there is no sufficient information / data for performing a study.

The main maintenance operations are:

- Reduce the track geometric defects by non-machining methods.
- Tamp the ballast.
- Mechanical track stabilization.
- Grind and re-profile the rails.
- Tighten the track fastenings.
- Repair the catenary, the contact wire, or the electrification equipment.
- Repair the track equipment (switch gears, etc.), or the signalling and safe equipment, due to track deterioration and maintenance needs.

Levelling operations correct longitudinal level defects, cant and twist detected are evaluated by auscultation systems. These operations are performed by machines called "levelling machines". The levelling machines are equipped with three contact probes for each rail, a few fasteners for securing the rail and some rail-lifting jacks whose strength can place it into the correct position. Between the two extreme probes a steel rope is hung or a beam of infrared light is shone.

Once the level of the ends of the rope, or the beam between probes A and C, is set with the appropriate corrections, the intercepting element corresponding to probe B is aligned with the rope or the defined ray. This work can be done using the auscultation data - for example, obtained from a topographic levelling measurement system - which are introduced into the levelling machine to correct the positions of A and C. This method is called "absolute base levelling" or "accurate tamping". It is possible to dispense with any previous auscultation work and perform the levelling operation without correcting the positions of the ends of the rope. In this case, a smoothing of the track irregularities is achieved, but without correcting

entirely the defects. This second method is called "relative base levelling" or "automatic tamping".

In longitudinal levelling, the levels of the ends of the rope A and C are arranged in accordance with the track raising calculated at the nearest point of the rail. Thus, the rope (or the infrared beam) is placed parallel to the rail profile. Then the track raising device operates until the intercepting element corresponding to probe B is aligned with the rope. From this moment, only it will be necessary to correct the position of A, since the extreme C is already on the levelled rail.

Levelling a section where there is a transition between subgrades consists of performing the same operations that were contemplated by levelling a section with constant grade, and correcting the extreme A of the rope according to guide value.

To carry out cross levelling works, the levelling machines are equipped with pendulums at points C and B. In B the operator enters the value of cant for the point that is going to be tamped, while for C it is necessary to check the resulting track cant. The latter measurement also allows knowing the remaining track twist. At point A, a pendulum is also available. In this case, its purpose is to correct errors that could be introduced into the levelling and alignment operations, due to defects in the track cant.

Levelling operations, in some cases, require adding ballast to the track. To carry out this operation, the maintainer needs hoppers for the transport and dumping of ballast, a track bed profiler to distribute and to arrange a correct track alignment.

Furthermore, the alignment operations are performed by special machines which are known as "track aligners". The basic elements are the probes (3 or even 4 contact probes for each rail) and some fasteners used to secure the rail head and place it in its correct position using the force from some jacks. The aligner does not have any restrictions in corrective operations and can move the rail on both sides.

The conventional aligners can work according to two general methods: 3 point based alignment and 4 point based alignment. In the first method, the alignment operation is that, fixed the levels of the ends of a rope between A and C with appropriate adjustments, the intercepting element corresponding to probe B is aligned therewith, or, without corrections, the sag read at B is correct. For the alignment based on 4 points, the method consists of keeping constant the relationship between the sag read at point B and the sag at point C, in respect to the chord drawn between A and D.

Analogously to the levelling operations, the alignment can be performed in absolute base or relative base.

Tamping operations are carried out by ballast tampers, whose performance in some models exceeds 200 m/h and perform at the same time levelling and alignment operations. Track tamping consists of vibrating the ballast to secure the sleeper bed and overcome any clumping to increase the track drainage. This is performed by the penetration of vibrating arms in the ballast layer on both sides of a sleeper, and the subsequent compaction through the relative movement of these arms.

The tamping arms undergo three types of movements: penetration into the ballast layer, closing movement and vibration. The tamping depth measured from the top of the rail and the top of the arm block, is 450 mm for the tamper Matisse B-50.

According to the closing movement of the arms, there are two types of tamping: synchronous tamping, in which all arms cover the same distance and stop when just one of them meets a drag equal to or greater than the adjusted compacting pressure; the asynchronous tamping,

where each arm works independently from the other arms. Finally, the ideal range for the amplitude of the vibration is from 3 to 5 mm.

The tamping action modifies the position of the ballast contributing to the reduction of the lateral track resistance which can require the establishment of speed restrictions until the traffic has been sufficient to increase the lateral strength. To avoid speed restrictions, immediately after tamping, dynamic track stabilization is performed by applying a combination of horizontal vibration and a constant vertical load. Thus, the dynamic stabilization creates the track bed that the track would have been experienced with the proper dynamic loads of vehicles.

The dumping operations and the profiling of ballast borders are carried out using hoppers which move the ballast to the sections which require it, and dump it on the outer side of each rail. To spread the ballast and give to the track its right section, a "track bed profiler" is required. This machine picks up with some external ploughs the ballast and conveniently distributes it throughout the track.

Furthermore, rail corrugation, which occurs mainly on those lines where trains run with the same speeds (typically suburban service and passengers high speed lines), requires rail grinding. For this purpose special machines abrade the rail head with grinding stones restoring the proper contact geometry. Rail grinding is sometimes carried out before the commissioning of new high-speed lines in order to correct the point defects in the track geometry due mainly to the collision with the ballast particles at the laying time.

2.1.3 Renewal operations

Besides the works for correcting the track geometry, previously mentioned, there are other more occasional works, such as the replacement of sleepers and fastenings, and the injection of mortar cement into embankments to ensure the slope stability.

The most important renewal operations are:

- Renovate completely the track or:
- Renovate the track bed, the sub-base or the track formation.
- Clear or remove the ballast and/or sub-ballast.
- Remove the sleepers or the rail fastening.
- Remove the rails.
- Remove the catenary, the contact wire, or the electrification equipment.
- Remove the track equipment (switch gears, etc.), or the signalling and safe equipment, due to track deterioration and maintenance needs.

The useful life can be determined independently for each track component, or for the whole track. The different useful lives of the track components generally do not overlap in time with the renewal needs. Therefore it is possible to carry out the complete track renewal through partial replacements at different times (eg. rail renewal after 25years, renewal of sleepers and fastenings after 30 years, renewal of ballast at age 20, etc.). Each partial replacement helps to extend the life of the system, which can be kept in service indefinitely through successive renewals. This peculiarity affects the choice of the time necessary for the economic comparison of the two systems.

The useful life depends on several factors, among which the foremost is the intensity of use to which each component is subjected. The peculiarities of design, commissioning, weather conditions or the track maintenance policy may also be relevant to determining the duration of the useful life. There is a close relationship between the renewal activities (associated with the useful life of the track components) and maintenance activities carried out on the track. In general a well maintained track has fewer geometrical defects, and this limits instances of dynamic overloads and thus increases component lives.

2.1.4 Intervals and intervention levels

Essentially there are two methodologies to estimate a priori the maintenance needs of a track system:

- Modelling based on the results from the two auscultation systems (geometric and dynamic auscultation) under the same boundary conditions
- Analysis from previous experience and data.

The definition of maintenance requirements from the modelling of the degradation of different track systems requires the definition of intervention criteria for the different geometrical parameters, so that variations in track geometry can be translated directly into intervention frequencies. Thus the first section of this chapter is dedicated to present synthetically the applicable intervention criteria. This will provide a suitable tool for interpreting the results of modelling conducted in the previous subprojects.

The definition of maintenance requirements based on previous experience is proposed in the second section of the chapter, which directly shows the frequency of maintenance actions observed on several lines. Logically, most of the experience available is for lines built with ballasted track, which will provide a frequency reference for this technology.

2.1.5 Gathered information regarding the selected routes

2.1.5.1 Network Rail

There are two main types of inspection defined by Network Rail:

- Safety Inspections to confirm that permanent way is fit to use
- Asset Management Inspections - based on historic trends and known deterioration

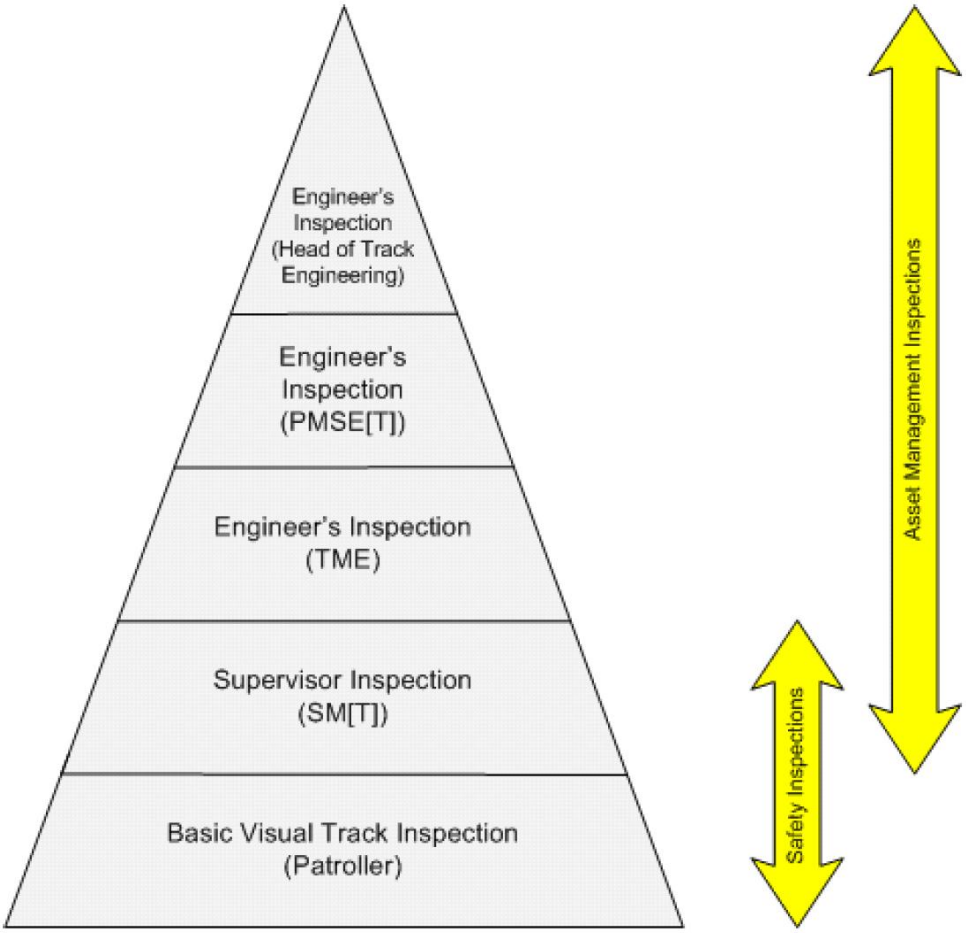


Figure 2.2: Hierarchy of inspection.

Basic visual track inspections identify any immediate or short term actions required. These will generally be defects that require action within four weeks.

Supervisor visual track inspections identify work to be planned and carried out, review trends in condition, identify items to be proposed for renewal and check that basic and special track inspections, maintenance and renewal work are effective. They include measurements of gauge, cross-level and other features.

The Track Engineer's inspection confirms the integrity of the track and reviews condition, trends, work sufficiency, proposals for renewals or refurbishment work, quality of maintenance and renewal work.

The Principal Engineer (PMSE[T]) carries out sample track inspections and cab riding to monitor condition, trends and fitness of the track and directs the TME concerning renewals or refurbishment proposals and additional work items.

All inspections consider the fitness of the geometry, components and lineside features for the speed, traffic and other conditions. Inspection frequencies depend on the Track category as defined Figure 2.3.

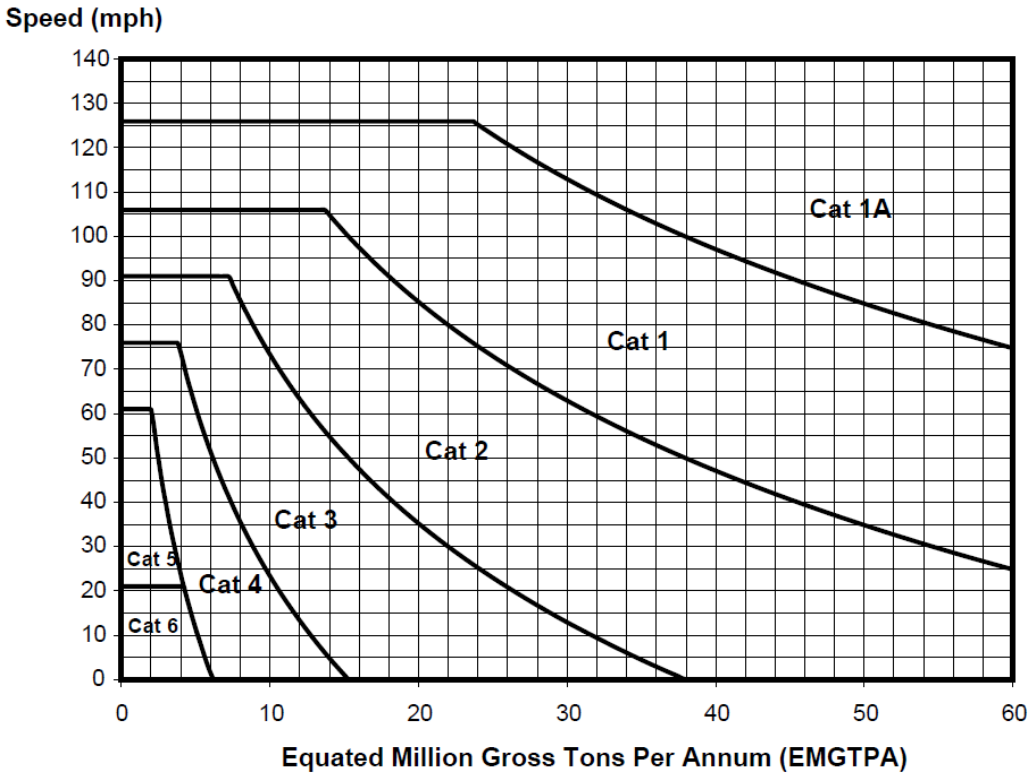


Figure 2.3: Track Category Matrix – NR/L2/TRK/001/A01.

Based on this definition of Track Category the inspections frequencies are given in Table 2.2.

Table 2.2: Inspection frequencies. Network Rail.

	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 2.3 shows an analysis of the two Network Rail selected freight routes, classified by track category.

Table 2.3: Network Rail route classification.

Track category	Felixstowe to Nuneaton (km)	Southampton to Nuneaton (km)
1A	37	51
1	82	194
2	104	35
3	116	16
4	16	9
5	3	4
6	0	0
	359	**308**

In addition to the inspections listed in Table 2.2, inspections by track geometry trains and Ultrasonic test trains are carried out. Inspection frequencies may be increased if there is:

- above-average incidence or rising trend of broken or defective rails;
- vandalism;
- poor track geometry;
- evidence of track bed failure;

- S&C with a history of worn or missing components;
- a history of rolling contact fatigue;
- turnout or crossover routes used by freight traffic;
- Short transitions with steep designed cant gradients.

Ultrasonic testing frequencies are covered by Table 2.4.

Table 2.4: Network Rail Ultrasonic testing frequencies.

Track Category	Pedestrian UT Inspection Interval (weeks) Plain Line	Pedestrian UT Inspection Plain Line Maximum Interval Between Inspections (weeks)	Pedestrian UT Interval S&C, Adjustment Switches, Level Crossings, Tunnels, Joints (see 4.3). (weeks)	Pedestrian UT Inspection S&C, Adjustment Switches, Level Crossings, Tunnels, Joints (see 4.3). Maximum Interval Between Inspections (weeks)	Interval (weeks) UTU	Maximum Interval UT Inspection (weeks) Plain Line UTU Compliant Routes
1A	13	15	8	10	8	10
1	26	30	13	15	8	13
2	52	56	26	30	16	26
3	104	112	52	56	26	34
4	104	112	52	56	26	34
5	104	112	52	56	26	34
6	104	112	104	112	52	78

Network Rail maintenance operations

The maintenance operations are based in most cases on the Equivalent Million Gross Tonnes Per Annum (EMGTPA). It is a measure of the annual tonnage carried by a section of track, taking into account variations in track damage caused by normal traffic.

For example rail grinding is undertaken as a planned maintenance activity on a cyclic basis. Curves with a radius less than 2500 m are planned to be ground every 15 EMGT with all other track ground every 45 EMGT.

Table 2.5: Network Rail maintenance interventions.

National network routes	Intervention/immediate action geometry faults per 100km/yr	Civil's assets subject to additional examinations/100km/yr
Primary routes	29.2	296
Secondary and Freight trunk routes	40.4	416
Rural and freight only	3.8	110

Network Rail renewals target

For the case of renewal of the track, the EMGTPA index is taken into account. Table 2.6 shows the renewal target for the Network Rail network.

Table 2.6: Network Rail Renewals target 2011/2.

Renewals target 2011/2	Track km	% of total track
Rail	777	2.5%
Sleepers	499	1.6%
Ballast	607	2.0%

2.1.5.2 ADIF

In general, ADIF manages the maintenance needs of its networks under the so called "maintenance by state" in which the opportunity to carry out an action is determined by prefixed intervention criteria and the results of periodic network auscultations. Thus, depending on the measured values and on the thresholds laid down, three kinds of interventions can be carried out:

- Normal track monitoring
- Scheduled actions for defect correction
- Urgent actions for defect correction

ADIF provides three levels of control in establishing the relevance of the maintenance actions.

The first level takes into account the existence of point defects in the track alignment and levelling. The first control level establishes as a criterion for intervention, some thresholds referred to the longitudinal levelling, cross levelling, alignment and the track gauge variation in some track points. These thresholds depend on traffic speed, being stricter as the speeds are higher. When a measurement punctually exceeds the threshold, the affected section is included in intervention programs. The used thresholds are those indicated in Table 2.7.

Table 2.7: Corrective action thresholds for point defects (wavelength 3-25 m).

Speed (km/h)	Longitudinal levelling (mm)	Cross levelling (mm)	Alignment (mm)	Trackgauge (mm)
V ≤ 80	+/-16	+/-10	+/-14	+/-9
80 <V≤120	+/-12	+/-8	+/-10	+/-8
120<V≤160	+/-10	+/-7	+/-8	+/-7
160<V≤200	+/-9	+/-6	+/-7	+/-6
200<V≤240	+/-8	+/-5	+/-6	+/-5
240<V≤280	+/-7	+/-4	+/-5	+/-4
280<V≤320	+/-6	+/-3	+/-4	+/-3
V>320	+/-5	+/-2	+/-3	+/-2

The second level considers the track geometric quality in larger control sections. The second control level set as thresholds for corrective intervention program the ones indicated in the following three tables.

Table 2.8: Corrective action thresholds for track quality (wavelength 3-25 m).

Speed (km/h)	Longitudinal levelling (mm)	Cross levelling (mm)	Alignment (mm)	Trackgauge (mm)
V ≤ 80	2.5	2.4	1.8	2.0
80 <V≤120	2.1	1.9	1.5	1.7
120<V≤160	1.8	1.5	1.3	1.5
160<V≤200	1.5	1.2	1.1	1.3
200<V≤240	1.3	1.0	1.0	1.1
240<V≤280	1.1	0.8	0.8	1.0
280<V≤320	1.0	0.7	0.7	0.9
V>320	0.9	0.6	0.6	0.8

Table 2.9: Corrective action thresholds for track quality (wavelength 25-70 m).

Speed (km/h)	Longitudinal levelling (mm)	Cross levelling (mm)	Alignment (mm)
V ≤ 80	-	-	-
80 <V≤120	4.4	3.3	3.3
120<V≤160	3.8	2.8	2.7
160<V≤200	3.2	2.3	2.3
200<V≤240	2.7	1.9	1.9
240<V≤280	2.3	1.6	1.6
280<V≤320	2.0	1.3	1.3
V>320	1.7	1.1	1.0

Table 2.10: Corrective action thresholds for track quality (wavelength 70-120m).

Speed (km/h)	Longitudinal levelling (mm)	Cross levelling (mm)	Alignment (mm)
V ≤ 80	-	-	-
80 <V≤120	-	-	-
120<V≤160	-	-	-
160<V≤200	4.4	3.6	5.5
200<V≤240	3.7	3.0	4.7
240<V≤280	3.2	2.4	4.0
280<V≤320	2.7	2.0	3.4
V>320	2.3	1.6	2.9

The third level assesses the state of the track elements (running surface, rail wear, wear track and sleeper-fastening set). This is a criterion oriented to assess the state of the track elements and which deterioration may be the cause of some of detected defects. In this case the action levels are defined using the axle box accelerations (Table 2.11).

Table 2.11: Corrective action threshold for running surface, rail wear and sleepers-fastening set.

	Axle box acceleration		Levelling
Speed (km/h)	0.03-0.1 m	0.1-0.3 m	1-3 m
V ≤ 80	2.1	2.1	0.6
80 <V≤120	1.6	1.6	0.5
120<V≤160	1.2	1.2	0.4
160<V≤200	1.0	1.0	0.3
200<V≤240	0.8	0.8	0.2
240<V≤280	0.7	0.7	0.2
280<V≤320	0.6	0.6	0.2
V>320	0.5	0.5	0.1

When ADIF needs to interpret the frequency of maintenance actions, it takes into account the parameters governing the track deterioration: traffic density, type of operation, speed, axle loads and track characteristics (particularly its vertical stiffness).

ADIF has the following auscultation plan for the Mediterranean Corridor, a line with special features since it is a high speed line (220 km/h) and allows the freight traffic at medium speeds (up to 120 km/h):

- Geometric track auscultation: every 6 months.
- Ultrasonic rails auscultation: every 6 months.

In terms of maintenance interventions on the infrastructure, these are run by track state according to inspections or auscultation data. There are no consolidated data about the maintenance operations carried out, since these depend on each maintenance management department.

The renewal operations are carried out similarly; they are based on the track status and its components.

In case there are uncorrected maintenance defects, as general rule, ADIF sets speed limits to 20 km/h for running at sight, or 60 km/h after tamping operations; these limitation are not removed until the correct track state is checked again by geometric auscultation.

2.1.5.3 NRIC

There are two main types of inspection defined by NRIC:

- Track inspections to confirm that permanent way is fit to use
- Catenary and electric equipment inspections.

For track, the main types of inspection and its regular frequencies are:

- Inspection of the track by inspection coach: twice a year and accidentally, after every renovation;
- Inspection by trolley: once per 5 years;
- Inspection by laser laboratory "Chevrolet Silverado": once per 5 years;
- Inspection by non-destructive ultrasonic test equipment: twice a year;
- General inspection of railway structures (bridges & tunnels): once per 5 years;
- Inspection by linesmen' non-machining measurements and visual inspection: every day"

For the case of catenary, contact wire, and the electrification equipment (substation, neutral zone, catenary supports, etc.) inspection or examination and its regular frequencies are:

- Examinations of catenary devices, by electricians' inspection: 2-4 times per month;
- Examinations of catenary devices, by energy section specialists' inspection: twice a year;
- Examinations of catenary devices, by a commission's inspection: once a year;
- Examinations of electrification equipment, by inspection from the head of PDS (power distribution subdivision) with an electric locomotive or a motor coach: twice a month;
- Measurements of zigzag and height of contact wire during pantograph passing, by catenary inspection coach: twice a year for main track sections and once a year for secondary tracks; accidentally, after every renovation;
- measurements of contact wire wear : once per 2 years;
- Measurements of catenary support clearance and transience resistance: once per 5 years;
- Check-up of catenary support numbering : once a year;
- Measurements of distances from the track axis to catenary's elements, by laser laboratory "Chevrolet Silverado": once per 5 years;
- Measurements of insulator discharge characteristics – depending on operational circumstances"

Table 2.12 shows the inspection done in the selected line from 2006 to 2010.

Table 2.12: NRIC Inspection done in the selected line from 2006 to 2010.

Examinations and monitoring or prevention operations done from 2006 to 2010					
All the selected line.	**Length of the line (km)**				
	2006	**2007**	**2008**	**2009**	**2010**
Length of the line (km) over which the track have been examined in order to know the state or prevent future defect.					
Track inspection coach	998	446	499	0	0
Ultrasonic testing of rails	1080	1080	1080	1080	1080
Length of the line (km) over which the catenary have been examined in order to know the state or prevent future defect.	383	383	383	383	383
All the selected line.	**Number of operations done**				
	2006	**2007**	**2008**	**2009**	**2010**
To test several geometric parameters of the track (vertical and lateral alignment, levelling, twist and track gauge) and parameters related to the track (curve radius, superelevation of the track, gradient, and profile) without obstructing normal railroad operations.	2	1	1	0	0
Ultrasonic testing of rails.	2	2	2	2	2
To gauge the rail wear	2	2	2	2	2
To monitor the state of the ballast and the ballast subbase(track ballasting, inspection of the setting bed, ballast thickness, ballast limestone, uses of ground-penetrating radar, etc.).	2	2	2	2	2
To examine the catenary, the contact wire, or the electrification equipment.	2	2	2	2	2
To check and verify the other track equipment, switch gears, etc.	12	12	12	12	12

NRIC has a control level established as a criterion for intervention, some thresholds referred to the alignment, track gauge and superelevation variation in the track sections. These thresholds for unloaded conditions depend on traffic speed, obviously being stricter for higher speeds.

Table 2.13: NRIC corrective action thresholds for track quality.

Speed (km/h)	Alignment (10/20m)	Trackgauge (mm)	Cant H(mm)
V ≤ 60	24/48 mm	+13; -4	±15
60<V≤80	15/31 mm	+13; -4	±10
80<V≤100	14/28mm	+13; -4	±10
100<V≤120	14/28mm	+8; -4	±6
120<V≤130	10/20mm	+5; -4	±6
130<V≤140	10/20mm	+5; -4	±4
140<V≤160	10/20mm	+4; -4	±4
V<160	10/20mm	+2;-2	±4

NRIC maintenance operations

The emergency operations are carried out by a team from recovery units and infrastructure functionaries as demanded by the leader of urgent maintenance. The leader of urgent maintenance at heavy failures is the head of Regional Safety Inspection or his deputy; at slight failures – a safety inspector from Regional Safety Inspection; at technological failures – the station master.

When it is not possible to make emergency maintenance operations, speed restrictions and limited traffic are implemented according to Bulgarian Decree №58. Speed restrictions are given because of technical state of infrastructure (defects found by measurements, examinations, visual control etc.) and in case of urgency, by an infrastructure functionary with capacity and qualification (General Director, Regional Director, Technical head etc.) or the control body Executorial Agency "Railway Administration" or other functionary authorized by Bulgarian administrator.

Officials take the necessary operations immediately according to defect stage by determination of the restriction: speed, length, place etc. Sections with speed restrictions are specially controlled and signalled. The General Director has to provide all resources for speed rehabilitation. Traffic is limited by an infrastructure functionary with the capacity and qualification or by the train head on duty. The traffic is restored by an infrastructure functionary after elimination of the reasons for the limitation.

Routine interventions on the track superstructure are carried out by railway sections for the maintenance, regularly according to schedule after carrying out measurements, examinations, visual control etc. Operations include: the single replacement of rails, sleepers, fastenings, tightening of fastenings, geometry correction etc. so to realize safe transport with definite speed.

Table 2.14 shows the maintenance operations carried out on the selected line from 2006 to 2010, by length of track and number of operations done.

Table 2.14: NRIC maintenance interventions done in the selected routes from 2006 to 2010.

Maintenance operation done from 2006 to 2010					
All the selected line.	**Length of the line (km)**				
	2006	**2007**	**2008**	**2009**	**2010**
Length of the line (km) over which have been done track maintenance operation.	540	540	540	540	540
Length of the line (km) over which have been done catenary maintenance operation.	170	250	383	383	383
Dimitrovgrad JS – Sofia (Track 1)	**Number of operations done**				
	2006	**2007**	**2008**	**2009**	**2010**
To reduce the track geometric defects by non-machining methods.	93	98	92	89	81
To tamper the ballast, or something similar.	67	67	51	65	48
Mechanical track stabilization.	0	0	4	0	0
To tighten the track fastenings.	50	54	32	44	44
To repair the catenary or the contact wire.	1	5	13	8	12
Sofia - Plovdiv (Track 1+Track 2)	**Number of operations done**				
	2006	**2007**	**2008**	**2009**	**2010**
To reduce the track geometric defects by non-machining methods.	1277	1292	1291	1299	1331
To tamper the ballast, or something similar.	101	196	196	202	231
Mechanical track stabilization.	12	0	0	0	10
To tighten the track fastenings.	189	201	199	204	200
To repair the catenary or the contact wire.	8	9	26	24	34
Plovdiv - Svilengrad (Track 1)	**Number of operations done**				
	2006	**2007**	**2008**	**2009**	**2010**
To reduce the track geometric defects by non-machining methods.	1189	1150	1291	823	632
To tamper the ballast, or something similar.	13	12	11	10	9
Mechanical track stabilization.	0	2	9	0	4
To tighten the track fastenings.	15	15	15	15	15
To repair the catenary or the contact wire.	0	0	3	8	0

NRIC renewals and repairs targets

Renovations and repairs are carried based in most cases on the Equivalent Million Gross Tonnes Per Annum (EMGTPA):

- Renovation every 36 years at less than 6 gross-ton-kilometres per year;
- Repair every 12 years at less than 6 gross-ton-kilometres per year.

The final works have to be approved according to the Territory Arrangement Law or by a commission fixed by General Director. They are legalized by receiving reports.

Usually renovations are done through an external supervisor, depending on Public Orders Law but repairs – through own recourses."

Table 2.15 Shows the renewal target for the NRIC studied lines from 2006 to 2010.

Table 2.15: NRIC renewal interventions done in the selected routes from 2006 to 2010.

Renewal interventions done between 2006-2010					
All the selected line.	**Length of the line (km)**				
	2006	**2007**	**2008**	**2009**	**2010**
Length of the line (km) over which the track have been renewal.	10.9	3.4	15	0	4.8
Length of the line (km) over which the catenary have been renewal.	0	0	0	0	0
Dimitrovgrad JS – Sofia (Track 1)	**Number of operations done**				
	2006	**2007**	**2008**	**2009**	**2010**
To renovate completely the track.	2	0	3	0	0
To renovate the track bed, the subbase or the track formation	0	0	0	0	0
To clear or remove the ballast and/or subballast.	0	0	0	0	0
To remove the sleepers or the rail fastening.	270	235	134	157	172
To remove the rails.	82	434	189	344	199
To remove the catenary or the contact wire.	0	0	0	0	0
Sofia - Plovdiv (Track 1+Track 2)	**Number of operations done**				
	2006	**2007**	**2008**	**2009**	**2010**
To renovate completely the track.	3	1	0	0	0
To renovate the track bed, the subbase or the track formation	10	0	0	0	0
To clear or remove the ballast and/or subballast.	12	0	0	0	0
To remove the sleepers or the rail fastening.	765	751	664	669	809
To remove the rails.	146	215	155	143	279
To remove the catenary or the contact wire.	0	0	0	0	0
Plovdiv - Svilengrad (Track 1)	**Number of operations done**				
	2006	**2007**	**2008**	**2009**	**2010**
No renewal operation done from 2006 to 2010	-	-	-	-	-

2.2 IMs requirements and equipment for maintenance

An appropriate maintenance infrastructure is essential to carry out the maintenance work; this resides primarily in the service centres that have multiple uses: offices for management tasks and scheduling, vehicle parking, tools storage, material storage, etc...

Most of the costs of a railway infrastructure manager, usually over 50%, correspond to the infrastructure maintenance. Of this total, approximately 75% are staff costs. This percentage may vary according to the outsourcing of services, currently a growing trend.

In the railroad industry the delay in the implementation of innovative methods applied to infrastructure maintenance is remarkable, especially when compared to other fields such as automotive and airports. Since 1950 the railway sector suffered from a degree of stagnation, especially in regard to the maintenance of conventional lines (though not in the case of high speed lines where standards and maintenance are very demanding).

Since 2000 this stagnation of maintenance methods has gradually begun to be questioned in order to achieve lower costs, especially personnel costs, and better results, by increasing automation and preventive maintenance, with elements such as auscultations, inspections and reviews.

Preventive maintenance methodologies have been incorporated; this new approach allows providing technical rigor to the auscultations and inspections, so these are not just visual and therefore subject to the expertise and experience of the observer (as was the case until recently).

2.2.1 Means for preventive maintenance. Auscultation vehicles

The infrastructure managers have a fleet of vehicles for auxiliary uses such as preventive maintenance of facilities. There are mainly two auscultation techniques: the geometrical auscultation methods and dynamic auscultation methods.

There is a great variety: they may be old passenger vehicles that, after having been taken out of service, have been modified for new roles, or new vehicles properly built for maintenance operation. The propulsion can be electric or diesel. Also there are some without their own traction, which are towed by locomotives, or there are instrumented passenger vehicles.

Vehicles are becoming more sophisticated in terms of the parameters they are able to inspect. The trend is to group in the same vehicle different measuring systems and perform auscultations at operating speeds; in this way the measurements interfere as little as possible with the railway traffic and data collection is performed at line speed.

The standard EN 13848-2 “Railway applications - Track - Track geometry quality - Part 2: Measuring systems - Track recording vehicles” specifies the requirements for the auscultation vehicles.

The track auscultation can be of different types:

- Geometric track auscultation: vertical and lateral alignment, levelling, warping, cant and track gauge are directly recorded
- Dynamic track auscultation: the vehicle response by interacting with the track is recorded measuring the different accelerations perceived inside to know the defects affecting ride comfort.
- Measurement of track wear and ultrasonic inspection of rails.

For the case of the catenary:

- Geometric auscultation of the catenary: the parameters of the contact wire as height, off centring and grade are gathered.
- Dynamic auscultation of the catenary: the interaction between pantograph and overhead contact line is analysed, recording the contact force and electric arcs.
- Record of the contact wire wear through probes or video inspections.
- Measurement of thermal parameters of the catenary using thermography systems.

Once the tracks have been auscultated, the quantification of the defects is obtained by the difference between the actual geometry of the measured parameter and theoretical perfect geometry of the track.

The intervention criteria (or the decision on performing maintenance work) depend mainly on three types of statistical quantifiers: the mean, the standard deviation and the extreme values.

Both the mean and the standard deviation (of parameters such as alignment, longitudinal levelling, etc.) allow the calculation of the overall quality of the track. In contrast, the extreme values contribute to the detection of point defects.

Here below are some of the most important criteria used by the Infrastructure managers are presented.

2.2.1.1 Network Rail

Network Rail makes use of a variety of different track vehicles for maintenance works. It also uses monitoring equipment installed along the infrastructure to facilitate the preventive maintenance.

Network Rail New Measurement Train (NMT)

The NMT is owned and operated by Network Rail, Britain's infrastructure manager. The train is run over the main rail network (excluding the Southern region) every two weeks at speeds of up to 176km/h.



Figure 2.4: New Measurement Train (Copyright Network Rail)

Data is collected on:

- Track geometry
    - Top (vertical left and right rail profiles)
    - Cross level
    - Cant
    - Gauge
    - Curvature
    - Cyclic top
    - Lateral alignment
- Rail
    - Profile
    - Wear
- Overhead catenary
    - Position
    - Wear
- High definition cameras
    - Track ahead
    - Wheel/rail interface
    - Individual clips and sleepers
    - Check the six foot
    - Observe vegetation
    - Signal sighting.
- Microphones to monitor ‘excessive bogie noise’
- Radio survey to check the state of the radio communications infrastructure

Network Rail Southern Measurement Train (UFM160)

The Southern Measurement Train covers the area directly south and south-east of London which has 3rd Rail 750V DC supply. The train runs at speeds of up to 100mph. Data is collected on:



Figure 2.5: Southern Measurement Train (Eurailscout UFM160)

- Track geometry
  - Top
  - Alignment
  - Cant
  - Twist
  - Cyclic top
- Rail
  - Height
  - Head width
  - Cant
  - Type.
- Rail surface
  - Rail cracks
  - Rail joints
  - Burns
  - Wear on welded joints
  - Short wave wear
  - Missing fasteners
- Video observation
  - Rail, track
  - Rail surroundings
  - Signal visibility
  - Vegetation check
  - Third rail position
- D-GPS Positioning

Network Rail Track Recording Unit (TRU)

The track recording unit can operate at up to a maximum speed of 75 mph. It records track geometry in the same way as the new measurement train and is also fitted with radio survey and ground penetrating radar equipment which is used to identify voids, wet spots and other issues underground.

Network Rail Ultrasonic Test Units (UTU)

Network Rail owns thee ultrasonic test units (UTU). They are diesel powered and can transit between tests at 96km/h. During tests they run at 48km/h and detect cracks within rails in order that they can be rectified before they reach a dangerous length. Network Rail carries out rail inspection using the ultrasonic methods as described in Specification NR/TRK/SP/055. Network Rail uses both the manually operated portable ultrasonic test equipment and the ultrasonic test unit vehicle.

Ground Penetrating Radar (TRU and UTU)

Ground Penetrating Radar is a non-intrusive investigation technique used to examine the depth and condition of the track bed. Radar is fired into the trackbed and reflections occur at the boundaries between materials that have different radar conductivities, e.g. a radar pulse moving from dry ballast to wet clay will produce a strong reflection while a radar pulse moving from ballast contaminated with moist fines to a moist silt layer will produce weaker reflections. These reflections make up a Radargram.

The standard Radargrams are based on 1 GHz antenna data for assessing ballast condition; these are augmented by output from a 400 MHz antenna which looks at deeper layers providing an interpretation of ballast layer depths. This Ground penetrating radar was developed by GSSI and is fitted onto two of the Ultrasonic Test Trains (**UTU**) and the Track Recording Unit (**TRU**).

Current benefits include a reduction in the need for trial holes (less need for workers on the track and possessions) and better targeted maintenance & QC of maintenance done

Future benefits:

- high output ballast cleaner optimisation – being able to tell how deep the ballast needs to be cleaned means that less time is spent cleaning ballast that is clean enough, allowing more time on ballast hat does require cleaning.
- residual ballast life prediction
- combined with track geometry data to produce exceedance type reports & monitoring of trackbed deterioration
- The diagram below demonstrates the output of Ground Penetrating Radar which shows soft clay under a thin chalk bed which is not supporting the track bed. The large dip in the brown ballast layer shows that ballast has been added to the site over a number of years.

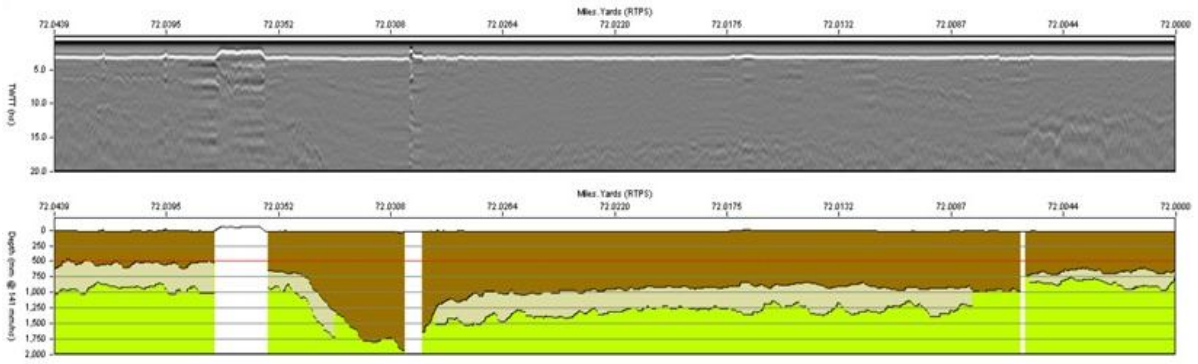


Figure 2.6: Output of Ground Penetrating Radar.

2.2.1.2 ADIF

ADIF has several of its own vehicles for inspecting its lines, for both Spanish and UIC gauge. This section will only consider those that might run on conventional freight lines (Iberian gauge) as for the case of the Mediterranean Corridor. ADIF's trains for preventive maintenance include:

- Track car for geometric track auscultation
- Probes with contact (track geometry)
- Non-contact probes (track geometry)
- Vehicles for geometry auscultation of the overhead contact line
    - geometry
    - contact wire wear
- Dynamic auscultation vehicle for overhead contact line
    - elasticity of the catenary
    - pantograph-catenary interaction
    - Measurement of arcs.

The most prominent in ADIF's fleet are the Seneca laboratory train (exclusive for UIC gauge) and Talgo XXI (Talgo BT), which perform both dynamic and geometric auscultation of track and catenary as well as testing and monitoring of signalling systems and communication lines. Both trains measure the following parameters:

- Profile section of the rail head
    - Vertical rail wear
    - Lateral rail wear
    - Total wear
    - Medium wave corrugation at (filtered 0.1-0.3m)
    - Short wave corrugation (filtered at 0.03-0.1m)
    - Long wave corrugation (1-3m).
- Accelerations in axle box:

- Longitudinal levelling:
    - Levelling defects (0.3-1m)
    - Shot wave (3-25m)
    - Medium wave (25-70m)
    - Long wave (70-120m)
- Cross Levelling
    - Shot wave (3-25m)
    - Medium wave (25-70m)
    - Long wave (70-120m)
- Twist
    - Short wheelbase (3m base)
    - Medium wheelbase (5m base)
    - Long wheelbase (9m base)
- Alignment
    - Short wave (3-25m)
    - Medium wave (25-70m)
    - Long wave (70-120m)
- Gauge
    - Gauge variation (3-25m)
    - Medium gauge(0-70m)
- Curving
    - Line layout – radius
    - Derivative of curvature with respect to space
    - Derivative of curvature or with respect to time
- Cant of the track
    - Line layout –cant of curves
    - Derivative of cant with respect to space
    - Derivative of cant with respect to time
    - Insufficient or excessive or cant
    - Derivative of the cant deficiency over time.
- Profile
    - Line layout elevation (0-200m)

Talgo XXI

Talgo XXI was a project for a high speed diesel-powered train, which operates in push-pull with one power cars and Talgo VII intermediate coach. The train has reached speeds of 256

km/h on the Olmedo - Medina del Campo high speed experimental line on 9 July 2002. After the test runs two trains was sold to the Spanish infrastructure authority ADIF as a measuring train for high speed lines.

Thanks to the gauge changer system and the diesel traction, these trains are able to work on all Spanish lines. One of them is used to measure the track dynamics of track in the Mediterranean Corridor and for ERTMS tests. They have also been used to test the gauge changers.



Figure 2.7: TALGO XXI.

Track geometric auscultation vehicle SIV 1002

This is an adaptation of a passenger coach. It is used to auscultate twice a year the entire railway network, conventional lines and high speed lines (for which the bogies are changed). It can perform recording tasks at two hundred kilometers per hour, coupled to conventional trains or hauled by a locomotive.



Figure 2.8: UIC: 607199960016. Coach for geometric track control (SIV1002).

Initially it had a computer system for auscultation and analysis, and later a GPS and a monitoring and control system was incorporated through automatic image processing. This system visually detects significant defects on the head of the rails, sleepers, fastenings and ballast, and it is based on digital image analysis.

Others

Rounding up the fleet of auscultation vehicles are: a geometric control coach for the catenary of the conventional lines (MIE 1001), a track car for the geometric auscultation of conventional lines, and several track cars that perform geometric auscultation of the catenary.

There is also available a coach for auscultation of the train-ground communication on conventional lines, and a track car for ultrasonic inspection of rails.



Figure 2.9: UIC: 607199980105. Catenary auscultation (MIE 1001).



Figure 2.10: Auscultation track car composed by two semitrailer.

(VUR 606) UIC 92760120030)



Figure 2.11: Auscultation track car: UIC 927160120022

2.2.1.3 NRIC

For examination of the track state and running order, NRIC has the following advanced track vehicle for inspection:

- Track inspection trolley SGMT5-D "Geismar"" for track & switch geometry. The technical staff are 3 persons: 2 for measurements and 1 for results
- Non-destructive ultrasonic test equipment ""RDM"" for rail defects. The technical staff are 6 persons for measurements & results (2 persons in Sofia region and 4 persons in Plovdiv region)"
- Track inspection coach EM-120 "Plasser & Theurer" for track geometry – 1 item

Also for examination of the catenary state, the main track equipment are:

- Catenary inspection coach "Geismar" for catenary geometry – 1 item in Sofia
- Catenary inspection coach "Amerikan Plasser" for catenary geometry – 1 item in Plovdiv

But the most important inspection vehicle of NRIC is the Laser laboratory “Chevrolet Silverado”. It is a railway and road motion for clearance. The technical staff is composed of 3 operators; 2 for measurements and results and a driver. It also could be used for examination of the catenary state, checking the distances from the track axis to catenary’s elements.



Figure 2.12: NRIC Laser laboratory “Chevrolet Silverado"

2.2.2 Track advanced equipment.

This section includes advanced solutions based on the equipment installed in the infrastructure. The use of these elements allows the state control, and thus facilitates preventive maintenance.

2.2.2.1 ‘WheelChex’ - Wheel Impact Load Detector on Network Rail

'WheelChex' is a lineside (wayside) measurement system that monitors rolling stock as it passes. The system consists of loading (force) measurement components that are connected to a PC based logging system. The 'WheelChex' system is capable of rapid interpretation of complex information to provide data on the condition of individual wheels and axles. Since trains in the UK are not routinely tagged, the data from a 'WheelChex' system is uploaded to a central server each night where it is combined with other data and passed on to the appropriate TOC/maintainer. The maintainer uses this information to identify and rectify faulty wheelsets.

Wheelchex® was developed by AEA Technology Rail and first installed on UK infrastructure in 1998. Currently there are 28 installations across the UK listed in Table X. The original need for the technology came from the Infrastructure owner, Network Rail:

> *“As Wheelchex was originally perceived to be a track “tool”, it was assumed to be an aid to remove vehicles that failed to meet the Railway Group standard limits. However, as the System team recognised, the actual data “owner” should have been the train operator as early detection of deterioration was perceived to be a better use of the system.”*

The system uses a series of strain gauges attached to the rail with equipment positioned between sleepers and trackside. The device is sufficient in length to recorded rail stresses for the complete wheel circumference. All recorded data is sent electronically to a central support centre where it is post-processed and presented using software developed in-house.

Faulty wheels are identified in real time and fault reports are sent immediately to notify the Infrastructure owner and the relevant RS operator of severe wheel faults causing dynamic impact loads over 350kN

There are four levels of alarm at ‘Wheelchex’ sites, level 1 (200-350 kN), level 2 (350-400kN), level 3 (400-500 kN), level 4 (> 500 kN). A level 1 alarm is advisory and the control centre does not need to stop the train. A level 2 alarm requires a 30 mph (48 km/h) speed restriction for a freight train until it reaches a suitable location where it can be taken out of service. Levels 3 and 4 require 20 mph (32 km/h) and 10 mph (16 km/h) speed restrictions respectively. A report by the UK Rail Accident Investigation Board (RAIB Report 02/2009) shows a Wheelchex output for a train recorded at Eastrea on the EMP route near Peterborough.

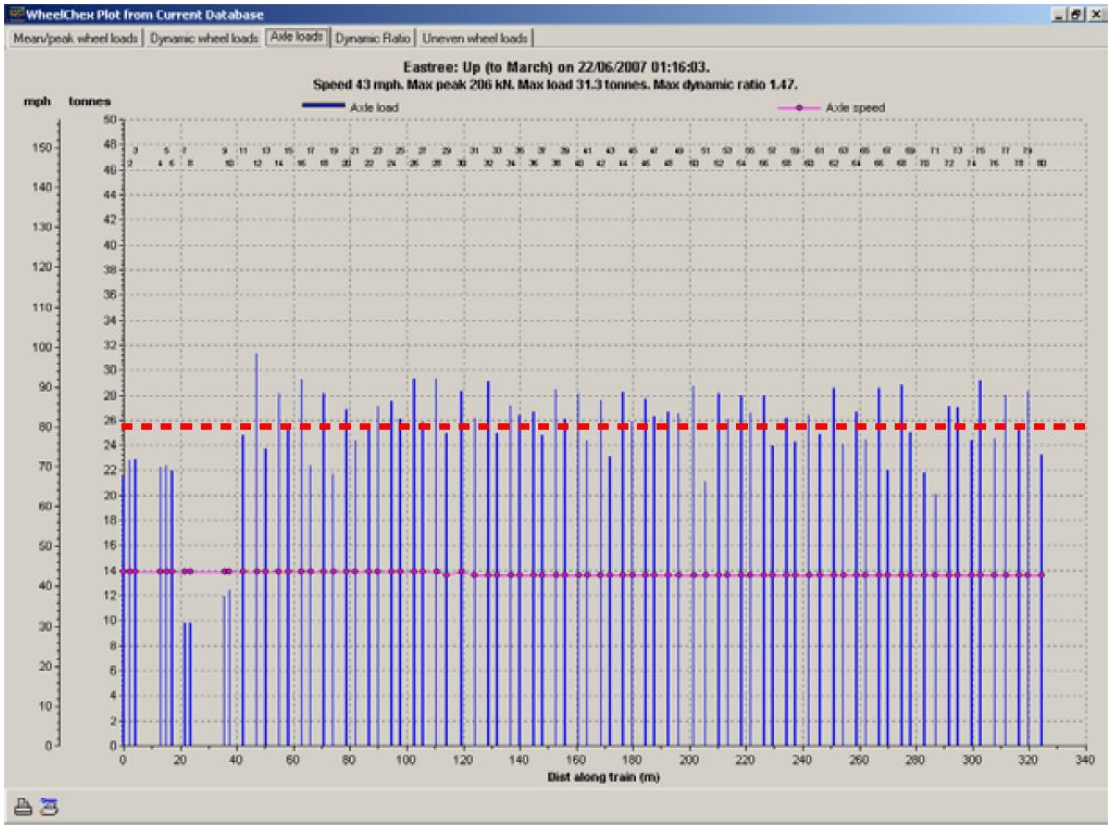


Figure 2.13: Wheelchex output for a train recorded at Eastrea

This was made up of two-axle PHA aggregate wagons. The red dotted line shows the maximum permitted axleload of 25.5 tonnes. The print out of individual axleloads along the train shows the uneven loading between ends with most of the rear axles being heavier. The total load of 52% of these wagons was above the permitted level. A Co-Co loco is seen at the front of the train followed by a 4-axle bogie wagon.

The table Table 2.16 in the report also showed that the Wheelchex could record uneven loading between wheels and identify cases of frame twist on wagons. This is shown on the PHA wagon 16002. The frame twist was thought to have been caused by a derailment 2 years earlier.

Table 2.16: PHA wagon 16002

16002	LEFT WHEEL		RIGHT WHEEL	
	kN	Tonnes	kN	Tonnes
LEADING AXLE	157.2	15.00	96.2	9.81
TRAILING AXLE	111.7	11.39	156.8	17.0

2.2.2.2 The Gotcha Asset Management System on Network Rail

The Gotcha Asset Management System's wheel-impact detection application has been in continuous use in the Netherlands for over 7 years. The system is currently installed in a number of light and heavy rail networks throughout Europe.



Figure 2.14: Gotcha Asset Management

There are now 3 systems installed on Network Rail including one at Banbury at the test centre near 86 miles on the DCL route between Didcott and Leamington Spa and one at Shawford on the BML1 route between Southampton and Basingstoke. Gotcha was installed at Banbury on 17 December 2007 and detects wheel loads and wheel unbalanced loads. There is also a portable system.



Figure 2.15: The Gotcha system installed at Shawford on BML1 near 69.5 mile post

The basic components of the Gotcha system are a set of fibre-optic sensors bolted to the rail linked to a trackside data analysis and storage capability with high-speed data links to operations, analysis and maintenance centres. The Gotcha system determines the local bending of the rail around each fibre optic sensor to determine the static and dynamic wheel impact load. Gotcha generates the following data of use to infrastructure and maintenance staff:

- Accurate and reliable identification of train or vehicle types
- Cumulative tonnages over each section of route
- Advanced warning of wheelset problems for operators
- Record of train speeds, lengths and loads
- Definition of type of problems with each wheel within train consist
- Dynamic and static load for each axle and vehicle, identifying overload and imbalance on any vehicle
- Permanent audit trail for allowing time series analysis of faults and incident investigation data for each vehicle

Figure 2.16 shows the measured deflection of the rail as the bogie passes over a single sensor. Data combined from multiple sensors ensures a high accuracy of output.

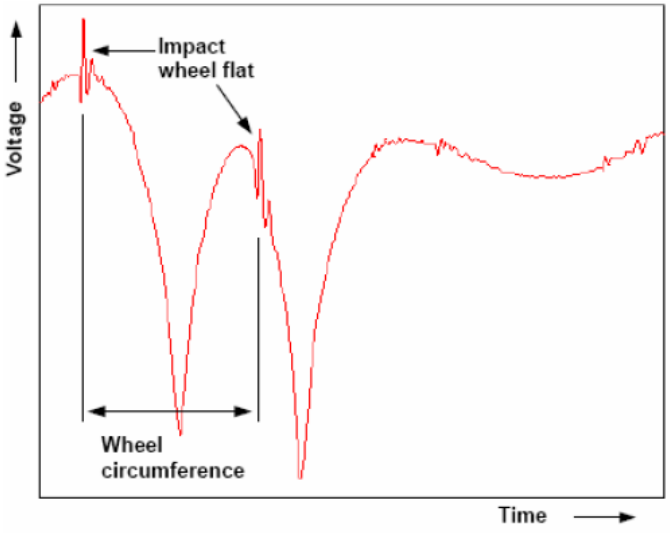


Figure 2.16: Deflection of the rail

2.2.3 Means for corrective maintenance and renewal

Track vehicles for corrective maintenance and track renewal are becoming more sophisticated by the increased mechanization involving maintenance. Standard pattern is that every time the infrastructure managers outsource more maintenance works.

The three maintenance works related to the track geometry that are most frequently performed on ballast lines are:

- Track levelling in order to correct longitudinal level, cant and buckling defects.
- Track alignment in order to correct misalignment defects.
- Ballast tamper. This operation should always be made every time there is a rail shift (both alignment and levelling operations).
- Overhead contact line maintenance: vehicle for overhead contact line lubrication and vehicles for overhead contact line maintenance at operative level, as electrification car, mast platform, spool carrier, calibrated/ verified measuring equipment, etc.

The standard EN 14033 ”Railway applications - Track - Railbound construction and maintenance machines” defines the technical requirements for this kind of machines.

2.2.3.1 NR.

The following table summarises the On-track maintenance machines that operate on Network Rail’s infrastructure. This list is not necessarily comprehensive and does not include the many wagons and vehicles that support these OTMs.

Table 2.17 On-track maintenance machines that operate on NR's infrastructure

On Track Machine	Number
Alignment regulator	2
Ballast Cleaner	2
Ballast cleaner train- High Output	1
Ballast Regulator	7
Crane	30
De-icing vehicle	3
Dynamic Track Stabiliser	3
Formation repair machine	1
Grinders - 64 stone grinding train	3
Grinders -32 stone grinding train	3
Grinders -Switch and crossing	5
Multi Purpose Vehicle	50
Sandite	3
Snowblower	2
Snowplough	32
Stoneblower - plain line	22
Stoneblower, Multi-Purpose	3
Tamper - Plain line	7
Tamper - Switch and Crossing / Universal	54
High Capacity Track Finishing Machine - AFM 2000-RT	2
High Output Track Renewal Train	2
Twin Jib Track Relayer	10
Inspection / Measurement vehicles/sets	
Electrification Measurement Coach	1
New Measurement Train	1
Radio Survey Coach	2
Structue Gauging Train	1
Track Recording Coach	3
Ultrasonic Test Unit / car	4

2.2.3.2 ADIF.

In Table 2.18 and Table 2.19 the maintenance vehicles in use by ADIF are presented. Table 2.18 contains the rolling stock not owned by ADIF that are subcontracted from his suppliers, while Table 2.19 contains his own rolling stock.

Table 2.18: Subcontracted maintenance rolling stock by ADIF.

	Total
Switch tamper	78
Levelling and aligning tamper	98
Ballast clearing machine	24
Dynamic stabilizer	34
Locomotive	44
Light rail motor tractor	6
Track bed profiler	107
Rails grinding machine	10

Table 2.19: ADIF's maintenance rolling stock.

	Overall network	Tarragona-Valencia	Other lines
Ultrasonic tester	1	0	0
Tamper	14	0	0
Self-propelled mast	0	0	3
Track car	0	0	29
Track examination car	2	0	0
Track car with crane	0	9	89
Track car with tower	0	8	68
Track car with tower and crane	0	7	51
Stabilizer	2	0	0
Locomotive	11	0	0
Rails grinding machine	10	0	0
Snow plough	0	0	2
Auscultation coach and auxiliary coach	18	0	0
Catenary auscultation coach	1	0	0
Flat wagon for maintenance operations	0	12	121
Electrification car for catenary maintenance	0	7	46

2.2.3.3 NRIC.

In the NRIC case, the equipment for examination and renovation is able to perform operations over the whole railway infrastructure and not only for the selected line.

There are 2 regions (Sofia – from Serbian boundary to Belovo and Plovdiv – from Septemvri to Greek and Turkish boundaries) for routine maintenance of the track with 14 railway

sections (Dragoman, Volujak, Sofia, Iskar, Vakarel, Kostenec, Belovo, Septemvri, Stambolijski, Plovdiv, Plovdiv iztok, Parvomaj, Dimitrovgrad, Svilengrad).

For routine maintenance of the track superstructure or catenary operations, the NRIC has a technical staff of 594 persons and a total of 72 items in Sofia region and 51 items in Plovdiv region, the most important are:

- Small-scale mechanization (rail die-cutting machine): 22 items
- Rail drilling machine – 25 items
- Sleeper drilling machine – 14 items
- Grinding machine – 5 items
- Rail tie-rod – 3 items
- Rail bending machine – 2 items
- Screw-driving machine – 37 items
- Nut-driver – 5 items
- Lifting jack – 10 items

There are also 7 power distribution subdivisions – PDS (Volujak, Sofia, Vakarel, Kostenec, Pazardjik, Plovdiv, Dimitrovgrad) for routine maintenance of the catenary. There are 121 persons working as technical staff.

There are 3 units (Sofia from Serbian boundary to Belovo; Plovdiv – from Septemvri to Parvomaj; Stara Zagora – from Parvomaj to Greek and Turkish boundaries) for urgent maintenance with 13 depots (Dragoman, Slivnica, Volujak, Sofia, Podujane, Iskar, Vakarel, Kostenec, Belovo, Septemvri, Stambolijski, Plovdiv iztok, Dimitrovgrad), and 50 persons as technical staff. The most important items for this works are:

- Railway crane ЕДК-300/5 with lifting capacity 50t – 2 items in Sofia
- Railway crane ЕДК-300 with lifting capacity 60t – 2 items in Plovdiv and Stara Zagora
- Railway crane ЕДК-300 with lifting capacity 80t – 1 item in Stara Zagora
- Emergency failure recovery automobile Unimog U1650L ""Mercedes Benz"" (railway and road motion)
- With lifting capacity 120t – 3 items in Sofia, Plovdiv and Stara Zagora
- Cross-country automobile – 1 item in Stara Zagora"

Renovations are done through an external supervisor, depending Public Orders Law. For railway track renovation, the most important items are:

- Renovation crane PTH-350 ""Geismar"" – 2 items
- Dynamic stabilizer: DGS-62N – 4 items; DGS-42N – 1 item
- Excavator KGT/V ""Geismar"" – 2 items
- Ballast screening machine RM76UHR – 2 items

- Elevator train for screenings (with 4 wagons) MFS-100 – 2 items
- Motor tractor ДГКУ-5 – 47 items
- Complex ballast tamper for track & switch B41UE – 2 items
- Ballast tamper for track: B45L – 2 items; 08-32 – 7 items; 07-32 – 2 items
- Ballast tamper for switch 07-275 – 1 item
- Ballast planning machine: RGL-600 – 2 items; SSP-203 – 4 items
- Grinding machine Atlas 16-2 – 1 item
- Specialized machine D912R – 1 item
- Ballast pit – 1 item with productivity 50 thousand cubic meters per year
- Heat-treatment shop – 1 item with productivity 1700 long rails per year
- Assembly depot – 5 items

And for catenary renovation:

- АГМу - ДМ 14 – 1 item in PDS Volujak
- АГМу - ДМ 15 – 1 item in PDS Volujak
- "GEISMAR" - CM 021 – 1 item in PDS Sofia
- "GEISMAR" - CM 024 – 1 item in PDS Vakarel
- АГМу - ДМ 19 – 1 item in PDS Kostenec
- АДМ - АДМ-715 – 1 item in PDS Kostenec
- АДМ - АДМ-716 – 1 item in PDS Pazardjik
- "GEISMAR" - CM 02 – 1 item in PDS Plovdiv
- АГМу - АГМу E-6 – 1 item in PDS Dimitrovgrad"

2.3 Maintenance and renovation cost

Having defined the maintenance and renovation needs required by each of the technological alternatives under consideration, this section presents quantitative data on the cost of such actions based on the state of the art and the data provided by the IMs on lines under study.

2.3.1 State of the art

In general, infrastructure and track maintenance has always represented between 40% and 67% of total maintenance costs (both high speed and conventional), while signalling costs vary between 15% and 45% of the total on conventional lines. The electrification and other costs are smaller percentages, although similar for both tracks types.

Regarding the maintenance costs of the ballasted tracks, the use of historical cost of conventional railway networks can be misleading: the improvements in the track technology, in the maintenance methods and in the rolling stock, can make such data obsolete and unreliable for predicting maintenance costs of a new line or one that has recently undergone a major renovation of its components.

Prices and costs in the railways sector". Baumgarter (2001) [2.1]

This famous study provides some orders of magnitude about the maintenance and renovation costs of some railway infrastructure components according to prices of the year 2000. It presents the following estimation of the average annual maintenance costs (long term) per track kilometre in terms of railway traffic and train speed (see Table 2.20).

Table 2.20: Maintenance track costs according to railway traffic and train speed. Source: Baumgarter (2001). Year 2000 prices expressed in Euro. Gross tons per track kilometre, including locomotive.

Maximum Speed (km/h)	$10x10^3$ TBK/day	$30x10^3$ TBK/day	$100x10^3$ TBK/day	$300x10^3$ TBK/day
100	7,000 €	15,000 €	30,000 €	60,000 €
	(5-10 k€)	(10-20 k€)	(20-40 k€)	(40-80 k€)
300	...	20,000 €	40,000 €	...
		(10-30 k€)	(20-60 k€)	

The author points out variation patterns of these costs, which increase with:

- increasing axle load,
- decreasing curve radius, or
- increasing maximum authorized speed.

"International benchmarking of track costs" Stalder, O. (2002) [2.2]

This study, part of the project INFRACOST, analyses the railway superstructure costs from the data provided by the infrastructure managers from twelve European countries (UK,

France, Italy, Ireland, Finland, Norway, Sweden, Switzerland, Czech Republic, Belgium, Netherlands and Denmark), five US railway companies (U.S. Class-I) and four Asian infrastructure managers.

Regarding the analysis of the renovation costs, the study provides ranges for various renovation projects (1 - rails, 2 - rails and sleepers, 3 - rails and sleepers including cleaning of ballast, 4 - rails, sleepers and ballast, 5 - sleepers, 6 - cleaning of ballast; 7 - rails, sleepers, ballast and sub-ballast, 8 - ballast; 9 - ballast and sub-ballast, 10 - ballast and sleepers). They are illustrated in Figure 2.17.

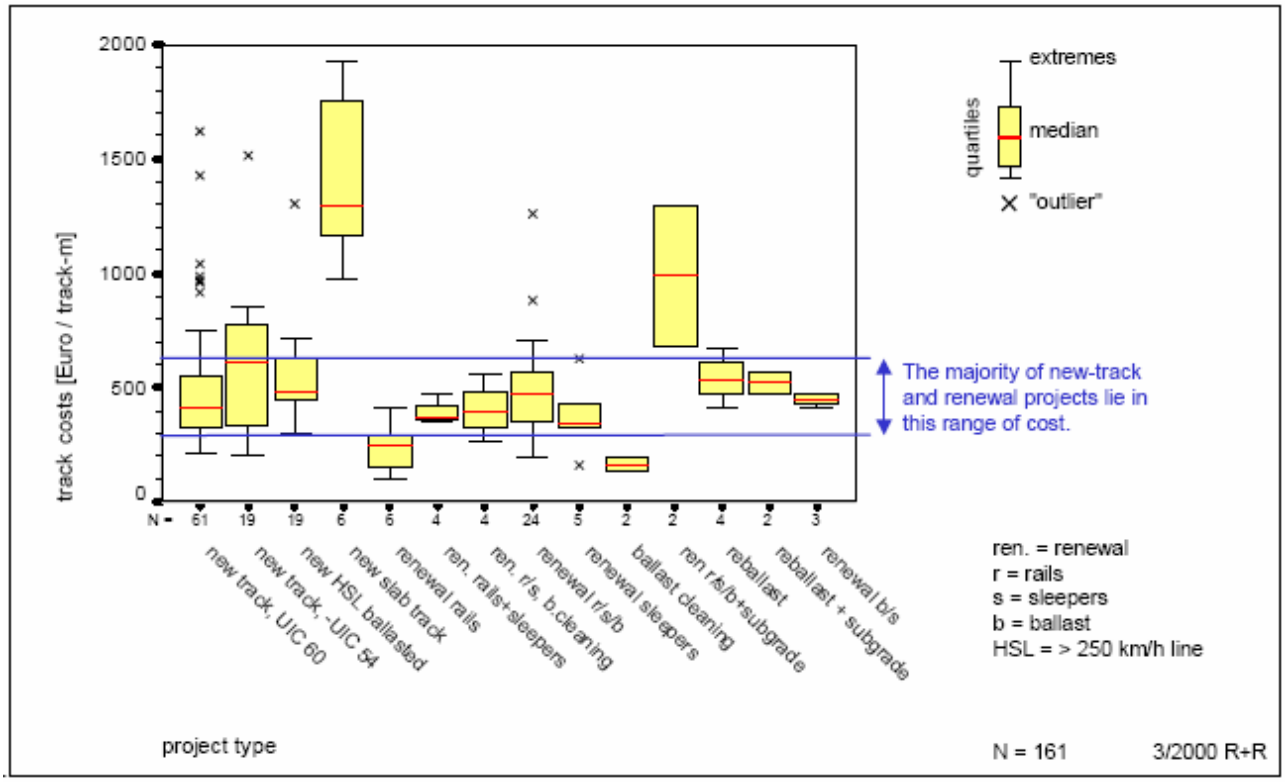


Figure 2.17: Analysis of the renovation costs. Source Infracost project.

The study provides additional information about the cost of the various renovation projects analysed and compared with a predetermined cost function (Figure 2.18).

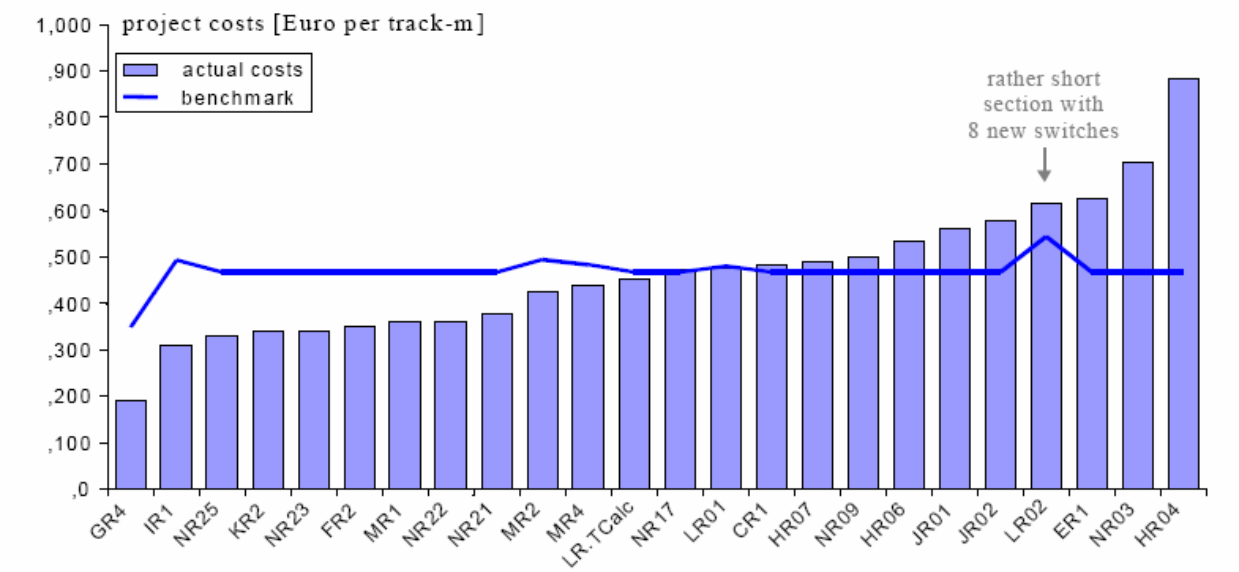


Figure 2.18: Renewal of rails, sleepers and ballast; no subgrade works. Source Infracost project.

Infracost – LICB (Lasting Infrastructure Benchmarking)

Infracost contains reports by BSL Management Consulting and R + R Burger und Partner AG. Subsequenty to these reports, the LICB study was conducted; it updated the results achieved by Infracost - this information is available in the presentation "Indication of infrastructure provision costs. UIC Benchmarking results" by Teodor Gradinariu (Chargé de Mission Infrastructure, UIC), and the study "Assessment Report on the Financial Model of the Slovene Rail Infra Manager AZP".

Lasting Infrastructure Cost Benchmarking (LICB 2008) is an international benchmarking project established by the Infrastructure Commission of the International Union of Railways (UIC). Fourteen European Infrastructure Managers participated in the project, and delivered information each year. Data since 1996 has been collected and is analysed so that it is possible to identify trends over time.

According to these studies, there are several network physical characteristics that have a significant impact on the maintenance and renewal costs:

- the density of switch gears,
- length of lines in tunnels and engineering structures,
- the length of double track
- the electrification level.

Other parameters such as the radius of curvature, the axle load and speed that also have an impact on the value of the life cycle costs.

Furthermore, the degree of utilization of the network has a very significant influence on the maintenance costs and life of the components. In this study two indicators of the use of the network are used: the average frequency of trains per year and the average annual gross tonnage (freight and passenger). This is because experience shows that maintenance costs are more dependent on the train frequency (due to the difficulties and costs related to interruptions in the operation) and the renovation costs are more related to the gross tonnage as having a major impact on the tracks wear and the ballast deterioration, and consequently in their life cycle. The appearance of the single track and double track is a key issue in the track

renewal. According to the study, data from the SNCF and surveys, it can be concluded that the maintenance cost per track kilometre for a single track is 40% higher than for a double track.

The document produced by the AZP in 2006 states that the average value of the maintenance costs of 12 of the 13 countries that participated in the LICB amounts up to € 47,476/km of track (not harmonized) and the average renovation costs are € 36,721/km of track, reaching a total of € 84,196/km of track.

The 14 IMs had together spent in 2007: 6.902 billion euros on maintenance of their networks and 8.643 billion euros on renewals averaging track maintenance and renewal costs of 73,900 euros per track km at 2007 prices.

In Figure 2.19 Network Rail for the years 2009/10 (at 2011/12 prices) spent 92,360 euros per track km for maintenance and renewals: maintenance cost was 28,720 euros/track km and renewals cost was 60,960 euros/track km.

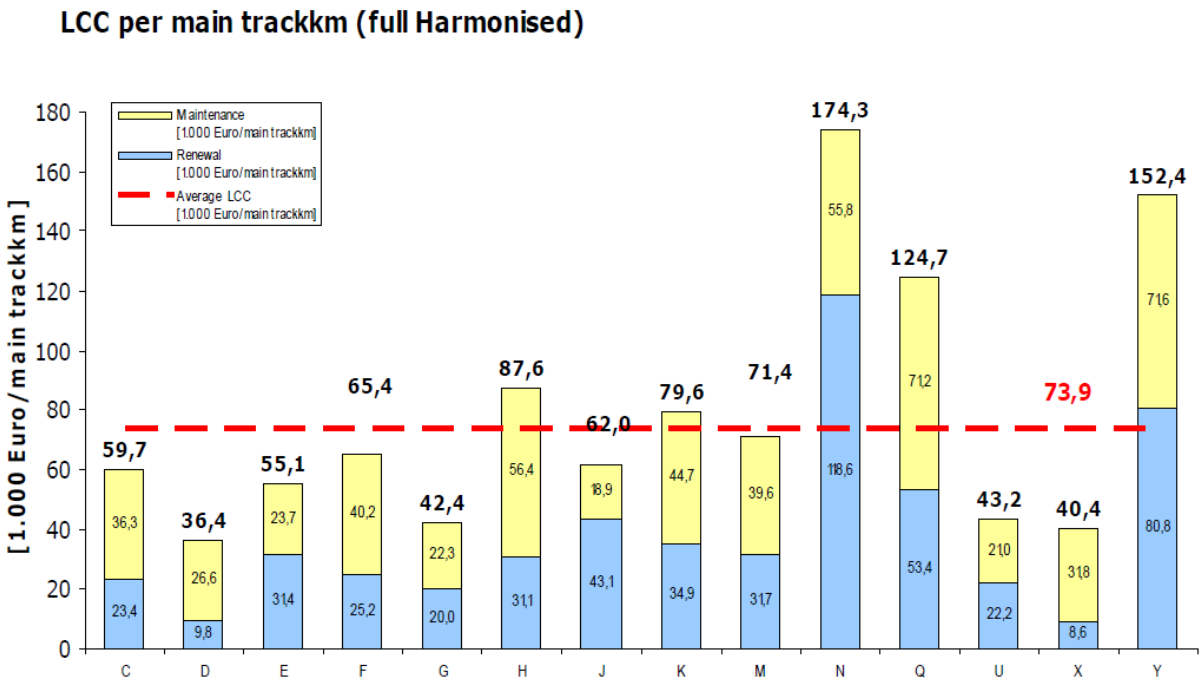


Figure 2.19: Maintenance and renewal costs for 14 EU IMs in the UIC Lasting Infrastructure Cost Benchmarking project (LICB) - Dec 2008 Average cost for 2007 was 73,900 euros per track km. Fully harmonized.

The LICB presentation states that the average value of maintenance costs plus the renewal ones is an indicator that reflects the life-cycle cost of the infrastructure and determines that, the average expenditure per track kilometre renewal and main maintenance is about 72,000 € / km of track (not harmonized).

Both the Infracost and LICB study tried to harmonize the differences in the networks regarding as much of the aspects mentioned (and others like the personnel costs). The harmonized results are also very different according to the Infrastructure Managers involved in the study. In the year 2000 document, corresponding to the Infracost study, it was stated that the average maintenance and renewal costs was 57,000 €/main track km (with a

maintenance cost of 33,000 €/track km and a renewal cost € 24,000/track km). In the update phase, Gradinariu's presentation proposed an average value of € 80,400 / main track km.

However, the AZP document that includes the same countries as above except one, concludes that maintenance and renewal harmonized costs can be estimated as € 69,650 / main track km. On the other hand, the presentation shows that the amounts for track renewal have increased up to 60% on average between 1996 and 2003 while maintenance cost has stabilized.

The 2001 report [2.3] divided the average costs studied for maintenance into:

- Earthworks, track, bridges and tunnels account for 57.7% of costs. In the case of renewals the first item is even more important with a weight of almost 70% of the total.
- Signalling and telecommunications 27.4%
- Electric traction (substations and overhead lines) 14.9%.

The same study also emphasizes that outsourcing does not reduce maintenance and renewal costs (in fact the observed trend is the opposite). Among the various items that represent the maintenance and renewal costs, the personnel cost accounts for 60% of the total in the first case and 30% in the second one. In addition, the need for the renovation work with uninterrupted train traffic represents 50% more cost (relative to comparable projects without interference with traffic). The purchase item is not significant in the maintenance (8%) but is very important in the renewal (35%).

Other relevant studies:

- **« Audit sur l'état du réseau ferré national français » (Rivier y Putallaz, 2005).**The paper seeks to assess the status and maintenance needs of the French rail network. The first section discusses the current state of the network and patrimony in general. The second section analyses the financial flows and maintenance techniques. In a third, an analysis of maintenance policies and commissioning, as well as recommendations and a study of future scenarios) are presented.
- **La maintenance de la voie de la ligne à grande vitesse Paris-Sud-Est (Thomas, 1991), Rail International, p. 42-47).** In this article the author gives an overview of the evolution of speed in the French high speed lines, the track design according to the SNCF, the maintenance organization and its cost (based on the analysis of the Paris-South-East Line).
- **Raisons fondamentales qui conduisent à une mécanisation poussée des travaux de voie à la SNCB » (Goosens, 1991).** In this document, the author carried out a description of the Belgian railway network at that time (1991), and reviews the evolution of the rolling stock in Belgium, renewal and maintenance methods and economic duration. Subsequently, the article compares the maintenance carried out by the own infrastructure manager and outsourced to external companies.

2.3.2 Gathered information regarding the selected routes

Data about maintenance and renewal cost has been gathered also for other task of the SUSTRAIL project. There is information regarding this aspect in the Work Package 1, deliverables 1.2 and 1.4.

2.3.2.1 UK routes

The information obtained from Network Rail has been summarised in the following tables and graphs.

Table 2.21: Total average estimated indicative maintenance and renewal costs for the two UK routes selected and the network average.

From	to	Cost (€/km/year)
Southampton	Warrington	60,300
Felixstowe	Warrington	45,000
Whole Network		37,500

Table 2.22: Maintenance cost divided in several items in the whole Network rail. Percentage of overall track maintenance costs from 2006 (grinding is now higher).

Maintenance Item	%
Plain line tamping	22
Inspection	19
Rail changing	18
S&C	15
Ballast Re- profiling	8
Re- sleepering	5
Weld repairs	5
Wet bed removal	3
Fish plate oiling	2
Insulated Joint renewal	1
Grinding	2
TOTAL	100

Figure 2.20 presents the cost drivers based on 2006 track maintenance cost estimated from BV and calculated as percentage on the overall cost.

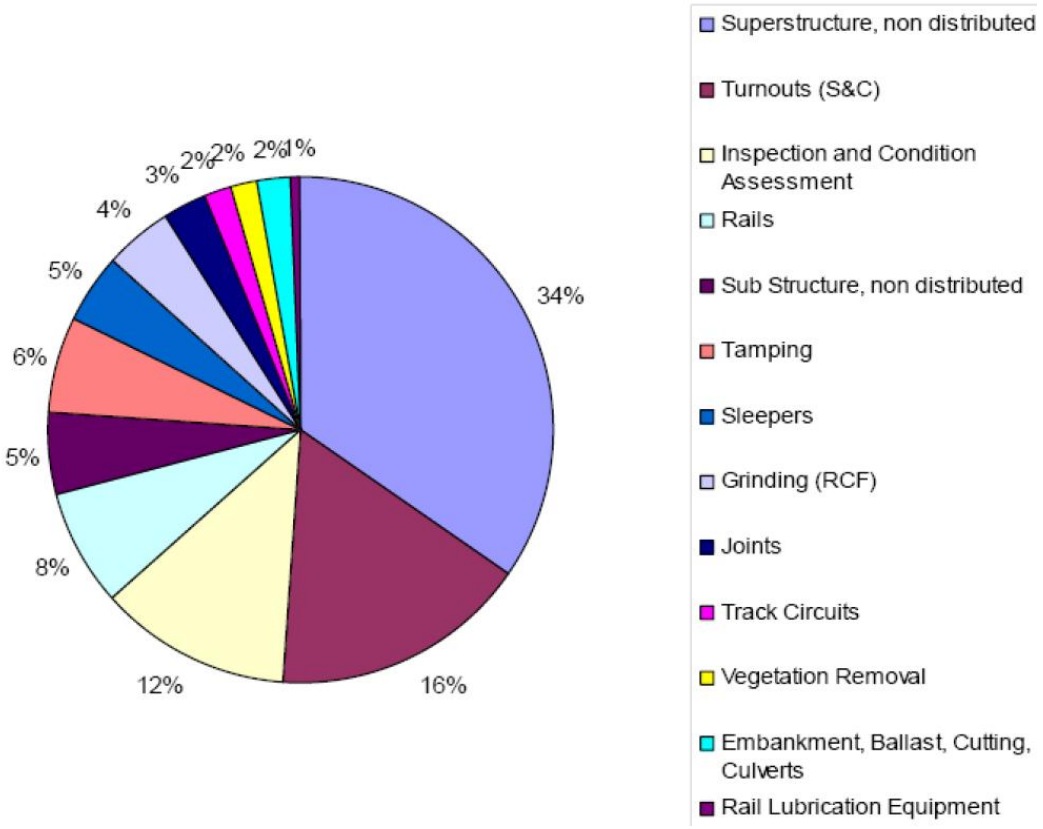


Figure 2.20: Cost drivers based on 2006 Track maintenance cost estimated from BV.

Table 2.23: Network Rail expenditure in England & Wales 2009-10 (2011/12 prices).

Category	£m	%	Commentary
Operating expenditure (less traction power for train operators)	1,164	18%	The single largest element is staff costs. Other significant costs include office accommodation and insurance. Some costs are considered ”non-controllable” including, business rates, British Transport Police costs and ORR fees. These represented one third of total operating expenditure.
Maintenance expenditure	1,051	16%	The maintenance function employs nearly half of the total Network Rail headcount in forty maintenance delivery units and a central unit. The single largest elements of headcount and expenditure are in track (40%) and signalling (16%).
Renewal expenditure	2,231	34%	£683m (31%) was spent on track, £419 (18%) on signalling and £302m (14%) on structures including bridges and tunnels.
Enhancement expenditure	942	14%	Expenditure included Thameslink Programme (£422m), Kings Cross Station (£92m), Reading Station (£32m), Access for All (£57m) and North London Line Capacity (£44m).

Category	£m	%	Commentary
Interest costs	1,166	18%	Finance costs on existing loans, the government guarantee and the increase in value of index linked debt.
Total	**6,556**	**100%**	

Table 2.24: Network Rail figures for 2010/11.

Network Rail Expenditure 2011	2011 Costs	Total of all Costs per track km in (£k)
Renewals	£2,200,000,000	£70.7
Including track renewals	£600,000,000	£19.3
Ops & Main Costs	£2,467,000,000	£79.3
Enhancements	£1,700,000,000	£54.6
Total (excluding interest costs)	**£6,367,000,000.00**	**£204.7**

2.3.2.2 Spanish route

Maintenance cost divided in several items in the whole ADIF conventional Network (not included High Speed Lines). Table 2.25 shows the percentage of overall track maintenance costs.

Table 2.25: ADIF's Percentage of overall track maintenance costs.

Maintenance Item	%
Track superstructure	51
Signalling	10
Electrification	12
Telecommunications	7
Track Infrastructure	12
Level crossing	4
Others	5
TOTAL	100

Data about track renewal costs of two sections of similar traffic characteristics than the Mediterranean corridor are also available:

- Section 1: 73.49 km of rails, 37 km of double track.
  - Cost 2007 works: 10,290,000 € for
  - Cost 2008 works: 25,720,000 €.
  - Cost 2009 works: 15,430,000 €.
- Section 2: 95.1 km of rails, about 47.5 km of double track.

- Cost 2007 works: 22,820,000 €.
- Cost 2008 works: 22,820,000 €.
- Cost 2009 works: 11,410,000 €.

2.3.2.3 Bulgarian route

Deliverable 1.2 contains information about maintenance and renewal cost for the Bulgarian routes.

Also the information obtained from NRIC for this specific subtask, has been summarised in the following table.

Table 2.26: NRICfigures from 2006 to 2010.

Cost including subcontract works (€).	**Year**				
	2006	**2007**	**2008**	**2009**	**2010**
Track examination or prevention.	6,200	12,000	13,500	-	-
Track maintenance without stations.	-	8,071,410	8,553,920	7,595,840	8,288,510
Track maintenance including stations	-	15,470,490	18,081,860	17,654,260	17,224,547
Track renovation.	5,982,780	1,691,160	2,262,920	395,890	3,229,890
Track renovation	4,807,010	584,420	846,660	243,590	76,110
Repairs of track	79,840	664,360	50,940	0	0
Repairs of structures and railway bed	1,095,930	442,380	1,365,320	152,300	3,153,780
Cost of modernization	-	-	-	-	10,256,400

2.4 Measures that support sustainable achievement of "towards Zero maintenance"

In order to analyse the measures that can reduce maintenance, it is important to firstly focus the parameters that can affect to greater extent on the track maintenance and renewal:

- Track state and type
- Traffic speed and kind of traffic
- Unsprung weight of the rolling stock.

Similarly, as formulated by Pru'dhomme, to reduce the loads on the track and therefore reduce its maintenance, it is necessary to work on two aspects of the infrastructure:

- To reduce the level of tolerable defects in the rails.
- To provide track having a stiffness the least as possible.

2.4.1 Track state and type

Many studies have been carried out comparing the characteristics of the track set on concrete slab with the track on ballast, especially taking into account the Japanese and German experience, and some studies carried out in experimental sections in Spain.

Comparing the costs of maintaining the technologies of slab track and ballasted track, faces several challenges, not least the few published data on the costs of these activities in the case of slab track. When quantitative data exists, the maintenance costs for slab track are usually expressed as a percentage of the total maintenance cost required by ballasted tracks. When there is a breakdown by activity, then numerous diffuse parameters are mentioned that prevent effective comparison and the drawing of meaningful conclusions.

Among all the selected studies and published data that clearly establish the track maintenance costs, as well as information confidentially communicated by experts and Infrastructure Managers contacted by the UPM team, it can be deduced that the maintenance unit costs are:

- Ballasted track - between 9 and 15 €/ track metre-year,
- Slab track systems in Japan -between 4 and 5 € / track metre-year
- Experimental slab track in Spain - 7 €/track metre-year.

2.4.2 Influence of traffic speed and types of traffic

The deterioration of the track components is a function of the loads transmitted to the superstructure, which can be expressed as a combination of static vehicle axle load and the dynamic overload they produce when they run on the track. This second term is directly related to the traffic speed and the weight per axle, which justifies the conclusion that the track deterioration increases as a function of axle load and speed.

The highest quality construction procedures are required for the design and construction of high speed lines. These are generally characterized by a more open line layout, which have large radius curves and rarely any curves of small radius and the high wear associated with them. High speed lines have more control over the quality of execution of the work, lower tolerances for alignment, levelling and track gauge defects, as well as imperfections in the running surface, limiting the presence of initial defects and imperfections which will adversely affect future maintenance.

The influence of maximum speed on unit maintenance costs is not clear, although, from the theoretical formulations about deterioration, it seems reasonable that its contribution is positive, but it was impossible to find in the literature a clear relationship between train traffic speed and maintenance fixing other parameters.

Regarding the traffic volume running along a line, this is known to be a determining factor for the track deterioration and therefore maintenance cost thereof. Anyway, the exact functional form that relates the maintenance costs and traffic volume is not known.

Neither is it possible to determine the relationship between traffic volume and maintenance costs from the data available from operators and infrastructure managers. It is expected that some relationships might be determined during this project.

Taking into account the data by Baumgather [2.1] referred to the cost in terms of traffic (gross tonnes-kilometers or GTK), it is possible to represent Figure 2.21.

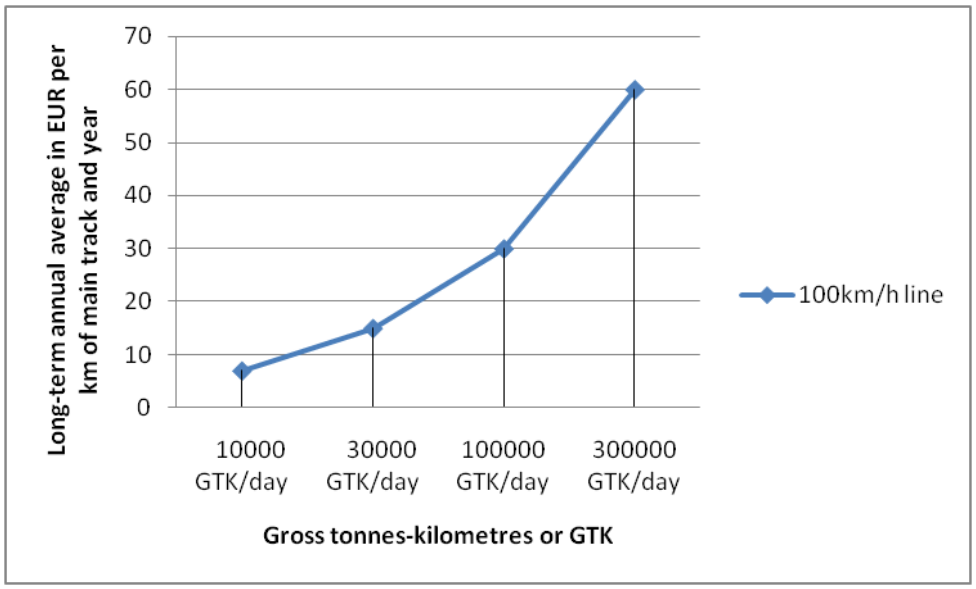


Figure 2.21: Long-term annual average in Euro per km of main track per year. Source Baumgather [2.1].

From the Figure 2.21 it can be deduced that maintenance costs increase with traffic in a non-linear-manner.

From the same reference, a similar graph can be presented showing the influence of traffic on track renewals (Figure 2.22).

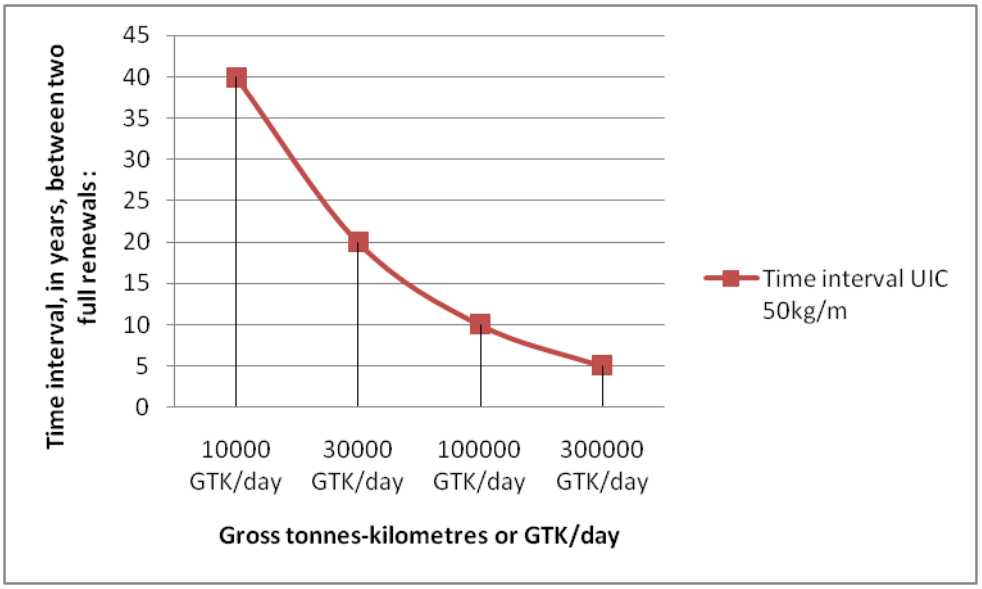


Figure 2.22: Time interval, in year, between two full renewals. Source Baumgather.

2.4.3 Unsprung mass of the rolling stock

The reduction in unsprung mass of the rolling stock has a positive effect on the maintenance, reducing the need for track maintenance, especially if the train traffic speed is increased.

For the case of passenger coaches, the unsprung mass is very low, and therefore they have a very little aggression on the track. For the freight case, with higher axle load, the unsprung mass can be very relevant.

In order to increase the speed and the axle load without increasing maintenance costs excessively, it is critical that freight wagons are equipped with proper suspension systems, and essential that the unsprung mass is reduced, which influences in an unavoidable manner the deterioration of the track geometry. Generally it is considered that the increase in maintenance costs in a mixed traffic line, compared to a strictly passenger line, can be quantified as between 15 and 20%. [2.4]

2.4.4 Tolerable defects in rails

This section considers data provided by Network Rail. Rails defects are responsible for a large part of the maintenance costs and other costs associated with the railway operation of the line.

Table 2.27 shows the rail defects found in selected sections.

Table 2.27: Defect rate per 100 km/year in Network Rail selected sections.

	Defect rate per 100 km/year	
Route	**Actionable**	**Serious + breaks**
DCL: Anyho to Leamington Spa	333.7	6.2
DCL: Chester Lime to Anyho	95.9	2.8
EMP: Ely North to Peterborough	78.1	3.3
BML1: Northam Short to Basingstoke	59.7	9.3
WCML: Nuneaton to Crewe	42.9	1.0
Network average	73	5.1

The high value on the northern DCL section between Anyho and Leamington Spa may be because along this stretch of the route 75% of the rails were over 30 years old whereas for the southern section between Didcott and Anyho only 21% of the rails were older than 30 years. (These old rails are currently being replaced)

Similarly for BML1 only 14% of rails were older than 30 years. On the EMP route 50% of the rails are older than 30years but the EGMTA is only half that of the DCL route with slightly lower line speed. In the last 2 years the 32.3 route km from Anyho junction to Leamington Spa on DCL have averaged 108 actionable defects per year making 333.7 actionable defects per 100 km.

Plotting a graph of actionable defects against residual life of the rails over each section gives the interesting relationship of Figure 2.23.

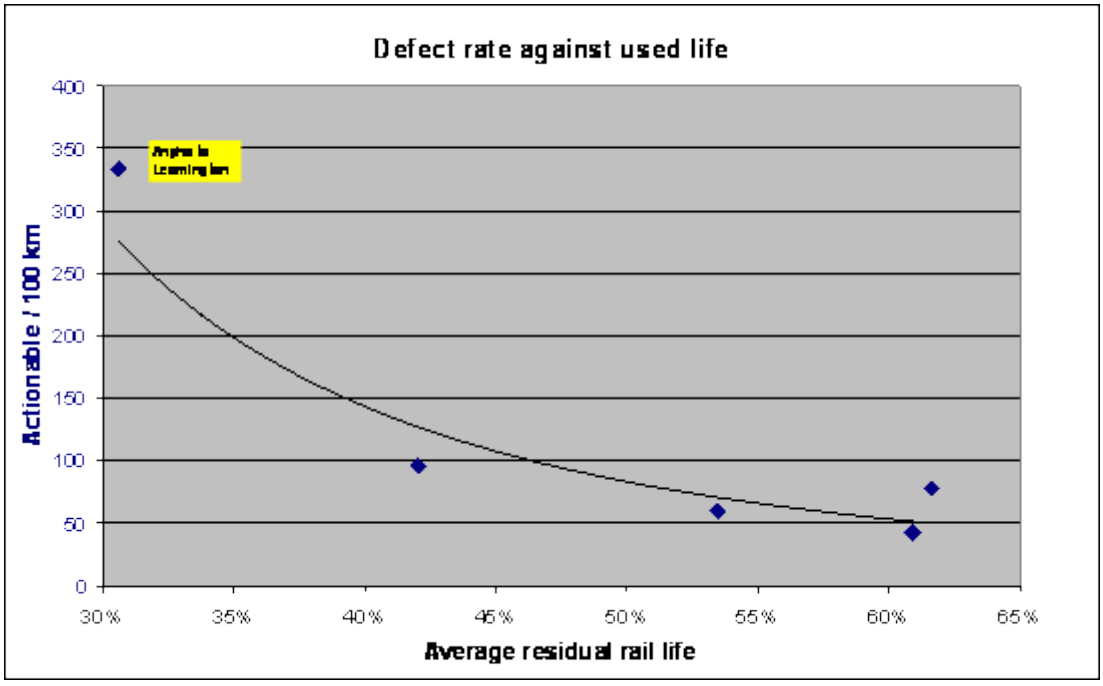


Figure 2.23: Defect rate against used life. Source Network Rail.

A breakdown of the defects over the 32.3 km of route between Anyho and Leamington Spa are presented in Table 2.28.

Table 2.28: Defects over the 32.3 km of route between Anyho and Leamington Spa.

Defect Group	2009	2010
Lipping & sidewear	1	3
Other	8	8
RCF	2	
Squat	81	59
Tache Ovale	1	
Weld	32	20
Wheelburn	1	
Grand Total	**126**	**90**

Only less than 1% of these defects cause any delay to the railway as they are usually detected and repaired well before they can cause any operational safety risks. Over the network it has been estimated that.

Table 2.29: Failures causing delay.

Failures causing a delay	
Element	**No. per 100km route/yr**
Track	0.36
Points	0.32
Signalling	1.37

Table 2.30 and Table 2.31 give a breakdown of Year to Date figures for all incidents and failures across the whole rail network at the end of Period 11 for 2011/12 causing a delay to trains. To estimate full year figures one might multiply the data by 13/11 as there are 13 4-weekly periods. On average across all the incidents over the last 3 years each incident caused 91 minutes of train delay.

Table 2.30: Incidents and failures causing train delays across the rail network – Comparing Year to Date up to the end of Period 11 out of 13.

Year	Points failures	Level Crossing failures	TSRs due to condition of track	Track faults including broken rails	Gauge corner cracking	Civil engineering-structures, earthworks	Other infrastructure failures	Track patrols & related possessions	Mishap with infrastructure	Fires on NR infrastructure	OLE/Third rail	Signalling failures	Track circuit failures	Axle counter failures	Power supply failures	Other signalling equipment failures	Telecoms	Cable faults	Bridge Strikes	All
2011/12	4628	1634	549	4048	39	253	3352	1733	1602	231	1070	4290	3756	575	3551	1421	1041	472	944	35225
2010/11	5380	1681	778	4247	54	322	2923	2064	1342	227	1104	4349	3981	564	3837	1470	1056	469	1068	36916
2009/10	6513	1901	998	4608	122	366	3026	2458	1263	175	1080	5365	4539	810	3485	1414	1170	458	974	40725

Table 2.31: Estimate of the full year by multiplying Table 2.30 by 13/11 (or 1.1818)

Full Year estimate	Points failures	Level Crossing failures	TSRs due to condition of track	Track faults including broken rails	Gauge corner cracking	Civil engineering-structures, earthworks	Other infrastructure failures	Track patrols & related possessions	Mishap with infrastructure	Fires on NR infrastructure	OLE/Third rail	Signalling failures	Track circuit failures	Axle counter failures	Power supply failures	Other signalling equipment failures	Telecoms	Cable faults	Bridge Strikes	All (Full year estimate)
2011/12	5469	1931	648.8	4827	46.09	299	3961	2048	1893	273	1265	5070	4439	679.5	4197	1679	1230	557.8	1116	41629.5
2010/11	6358	1987	919.5	5019	63.82	380.5	3454	2439	1586	268.3	1305	5140	4705	666.5	4535	1737	1248	554.3	1262	43628
2009/10	7697	2247	1179	5446	144.2	432.5	3576	2905	1493	206.8	1276	6340	5364	957.3	4119	1671	1383	541.3	1151	48129.5

2.4.5 The role of vertical track stiffness

Studies carried out on the French TGV [**¡Error! No se encuentra el origen de la referencia.**] show that as the vertical track stiffness decreases, the dynamic loads on the rail decrease. On the other hand, by reducing the vertical track stiffness, the energy dissipation in itself would be greater, and hence traction costs would be higher [2.6].

More recent studies on this aspect [2.7] suggest a relationship between maintenance costs and traction according to the vertical track stiffness.

Other studies [2.8] on the influence of vertical track stiffness on track deterioration, also show that with vertical track stiffness between 50 kN/mm and 100 kN/mm, the degradation of the geometric track quality would be minimal.

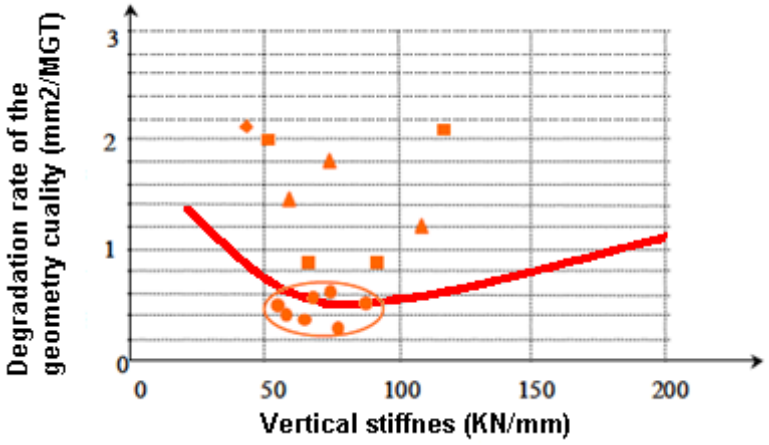


Figure 2.24: Relation between vertical stiffness and degradation rate. Source [2.8].

For a given route, the three elements on which to act to change the vertical track stiffness are:

- Bearing plate between rail and sleeper
- Elastic sole under the sleepers
- Elastic pad under the ballast.

The optimization of the vertical track stiffness for each line, taking into account the traffic can be very important in order to reduce the associated maintenance costs.

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3. TRACK DESIGN AND DUTY REQUIREMENTS TO MEET THE IMPACT OF CLIMATE CHANGE AND ENVIRONMENTAL LEGISLATION.

This section includes the results of the subtask 2.3.2. The objective of this task is to define track design and component duty requirements to meet the impact of climate change and environmental legislation.

Also the duty requirements have been identified that will contribute to mitigating the impact of climate change on rail maintenance and the constraints that may be imposed by carbon targets. Other issues that duty requirements will address include the impacts and constraints on the availability of new infrastructure components such as ballast and sleepers, and their disposal at end of life, and the impact of climate change on structures.

This subtask has been developed by the UPM team, with the contribution of TATA Steel, who assesses changes in the rail section for manufacturability and also recycling and the effect of carbon targets on lifetime of rails. TATA also provided first-hand information about current performance of rail and steel sleepers.

3.1 Introduction: Observed changes in the climate

In the Climate Change 2007 Report, the Intergovernmental Panel on Climate Change (IPCC) has observed some changes in the climate pattern over the last few decades [3.1].

This kind of study has always an uncertainty guidance note, because they have judged the results using a statistical treatment of the data. There are defined some likelihood ranges in order to express the assessed probability of occurrence:

- Virtually certain >99%
- Extremely likely >95%;
- Very likely >90%;
- Likely >66%;
- More likely than not > 50%;
- About as likely as not 33% to 66%;
- Unlikely <33%;
- Very unlikely <10%;
- Extremely unlikely <5%;
- Exceptionally unlikely <1%.

Considered the purposes of this document, there are going to be considered as certain climate change impacts the ones that are, at least, likely (>66%).

IPCC considers that warming of the climate system is evident. They can assure it because of their observations of increases in global average air and ocean temperatures, melting of snow and ice and rising global average sea level, as seen in Figure 3.1.

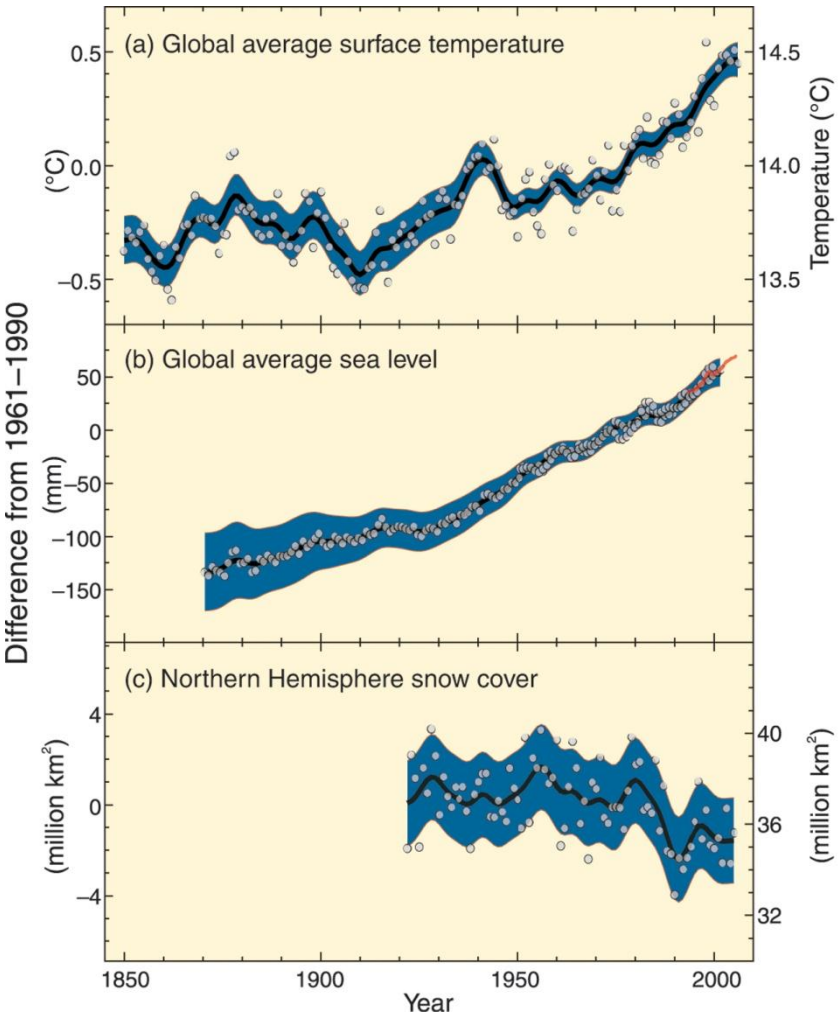


Figure 3.1: Temperature, sea level, snow cover. Source [3.1].

An increase of the temperature during the 50 years from 1956 to 2005 has been observed. This increase is higher in northern latitudes, and higher in land regions than in the oceans, as shown in Figure 3.2.

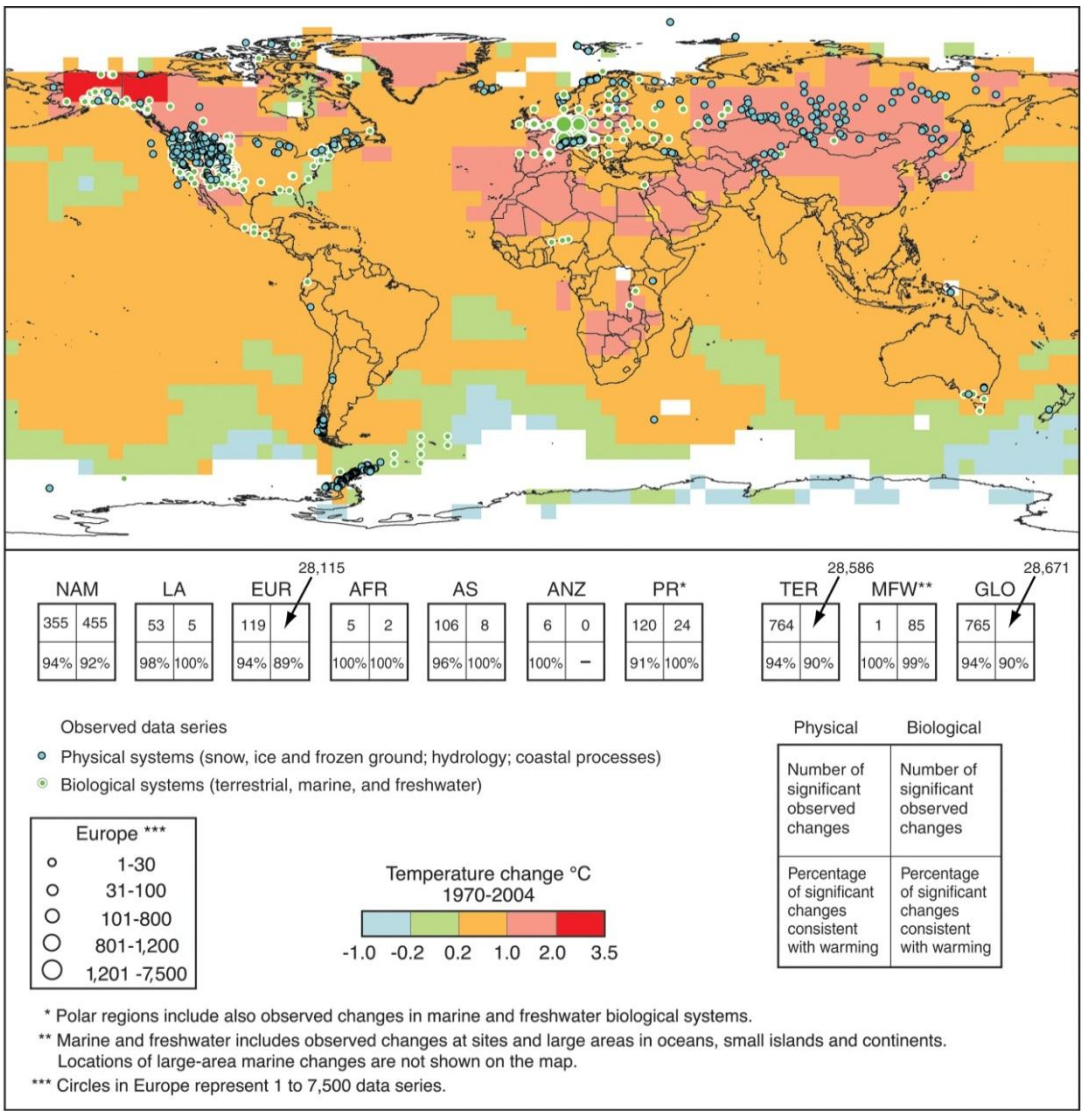


Figure 3.2: Temperature change 1970-2004. Source [3.1]

The following recent changes in climate have been observed:

- Sea level has suffered an average increase of 3.1 [2.4 to 3.8] mm per year in the decade from 1993 to 2003.
- Precipitation levels have increased in some regions, such as Northern Europe, but they have decreased in others, for example in the Mediterranean area.

It is important to note that some extreme weather events have changed their frequency and/or intensity. These kinds of events are the most damaging ones for infrastructures, so they are going to have the greatest influence for railway operation or maintenance.

- It is very likely that cold days, cold nights and frosts have become less frequent over most land areas, while hot days and hot nights have become more frequent.
- It is likely that heat waves have become more frequent over most land areas.
- It is likely that the frequency of heavy precipitation events (or proportion of total rainfall from heavy falls) has increased over most areas.

- It is likely that the incidence of extreme high sea level has increased at a broad range of sites worldwide since 1975.
- In mountain regions, warming has increased ground instability because of increased runoff and earlier spring peak discharge in many glacier- and snowed rivers. Snow avalanches will also increase because of the growing surface temperature.

To summarize, the changes that will happen are:

- Hotter, drier summers.
- Warmer, wetter winters.
- Increased frequency of extreme events.
- Sea level rise.

These changes in the climate are expected to have an impact on many of the railway system components (for example traction, services, staff, subsystems covering track, rolling stock, stations, depots, structures, electrification and signalling and other train control systems). In particular, the railway industry is focused on how the current and future climate could affect the ability to achieve and deliver:

- A safe railway
- A highly reliable railway
- Increased capacity
- Value for money
- A 'predict and prevent' asset management policy

3.2 Assess climate change and environmental legislation impacts on future track design

It is critical that the rail industry actively engages in the shaping of policy and legislation in Europe. Rail is an inherently sustainable form of transport, but the opportunity for rail to improve its own performance and to contribute to an integrated transport system is significantly influenced by policy and current or future legislation changes.

In the 2001 White Paper “European transport policy for 2010: time to decide" [3.2], some measures were proposed, following the objective of revitalising the railways by creating an integrated, efficient, competitive and safe railway area and to set up a network dedicated to freight services. This measures were called the Second Railway Package (following the First Railway Package adopted in 2001), and were adopted in 2004. Among the measures adopted in the Paper was improving the environmental performance of rail freight services.

In 2003, the EU Emissions Trading directive [3.3] came into force, which resulted in the implementation of an emissions trading scheme as a mechanism of reducing carbon emissions from a number of key industrial sectors (e.g. steel, cement and power). The European emissions trading scheme, which started in 2005, provides a means for companies to buy and sell the carbon allowances and, with time, these allowances will reduce thereby increasing the cost of emitting carbon and thereby incentivising carbon emission reduction schemes.

Although at this moment there is no environmental legislation about railway infrastructure and climate change, the position of the European Commission about the environmental legislation has some items that could be very interesting, and will make the first step for future legislation [3.4]:

- The transport sector has a considerable impact on the environment and on people's health and quality of life, and, whilst facilitating people's private and professional mobility, was responsible, as a whole, for 27 % of total CO2 emissions in 2008, and while this figure has since risen even further; road transport accounted for 70,9 %, aviation for 12,5 %, sea and inland waterways for 15,3 % and railways for 0,6 % of total CO2 emissions from the transport sector in 2007.
- The financial and economic crisis has hit the transport sector hard. However, this situation should, be taken as an opportunity to support and promote the transport industry in a forward-looking way, especially through promoting the sustainability of transport modes and investments in, among other things, rail and waterway transport. This should ensure a more level playing field in the market.
- Calls on the Commission and on Member State authorities to facilitate the completion of the liberalisation of cabotage transport, to reduce the prevalence of empty mileage and to provide for a more sustainable road and rail network in the form of more freight transport hubs.

This resolution of 2010 calls for compliance with clearer, more measurable targets to be achieved in 2020 with reference to 2010, and therefore proposes the following relative to the railway operation and climate change:

- 20 % reduction in the energy used by rail vehicles compared with the 2010 level and capacity and a 40 % reduction in diesel used in the rail sector, to be achieved through targeted investments in rail infrastructure electrification;
- Fitting an ERTMS-compatible and interoperable automatic train speed control system to all new railway rolling stock commissioned from 2011 onwards, and to all new and rehabilitated link lines starting in 2011; stepping up EU financial efforts for the implementation and extension of the ERTMS deployment plan;

In the European Union guidelines for the development of the trans-European transport network, it is important to improve the resilience of rail infrastructure to climate change and disasters. During infrastructure planning, Member States and other project promoters shall give due consideration to the risk assessments and adaptation measures adequately improving the resilience to climate change, in particular in relation to precipitation, floods, storms, high temperature and heat waves, droughts, sea level rise and coastal surges, in compliance with any requirement which may be set out in relevant Union legislation.

Where appropriate, due consideration should also be given to the resilience of infrastructure to natural or man-made disasters in compliance with any requirements which may be set out in relevant Union legislation.

The 2011 European White Paper [3.5] has the objectives of preparing the European transport area for the future, creating a vision for a competitive and sustainable transport system and defining the future strategy (what needs to be done). Some points noted in the White Paper are:

- Oil will become scarcer in future decades, sourced increasingly from uncertain supplies.

- At the same time, the EU has called for, and the international community agreed, on the need to drastically reduce world greenhouse gas emissions, with the goal of limiting climate change below 2ºC. Overall, the EU needs to reduce emissions by 80-95% below 1990 levels by 2050. A reduction of at least 60% of GHGs by 2050 with respect to 1990 is required from the transport sector. By 2030, the goal for transport will be to reduce GHG emissions to around 20% below their 2008 level. The challenge is to break the transport system's dependence on oil without sacrificing its efficiency and compromising mobility. In practice, transport has to use less and cleaner energy, better exploit a modern infrastructure and reduce its negative impact on the environment and key natural assets like water, land and ecosystems.
- Action cannot be delayed. Infrastructure takes many years to plan, build and equip – and trains, planes and ships last for decades – the choices we make today will determine transport in 2050. We need to act on a European level to ensure the transformation of transport is defined together with our partners rather than determined elsewhere in the world.
- Rail, especially for freight, is sometimes seen as an unattractive mode. But examples in some Member States prove that it can offer quality service. The challenge is to ensure structural change to enable rail to compete effectively and take a significantly greater proportion of medium and long distance freight. Considerable investment will be needed to expand or to upgrade the capacity of the rail network. New rolling stock with silent brakes and automatic couplings should gradually be introduced.
- 30% of road freight over 300 km should shift to other modes such as rail or waterborne transport by 2030, and more than 50% by 2050, facilitated by efficient and green freight corridors. To meet this goal will also require appropriate infrastructure to be developed. This is one of the Ten Goals.
- Ensure that EU-funded transport infrastructure takes into account energy efficiency needs and climate change challenges (climate resilience of the overall infrastructure, refuelling/recharging stations for clean vehicles, choice of construction materials, etc.). This can be found in the list of initiatives.

Nowadays, only locomotives' emissions are regulated. As can be seen above, the need to make am environmental friendly railway infrastructure has already been mentioned in European Papers and working documents. Although infrastructure is not regulated yet, a European objective should be to include infrastructure in legislation in the future. Different studies [3.6] made in Europe point to five areas of study:

- Improving noise performance of the railway mode.
- Reduce emissions to the environment.
- Reduce operational energy consumption.
- Design for the environment.
- Development and deployment of emerging technologies.

Reducing noise is the objective in which Europe has made most effort. This is about environment, because noise is a kind of pollution, but has nothing relative to the climate change. Track must be designed to reduce noise pollution.

The other areas of study are focused on reducing energy consumption and, subsequently, emissions. Track must be designed to reduce consumption and emissions.

From 1990 to 2005, European railways CO_2 emissions were reduced by 21% in absolute terms. Specific CO_2 emissions were reduced in 14% (emissions per passenger-km) for passenger transportation, and by 28% (emissions per tonne-km) for freight transportation. In May 2008, the members of CER (Community of European Railways) agreed to a target of an average sector-wide cut of 30% in specific emissions over the 1990-2020 periods [3.7]. This is not a legal requirement, but it has to be taken into account.

3.3 Identify impacts of climate change on actual railway structures.:- Background projects

Many railway services across Europe strongly depend on weather conditions. Transport delays and especially interruptions caused by weather events lead to high social and economic costs. Hence, it is important to understand if and how these railways services should adapt to current and predicted future climate change. Railways have an extremely long life time and are constructed to withstand natural hazards, such as the 100 year flood. However, as the number and the intensity of incidents caused by extreme weather events will increase in the future, the pressure on the capacity of the rail system will rise together with the costs for the sector.

While we have an understanding of the causes of climate change, the consequences will advance quickly and are hard to predict. Traditionally, railways were constructed to "survive" natural hazards as infrequent phenomena. When extreme weather becomes normal the whole railway system will need to be even more robust.

The industry has completed research into the effects of climate change on the railway infrastructure. One of the most important studies is "Tomorrow's railway and climate change adaptation (TRaCCA) [3.8], carried out by Network Rail in the UK. This research is included in the UIC's project Adaptation of Railway Infrastructure to Climate Change (ARISCC) [3.9].

The observed changes in the climate will certainly affect the railway infrastructure. Indeed, some of the effects have been noticed already. The transport sector is particularly vulnerable to climate change [3.1]. Railway infrastructure is affected by extreme weather (e.g. flooding of railways, threats to passenger safety during heat waves, delays due to storms), and by continuous climate change (e.g. ballast degradation). Since the railway sector depends on long-lasting infrastructure (e.g. track, bridges, tunnels, stations), anticipatory adaptation is needed.

The most remarkable change is the rise of the temperature. Not only the average temperature is increasing, but also heat waves are becoming more frequent. This may affect railway infrastructure in different ways. The first effect affects the track itself: buckling. It will produce speed restrictions in some stretches. There will be also effects on the signalling and telecom systems: Floating electrical earths will lead to stray earth currents caused by dry ground/ low groundwater. Heat, as solar gain, will affect lineside equipment. It will appear as more sag in tethered overhead line systems at terminal stations [3.10].

The rise of sea level will only affect coastal and estuarine defences, which waves could overtop and flood the tracks [3.10][3.11].



Figure 3.3: Sea waves in Dawlish, Devon, England. Source [3.12].

Increasing precipitation levels, especially in Northern Europe, will cause surface runoff and increasing of ground water level. This may increase corrosion in the track and in bridges. But, also, will accelerate the scouring of embankments and sub-structure, and could even remove ballast. In the Mediterranean area, the level of precipitation is decreasing, but extreme events, such as heavy rainfalls, are growing. The effects are, more or less, the same that in the precipitation level increase, but they happen suddenly. This is more dangerous because progressive infrastructure deterioration cannot be detected and repaired [3.10, 3.11].



Figure 3.4: Effects of 2002 Elbe flood in Germany. Source [3.9].

In mountain regions, all the observed effects increase ground instability, because of increased runoff and earlier spring peak discharge in many glacier- and snowed rivers. Snow avalanches

can make some lines close because they may be blocked [3.10]. As it is mentioned above, extreme weather events will be usual. For example, gales are especially dangerous for railways, because they can make things fall in the track. These things can block the line or even cause accidents [3.10].

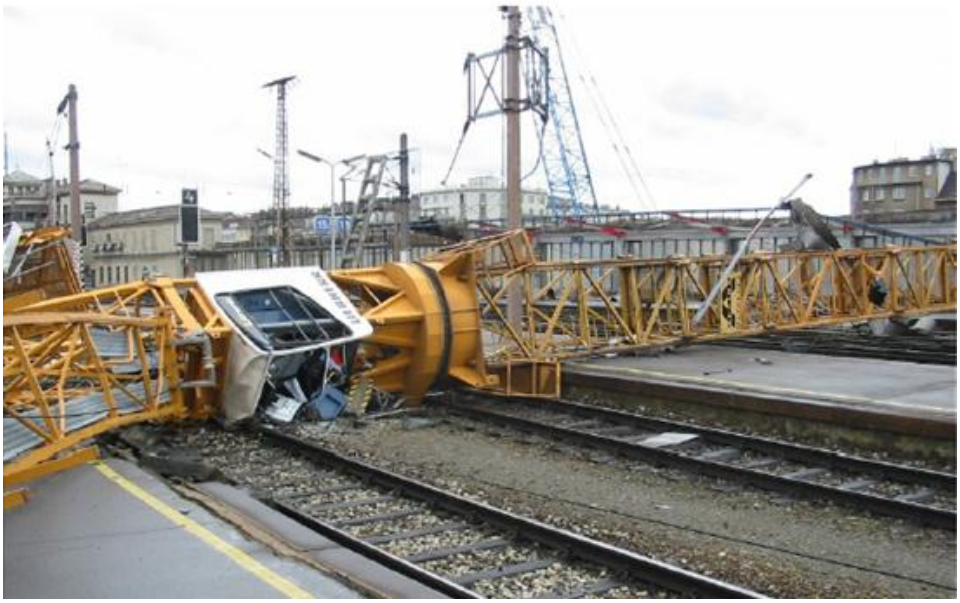


Figure 3.5: Effects of 2008 Gale Emma in Austria. Source [3.13].

Wind can also limit the train operation speed. Wind measuring process consists in measuring, with meteorological stations placed along the railroad, the speed of the wind and its direction, and by means of different calculations, evaluating the risk for the train. According to these calculations, in strong cross winds areas braking actions or speed limit decrease are carried out. In order to evaluate the risk the Characteristic Wind Curve is used. This curve relates the maximum speed of the wind allowed with the train speed and the operating conditions. In Europe these curves are defined in the Technical Specification of Interoperability (TSI) [3.14].



Figure 3.6: Characteristic Wind Curve of high-speed trains. Source [3.14].

The likelihood of dewirement (the pantograph losing contact with the overhead wire) and the possibility of train overturning and derailment will both increase [3.12].

3.4 Identify duty requirements that will contribute to mitigating climate change and environmental legislation impacts

Railway is the most environmental friendly transportation mode. Emissions, measured in CO_2 per kilometre, for different modes are contained in Table 3.1.

Table 3.1: Emissions per transportation mode. Source [3.15].

Mode	Emissions (g CO_2 /pkm)	% change 1995-2007
Rail diesel	69	-22
Rail electric	51	-28
Rail overall	58	-25
Car and taxi	104	-9
Domestic air	227	+11

Train is less carbon intensive than plane or cars. Emissions of both modes are compared in the following Table 3.2 for some usual journeys across Europe.

Table 3.2: Emissions per mode. Source [3.16].

Route	Emissions by train (kg CO_2 /passenger)	Emissions by car (kg CO_2 /passenger)	Emissions by plane (kg CO_2 /passenger)
Madrid-Barcelona	7.9	67.8	87.6
Madrid-Paris	28.2	139	139.2
Berlin-Paris	31.4	115.5	116.9
London-Brussels	10.1	47.9	66
Rome-Amsterdam	51.7	182	212
Vienna-Munich	11.5	47.7	72.3
Lisbon-Warsaw	139.2	367	355.4

Environmental legislation, as we can see in EU documentation [3.17], will focus on reducing noise emissions. The most important source of noise is the wheel-rail contact. To mitigate noise generation, some measures should be taken in both rolling stock and infrastructure.

For infrastructure, there are some things that can be done: Reducing the roughness of tracks (by maintenance or renewing), using lubricants to reduce friction, using rail dampers or under sleeper pads and removing level crossings.

Noise transmission can also be reduced by installing noise barriers and sound absorptive claddings. Also, in troubling areas, the track can be tunnelled [3.18]. But environmental

legislation will include not only noise but some other environmental-friendly steps to be taken.

Anther objective is the elimination of materials with a negative environmental impact. This could be achieved using recycled materials for both the rolling stock and the track component. In the track, ballast, overhead lines or rails can be recycled taking into account constraints imposed by carbon targets; these constraints limit the re-melting of metal components (steel, aluminium, or copper for example).

The track should be designed to reduce energy consumption. This can be achieved by lower gradients or smoother rails (this is also good for reducing noise) but, probably, the most effective policy to reduce emissions is to electrify more kilometres of lines. Approximately 85% of total energy consumed by the rail sector is used directly for rail traction [3.7], and, as we can see in Table 3.1, electric traction is less carbon-intensive than diesel traction.

In the European Directive 2004/26/EC [3.19], emission of gaseous and particulate pollutants in non-road machinery is regulated. This directive can be achieved in two ways.

Firstly, the cheapest and fastest way is to renew the diesel locomotive fleet. There are hybrid and low emission locomotives. Nowadays, many old locomotives are used for freight transportation. New ones reduce the emission levels, both gaseous and particulate.

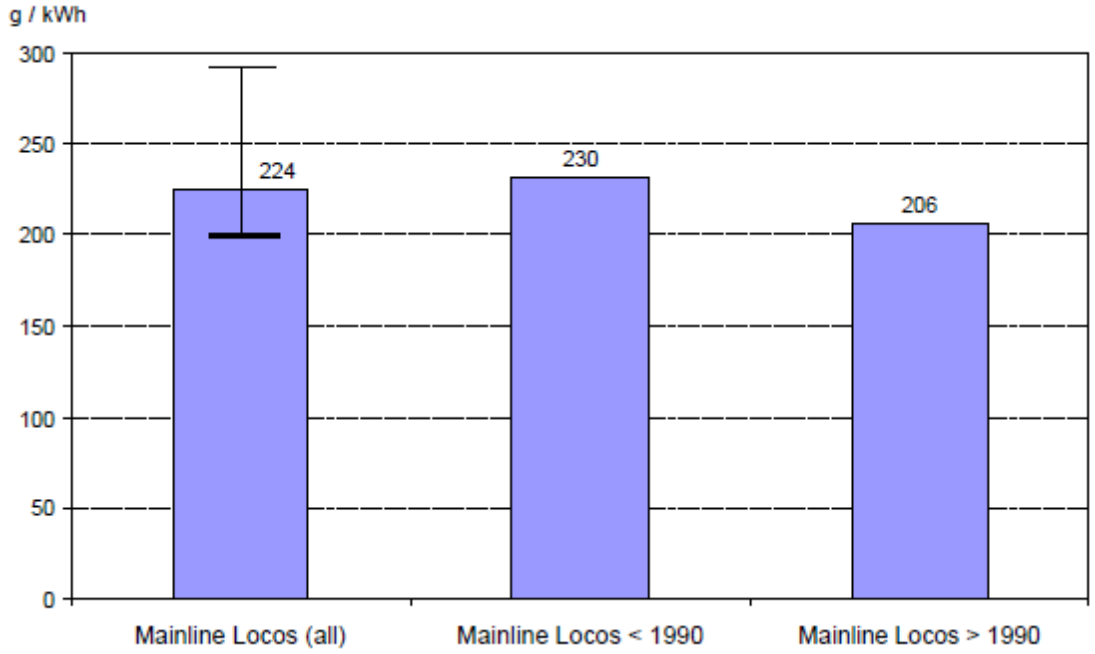


Figure 3.7: Average fuel consumption for diesel locomotives. Source [3.20].

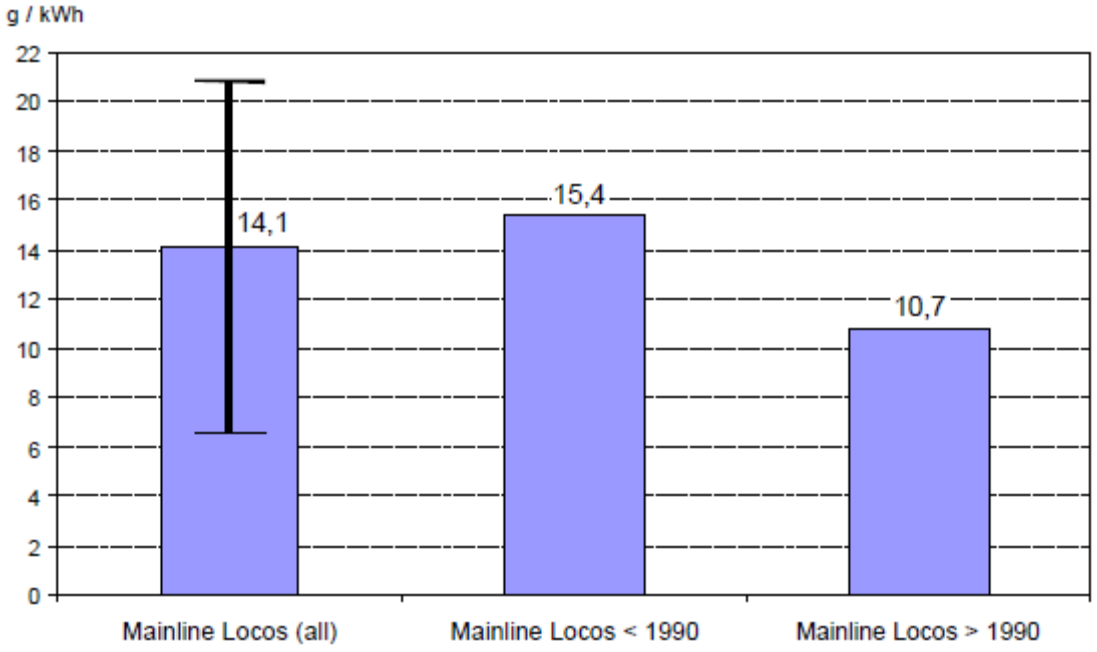


Figure 3.8: Average ranges of NOx emissions in diesel locomotives. Source [3.20].

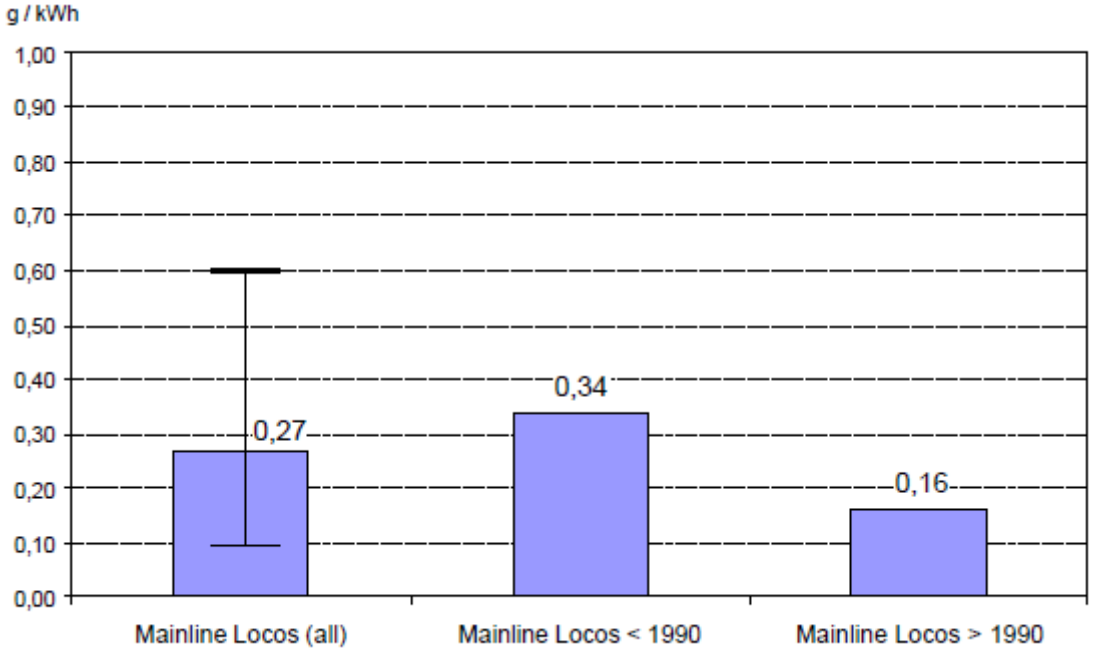


Figure 3.9: Average ranges for PM emissions for diesel locomotives. Source [3.20].

Nowadays, according to UIC, electric traction accounts for 80% of rail production in Europe (measured in passenger-km and tonne-km) [3.20]. But, in the medium-term, the objective should be to electrify all railway lines. Reaching 100% would be a good way to reduce significantly emission levels.

CO_2 emission levels depend on the energy mix in each country, but, by using electrified railway lines, a zero carbon footprint can be achieved in some cases (nuclear or renewable energies generations).

The use of route planning tools will also reduce emissions by facilitating energy-optimized timetabling. One system that allows this is the regenerating brake. It consists of recovering braking energy from a train feeding it back into the power system and using it in different train traction. Employing regenerative braking in trains can lead to substantial CO_2 emission reductions. This effect is especially remarkable in service commuter trains (8 – 17%) [3.21] and in very dense suburban underground lines (~ 30%), such as Delhi [3.22]. When applied to freight trains, regenerative braking can reduce CO_2 emissions, but this reduction would be considerably lower than for stopping passenger service trains.

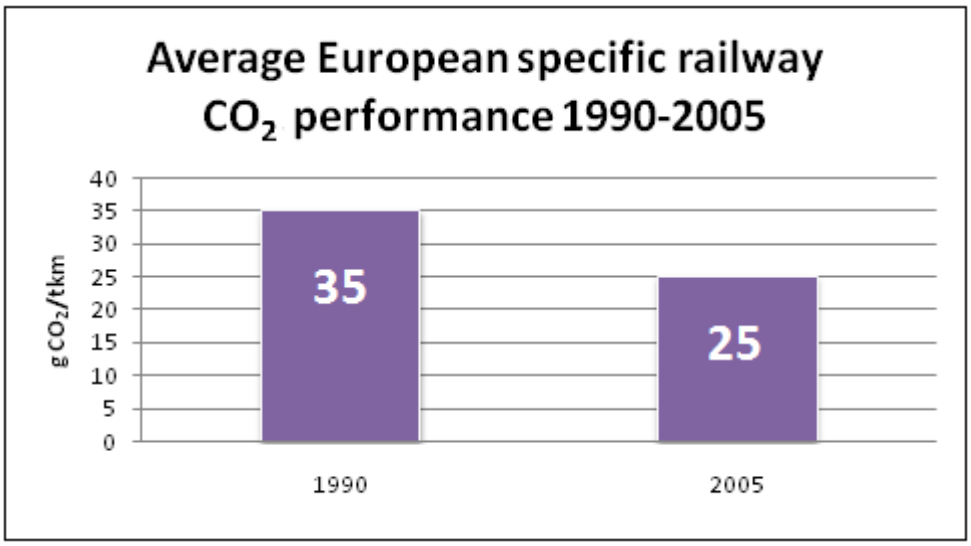


Figure 3.10: Specific emissions for freight transportation by year. Source [3.7].

To mitigate climate change impact itself, and not only new legislation, some other efforts should be made. The main changes in climate and their effects were mentioned before. For example, ADIF has developed a project of "ferrolinera" (railway electric filling station). It consists of using the recovered traction or braking energy from the train to charge batteries of electric cars parked in the station [3.23].

To face the rise of temperature, northern European countries should look to the South, and see how they work. For example, in the case of Spain, the railway component like switch motors, for example, may be manufactured to withstand temperatures of 70 º C (ADIF Technical specification).

According to studies made, not only the sea level will rise, but also waves will be higher and stronger. These two effects can be avoided by building higher and stronger estuarine defences. At least, higher than the expected waves, in order to prevent flooding in the track [3.24].

To face surface runoff and ground instability, some important actions to take are to reinforce earthworks, to build bigger drainages for the higher water flow.

To deal with gales, snow avalanches and sudden storms, the most effective solution is to have on-time weather forecasts [3.13]. Using this meteorological information, a warning system can be implemented. Although the track would be blocked if something falls on it, accidents can be prevented, and traffic could be quickly adapted to the new situation.

3.5 Identify constraints that limit the re-melting of rails

3.5.1 Life Cycle Greenhouse Gas Emissions of Railway Systems

Life Cycle Greenhouse Gas Emissions are often abbreviated to the term Carbon Footprint, which is the sum of all emissions of greenhouse gases associated with a product or service over its complete life cycle.

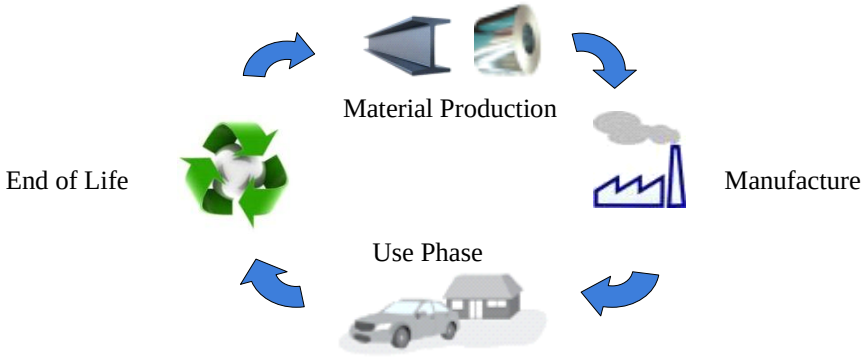


Figure 3.11: A typical Product Life Cycle

The methodology that is widely used to evaluate a carbon footprint is based on the technique of Life Cycle Assessment (LCA), which is described by a number of international standards on LCA (ISO14040 and 14044). Important aspects of any LCA study are the definition of the product system, its system boundaries and the goal of the study. Carbon Footprint is just one of the outputs from an LCA study and a complete LCA study would consider a broad range of potential environmental impacts beyond the issue of global warming.

Greenhouse gas emissions from a railway system arise throughout the life cycle, including from the manufacturing phase, the operation (use) phase, including maintenance and finally end-of-life. This is sometimes known as ‘cradle to grave’ as it considers everything extracted from the earth right through to treatment of materials at end-of-life. The system boundaries, which could be included in a full LCA, for a railway are shown in figure below.

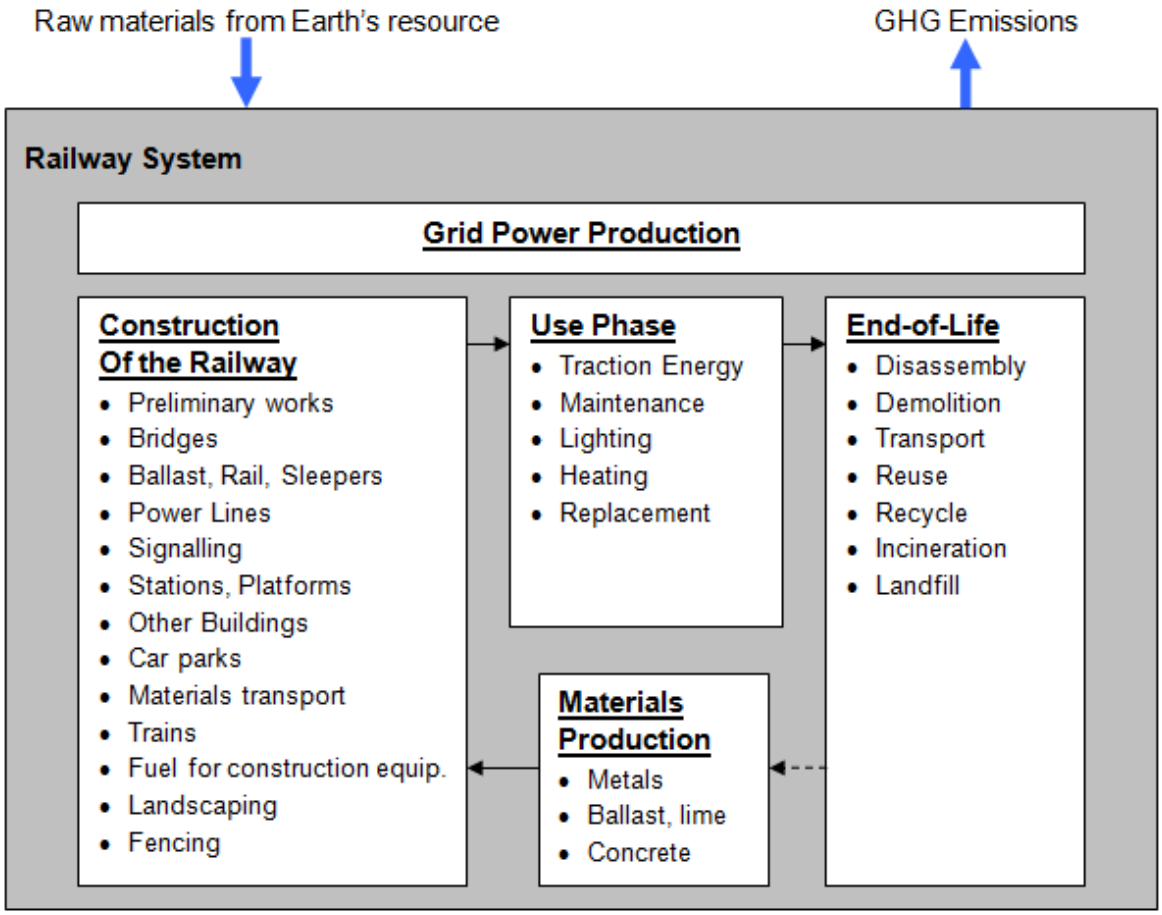


Figure 3.12: Rail Track system LCA system boundary

The relative proportion from each life cycle phase depends upon several key factors, including the energy technologies serving the electricity grid and the amount of infrastructure (including bridges and tunnels) required on a particular line or network. From a life cycle perspective, studies of high speed rail lines have shown that between 15-70% of the GHG emissions from the railway are due to infrastructure and the remainder due to operation of the railway over a typical 30 year life [3.25]. One of the reasons why infrastructure can be a relatively high proportion of the overall impact is that the use phase of the railway system can be relatively carbon efficient compared to other forms of transport (e.g. conventional road vehicles and aeroplanes), particularly in the case where countries have a high degree of electrified railways and a high proportion of renewable or nuclear energy in the electricity grid mix.

Infrastructure includes not only the steel rails but also sleepers, ballast, bridges, tunnels & other structures, buildings, stations and power lines. Most existing LCA studies focus on environmental impacts associated with energy and electricity consumption during the use phase of the railway system, but there are also operational impacts due to repair and replacement of the track system that should be taken into account. If a railway line has to undergo maintenance or renewal, not only are there cost and environmental implications associated with the replacement of the rail, sleepers, ballast and other components, there are other important considerations, such as disruption to passenger and freight rail users.

The end-of-life of rail track systems is another important aspect of the rail life cycle as some materials, such as steel, have an economic value as scrap, which means they are remelted to

make new steel products. This helps to offset some of the initial GHG emissions associated with manufacturing the initial rail product due to the environmental benefits of recycling. Economics and the value of scrap metal means it is always worthwhile to recover steel components from the railway and this is reflected in high recycling rates Steel rail can also be reused and through a process of cascading elements of the track can be used in different parts of the rail network, which saves further GHG emissions.

3.5.2 Life Cycle Assessment (LCA) of Steel Production

An authoritative source of data for LCA studies involving steel is the World Steel Association (Worldsteel). Worldsteel collect data from steel companies on the manufacture of basic steel products in order to produce Life Cycle Inventories (LCIs), which can be used in LCA and environmental footprinting studies. LCIs are available for many finished products having taken a 'cradle-to-gate' approach, and also account of recycling [3.26]. The methodology has been critically reviewed by a panel of experts to demonstrate conformance with international standards on LCA.

There are two main steel production processes that are well-established throughout the world, both of which require the use of scrap steel:

- Blast furnace (BF/BOF) integrated steelmaking (using iron ore, coking coal and 10-30% scrap).
- Electric arc furnace (EAF) steelmaking using up to 100% scrap.

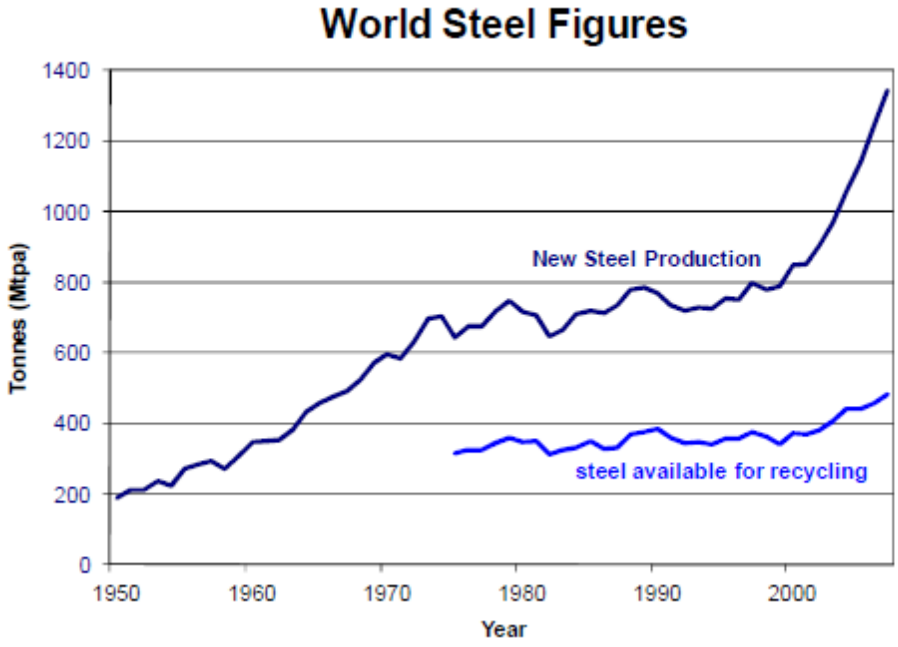


Figure 3.13: Global steel production and steel scrap availability. Source [3.29].

As a result of there being insufficient scrap steel to meet current global demand for new steel (Figure 3.13), the environmental impact of the steel produced via these two manufacturing routes can be demonstrated to be equivalent in life cycle terms, there is no environmental benefit in specifying or demanding steel from one manufacturing route in preference to the other. For all steel users, including the rail sector, this means there is no life cycle benefit from specifying a material with a higher recycled content than another. The reasons for this

are explained in more detail in a declaration by the metals industry [3.27] and the main points are summarised here:

- Steel scrap has significant economic value which means that where scrap is recovered it will be used for recycling. This means there is no requirement to create a demand for recycled material as this market is already well established.
- Steel is recycled in a closed material loop such that the inherent properties of the primary and secondary product are equivalent. In other words, the production of secondary material displaces primary production.
- The magnitude of steel recycling is driven by end of life recycling rates, not recycled content, and an end-of-life approach captures the impact of different recycling rates in different regions and for different end-product categories.
- The global demand for steel scrap exceeds the availability of scrap. This is magnified partly due to the long lifetime of steel products. Designing products for easier end-of-life disassembly and recycling will enable more steel scrap to be recycled.

In the context of steel railway components, this means ensuring that the material is more durable, thereby delaying the need to manufacture a replacement and when the system reaches the end of its life, is easily made available for recycling.

Both EAF and integrated steelmaking processes accept a wide range of used steel from many market sectors, including, from the railway network, steel rails and steel sleepers, as well as steel used in other parts of rail infrastructure. All of these can be recycled indefinitely into an unlimited range of new steel products without any loss of quality.

In the case of steel rail, the European average figure for these products is currently 1.29 tonnes CO_2 equivalent per tonne. For obtaining this number, it has been assumed that the recyclability of the steel rail is at a rate of 75%. This percentage includes losses due to the wear of the rail during the use phase, but there are no other technical constraints.

3.5.3 Legislative perspective

The implications of legislation for rail design are that materials will become more expensive as steel producers invest in CO_2 reduction and a greater emphasis will be placed on extending product life. In terms of re-melting and recycling, this will become a last resort after options such as extending product life and re-use (e.g. in a less demanding rail application) have been exhausted. When a rail product has reached the end of its useful life it will still be just as attractive as it is to today to recycle the material because this saves carbon emissions associated with the primary manufacturing route and the inherent properties of the material can still be maintained.

Regulations about emissions trading have the potential to influence the future supply of materials, is the threat of imports from outside Europe. If the financial cost of emitting carbon emissions in Europe in comparison to less heavily regulated regions of the world, steel products can be imported to Europe from those regions. Until there is a global agreement on carbon emissions reduction, this, known as ‘carbon leakage’, can lead to an increase in emissions due to additional transport emissions and/or manufacturing emissions.

3.5.4 Designing Rail for Low Carbon Footprint

3.5.4.1 Design for durability and extended rail life

Studies have demonstrated that the maintenance and replacement of a rail track system are significant contributors to the overall carbon associated with a railway system. A key strategy therefore, to reduce life cycle impacts, is to make appropriate improvements in maintenance and replacement schedules of the system. This can be achieved through the installation of more durable rail products that require less frequent maintenance interventions and / or offer an extended life in useful service, including through re-use in less demanding applications [3.28].

Strategies for extending rail life can be classified into the following areas

- Changing the design of the rail section
- Altering the metallurgy (steel chemistry)
- Heat treatment
- Track design including supports
- Vehicle design
- Optimised rail maintenance during the use phase.

Premium rail products, with improved wear resistance or rolling contact fatigue (RCF) properties, can deliver on this strategy. The manufacturing of premium rail products may entail more processing and more environmental impacts associated with the manufacturing phase, although this is not necessarily the case, e.g. where functional properties are obtained through steel chemistry. However, whether there are any additional manufacturing impacts or not, the benefits attributable to more durable rail that can be realised during the use phase of the railway system will usually far outweigh any impacts associated with rail manufacture and can lead to significant emissions savings [3.28].

3.5.4.2 Design for Recycling

As has already been illustrated, the recyclability of steel is an important aspect of the carbon footprint of the railway. The recycling process is an essential and integral part of steel production, which is why over 475 million tonnes of steel scrap is recovered globally on an annual basis for recycling into new steel products [3.29]. This makes steel one of the most recycled materials in the world [3.30].

In addition to the large volumes of steel recycled, another important aspect of steel's recyclability is the ability to be recycled without loss of properties. This enables steel to be recycled over and over again, which makes a significant contribution to sustainability by saving earth's resources and emissions that would otherwise occur if the material had to be replaced with additional production from virgin sources. The ability of steel to be recycled and 'born again' back into new steel gives it a huge advantage over other materials, whose fate is often to be recycled into lower grade materials (down-cycled) or to be used for energy recovery and landfill avoidance. Steel is not consumed, because once made, it will be used again and again. Re-melting of rails is not limited.

Recycling one tonne of steel displaces the need for primary steel production which brings significant environmental savings including 80% of the CO_2 emissions required to make primary steel. Given the environmental benefits of recycling steel it is therefore essential that

the amount of steel lost from society is minimised and that recovery at end-of-life is maximised in order to keep steel in circulation for future generations. Increasing recovery / recycling rates is a key strategy in improving the greenhouse gas emissions associated with steel products.

In terms of rail, a premium rail product which is more resistant to degradation mechanisms in service will last longer before maintenance interventions (e.g. grinding) are required and provide associated benefits in terms of reduced GHG emissions.

3.5.5 Carbon footprint assessment of different rail and sleeper types

The benefit of extending rail life, in terms of reduced GHG emissions, can be demonstrated by considering how the wear and fatigue rates determine how often the rail track has to be renewed. Replacing rail track is expensive not only in terms of materials but also in terms of lost track time and potential disruption to the rail network. Frequently, to minimize disruption, at a later date, the entire rail track system is replaced if one component is near the end of its useful life, which also adds additional cost. Rail life and associated wear rates, can therefore have much wider environmental, social and economic impacts beyond the need to replace the steel rail itself.

Tata Steel in Europe manufacture standard rails, heat treated rails and a rolled premium grade rail. The remarked benefits of the heat treated and rolled premium products are that they have improved wear rates and therefore a longer life in demanding applications. They also have the additional benefit of improved rolling contact fatigue (RCF) performance, which means there are fewer requirements for maintenance grinding of the rail head and therefore rail life is extended in locations were RCF is a significant issue.

Within Tata Steel, a Rail Track LCA model has been developed which considers the cradle to grave impacts of manufacture, installation and end of life of a rail track system. This includes the different rail types, sleepers, clips and ballast. A system diagram for this model is shown in Figure 3.14. Using this model it is possible to generate environmental data on the life cycle of the rail track system, which includes an assessment of GHG emissions.

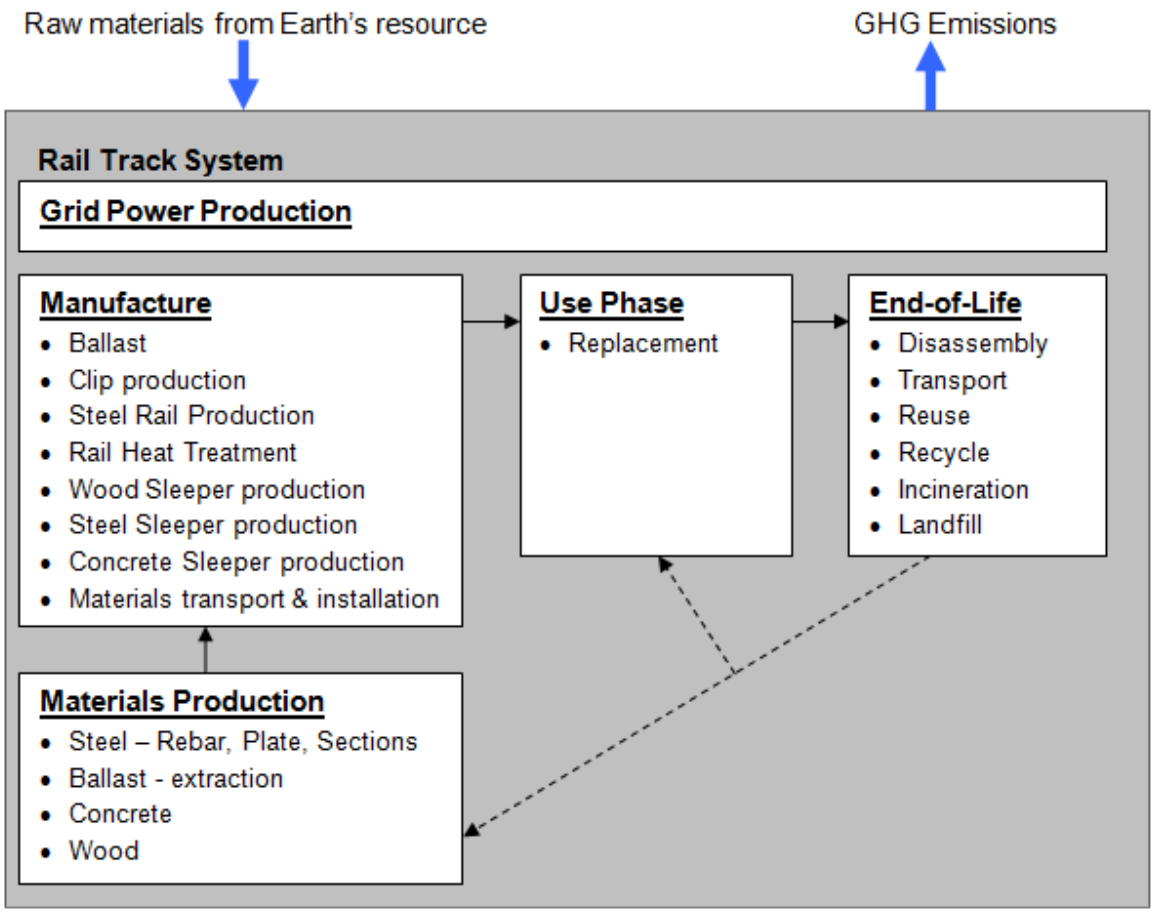


Figure 3.14: System Diagram for a Rail Track model

Within the LCA model it is also possible to set a lifetime on the components and this determines how many rail track systems have to be replaced and installed over a given period of time. If the wear and RCF rates determine the frequency of replacement then these can be used within the model to determine the relative GHG emissions of the different rail types. The results from this type of analysis are shown in Figure 3.15.

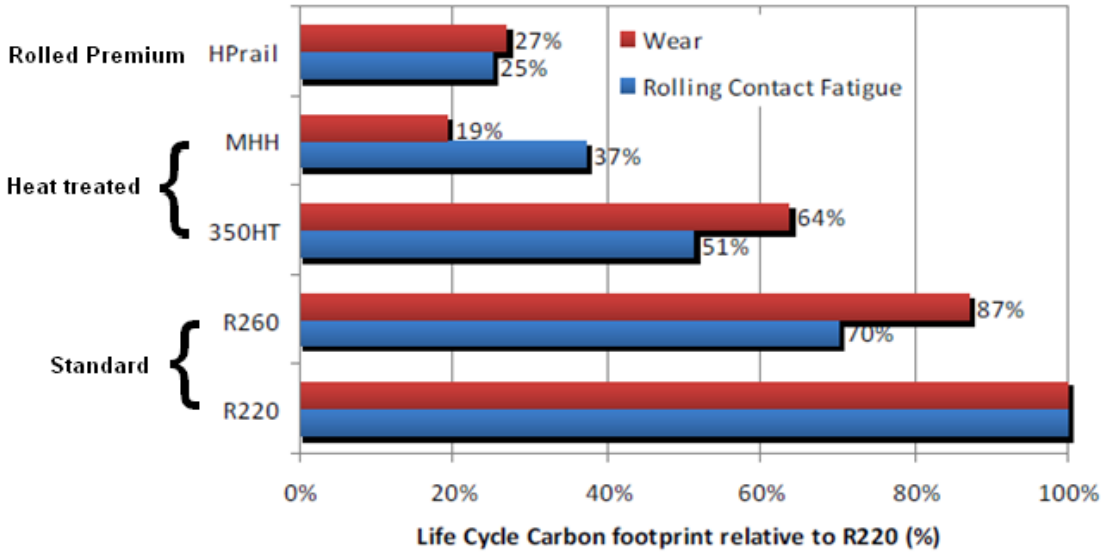


Figure 3.15: The relative carbon footprint of different rail types when the life of the track system is determined by either wear or RCF rates (relative rail life is shown on the right).

Figure 3.15 shows that improvements in both RCF and reduced wear can have a significant impact on the Life cycle Carbon Footprint. Rolled Premium Grade rail offers the potential to reduce GHG emissions by up to 75% compared to standard grades. A heat treated rail also offers a major reduction in life cycle emissions, despite the additional heat treatment process. This is because heat treatment is a relatively small impact over the entire life cycle compared to the improvements in wear performance and rail life.

By looking at the particular application of the rail, and location of installation, an assessment of relative wear and rolling contact fatigue rates can be used to determine the rail type that is best suited, for a given situation, in terms of extending life and reducing carbon footprint.

Beyond the steel rails, there are also options in terms of the type of sleeper that can impact on the life cycle. An analysis of the carbon footprint dependency on sleeper type is shown in Figure 3.16.

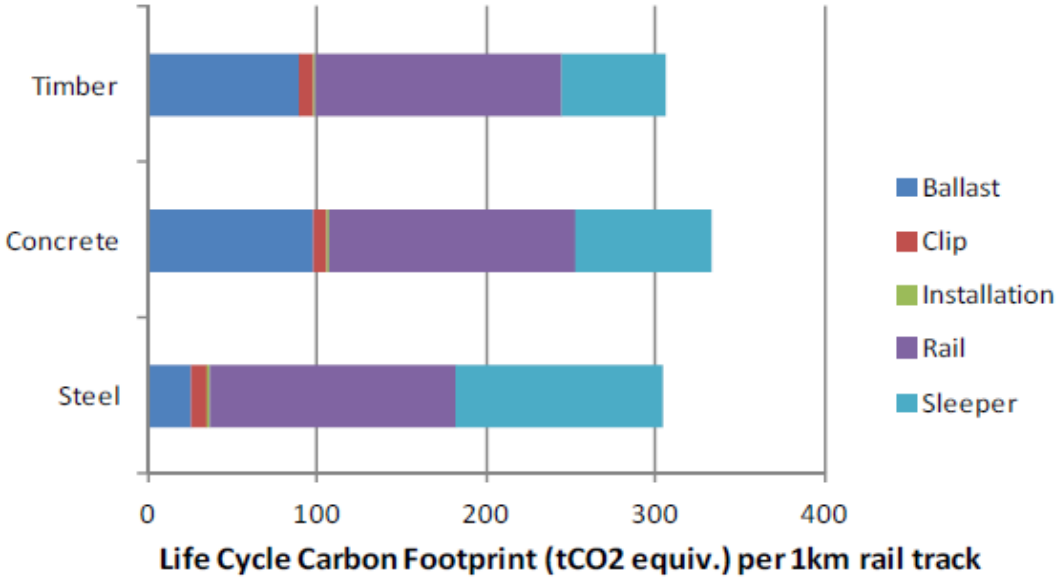


Figure 3.16: Carbon Footprint Dependency on Sleeper System.

This analysis shows that while the steel sleeper has a larger manufacturing impact this is compensated for by the requirement for less ballast in the rail track system. As part of this analysis, a number of model parameters were selected and assumptions were made about the likely recyclability of the different materials. These were as follows:

- all sleeper types were assumed to have the same relative life;
- rail type was standard rail (R260);
- 50% of ballast recycled at end of life;
- transport distance for the ballast was assumed to be 100km;
- sleeper end of life:
    - timber: 50% of sleepers incinerated and 50% recycled or reused;
    - concrete: 50% are recycled to make aggregate and the rebar is recycled;
    - steel: 100% recycled.

In addition, scenarios for reuse were also considered for cascading the steel and concrete sleepers into other rail tracks before the end of their useful life span but for a life-for-like comparison this was considered to be included in the 1st life cycle and therefore did not alter the results.

For the assessment of timber sleepers, it was assumed that the wood was sourced from a sustainably managed forest and that carbon dioxide was sequestered in growing the tree. Some of the sequestered carbon was then released at end of life through either through landfill or incineration.

3.5.6 Summary

As greater demands are placed on the transport infrastructure, and the need to reduce GHG emissions grows, improvements in the European rail network will become increasingly important. Since rail track maintenance and replacement costs, both economic and

environmental, are often significant it is important that future steel rails are designed with an extended product life. Processes such as heat treatment or new developments in steel grades, have been shown to have significant benefits in terms of reducing the overall life cycle carbon footprint of the rail track system.

3.6 A Review of the study 'Assessing the CO2 impact of current and future rail track in the UK' [3.32]

A recent UK study, by Allwood et al., also recognised the CO2 benefits of maximising the life span of rail track components [3.32]. This study focused, primarily, on the impact of extending the rail life by taking a slightly different approach to improving replacement rates. Rather than looking at improving wear rates through tailoring the metallurgical properties of the rail, which was described in the previous section (3.5), a multiple head rail (double or quadruple) concept was considered (Figure 3.17). The benefit of this being that that after one rail head had reached the end of its useful life the entire rail could then be rotated to make use of an unworn rail head. One of the claimed benefits of this approach is better utilisation of the steel as the service life could potentially be doubled with less than double the amount of steel.

Implications of changes in the rail track (eg fixings and sleepers), to accommodate the new rail designs, were also considered as part of a simplified carbon footprint assessment of these systems, which excluded the benefits of material recovery and recycling at end-of-life.

For the double headed rail a conventional sleeper/ballast system was considered in addition to an embedded rail section, which avoided the need for ballast. For the quadruple-headed rail track it was necessary to have an embedded rail track in order to contain the sides of the rail. Whilst the double headed rail did not add much additional steel to the sections profile; the quadruple headed rail used considerably more steel although since its cross sectional area was not double that of the double headed system some small CO2 benefit was seen. The study therefore concluded that the double headed rail had the greatest advantage. However, in practical terms there would need to be a considerable amount of engineering and test work to be carried out to prove the concept of multiple rail heads. Rotating the rail head might also be a time and resource consuming procedure which would have to be considered in terms of the impact on the lifecycle assessment of the rail.

Extending rail life by changing the properties and dimensions of the rail head have been more widely investigated than multi-head rails. This is because these changes are relatively easy to implement and do not require significant modifications to the existing infrastructure [3.33]. Changes in the properties of the rail can be achieved by processes such as heat treatment or by altering the steel chemistry (as described in 3.5). Alternatively a heavier rail or better utilisation of steel across the rail profile have been investigated. However, these options need to be assessed in terms of their trade-off of increased weight vs. increased life span. For example, a heavier rail would increase the amount of material required per km of rail and thus the carbon footprint, whereas careful use or redistribution of the steel across the profile might help to minimise increases in rail weight and therefore carbon footprint i.e. increasing the rail head size and reducing the overall height of the section. It has also been suggested that rolling contact fatigue (a common degradation mechanism that can significantly curtail the useful lifetime of a rail) can be reduced by engineering the contact surfaces via a 'clad' surface layer on the rail. Such changes might also have knock-on environmental benefits in terms of reduced noise emitted from the wheel-rail interface. Steel 'composite' rails might also provide opportunities for increased life span with the head/crown, gauge corner and gauge face

contact surfaces engineered independently to suit the local duty conditions. However, the carbon footprint of these solutions would need to be assessed against the use-phase benefits of increased life-span to avoid any unintended emissions across the life cycle; particularly at end-of-life and during manufacture.

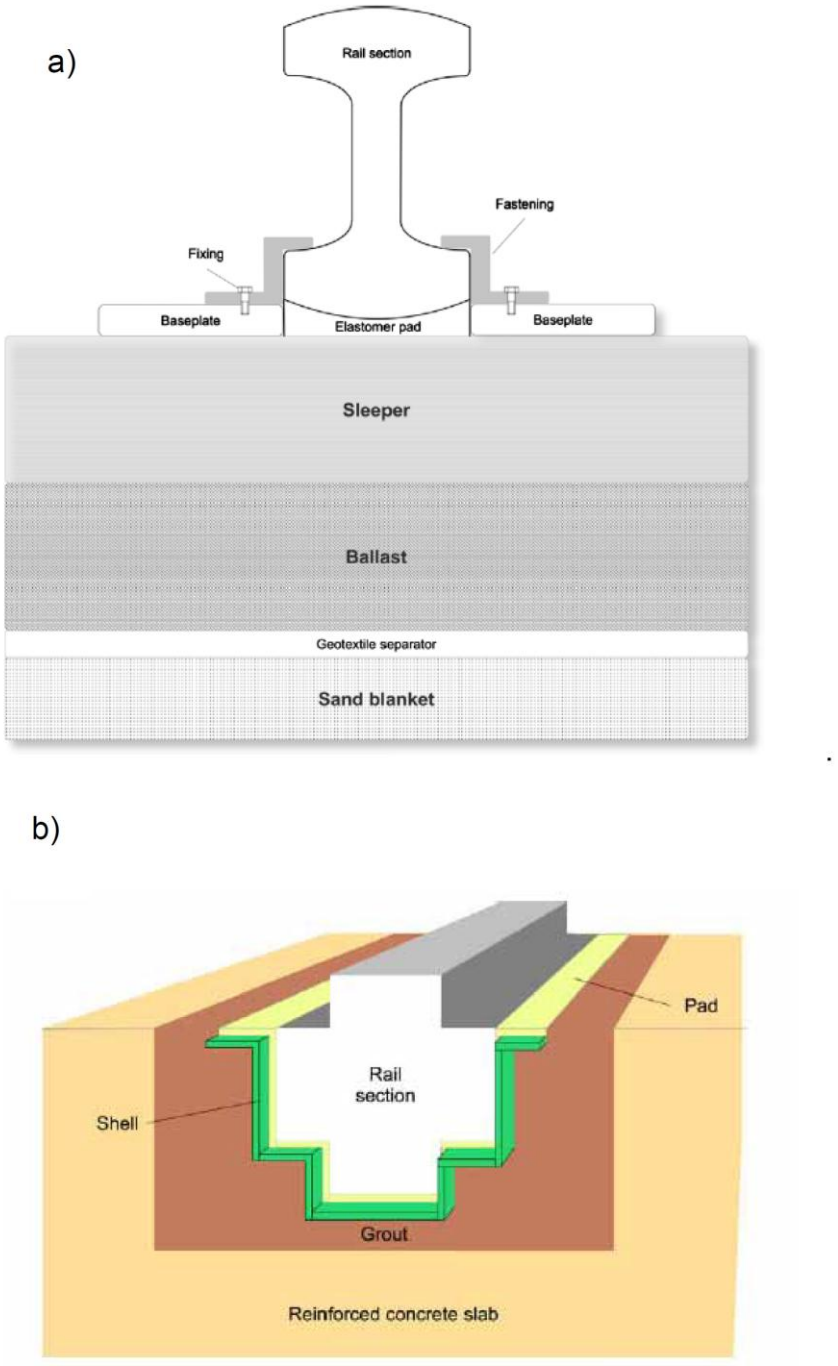


Figure 3.17: a) A double head rail supported on a sleeper. b) A Quadruple head rail which is embedded in a concrete slab. Source [3.32].

In summary, this work has shown that overall the most effective method of reducing the carbon footprint of the rail is to increase the in-use phase (service life) of the rail. Allwood suggests that the carbon emissions associated with the UK rail track network could be reduced by 11% if the service life of rail sections were increased by 50%.

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4. TRACK COMPONENT DUTY REQUIREMENTS.

4.1 Introduction

This section of the present document is based on the subtask **2.3.3. Define track component duty requirements**. The main objective of the subtask is to define track component duty requirements in terms of fatigue, wear, noise, geometry/dynamics, and tolerable long wavelength defects, also including the life of bridges, embankments and other civil engineering structures. It has been focused on quantities which are practical to measure and quantify.

In a railway line there are three important objectives with regard to their maintenance and conservation:

- The track should be installed so that the trains circulating through it do not cause excessive environmental pollution, noise or vibration.
- The total cost of the life of the track should be as low as possible.
- The maintenance of the track should be as low as economically as possible, under the safety and quality parameters setting by the regulations.

The infrastructure of a railway has basically three essential elements that should be controlled, such as the condition of the track components (rails, sleepers, fastenings, ballast, etc.), the track geometry, and the civil engineering structures (bridges and embankments, etc.).

This section has been divided into two main paragraphs:

- Define the main track component duty requirements in terms of fatigue, wear, life cycle cost, etc.
- Define duty requirements and LCC (Life Cycle Costs) on bridges, embankments and other civil engineering structures.

4.2 Main track component duty requirements

First of all it is important to define the main track component, in order to divide the study:

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

4.2.1 Ballast and/or sub-ballast

Ballast and sub-ballast are some of the most important track components and are responsible for most of the track geometry quality. In fact, the track bed depends directly on the ballast seat. The ballast consists of a mixture of sizes, expressed normally as percentage by weight. Each infrastructure manager has their own standards in order to regulate the granulometric composition of the ballast.

The European Standard EN 13450 specifies the properties of aggregates obtained by processing natural, manufactured or recycled crushed unbound aggregates for use in construction of the upper layer of railway track. For the purposes of this standard, the aggregate is referred to as railway ballast and sub-ballast.

According the Spanish regulations, ballast hardness and type are defined in accordance with the speed, the gauge, and the line type.

Table 4.1: Spanish type of ballast. (*)AVE: Spanish High Speed Lines. **Secondary lines with low traffic, less than 8 per day.

Track gauge (mm)	Line maximum speed	Line type	CLA	Ballast type	Category of ballast according the European Standard
≥1435	≥200km/h	AVE*, A, B	≤14%	Type 1	$LA_{RB}14$
≥1435	<200km/h	AVE*, A, B	≤16%	Type 2	$LA_{RB}16$
≥1435	-	C**	≤20%	Type 3	$LA_{RB}20$

4.2.1.1 Ballast types on the selected routes

UK Routes:

The two strategic freight routes are ballasted throughout their length. Network Rail specifies two sizes of granite ballast to BS EN 13450 – 31.5/50mm and 31.5/63mm; ballast is designated by a pair of sieves with 31.5mm being the lower grid size and 50mm or 63mm being the upper limit.

Spanish Routes:

For the case of the Spanish route, information has been gathered about the type of ballast along the entire Mediterranean corridor. For the main line there is silica ballast type 1. Also there are a 44km of ballast less track that was an experimental track section done by ADIF in order to prove this kind of infrastructure.

There are other type of ballast used, but not in the main line, there have been used for secondary lines in station, sidings, stablings, etc.

Table 4.2: Mediterranean corridor type of ballast. Length of track (km)

Ballast Types	Valencia-Castellón	Castellón-Vandellos	Vandellos-Tarragona	Total
Ballastless track	31.98	12.66	0.00	44.63
Siliceous Type 1	144.25	469.43	12.43	626.11
Siliceous Type 2	6.35	16.63	0.00	22.97
Porphyry	0.00	0.49	0.00	0.49
1001480	2.15	0.11	0.00	2.25
Others	28.35	12.86	5.04	46.25
TOTAL	213.07	512.16	17.47	742.70

Bulgarian Routes:

There is no detailed data for the Bulgarian routes, it is only said that the entire network is ballasted.

4.2.1.2 Intervention criteria

To check the status of the ballast, according to the Spanish standards, two samples of ballast must be taken, one on each line of the track, and each one must have the quality levels required in the standard (NRV3400). Also, the thickness of the ballast and sub-ballast must be checked (according NRV3410), as well as the pollution level and the facilitating in rainwater drainage.

In the Mediterranean corridor type of lines (type A), the ballast renewal must always be silica type. Several studies conclude that the material used is very important, because the limestone ballast has a maintenance cost 15% - 25% greater.

4.2.1.3 Life cycle cost

It is very difficult to take into account how much of the cost of maintenance is due to the poor quality of the ballast. It depends on several factors, traffics, type of rolling stock, speeds, track geometry quality, maintenance operations, etc. To make a particular study it is necessary to know:

- Geometry properties of the track cross- sections.
- Properties of the ballast and subballast.
- Gap between sleepers
- Weather conditions
- Track lifter and tamping operations carried out.
- Grade of pollution.

In this study it has not been possible obtain this information from the Infrastructure Managers, however general data about averages could obtained and used to make some estimates.

It is suggested that the ballast renewal has been done once per 10-20 years in high traffic lines and 25-35 years in low traffic lines. In general, it is considered that the renewal of the ballast is appropriate when there are more than 30% of fines, or there are too many particles less than 22mm in size. The lifetime of ballast can be increased by using stones of greater hardness, by making the depth of ballast layer greater and by realizing a more homogeneous compacting of the ballast layer.

Table 4.3: Ballast average life in the Network Rail routes.

	Track length (km)	Ballast average life (years)
DCL: Didcott to Leamington Spa	84.6	16.9
Southampton to Nuneaton	216	21.6
Felixtowe to Nuneaton	261	24.0
EMP: Ely to Peterborough	62.7	32.4
BML1: Southampton to Basingstoke	48.6	22.9
WCML: Nuneaton to Crewe	98	14.7

For the Bulgarian routes, the ballast renewal has been done once per 12 years or the equivalent to 80.10^6 tonnes in the selected line.

When there is more than 40% of polluted ballast, it is strictly necessary for it to be washed. The ballast renewal could be washed and re-used as sub-ballast or as formation layer for the renewal of secondary lines. The cost of re-used ballast compared to the cost of new ballast may be taking into account in order to plan the maintenance operation.

The density of the ballast is in the range between 1.5 and 1.9 t/m^3 and changes over time depending on the cycle of loads. Research and experiments, for example ORE 1970[4.1] were able to obtain equations relating the seat of the ballast depending on the traffic loads.

4.2.1.4 Related Standards:

NR internal standards:

- NR/L2/TRK 8100 Issue 4 June 2009 Railway Ballast and Stoneblower aggregate
- NR/SP/ENV/044 Track maintenance, renewal or alteration – used ballast handling

- NR/L2/TRK/2102 Track construction standards
- NR/L2/TRK/001/A01 2009, Inspection and maintenance of permanent way – Inspection

Spanish internal standards:

- N.R.V. 3-4-0.0.Balasto. Características determinativas de la calidad. 1ª Edición, Septiembre 1987.
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4.2.2 Sleepers

The sleepers have several functions, such as appropriate load transfer and distribution from the rails to the ballast, constant rail spacing, and adequate mechanical strength in both vertical and horizontal direction and the electrical insulation of each rail from the other.

There are three main types of sleepers, depending on the materials and the typology: wooden sleepers and concrete sleepers, both mono-block and twin-block.

In Spain, due to the Iberian gauge, there is a type of mono-block multi-gauge sleeper. It is being installed in the new and renewed lines in Spain, including the Mediterranean Corridor. The use of these sleepers allows several track configurations: UIC gauge, Iberian Gauge and three rail track (in these tracks trains in both gauges can circulate).

According to ADIF standards, the properties of the sleepers used in the Spanish routes are the ones of Table 4.4.

Table 4.4: Properties of the sleepers used in the Mediterranean Corridor

NRV	Type	Mass (Kg)	Length (mm)	Width (mm)	Height (mm)
3131	RS for UIC54	220	2,380	290	220
3131	Stedef for VSB		2,507	290	345.5
3121	PR-90		2,600	300	245/249/257
3121	DW		2,600	300	249
3121	MR-93		2,600	300	249

4.2.2.1 Sleeper types in the selected routes

UK Routes:

- From Southampton to Nuneaton, most sections have between 90-98% concrete with most of the remainder in hardwood.

  - However the northern part of DCL route section only has 56% concrete and 44% hardwood.
  - From Southampton to Basingstoke, 98% is concrete, 1% hardwood and 1% softwood.
  - In the route from Didcot to Leamington Spa, two stretches are different: South of Anyho: 90% concrete; 9% hardwood; North of Anyho: 55% concrete; 43% hardwood.
- From Felixtowe to Nuneaton, it varies along the route with 30-40% concrete 50-60% hardwood; 10% softwood.
  - EMP Section from Ely to Peterborough: 36% is concrete; 54% hardwood and 10% softwood
- From Nuneaton to Crewe, 62% is concrete, 35% hardwood and 2% softwood.

Spanish Routes:

The data about sleepers in the Mediterranean Corridor is in Table 4.5.

Table 4.5: Sleepers used in the Spanish routes. Length of track (km)

Sleeper Types	Valencia-Castellón	Castellón-Vandellos	Vandellos-Tarragona	Total
Twin-block (Iberian Gauge) RS	21.38	0.00	0.00	21.38
Twin-block Stedef (Iberian Gauge) for VSB	3.47	0.00	0.00	3.47
Mono-block (Multi-Gauge) PR-01	0.75	0.00	6.49	7.24
Mono-block (Multi-Gauge) PR-90	27.68	140.89	8.31	176.88
Mono-block (Iberian Gauge) DW	14.55	0.00	0.00	14.55
Mono-block (Iberian Gauge) MR-93	0.00	0.00	24.51	24.51
Tranosa Extractable Block (Iberian Gauge) for VSB	0.00	4.27	0.00	4.27
Ballastless Experimental Track	0.00	3.16	0.00	3.16
TOTAL	67.83	148.33	39..31	255.47

Bulgarian Routes:

Sleepers used in Bulgaria are CT 4, CT 4T, CT 6 and wood, being CT 4 the most widely installed.

4.2.2.2 Intervention criteria

It is possible to detect failures in sleepers observing or measuring the distance between rails and the track geometry. There are several causes for the failure:

- Cracking of concrete sleepers (loads excess, manufacturing defects...)

- Looseness of the sleepers, what causes movements when passing trains and, subsequently, wear in the sleepers.
- Basement braking, especially for timber sleepers.
- Rottenness of timber sleepers.
- Incorrect support of the sleeper on the ballast.

If any of these characteristics are observed, the sleeper must be replaced.

The most important causes of cracking are the mechanical ones, concrete shrinkage during solidification and chemical transformations of cement. These processes can be produced during manufacturing as well as during installation, for example when screwing.

It is difficult to build a failure model to predict renewal, because of the different behaviour that the sleepers and fastenings have. Each one behaves in different ways, depending on materials and shape. As sleepers are expensive, many different models have been designed. A common observation in these studies is that the more elastic a sleeper is, the cheaper is its maintenance, although elasticity is limited by the track stability.

To predict sleeper failure, the following data is needed:

- Infrastructure data.
- Date and number of sleeper substitutions.
- Reasons for the renewal.

In Spain, these defects must be checked according with the standard (NRV 7380). It is recommended to check 20 sleepers, observing the distance between axis and the imbalance. It is mentioned that the useless sleepers are:

- Timber sleepers: Buried, rotten, broken and the sleepers longitudinally slotted in the drills.
- Concrete mono-block sleepers: Rifted or broken sleepers and the ones where the correct positioning of the fastening is not possible.
- Concrete twin-block sleepers: Rifted or broken sleepers and the ones where the correct anchorage of the fastening is not possible. The brace must be also checked.

It is considered that a twin-block sleeper is useless when the brace is broken or twisted, when its imbalance is wider than 6 centimetres or when the theoretical distance between axes is wider than 5 centimetres. The limit case is 3 or more useless sleepers in a row.

Another problem is “dancing” sleepers. It is considered that a sleeper is well supported (and does not dance) when its settling is lower than 1 millimetre.

The last point to be taken into account is the difference between the real and the theoretical position of the sleeper. The NRV limits this value to 30 millimetres, due to quality conditions.

4.2.2.3 Life cycle cost

Timber sleepers have a life reference time of 15 years; concrete sleepers are estimated to last 50 years. But, usually, they are renewed at the same time as the rails (20-25 years), using the sleepers removed from the main lines in the secondary lines. The used life of sleepers in the British route is in Table 4.6, and the average life of sleepers in the Table 4.7.

In the Bulgarian case, the sleepers are renewed at the same time that the rails (36 years or the equivalent to 240.10^6 tonnes)

Sleepers account for a large proportion (from 40% - 60%) of the cost of new infrastructure. Management of this asset, its maintenance and renewal costs play a key role in the optimisation of track maintenance costs.

Table 4.6 Used life of sleepers

Sleeper used life	0-25%	25-50%	50-75%	75-100%	Extended
DCL: Anyho to Leamington Spa	23%	12%	14%	45%	6%
DCL: Chester Line to Anyho	33%	3%	9%	22%	34%
EMP: By North to Peterborough	7%	24%	42%	16%	11%
BML1: Northam to Basingstoke	33%	11%	20%	30%	6%
WCML: Nuneaton to Crewe	47%	5%	24%	16%	8%

Table 4.7: Sleepers average life in the Network Rail routes.

	Track length (km)	Sleepers average life (years)
DCL: Didcott to Leamington Spa	84.6	28.8
Southampton to Nuneaton	216.0	26.3
Felixtowe to Nuneaton	261.0	30.4
EMP: Ely to Peterborough	62.7	33.3
BML1: Southampton to Basingstoke	48.6	23.4
WCML: Nuneaton to Crewe	98.0	21.9

4.2.2.4 Related Standards

NR internal standards:

- NR/SP/TRK/029 Issue 4 Dec 2005: Wood sleepers, bearers and longitudinal sleepers
- NR/SP/TRK/030 Issue 2 Aug 2003 Concrete Sleepers and bearers
- NR/L2/TRK/2049 2010, Track Design Handbook includes lists types of sleepers in Section F2

ADIF internal standards.

- N.R.V. 3-1-0.0.Traviesas. Traviesas y cachas de madera. 1ª Edición, Marzo 1981.
- N.R.V. 3-1-2.1.Traviesas. Traviesas monobloque de hormigón. 1ª Edición, Diciembre 1997.
- N.R.V. 3-1-3.1.Traviesas. Traviesas bibloque de hormigón. 1ª Edición, Septiembre 1999.

4.2.3 Rail fastening

As fastenings are termed the set of parts and materials ensuring the rail-sleeper connection, and they should provide the following properties:

- Keep track gauge and transverse rail inclination.
- Transfer loads form, the rail to the sleeper.
- Attenuate and dampen vibrations caused by train traffic.
- Easy installation and maintenance.
- Electrical insulation.
- Resilience and adequate deflection.
- Avoidance of abrasion between components and of over-stressing.
- Adequate corrosion resistance.
- Reasonable cost and lifetime compatible to that of sleeper.
- Resistance to vandalism.

There are two types of fastenings, rigid and elastic, being the elastic ones the most widely used.

4.2.3.1 Fastening types in the selected routes

UK Routes:

There are a large variety of fastenings and baseplates in use along these routes on the various wood and concrete sleepers. These are being standardised to use thicker underseat pads. However there can still be found 25 types of baseplates and 17 types of fastenings along such variable routes. On main passenger routes the number of baseplates and fastenings is somewhat less and more standardised.

Spanish Routes:

The data about fastenings in the Mediterranean Corridor is in Table 4.8.

Table 4.8: Fastenings used in the Spanish routes. Length of track (km).

Fastening Types	Valencia-Castellón	Castellón-Vandellos	Vandellos-Tarragona	Total
Elastic HM for UIC-54 on DW sleeper	14.55	0.00	0.00	14.55
Elastic J-2 for UIC-54 on RS sleeper	72.63	0.00	0.00	72.63
Elastic VM (improved Vossloh) for UIC-54 on PR-01 sleeper	0.75	0.00	6.49	7.24
Elastic Vossloh for UIC-54 on MR-93 sleeper	0.00	0.00	24.51	24.51
Elastic Vossloh for UIC-54 on PR-90 sleeper	0.77	0.00	9.26	10.03
Elastic Vossloh for UIC-60 on PR-90 sleeper	27.01	140.89	0.00	167.90
Elastic Nabla for UIC-60 on Stedef for VSB sleeper	3.47	0.00	0.00	3.47
Elastic for UIC-60 on Tranosa Extractable Block sleeper	0.00	4.27	0.00	4.27
TOTAL	115.71	140.89	40.26	296.86

Bulgarian Routes:

It is mentioned that in newer sections, the Vossloh W 14 rail clamp (see Figure 4.1) is used instead of the traditional tie-plate fastening with pressing clamp.



Figure 4.1 Vossloh W 14 rail clamps on concrete sleepers west of Dragoman (left) and at Pazardjik (right).

4.2.3.2 Intervention criteria

It is important to check the tightening torque, when installing. It must be enough to support the rail, but not strong enough to damage it. In the periodical interventions the tightening

function must be checked. There must not be any broken or loose fastenings because they may cause dangerous traffic situations, especially in transitions and curves, where the rail has higher mechanical loads.

The Spanish N.R.V. 7-3-8.0. standard indicates the tolerances and characteristics of each fastening type. Generally, the clearance between the rail and the fastening is limited in several points.

In timber sleepers, the train traffic can produce wear in the joint between the fastening and the drill. Due to this wear, water and other corrosive agents can act and damage the fastening properties. Other phenomena such as rottenness or timber wear (produced by several causes) can loosen the fastening.

Re-tightening is useful for short periods of time, but, in the medium-term, the sleeper should be replaced. The best solution is to reduce the clefts by inserting new material and drilling new holes, and replacing the old lags by new ones. It is also possible to insert Votok spirals (to avoid the new drilling operations).

In twin-block concrete sleepers, the fastenings allow gauge widening. This is the reason why checking the installation and positioning is even more important. In mono-block, this is done using angled plates.

4.2.3.3 Life cycle cost

No data has been gathered about the fastenings and their relationship to track maintenance. Obviously, the fastening could have a very important role in the life cycle cost for the whole track, because an efficient fastening could reduce vibration and extend the life of the ballast, rails and sleepers.

4.2.3.4 Related Standards:

NR internal standards:

- NR/L2/TRK/2049 Track Design Handbook includes lists of Railpads, Clips and insulators in Table D4.1ª related to the types of sleepers

ADIF internal standards:

- N.R.V. 3-2-1.0.Sujecciones de carriles. Sujeción elástica R.N. 1ª Edición, Julio 1982.
- N.R.V. 3-2-1.1.Sujecciones de carriles. Sujeción elástica P-2. 1ª Edición, Septiembre 1985.
- N.R.V. 3-2-1.2.Sujecciones de carriles. Sujeción elástica Nabla. 1ª Edición, Agosto 1992.
- N.R.V. 3-2-1.3.Sujecciones de carriles. Sujeción elástica J-2. 1ª Edición, Febrero 1994.
- N.R.V. 3-2-2.0.Sujecciones de carriles. Sujeción elástica H.M. 1ª Edición, Julio 1982.
- N.R.V. 3-2-2.1.Sujecciones de carriles. Sujeción elástica SKL-2. 1ª Edición, Agosto 1992.

- N.R.V. 3-2-3.0.Sujecciones de carriles. Sujeción elástica Pandrol. 1ª Edición, Septiembre 1985.
- N.R.V. 7-3-8.0. Estados de los materiales de la vía. 1ª Edición, Agosto 1984.

4.2.4 Rails

The rails are directly responsible for supporting the weight of the rolling stock and the dynamic actions generated by the circulation and the condition of tracks and vehicles.

There is a classification of the rails according to their weight per meter. The following table shows some properties that define the most important types of rails by the European standard EN 13674-1 [4.2].

Table 4.9: Properties of the rail profiles. EN 13674.

EN	Type	Mass per metre (Kg/m)	Cross sect. area (cm^2)	M. Inertia vertical (cm^4)	Head width (mm)	Rail height (mm)	M. Inertia horizontal (cm^4)	S. modulus. Head (cm3)	S. modulus. Base (cm3)	S. modulus. hor (cm3)
60E1	UIC60	60.2	76.7	3,038.3	72.0	172	512.3	333.6	375.5	68.3
56E1	BS113lb	56.3	71.7	2,321.0	69.9	158.8	421.6	275.5	311.5	60.2
55E1	U55	56.0	71.4	2,150.4	62.0	155	418.4	255.2	304.0	62.4
54E3	DINS54	54.6	69.5	2,074.0	67.0	154	354.8	262.8	276.3	56.8
54E2	UIC54E	53.8	68.6	2,307.0	67.0	161	341.5	276.4	297.6	54.6
54E1	UIC54	54.8	69.8	2,337.9	70.0	159	419.2	278.7	311.2	59.9
52E1	52RATP	52.2	66.4	1,970.9	65.0	150	434.2	247.1	280.6	57.9
50E6	U50	50.9	64.8	2,017.8	65.0	153	396.8	248.3	281.3	56.7
50E5	50UNI	49.9	63.6	1,844.0	67.0	148	362.4	242.1	256.6	53.7
50E4	UIC50	50.5	64.3	1,934.0	70.0	152	315.2	252.3	256.6	50.4
50E3	BV50	50.0	63.7	2,057.8	70.0	155	351.3	259.5	271.8	52.8
50E2	50EB-T	50.0	63.7	1,988.8	72.0	151	408.4	248.5	280.3	58.3
50E1	U50E	50.4	64.2	1,987.8	65.0	153	365.0	246.7	274.4	54.5
49E4	HUSH113lb	49.5	63.0	875.1	70.0	110	417.4	145.9	175.0	59.6
49E3	DIN549b	47.8	60.9	1,705.0	67.0	146	310.8	227.2	240.4	49.7
49E2	S49T	49.1	62.6	1,796.3	67.0	148	318.4	239.4	246.2	50.9
49E1	DINS49	49.4	62.9	1,816.0	67.0	149	319.1	240.3	247.5	51.0
46E4	46UNI	46.9	59.8	1,688.0	65.0	145	338.6	221.6	245.2	50.2
46E3	NP46	46.7	59.4	1,605.9	73.7	145	307.5	224.2	228.2	51.3
46E2	U33	46.3	58.9	1,642.7	62.0	145	329.3	213.0	242.1	49.1
46E1	SBB I	46.2	58.8	1,641.1	65.0	145	298.2	217.0	236.6	47.7

In addition to its section, the rails are characterized by their metallurgical composition, which has a relation with the certain level of resistance. The resistance of steel to be used is a function of traffic and the curve radius.

In freight tracks, rails are used whose resistance is of the order of 700 N/mm^2. However, for high-speed lines hard steel rails are in widespread use, with a breaking point in the range of 900 N/mm^2 -1100N/mm^2.

There are some studies that relate the rail mass and the maximum traffic load depending on curve radius, circulation speed, higher axle load and traffic (as for example Shajunianz Professor's formula).

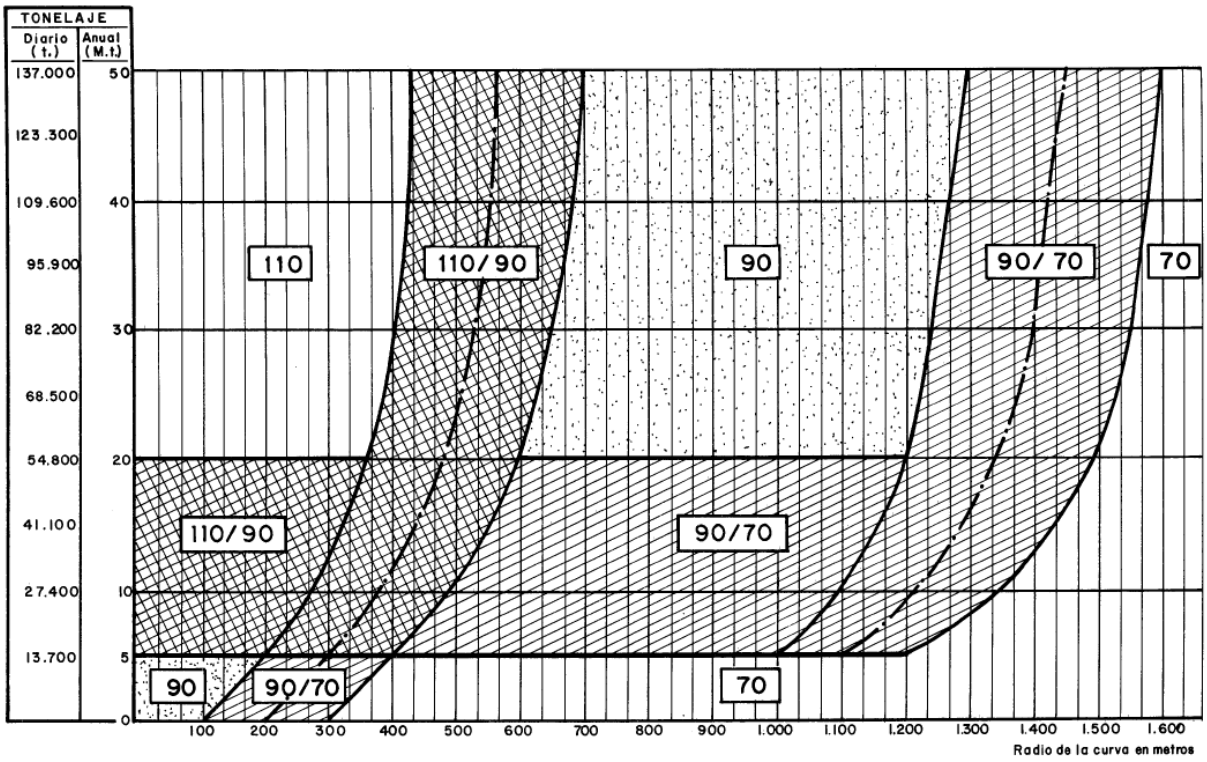


Figure 4.2 Domain of use of rails(70 daN/mm2, 90 daN/mm2, 110 daN/mm2) function of radius of curvature, and the traffics forecasting. ADIF´s standard.

4.2.4.1 Rail types in the selected routes

The rail type in a line depends of several factors (both economic and about properties of the rolling stock or the track geometric as example). Below there are classifications of the rail types in the selected routes.

UK Routes

- From Southampton to Warrington 67% is UIC54 equivalent; 17% is UIC 60; 14% is unknown.
    - BML1 Section from Southampton to Basingstoke 89% is UIC54 equivalent; 6% is UIC 60.

- DCL Section from Didcott to Leamington Spa: 72% is UIC54 equivalent; 16% is UIC 60.

- From Felixstowe to Nuneaton 72% is UIC54 equivalent; 20% is UIC 60; 8% is unknown.
  - EMP Section from Ely to Peterborough: 52% is UIC54 equivalent; 0% is UIC 60.
- From Nuneaton to Crewe 50% is UIC54 equivalent; 37% is UIC 60; 13% is unknown.

Table 4.10: Rail types in the NR routes.

Rail Types	Felixstowe to Nuneaton and up WCML	Southampton to Nuneaton and up WCML	Total
UIC 60 Flat bottom Rail	60.1	60.2	120.3
BS113A Flat bottom Rail	172.9	199.9	372.8
BS110A Flat bottom Rail	22.8	11.8	34.6
113lb Flat bottom Rail	22.4	5.0	27.4
109lb Flat bottom Rail	21.1	5.4	26.5
98lb Flat bottom rail	2.8	0.6	3.4
95lb Bullhead rail	6.4	1.2	7.6
95lb Flat bottom Rail	0.6	0.0	0.6
Transition rail	0.8	0.6	1.4
Rail weight unknown	49.4	23.5	72.9
TOTAL	359.3	308.2	667.5

Table 4.11: Plain line rail in the NR routes

Plain Line Rail	UIC 60	BS133lb	Other	Unknown
DCL: Anyho to Leamington Spa	13%	73%	1%	13%
DCL: Chester Line to Anyho	18%	69%	13%	0%
EMP: Ely North to Peterborought	0%	52%	21%	27%
BML1: Notham to Basingstoke	6%	89%	5%	0%
WCML: Nuneaton to Crewe	37%	50%	1%	12%

Spanish Routes:

There are only two main types of rail sections in the Mediterranean Corridor, UIC 54 and UIC 60. There are other rail sections (RN45) but not in the main line, there are in stations or marshalling yards, and mostly are planned to be renewed.

Table 4.12: Plain line rail in the ADIF routes.

Rail Types (rail km)	Valencia-Castellón	Castellón-Vandellos	Vandellos-Tarragona	Total
UIC 54 (54E1)	79	0	80	159
UIC 60 (60E1)	66	296	0	362
TOTAL	145	296	80	521

Bulgarian Routes

The main used rail sections for the Bulgarian routes are UIC 49 or equivalent. For the case of renewed track, older rails have been replaced by UIC 60.

4.2.4.2 Intervention criteria

The maintenance or replacement of rails takes place when defects appear or there is excessive vertical/side wear, and it is no longer strong enough to continue its role of supporting rolling stock.

Often, although an intervention is justified due to the risk of failure involved, the final scheduling of maintenance has to take into account other factors such as, safety issues, intervention costs, cost of alternative options, remaining life of rails, schedule of future or current train routes, availability of maintenance equipment, etc. In most cases, especially in low probabilities of failure, limitations to traffics loads of velocity are imposed, until more permanent measures are taken to treat the problem.

A detailed classification of rail defects can be found in the UIC leaflet 712R [4.3]. This leaflet contains recommendations for identifying and classifying rail defects and compiling statistics. These defects are coded, described and illustrated. Usually the infrastructure managers have they own standards, like Network Rail (NR/L2/TRK/001/B01) or ADIF.

The wear of the rails is produced by the action of dynamic loading of the wheels and the effect of corrosive environmental phenomena. The intervention criteria for replacing a rail are defined mostly by the cross-section loss.

Table 4.13: Limit wear for the Spanish standards.

Maximum speed.(Km/h)	Max vertical rail wear (mm.)			Max side head wear (mm.)			Max total lateral wear (mm)		
	UIC60	UIC54	UIC45	UIC60	UIC54	UIC45	UIC60	UIC54	UIC45
V≤80	21	19	17	12	10	8	27	24	21
80<V≤120	20	18	16	11	9	7	25	22	19
120<V≤160	18	16	14	10	8	6	23	20	17
160<V≤200	16	14	-	8	7	-	20	18	-
200<V≤240	14	-	-	7	-	-	17	-	-
240<V≤280	12	-	-	7	-	-	15	-	-
280<V≤320	10	-	-	6	-	-	13	-	-
V>320	8	-	-	6	-	-	11	-	-

Corrugation:

- Short-wave defects are tolerable between 3 and 8 cm (series of alternate high and low points on the running surface and or running edge of the rail).
- Mid-wave defects are tolerable between 8 and 30 cm (series of alternate high and low points on the running surface and or running edge of the rail).
- The crest for both defects is usually between 0.2 and 0.3 millimetres wide.

Table 4.14: Limit wear for the British standards.

Maximum speed.(km/h)	Head width when new (mm)		Max side head wear (mm)		Min head width (mm)	
	CEN60	Rest	CEN60	Rest	CEN60	Rest
V≤130	72	70	9 on each side	9 on each side	54	52
130<V≤200	72	70	9 over both sides	9 over both sides	63	61

The rail depth, as measured outside any gall, shall not be less than the values in Table 4.15 within 9 m of any fishplate.

Table 4.15: Absolute minimum rail depth (without sidewear).

Rail Section types	Minimum depth (mm)
CEN60 flat bottom plain line	158 + L
CEN 60 flat bottom S&C	162 + L
109 / 110A / CEN56 (113A) flat bottom	145 + L
98 flat bottom / 95 and 97.5 bullhead	131 + L
85 bullhead	127 + L

L is the natural head loss on the current running face of the rail due to sidewear, measured 14 mm below the crown of the rail.

In the British standard, corrugation is defined as a series of alternate high and low points on the running surface and or running edge of the rail. The frequency of the corrugation is defined by the wavelength. Long wavelength corrugation is defined as cyclic undulations with a wavelength greater than 500 mm. Short wavelength corrugation is defined as undulations with a wavelength between 25 and 500 mm. There are no limited boundaries for corrugation.

In the Bulgarian routes, rails have to be renovated in terms of 24 hours, 3 days, 1 month etc. according to appearance of defects with size determinate in NRIC standard document. According to rail type admissible values are:

- for side wear 13,5mm for 49kg/m and 11,0mm for 60kg/m;
- for vertical wear 24mm for 49kg/m, 22mm for 60kg/m and 8mm for 49-60kg/m;
- for total summarized wear (depending also from line category) 12mm

4.2.4.3 Life cycle cost

The interval between two renewals on a high traffic line (50000 to 60000 tonnes per day), is situated between 20 and 25 years, in terms of rail life. An average time interval between two renewals is in Table 4.18. Rails account for a large proportion (from 30% - 50%) of the cost of new infrastructure. Management of this asset, its maintenance and renewal costs play a key role in the optimisation of track maintenance costs. Maintenance is key so that rail/wheel life is prolonged and maximised. In many instances rail/wheel wear can occur very rapidly when rail flange lubrication is not present.

Some parameters that have influence on the rail life are:

- Radius of curvature Wear always grows in reverse proportion to the curve radius.
- Curve cant. Low cant favours the external rail wear. High cant favours the internal rail crushing.
- Line traffic. Wear grows in direct proportion to the gross traffic in the line.
- Rolling stock nature. Bogies positioning and influence the damage on the rail. Especially when cornering.
- Axle load. Heavy axes favour the internal rail crushing.
- Rail Lubrication. Greasing is the most effective procedure to prevent lateral wear in curves. But an excessive lubrication can be damaging (Shelling effect).

Table 4.16: Used life of rails

Rail used life	0-25%	25-50%	50-75%	75-100%	Extended
DCL: Anyho to Leamington Spa	18%	3%	31%	31%	17%
DCL: Chester Line to Anyho	41%	6%	14%	10%	30%
EMP: By North to Peterborough	30%	45%	19%	6%	1%
BML1: Northam to Basingstoke	42%	12%	16%	27%	3%
WCML: Nuneaton to Crewe	58%	6%	16%	11%	9%

Table 4.17: Rail average life in the Network Rail routes.

	Track length (km)	Rail average life (years)
DCL: Didcott to Leamington Spa	84.6	27.55
Southampton to Nuneaton	216	23.45
Felixtowe to Nuneaton	261	24.525
EMP: Ely to Peterborough	62.7	28.575
BML1: Southampton to Basingstoke	48.6	18.25
WCML: Nuneaton to Crewe	98	16.75

Table 4.18: Time interval, in years, between two full renewals. Source: [4.4]

	Gross traffic (including locomotives) on one track (gross tonnes-kilometres or GTK)			
Rail section (kg/m)	$10x10^3$ GTK/day 2.5 to 3.6×10^6 GTK/year	$30x10^3$ GTK/day 7.5 to 11×10^6 GTK/year	$100x10^3$ GTK/day 25 to 36×10^6 GTK/year	$300x10^3$ GTK/day 75 to 108×10^6 GTK/year
50	40 (30 to 50)	20 (15 to 30)	10 (8 to 20)	-
60	-	25 (20 to 30)	12 (10 to 25)	6 (4 to 12)
70	-	-	-	7 (5 to 14)

In the Bulgarian case, the time interval between two full rail renewals is 36 years, or the equivalent to 260.10^6 gross tonnes kilometres.

4.2.4.4 Related standards

NR internal standards:

- NR/L2/TRK/001/B01. Inspection and maintenance of permanent way. Rail management.
- NR/L2/TRK/2049 Track Design Handbook

ADIF internal standards:

- N.R.V. 3-0-0.0.Carriles. Barras elementales. 1ª Edición, Febrero 1981.
- N.R.V. 3-0-1.0.Carriles. Barras largas. 1ª Edición, Marzo 1981.
- N.R.V. 3-0-2.0.Carriles. Barras regeneradas. 3ª Edición, Septiembre 1985.
- N.R.V. 3-0-4.0.Carriles. Carriles resistentes al desgaste. 1ª Edición, Octubre 1982.

4.2.5 Electrification equipment, catenary and contact wire

In electrification equipment, usual maintenance activities are being replaced by telecontrol. Nowadays, only the failure detection and the connection of systems in standby are among the central control centre duties. In the future, maintenance is to be transferred to them.

Electric traction has the function of moving trains (passenger trains or freight trains) with the aid of electrified traction lines. The requirements for the traction power systems are:

- The provision of uninterrupted traction power at the pantographs.
- The ability to absorb regenerated braking energy.
- Compliance with specified and standardised quality parameters.

There are several types of electrification. They can be classified in two big groups:

- Direct current systems, DC.
- Alternating current systems, AC.

Within each type, different systems are distinguished due to the voltage.

Direct current was used due to the favourable curve of the series commutator motors used as drives in railway applications. The low voltage used is a disadvantage as it needs high currents to transmit the traction power (that increases the energy losses). Nowadays, over half of all electric traction systems use DC. Usual voltages are 600V, 750V, 1500V and 3000V.

At the beginning of the 20th Century, efforts were made to combine the traction advantages of the series motor with the transforming capacity of AC. AC has proven to be powerful and effective for high-speed and high-capacity lines, and now is being installed all around the world. Usual voltages and frequencies are 15kV and 16.7Hz and 25kV and 50Hz.

Power is supplied to the trains using contact lines, which are electrical wires. In most of the electrified rail lines in the world, these wires are overhead catenaries.

The components of an overhead line are classified according to its loads in:

- Mechanical loads: Poles and support devices.
- Both mechanical and electrical loads: Contact wire, isolators...

4.2.5.1 Catenary types in the selected routes

UK Routes:

- From Southampton to Nuneaton (211.2 km), the first 48 km is electrified at 750V dc third rail; but there is no power on the rest.
- The electrified section is Southampton to Basingstoke.
- From Felixstowe to Nuneaton (256.6 km), the first 30 km is electrified at 25kV AC; but there is no power on the rest except for a short section of the East Coast Main Line that the route crosses.
- From Nuneaton to Crewe, all 101.6 km are electrified at 25kV AC overhead.

Spanish Routes:

All Spanish routes in the Mediterranean Corridor are electrified at 3000V DC.

Bulgarian Routes:

In Bulgaria, electrification at 25kV 50 Hz is installed in 276.53 km (65% of the lines). This is the stretch Dimitrograv-Krumovo. The remaining 155.4 km, from Krumovo to Kapikule, is not electrified.

4.2.5.2 Intervention criteria

Traditional maintenance done in overhead contact lines was scheduled or cyclical. This maintenance planning has been in use all over Europe until the late 80's. These procedures have changed, just as in rail maintenance, to reduce employed personnel using auscultation techniques and statistical analysis. Predictive maintenance has been implemented. Maintenance interventions (oiling, tightening...) were reduced by diagnosing the state of anchorages, etc.

The objective is to reduce maintenance costs, programming the wire substitutions. Investments in preventive maintenance reduce the cost of corrective maintenance and renewals.

- Corrective maintenance:
  - Statistical analysis.
  - Breakdowns study.
  - Ratios analysis.
- Auscultations:
  - Geometrical rates.
  - Contact wire wear rate.
- Preventive maintenance:
  - Corrective actions.
  - Non-compliance study.
  - Reliability ratios of the elements.
- Audits:
  - Non-compliances
  - Corrective actions

The catenary and electrical supply equipment have to be kept in safe limits as follows:

Table 4.19: Allowed wear in contact wire. Source [4.5]

Category of wear	%	Contact wire thickness		
		Ri 100 (mm)	Ri 120 (mm)	Ri 150 (mm)
I	100-94	12.0 to 11.0	13.2 to 12.0	14.5 to 13.3
II	95-77	10.9 to 10.2	11.9 to 11.0	13.1 to 12.3
III	78-80	10.1 to 10.0	10.9 to 10.0	12.2 to 11.1

Moreover, each IMs has they own standard for the catenary and electrical supply equipment, as for example NRIC has the following limits::

- 500A of maximum train current for connecting lines such as the selected one (Kalotina-Sofia-Plovdiv-Svilengrad);
- 17,500V of minimum alternating voltage (for not more than 2 minutes);
- 19,000V of minimum direct-current voltage;
- 25,000V of nominal voltage;
- 27,500V of maximum direct-current voltage;
- 29,000V of maximum alternating voltage (for not more than 2 minutes)
- The height of contact wire above rail head normally is 5,600mm, except some specific cases, as for example overpasses (5,100mm to 5,500mm) or railway crossings (6,000mm):
- The zigzag of contact wire is between -200mm and +200mm in straight sections and between -300mm and +300mm in curves."

4.2.5.3 Life cycle cost

The real service life of overhead contact lines for electric railways is high compared to other equipment. According to Baumgartner, catenary life is estimated to be between 30 and 50 years, of which contact wires are 5 to 30 years. The service life is dependent upon the development of electrically hauled transport, and also upon the speed development.

The contact wire is the wear-intensive element of an overhead contact line. The replacement of the contact wire during operational conditions is associated with high costs. The conductor cross sections influence the energy losses and the quality of the supplied voltage.

Also the mean time between failures (MTBF) is an important parameter to estimate the life cycle costs. There is some existing data about the different catenary components.

Table 4.20: Mean time between failures for different components. Source: [4.5]

Element	MTBF in years
Poles	10.5-17.6
Supports	2.4-2.8
Contact lines	1.5
Section insulators	21.5-30.4

The most common case for partial dismantling occurs during the replacement of the contact wire. Complete renewal of the system requires the complete removal of the overhead contact line. The removal of foundation parts is expensive; consequently, they are usually left in the place.

For the case of the Bulgarian routes, there are 7 power distribution subdivisions – PDS (Volujak, Sofia, Vakarel, Kostenec, Pazardjik, Plovdiv, Dimitrovgrad) for urgent maintenance of the catenary and electrical supply equipment in the selected lines. Renovations and repairs of the catenary and electrical supply equipment include:

- Replacements of strings, terminals (ears), transverse and longitudinal connectors, clamps, insulators: once per 5 years;
- Repairs and replacements (by necessity) of often switched section disconnectors: once per 6 years
- Replacements of tension guys and anchors: once per 20 years;
- Repairs of concrete foundations: once per 20 years;
- Replacements of contact wire
    - $30mm^2$ wear-out of cross-section $100mm^2$
    - $25mm^2$ wear-out of cross-section $80mm^2$
- Replacements of copper, bronze and bimetallic main cables: once per 50 years

4.2.5.4 Related Standards

NR internal standards:

- BS 7865 : 1997 Full Low, Specification for Steel electrical conductor rail for railway motive power supply
- GE/GN8600 2012, Guidance on the Conventional Rail Energy TSI

ADIF internal standards:

NRIC internal standards:

- Technical Specification for Operational Compatibility of "Power Engineering"
- Bulgarian Decree №57,

4.2.6 Track equipment - Switch and Crossings

Switches are the elements that allow the change of track for a train. Crossings allow two tracks to intersect at the same level. Different types of these track equipment are classified according to their elements or the angle of change.

The elements have a significant impact on life time and performance. The switch will behave in different ways on concrete or timber sleepers, in different fastenings or rails. All these features give the switch a maximum allowed speed for main and diverging way (this one is always less).

Beside the components, the switch's main characteristic is the angle between the main and the diverging track. This angle is very important because cant is not applicable to a switch. High speeds are desirable, but the centrifuge acceleration must be reduced using a small angle. Due to this, switches are longer.

4.2.6.1 Switch types in the selected routes

UK Routes

The number and summary of type of S&C along the two UK routes are given in the Table 4.21. Data about used life of switches is mentioned in the Life cycle cost point.

Table 4.21: Number and summary of type of S&C along the two UK routes

Number of S&C units along each route	Felixtowe Route	Southampton Route
A. NR-60	21	45
B. Concrete vertical	14	24
C. Timber vertical	85	64
D. Legacy inclined + bullhead	35	37
Total	155	170

Spanish Routes

Table 4.22: Switch type in Spanish Routes.

Switch type	Number	Sleeper type	Max Direct Track Speed	Max Diverted Track Speed	Rail Welding
A	11	Timber	140	30	No
C	52	Timber	160-200	45-60	Yes
V	24	Timber	200	100	Yes
P	6	Concrete	200	100	Yes

Bulgarian Routes

There is no existing data in the Bulgarian routes.

4.2.6.2 Intervention criteria

The life of a switch is characterised by its elements (sleepers, fastenings...) or its usefulness, for instance, the line speed.

4.2.6.3 Life cycle cost

Stadler study [4.6] mentions that the maintenance cost of switches and crossings are equivalent to 300 metres of track. The importance of switches can be pictured due to this number.

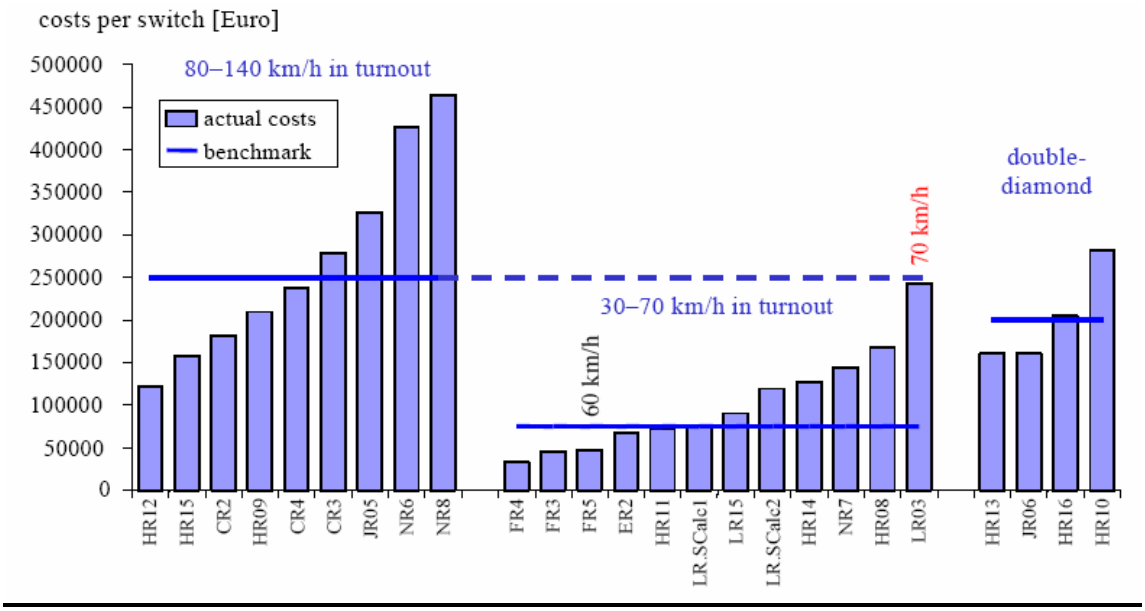


Figure 4.3: Costs per switch. Source: [4.6]

The data about switch used life in the different stretchs in the UK selected routes is in Table 4.23.

Table 4.23: Used life of switches

Switch used life	0-25%	25-50%	50-75%	75-100%	Extended
DCL: Anyho to Leamington Spa	56%	0%	16%	8%	20%
DCL: Chester Line to Anyho	43%	0%	20%	0%	37%
EMP: By North to Peterborough	9%	41%	24%	19%	8%
BML1: Northam to Basingstoke	66%	15%	3%	11%	5%
WCML: Nuneaton to Crewe	71%	7%	11%	12%	0%

4.2.6.4 Related Standards

NR internal standards:

- NR/L2/TRY/2049 2010 Track Design Handbook – Section E
- NR/L2/TRK/001/D01, Inspection and maintenance of permanent way – Switches and crossings.

ADIF internal standards

- N.R.V. 3-6-0.0. Desvíos. Descripción general. 1ª Edición, Julio 1991.
- N.R.V. 3-6-0.1. Desvíos. Características de los tipos y modelos. 1ª Edición, Julio 1992.

4.2.7 Track Geometry quality

There are some geometrical parameters that define QI (Quality Index). These parameters are:

- Longitudinal levelling of each rail (mm) → Galloping.
- Cross levelling of both rails (mm) → Rocking.
- Track gauge → Transverse movement.
- Alignment of each rail → Transverse movement.
- Rail warps (mm/m) → Derailment.
- Other parameters related to the track (radius, cant or gradient).
- Vertical and cross accelerations measured in the vehicles (commercial or inspection ones).

For conventional lines, track maintenance decisions are usually based on the visual observation of auscultation graphics. In recent years, statistical analysis has grown in importance. There are three limit values classifications that define the track quality:

- Limit values for new track.
- Reference values for maintenance.
- Immediate intervention values.

For example the UIC518 (1998) Leaflet, establishes some criteria to define the track quality for each stretch, for each maximum speed interval. Three quality levels are mentioned:

- QN1: Correct value.
- QN2: Defect value. Maintenance operations are necessary in the mid-term.
- QN3: Defect value. Non desirable situation.

Table 4.24: Longitudinal levelling allowable defects for QN1 and QN2 in UIC 518 leaflet. Source: [4.7]

Maximum speed.(km/h)	QN1		QN2	
	Max value (mm)	Standard deviation (mm)	Max value (mm)	Standard deviation (mm)
V<80	12	2.3	16	2.6
80<V≤120	8	1.8	12	2.1
120<V≤160	6	1.4	10	1.7
160<V≤200	5	1.2	9	1.5
200<V≤300	4	1.0	8	1.3

4.2.7.1 Track Geometry quality in the selected routes

UK Routes

The track quality data for sections along the two UK routes is given in the Table 4.25.

Table 4.25: Track quality data for sections along the two UK routes

Track quality	Good	Satisfactory	Poor	Very Poor	Super Red
DCL: Anyho to Leamington Spa	73%	24%	2%	0%	0%
DCL: Chester Line to Anyho	75%	20%	4%	1%	0%
EMP: Ely North to Peterborough	73%	18%	7%	2%	0%
BML1: Northam to Basingstoke	64%	18%	11%	6%	1%
WCML: Nueaton to Crewe	91%	8%	1%	0%	0%

The UK track quality definitions for “Good”, “Satisfactory” etc. are given in the Table 4.29

One analysis for the Short-wave (35mm) SDs gave the following distribution:

Table 4.26: Short-wave (35mm) SDs distribution

Vertical short wave (35m) SD	Felixtowe route (km)	Southampton route (km)
0-0.9	18.0	28.1
1-1.9	173.4	169.3
2-2.9	110.4	76.0
3-3.9	37.5	22.2
4-4.9	16.4	8.0
5-5.9	3.0	3.0
6-6.9	0.5	1.3
7-7.9	0.2	0.1
8-8.9	0.0	0.2
≥9	0.0	0.0
TOTAL	359.3	308.2

Or in track quality bands:

Table 4.27: NR routes classification in track quality bands

Track quality band	Felixtowe route (km)	Southampton route (km)
Good	271.0	238.7

Track quality band	Felixtowe route (km)	Southampton route (km)
Satisfactory	63.8	49.5
Poor	20.3	13.8
Very poor	3.6	4.9
Super red	0.7	1.3
TOTAL	359.3	308.2

Track geometry data for DCL and EMP sections from the two UK routes are given in Appendices B1 & B2

Spanish Routes

Data about the Spanish routes is detached in different speed ranks. Different parameters were measured. The higher the line speed is, the more data is provided. Figure 4.4 shows the data, in percentage of kilometres, for all the Mediterranean Corridor.

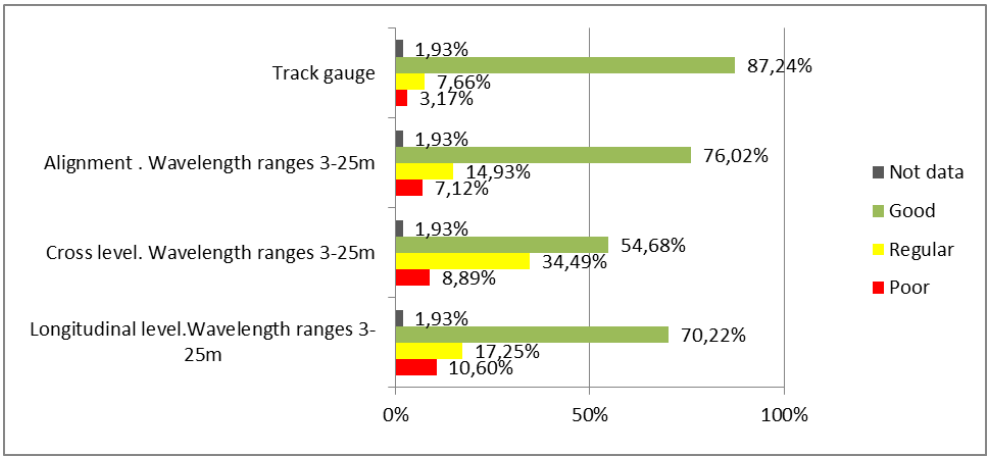


Figure 4.4: Quality ranks for the Mediterranean Corridor. Total.

Figure 4.5, Figure 4.6 and Figure 4.7 show the data divided by maximum speed track limits (200 to 220 km/h, 150-160 km/h and 60-145 km/h respectively).

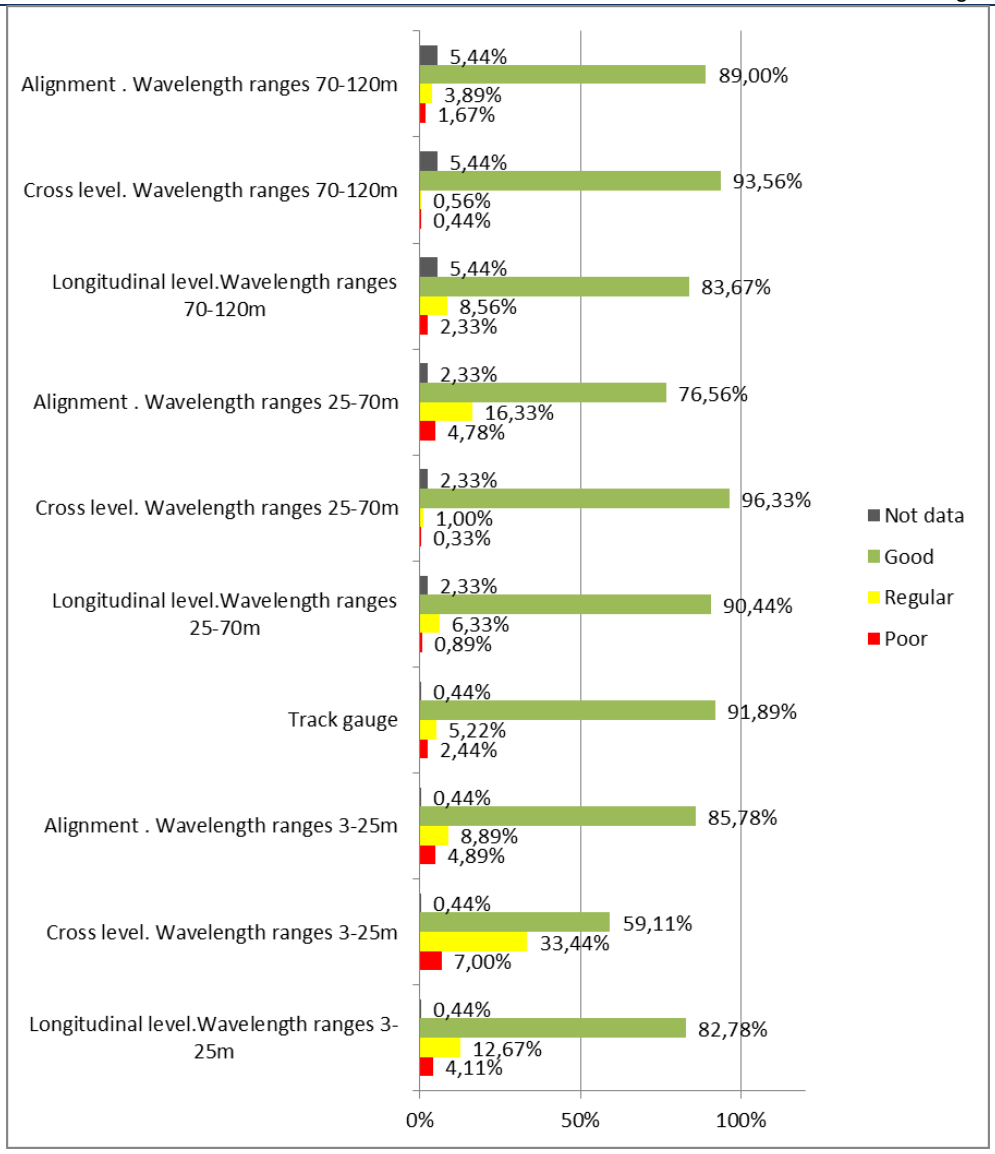


Figure 4.5: Quality ranks for the Mediterranean Corridor. 200-220 km/h.

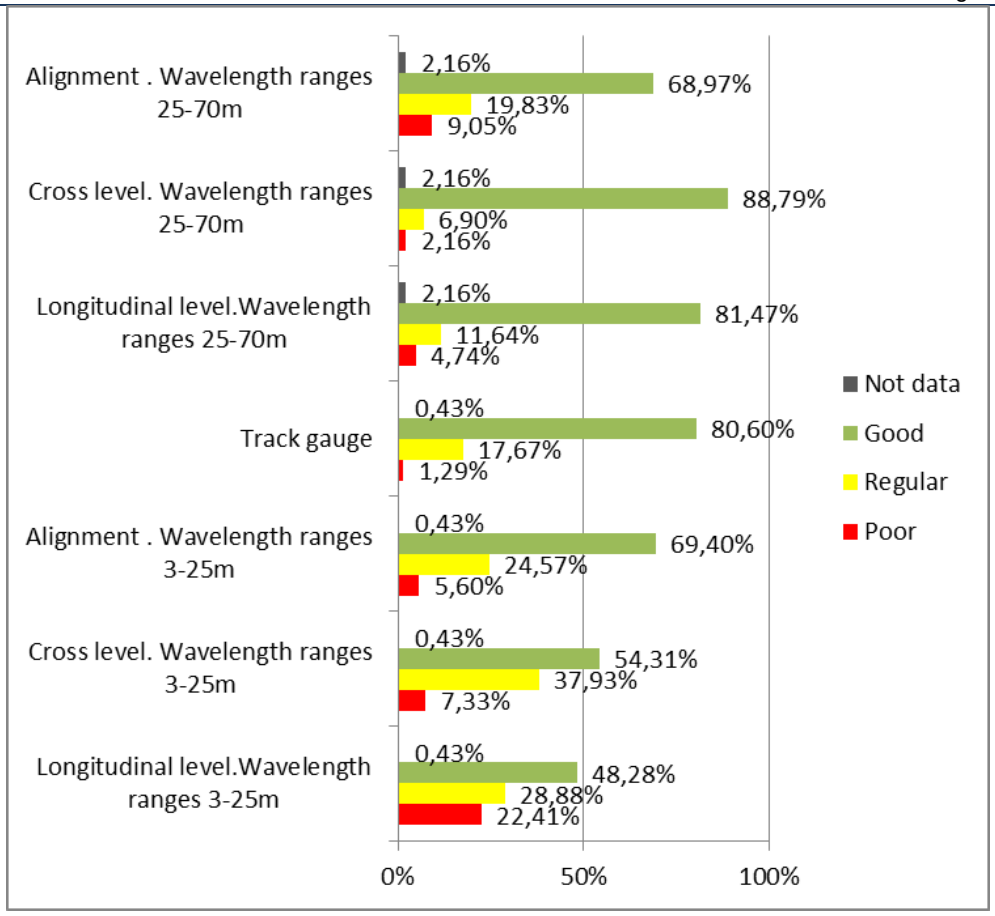


Figure 4.6: Quality ranks for the Mediterranean Corridor. 150-160 km/h.

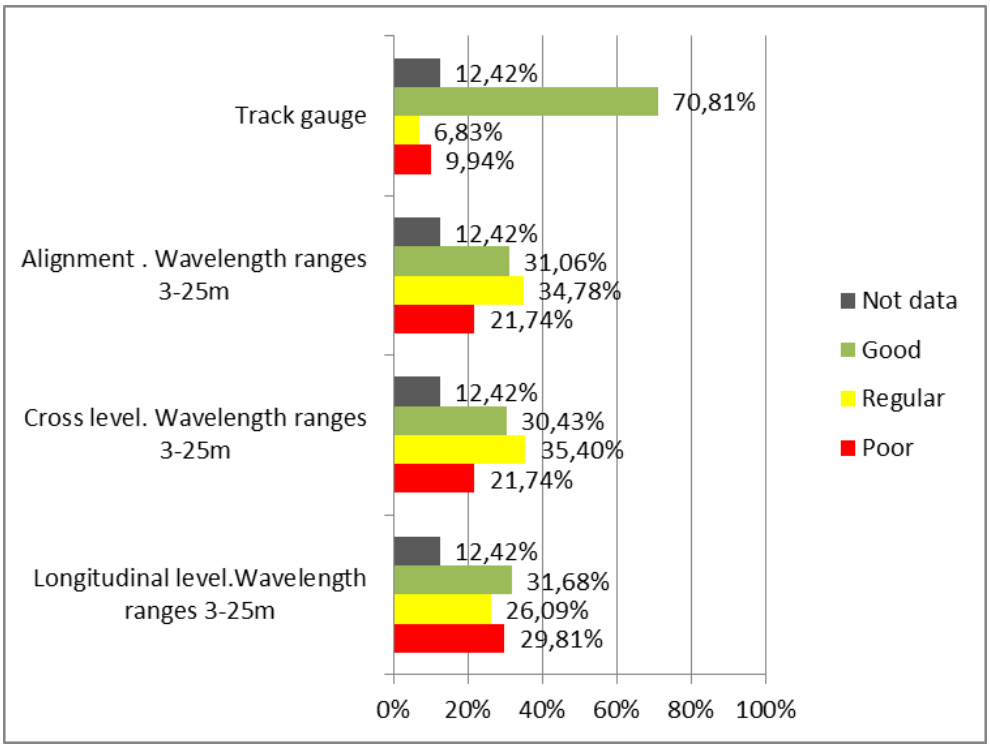


Figure 4.7: Quality ranks for the Mediterranean Corridor. 60-145 km/h.

Bulgarian Routes

The Bulgarian Route has 415 km. The value of QI (quality index) was measured by a motorailer EM-120 “Plasser&Theurer” in 2008. Figure 4.8 shows the class of distances based on geometry measurement according to project speed for 2008. Figure 4.9 shows the class of distances based on geometry measurement according maximum admissible speed for 2008.

The different classes by QI mean:

- Class "A" - new constructions or repairs must correspond to it.
- Class "B" - railway track does not need maintenance when correspond to it.
- Class "C" - railway track must correspond to it for safe operation.
- Class "over C", geometric troubles must be eliminated or speed should be decreased, used if does not corresponding to this criteria.

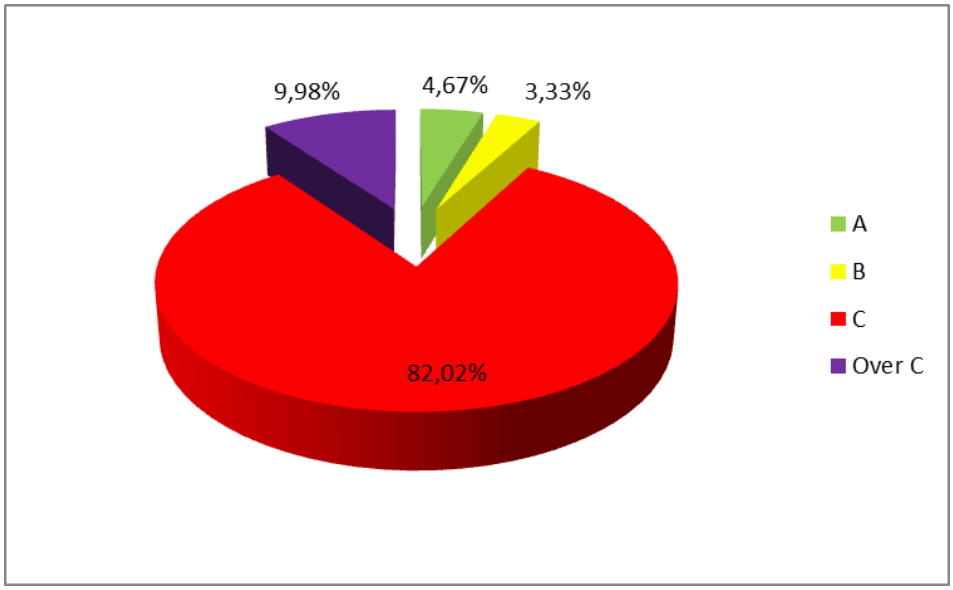


Figure 4.8: Class by QI at Project Speed.

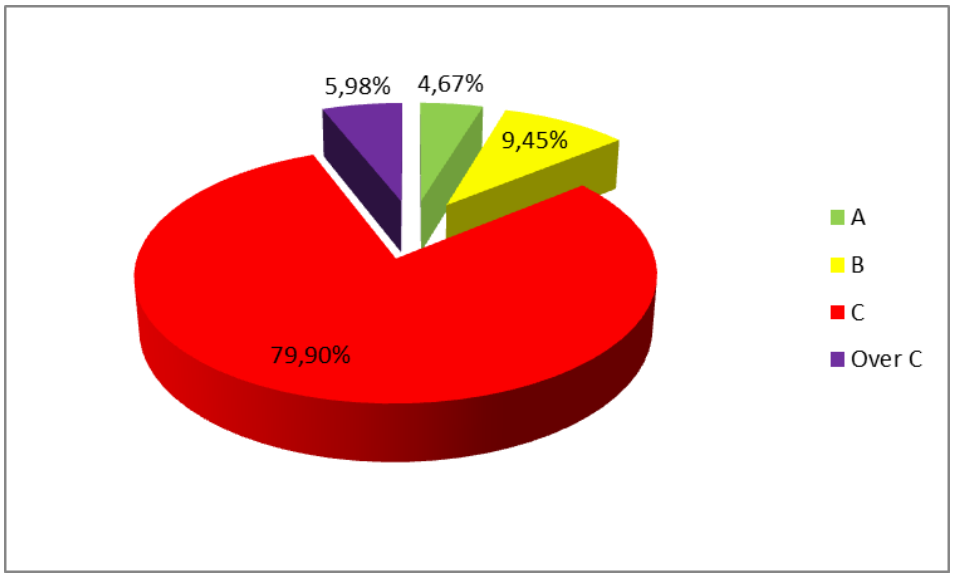


Figure 4.9 Class by QI at Maximum Admissible Speed for 2008.

Figure 4.10 shows the state of track, what means the state of station distances by track geometry according to project speed. It is divided into: good, sufficient and bad.

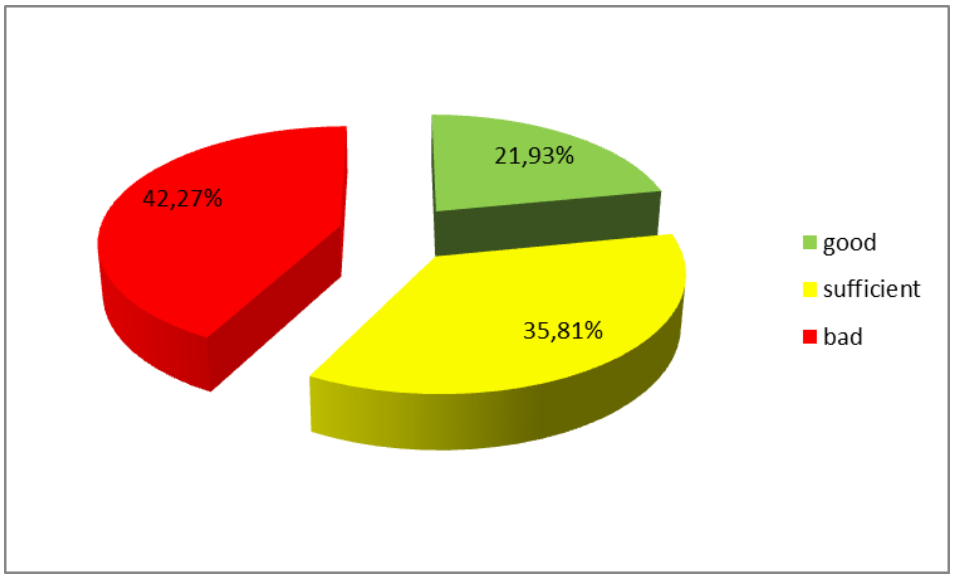


Figure 4.10 State of Track.

Figure 4.11 shows the substate of track: this means the substate of station distances by track geometry according to project and maximum admissible speeds. In this case, the "bad" and "good" states are subdivided into three sub states each – "worst", "worse", "bad"; "good", "better", "best".

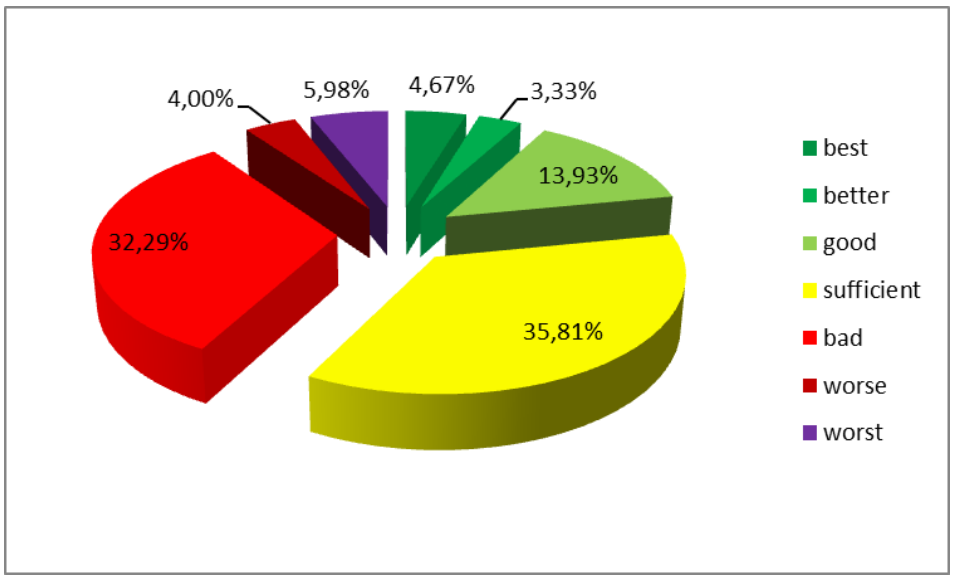


Figure 4.11 Substate of Track.

The track global quality classification in track quality bands along the complete NRIC route is given in the Table 4.28.

Table 4.28: NRIC routes classification in track quality bands

	2006		2008	
	Length	%	Length	%
a) Excellent	178.1	32.98%	117.3	21.72%
b) Good	167	30.93%	128.6	23.81%
c) Fair	158.4	29.33%	214.3	39.69%
d) Poor	36.5	6.76%	79.8	14.78%
TOTAL	540		540	

And it is represented in the graphic below in terms of percentage over the total length, with the data of 2006 in the left side and for 2008 in the right side.

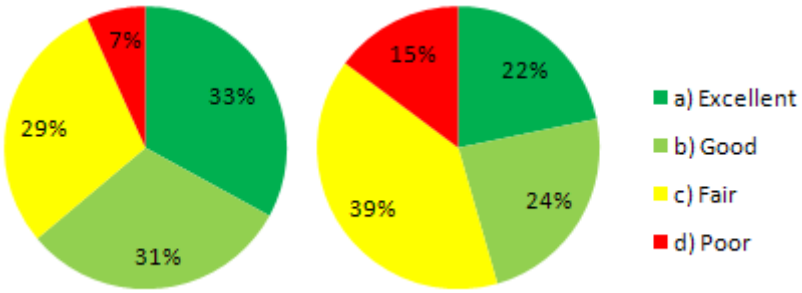


Figure 4.12 Track quality percentage over the total length of the NRIC route. Left side 2006 data, right side 2008 data.

4.2.7.2 Intervention criteria

The geometry of 18,500 miles of track is routinely recorded by Network Rail track recording vehicles at frequencies which vary according to line speed, traffic volume and tonnage. These measurements are of the vertical (rail top, both rails) and horizontal (centre line between the rails) geometry and rail-head profiles for every 200mm along the track. These outputs are filtered:

- For track at all line speeds a short-wave (35 metre) filter is employed which suppresses variations having a wavelength of 35m or more. This gives 35m vertical (top) and alignment (line) profiles.
- For track at 128km/h and above an additional pair of profiles, namely 70m top and line, are obtained using a long-wave (70 metre) filter.

For each eighth-mile (220 yards – 200m approx.) length of track a single standard deviation (SD) is calculated for the recorded variations for each of the four profiles and is expressed in mm. The Table 4.29 shows Network Rail standard targets to be achieved by 50%, 90% and 100% of track.

Table 4.29 extracted from Company Standard NR/SP/TRK/001, specifies threshold SD values, for each of the four principal Track Geometry parameters, to be achieved by 50%, 90% and 100% of the track. Eighth-mile SDs which breach the Maximum threshold on either or both parameters are referred to as "super-red."

Speed band		35m wave-length filter Parameter % targets								70m wave-length filter Parameter % targets					
QB	Speed range	Vertical top				Line alignment				Vertical top			Line alignment		
	mph	Good 50	Satis 90	Poor 100	Very poor	Good 50	Satis 90	Poor 100	Very poor	Good 50	Satis 90	Poor 100	Good 50	Satis 90	Poor 100
01	10-20	5.2	7.4	8.3	8.3	3.0	5.0	5.6	9.3	-	-	-	-	-	-
02	25-30	4.3	6.1	7.7	7.7	2.7	4.5	5.2	8.6	-	-	-	-	-	-
03	35-40	4.1	5.8	7.2	7.2	2.5	4.1	4.7	7.9	-	-	-	-	-	-
04	45-50	3.8	5.4	6.7	6.7	2.2	3.7	4.5	7.3	-	-	-	-	-	-
05	55-60	3.5	5.0	6.3	6.3	2.0	3.3	4.2	7.0	-	-	-	-	-	-
06	65-70	3.0	4.3	5.4	6.0	1.7	2.9	3.6	6.7	-	-	-	-	-	-
07	75-80	2.7	3.8	4.8	5.7	1.5	2.5	3.1	6.3	3.7	5.7	6.3	3.0	5.2	5.7
08	85-95	2.2	3.2	4.0	5.3	1.3	2.1	2.7	6.0	3.3	5.1	5.6	2.6	4.5	5.0
09	100-110	1.9	2.7	3.4	5.0	1.1	1.8	2.3	5.7	2.9	4.5	5.0	2.2	3.8	4.3
10	115-125	1.7	2.4	3.0	4.7	1.0	1.6	2.0	5.0	2.4	4.0	4.4	1.8	3.2	3.7
11	130-140	1.5	2.1	2.6	4.4	0.8	1.4	1.8	4.7	2.0	3.5	3.8	1.5	2.7	3.1

There are some discrete track faults classified as Level 2 excedences. Unlike the eighth-mile SD-based parameters discussed above these are distortions in track geometry identified for a short length of track. They include the following categories:

- Top: Individual top measurement exceeds threshold value, either rail.
- Alignment: Individual alignment measurement exceeds threshold value.
- 3m twist: Detected by an algorithm which combines the top measurements on both rails.
- Gauge: Detected by the alignment measurement system.
- Cyclic Top: Based on detection of a cyclic variation in successive top measurements on either rail. This cyclic variation can inter-react with the natural frequency of the vehicle suspension thus magnifying the effect of the track fault.

4.3 Bridges and other civil engineering structures

The railway infrastructure is the base that supports the "rail road". It is the base for both the tracks and the signalling, electrification and telecommunications installations that makes possible the circulation of trains on the network

First of all it is important to define the main civil engineering structures, in order to divide the study:

- Bridges and Viaducts
- Tunnels
- Embankment
- Other civil structures.

This section will deal exclusively with the conditions that apply to the bridges and civil engineering structures for the unique use of the rail rolling stock.

The information gathered is fairly limited because the main part of the maintenance operations related to civil structures is done by subcontract, and under special cost accountings.

4.3.1 Bridges and other civil engineering structures for the selected routes

United Kingdom routes

Table 4.30: Civil engineering structures in the United Kingdom selected routes.

Structures		Felixtowe to Nuneaton	Southampton to Nuneaton
Cavil's (km)	Station	5.3 km	6.5 km
	Tunnel	0.1 km	1.2 km
	Cuttings	93 km	99 km
	Embankments	165 km	120 km
Bridges	Underline	280	335
	Pipe	95	100
	Viaduct	22	32
	Over line	220	220
	Footbridge	53	72
	Intersection	4	5

Spanish routes

Currently, the railway network is made up of 17,694 km. of track, 1,274 tunnels with a total length of 667 km. and 6,618 bridges of 158 km., as well as a large number of cuttings and embankments, due to the complicated Spanish topography.

Table 4.31 contains the data for the selected section of the Mediterranean corridor.

Table 4.31: Civil engineering structures in the Spanish selected routes

Structures	Valencia- Sagunto	Sagunto- Villareal	Villareal- Tarragona
Tunnels	2.8 km	0 km	9km
Bridges	1 km	1.2 km	7km
Over line	20	28	61
Under line	6	31	138

4.3.2 Intervention criteria

The bridges and tunnels are important points of the railway network, so maintenance requires special attention. This requires carrying out technical inspections on a regular basis and if necessary, repairs, in order to avoid risks that may cause accidents and damage to persons or the disruption of the service. Also is necessary keep them in proper use, in order to minimize the costs associated with conservation.

Maintenance of the embankments and cuttings along the railway route is fundamental since, depending on the area, there may be shifts in the earth, landslides, etc. that could cause interruptions to the train traffic if they are not appropriately contained, drained and reforested. In some cases this maintenance requires the repositioning of embankments.

The inspection and intervention criteria for bridges and other structures, should pay attention to:

- Obvious new cracks or growth of existing cracks
- Signs of loose, displaced or fallen material
- Vandalism or accidental damage
- Signs of subsidence or ground movement
- Flooding and signs of obstructions against upstream faces
- Signs of misuse or significant change in the nature or extent of use in cold weather – icicles causing risk to traffic
- Signs of impact with platforms and structures by rolling stock
- Missing or damaged fixed track position data or datum plates.

And for cutting and embankment slopes:

- Signs of loose, displaced or fallen material (particularly after severe frost, heavy rainfall or thaw)
- Signs of cracking (particularly in clay slopes during very dry weather)
- Signs of movement where large trees are present that may fall onto the track.

Each Infrastructure Manager, or more over, each country, has standards and rules in order to keep in control the maintenance of these vital structures. Most of them are based in the UIC 776. 702 and 704.

For the Spanish case, bridge maintenance includes:

- The inspection of 250 bridges per year.
- 25 to 30 annual load tests per year.

By means of these tests ADIF can determine the actions needed, from the application of paint and small repairs to replacements of elements whose load capacity is weakened, in order to ensure appropriate levels of quality, safety and reliability.

Also, action is taken on 30 or 35 tunnels annually, repairing areas that need it. Artificial tunnels are built to protect the infrastructure from the aggressive environment and thus ensure the safety of train circulation.

4.3.3 Life cycle cost

Some specific data about Life Cycle Cost extracted from Baumgartner [4.8]:

- Investments
    - Bare tunnels :
        - Single track 20 (10 to 50) 10^6 EUR/km of track
        - Double track 30 (20 to 70) 10^6 EUR/km of track
    - Bridges and viaducts :
        - short span and/or easy foundation 15 (10 to 20) 10^6 EUR/km of track
        - long span and/or difficult foundation 30 (20 to 50) 10^6 EUR/km of track
    - Crossing of a railway line with a road : [106 EUR/unit]
        - road overpass 3 (2 to 7) 10^6 EUR/km of track
        - road underpass 6 (3 to 10) 10^6 EUR/km of track
- Infrastructure economic life [years]
    - tunnels 100 (50 to 100)
    - steel bridges 50 (50 to 80)
    - concrete bridges 50 (50 to 100)
    - underpasses and overpasses 50 (50 to 100)
- Maintenance cost

  Yearly maintenance costs, long term average (economic life or life cycle), at the prices applicable as of the date of commissioning of the equipment (yearly percentage of the investment):
    - Embankments, cuttings 0.5% (0 to 1%)
    - Drainage structures 2% (1 to 3%)
    - Walls 0.5% (0.1 to 1.5%)

- Steel bridges 1.5% (1 to 2%)
- Concrete bridges 1% (0.1 to 2%)
- Tunnels 0.5% (0.1 to 2%).

Also some data has been gathered about infrastructure maintenance on the ADIF network.

Following the Spanish standard ITPF 05 (Standard about the specific technical inspection in railways bridges.) the periodicity and cost of the main maintenance operations in railways bridges are contained in Table 4.32.

Table 4.32: Periodicity and cost of the main maintenance operations in railways bridges. Source ITPF 05.

	Periodicity	**Average cost**
Load test	Commissioning 15 years for screw connections or 30 years for welded joints.	30,000 €
Main inspection	Commissioning 15 years	2,000 €
Basic inspection	Annual	Not specific cost
Paint works	10 years (only for steel bridges)	42,000€
(*) It could be less time if the infrastructure Manager consider it, or after accidents, earthquake, etc.		

4.3.4 Related standards

UK internal standards:

- BS 5400: Steel, concrete and composite bridges. British Standard Institution.
- NR/GN/CIV/203, 2007 Evaluations and assessment of earthworks
- NR/L1/CIV/032: Managing existing structures
- NR/L2/CIV/086 2009 Management of existing earthworks
- GERT8006 Iss 2 September 2010 (A) Assessment of Compatibility of Rail Vehicle Weights and Underline Bridges
- GC/RT/5112, 2008 Rail traffic loading requirements for design of railway structures

Spanish internal standards:

- ITPF 05. Instrucción sobre las inspecciones técnicas en los puentes de ferrocarril, Ministerio de Fomento (Ministry of Public Works), 2007, Spain Government.
- IAPF 07. Instrucción sobre las acciones a considerar en el proyecto de puentes de ferrocarril. Ministerio de Fomento (Ministry of Public Works), 2007, Spain Government.

4.4 References Chapter 4

4.1. Office for Research and Experiments, ORE, 1970. Stresses in Rails, the Ballast and the Formation Resulting from traffic Loads. Question D71, Report No. 10, Vols. 1 and 2. UIC.

4.2. European standard EN 13674-1, February 2011.

4.3. UIC fiche 712R Rail defects, 4th edition, January 2002

4.4. Prices and costs in the railway sector J.P. Baumgartner. January 2001. Laboratoire d'Intermodalité des Transports Et de Planification. ENAC – Iinter. école polytechnique fédérale de Lausanne

4.5. Contact Lines for Electric Railways, Kiessling et al. Siemens, Second Edition 2009

4.6. Stalder, O. (2001) UIC - International benchmarking of track costs. Presentation of SBB AG,Bern.

4.7. López Pita, Andrés. Infraestructuras ferroviarias. Ediciones UPC, 1ª edición 2006.

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5. TRACK FORCES AND ENERGY DISSIPATION

5.1 Introduction

Forces and friction energy dissipation are very decisive for system performance. In this Section we investigate this further. A track force model developed by Andersson and Öberg [5.1] is presented and then used to investigate the influence of various parameters on the track forces. Finally the energy dissipation is analyzed by means of a multibody dynamic simulation.

5.2 General model of vertical dynamic wheel load

The axle load is a most decisive parameter for track deterioration. Dynamic wheel-rail forces are often processed by a 20 Hz low-pass filter, as prescribed in EN 14363. However, these forces may have large dynamic contributions with frequency content above 20 Hz (Wrang [5.2]; Andersson et al. [5.3]; Chaar and Berg [5.4] and [5.5]). The magnitudes of these dynamic contributions are approximately proportional to speed and are also dependent on the unsprung mass of the vehicle for stochastic track imperfections. The force magnitudes usually increase with increasing speed. The periodic 'high-frequency' content reflects the variation of track flexibility due to the discrete sleeper support of the rails, but the higher peak forces (being most decisive for track deterioration) usually reflects discrete track geometric imperfections. Therefore it is proposed to apply a low-pass filter at 90 Hz or just above the highest expected sleeper passing frequency. The high-frequency dynamic peaks determining the 99.85 % percentile usually depend on geometric and/or elastic discontinuities in the track. A model for the P2-force which uses a speed and unsprung mass dependence, which is approximately relevant also for continuously welded rails, is adopted.

Data from track force measurements on different rail vehicles have been used to calibrate the general model of vertical dynamic load. The vehicles are a Swedish standard Rc-locomotive, X2 (X 2000) high-speed power unit, Öresund train unit (OTU) and several loaded freight wagons with standard running gear. Especially the OTU vehicle has been subject to extensive testing and evaluation.

However, additional validation of the general model with unofficial but more recent proprietary test data, excluding the high-frequency contribution, has been performed. Track force measurements for two additional types of motor coaches, as well as for two additional types of freight wagons with bogies and single axle running gear respectively, have been studied.

The model accounts for track irregularities by a speed-dependent coefficient. Figure 5.1 and Figure 5.2 show the forces from measurements and calculations for the four vehicle types being the basis of the model. The total wheel loads measured correspond with high accuracy to calculated results. For the vehicle types being the basis of the model, the measured dynamic forces are low-pass filtered at 90 Hz.

The total vertical wheel load can be written:

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

where the quasi-static wheel load contribution is determined according to

$$|Q_c| = \frac{P_r}{2\,b_0} \times \left(\frac{|I|}{2000\,b_0} \times h + y\right) \times g$$

where b_0 depends on track gauge. For a standard track gauge of 1435 mm, b_0 equals 0.75 m. N.B! The cant deficiency I has to be given in (mm), and all other geometric measures in (m).

$$Q_{d20Hz} = 0.80 \times K_v \times K_s \times P \times (V + 760)$$
$$Q_{d\,hf} = 1.32 \times K_s \times V \times \sqrt{m_{u,w}}$$

where

K_v = 0.20 for passenger vehicles and motor coaches.

0.36 for locomotives and freight wagons (which regularly have a stiffer suspension than the previous vehicle types).

The value could differ from these if the vehicle is non-typical, if having 'track friendly' bogies etc. In these cases the actual forces may be used.

K_s = 0.0036 on tracks for speeds above 120 km/h.

0.0042 on tracks for speeds 120 km/h and below. (For freight trains in Sweden a mean value of K_s = 0.0039 has been used; they are running on both types of track.)

Figure 5.1 below summarizes the results of measurements and model calculations of total wheel loads for the vehicle types with known dynamic 90 Hz low-pass filtered data.

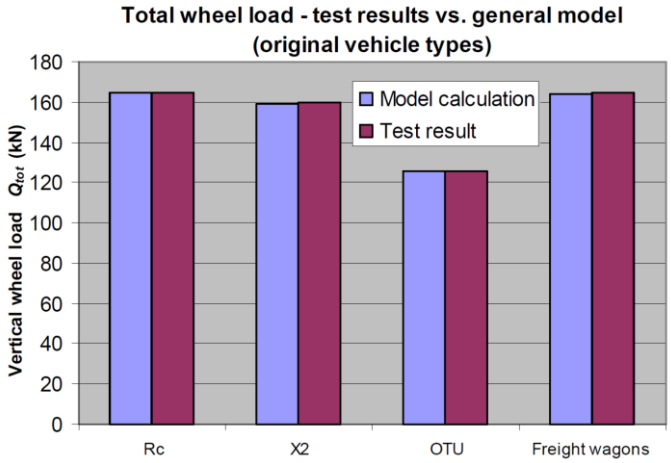


Figure 5.1: Comparison of wheel load measurements and model calculations (kN). The vertical dynamic wheel load is low-pass filtered at 90 Hz.

Figure 5.2 below summarizes the results of measurements and model calculations of dynamic wheel loads for the additional vehicle types with known dynamic 20 Hz low-pass filtered data. Due to proprietary test data the vehicle types are denoted 'A' and 'B' within each class.

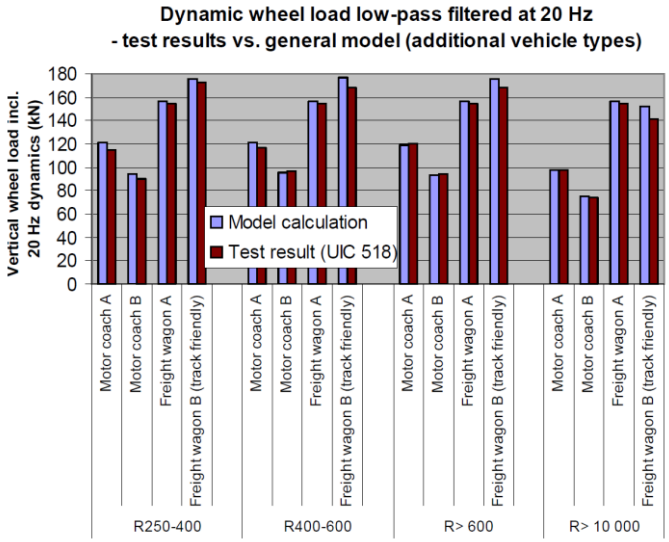


Figure 5.2: Comparison of wheel load measurements and model calculations of additional vehicle types (kN). The vertical dynamic wheel load is low-pass filtered at 20 Hz

To conclude, the general model satisfies test results from 7 different vehicle types within a few percent. The track friendly freight wagon (8th vehicle type) gives less dynamic forces than predicted by the model (some 5%). This can however be understood by its 'track friendliness'.

Both the static axle load and the unsprung mass per wheel are proposed to be evaluated as a cubic mean value for the whole vehicle if there are large differences between axles, say more than 20 %. The reason is that the cubic mean value is approximately representative for the deterioration due to vertical forces as the latter is determined as power three of the loads. This is to be applied on a vehicle level rather than on a train level.

$$P_{cubic\ mean} = \sqrt[3]{\frac{\sum_1^{n_v} |P|_i^3}{n_v}}$$

where

$P_{cubic\ mean}$ = cubic mean value of axle load (or analogously of unsprung mass)

P_i = axle load (or unsprung mass) of axle i

n_v = number of axles on the vehicle

5.3 Influence of parameters

Operational, vehicle and track parameters in the model presented in Section 5.2 are varied in order to show the influence on vertical dynamic wheel load. The parameter variation is done around typical values for freight wagons shown in table below.

Table5.1: Model parameters for freight wagons.

Parameter [unit]	Value	Notes
v [km/h]	120	Speed
I [mm]	100	Cant deficiency
y [m]	0.04	Lateral displacement of centre of gravity
h [m]	1.6	Height of centre of gravity
$m_{u,v}$ [kg]	750	Unsuspended weight
K_v [-]	0.36	Vehicle coefficient
K_s [-]	0.0042	Dynamic coefficient
P [tonnes]	22.5	Axleload

The contribution from each component to the total force is shown in the table below.

Table5.2: Track force contributions.

Q_i	Value [kN]	Q_i / Q_{tot}
Q_r	110.4	0.62
Q_c	21.6	0.12
Q_{d20Hz}	29.9	0.17
$Q_{d,hf}$	16.6	0.09
Q_{tot}	178.4	1.00

Axelload shown in Figure 5.3 is the most decisive parameter for total wheel force. Raising axelload with 10% increases the total wheel load with 9%.

Higher speed increases trackforces with 2% per 20 km/h. Here however, it must be pointed out that standard running gear for freight wagons in Europe, in many operational conditions have reached their limit [5.1]. Hence, increasing speed may lead to instability with substantially higher forces.

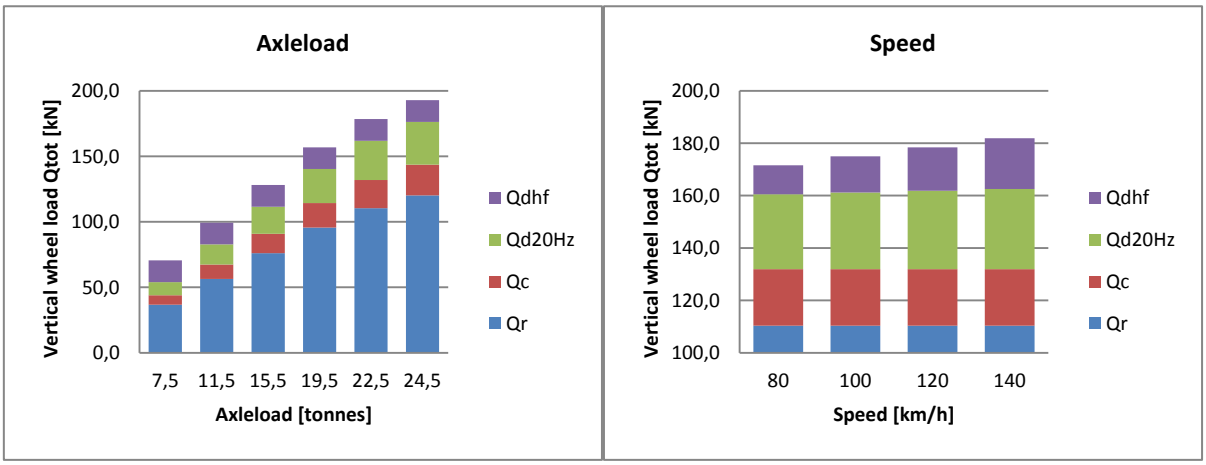


Figure 5.3: Influence of axleload and speed.

Parameter K_v=0.2 is representative for passenger vehicles and motor coaches. Figure 5.4 indicates the potential for reduction of track forces if the suspension design for freight wagons can be enhanced. Influence of the unsuspended mass is shown in the same figure. A weight reduction of the unsuspended mass of 10% reduces track forces by 0.5%. The reason for the low impact is the relatively low speed and the low contribution of the high frequency contribution to the total force.

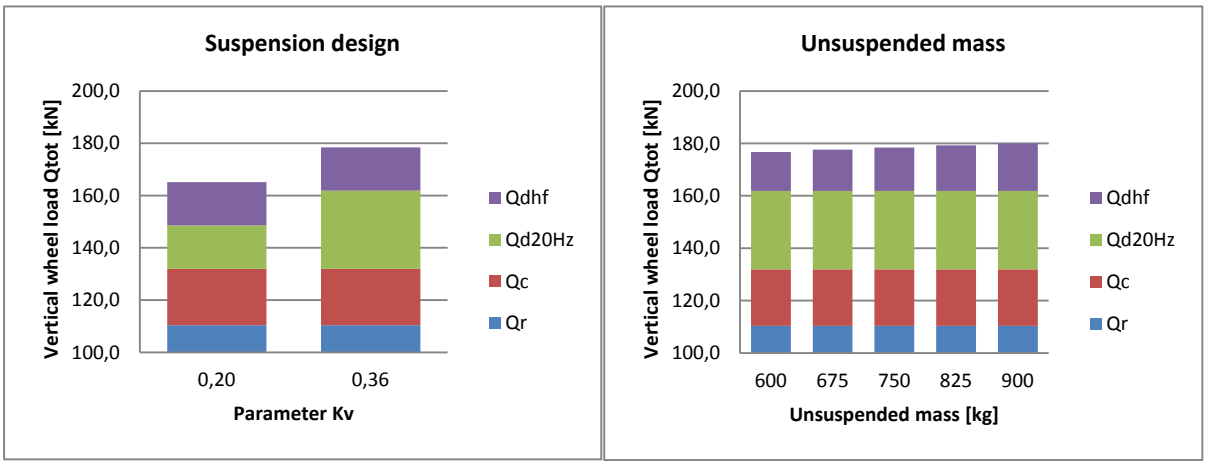


Figure 5.4: Influence of suspension design and unsuspended mass.

Influence of track quality is shown in Figure 5.5. K_s=0.042 is a representative value for tracks operated at speeds up to 120 km/h and the lower value for tracks operated at speeds above 120 km/h, cf. Table 4.24. The difference between these two cases is 4%.

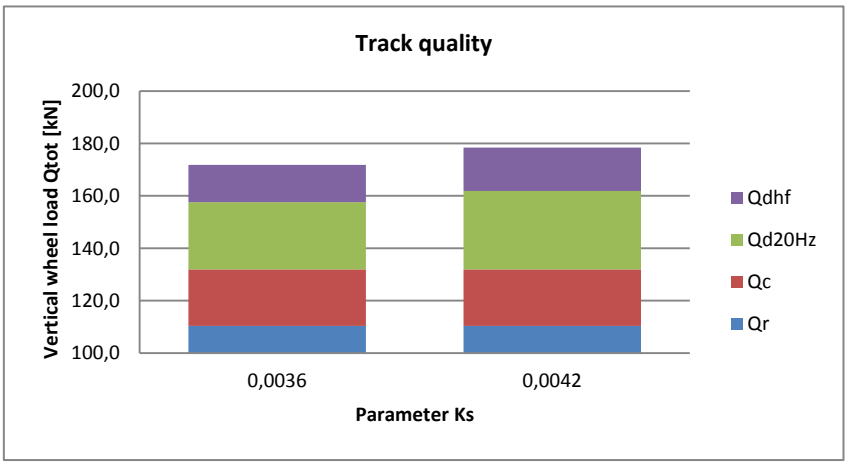


Figure 5.5: Influence of track quality.

5.4 Limit values in standards

For reasons of maintenance cost it is necessary to limit the lateral and vertical contact forces between wheel and rail. Limit values for track forces for acceptance test of rail vehicles are given in EN 14363. Allowable vertical dynamic force, low pass filtered at 20 Hz, depends on speed, V_{adm} and static wheel force, Q_0.

Speed	Limit value	Note
V_{adm} <= 100 km/h	90 kN + Q_0 <= 210 kN	225 kN < $2Q_0$ <= 250 kN
V_{adm} <= 160 km/h	90 kN + Q_0 <= 200 kN	$2Q_0$ <= 225 kN

The mean lateral guiding force, usually called the quasi-static guiding force, Y_{qst}, must be lower than 60 kN. These limit values assume a rail weight of more than 46 kg/m with a minimum strength of 700 N/mm^2.

Eurocodes are implemented in many countries building legislation and are thereby mandatory. In Figure 5.6 one of the load models, LM 71, used for designing railway bridges, is shown. The characteristic loads, Q_{vk}, and q_{vk} shall be multiplied with a factor α to obtain classified loads. α is a so called Nationally Determined Parameter, NDP, and shall be chosen between 0.75 and 1.46. It is recommended in the standard to use $\alpha \geq 1.00$ on international lines. Sweden uses 1.46 for heavy haul routes and 1.33 for the rest of the network, hence, Q_{vk}, is 332 kN respectively 365 kN [5.8].

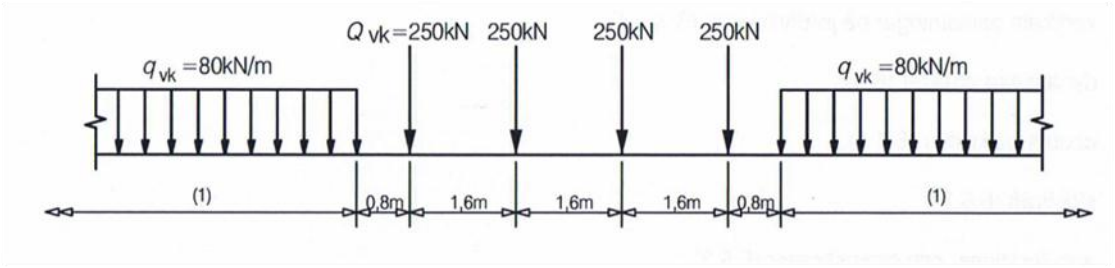


Figure 5.6: Forces on bridges. Load model LM 71 [5.7].

5.5 Energy dissipation

The dissipated energy in the wheel-rail contact is considered to be a good determinator for the overall volume of wear and partly of rolling contact fatigue, RCF. Energy dissipation includes the influence of many different factors such as wheel-rail geometry, wheel-rail forces, creep and friction.

The three types of European standard freight wagon running gear are shown in Figure 5.7.

Energy dissipation for this running gear is shown in Figure 5.8. A considerably difference between the Y25 bogie and the link suspension types can be observed.

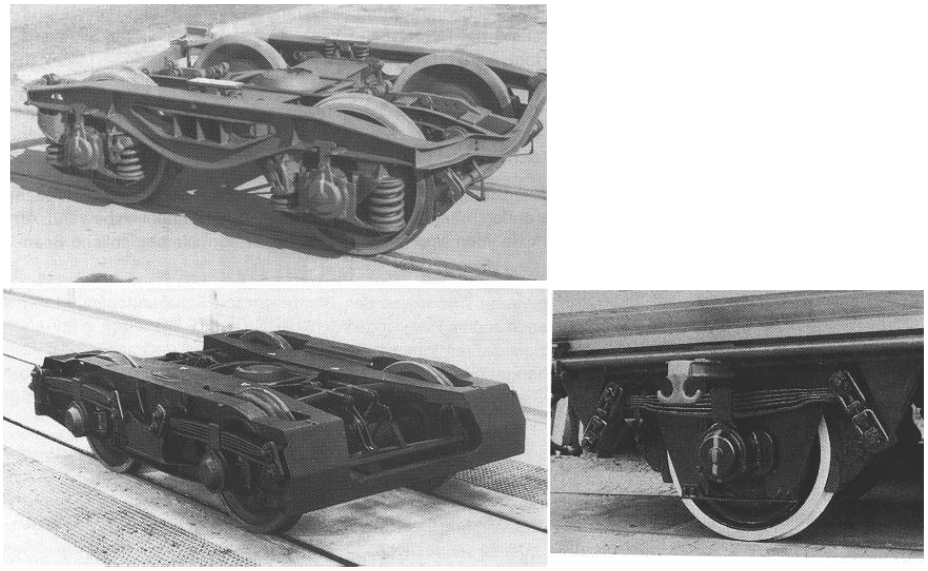


Figure 5.7: Freight wagon running gear. Y25 bogie. Link suspension bogie. UIC double link suspension.

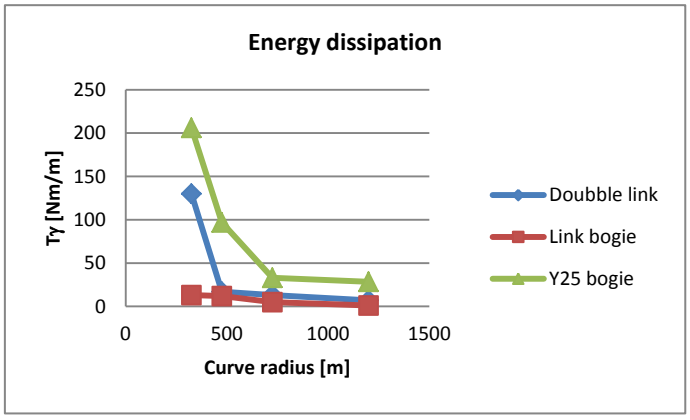


Figure 5.8: Energy dissipation for freight wagon running gear [5.6].

Simulations are performed in program system GENSYS [5.9]. A model of a BoBo vehicle is used. Curve radius, cant deficiency, friction and wheel/rail profiles are changed. Resulting energy dissipation on leading outer is shown in Figure 5.9. As long as the contact conditions are constant is the relation between guiding force and wear relatively linear. Limit value for lateral guiding force when testing new vehicles is 60 kN, hence, from Figure 5.9 we estimate max energy dissipation til 1000-1200 Nm/m.

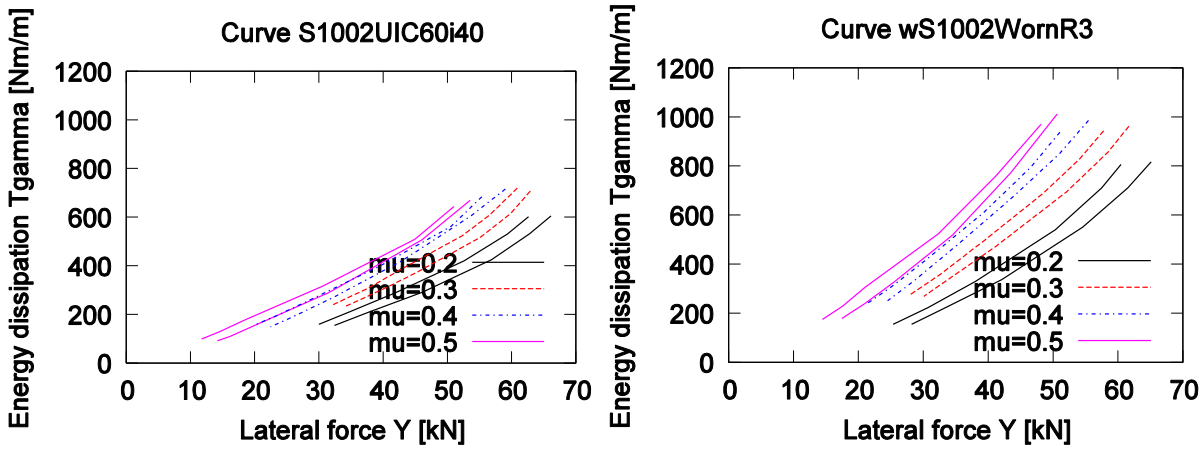


Figure 5.9: Energy dissipation for a BoBo vehicle.

5.6 Discussion

This Section address track forces and energy dissipation, i.e. key elements with respect to system performance and maintenance cost. The axleload is the most decisive parameter for the total wheel force, however, with an enhanced suspension design SUSTRAIL can reach a substantial reduction of the track forces. The curving performance for the link suspension types of running gear is good and shall be target for the new system.

5.7 References Chapter 5

5.1. Öberg J. et. al.:"Track access charging with respect to vehicle characteristics", Banverket, LA-BAN 2007/31, 2007.

5.2. Wrang M.: "OTU, Analysis of data from vehicle dynamics tests", MiW Konsult AB, 2006.

5.3. Andersson E. et. al.: "Allowing higher speeds on existing tracks – design considerations of the X2000 train for Swedish State Railways", Proc.IMechE, Vol 209, pp 93-104, 1995.

5.4. Chaar N. And Berg M.: "Vehicl-track dynamic simulations of a locomotive considering wheelset structural flexibility and comparison with measurements", Proc.IMechE Part F, Journal of rail and rapid transit, Vol 219, pp 225-238, 2005.

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5.7. CEN: "European Committee for Standardisation, "Eurocode 1: Actions on structures – Part 2: Traffic load on bridges", Swedish Standard SS EN 1991-2, SIS, 2003.

5.8. Boverket: "National annex for Eurocodes", BFS-2011-10-EK58", Boverket, 2011.

5.9. Persson I.: "Using GENSYS.1203", On-line manual, www.gensys.se, 2012.

6. CURRENT PERFORMANCE FOR TRACK COMPONENTS

6.1 Introduction

Sub-Task 2.3.5 of SUSTRAIL is described in the 'Work Package Description'. It is to:

"Define current performance (cyclic loading and overload limits) for track components (specifically sleepers, fasteners, joints and pads) to establish the baseline under controlled conditions to which new/replacement technologies can be compared. Do this through gathering manufacturer data and conduct modelling where necessary."

However, the commercial imperatives of business mean that the manufacturers of these products do not, apart from in general terms or for regulatory compliance, advertise the limits of their products. They address the concerns of their customers by investigating problems that arise in service and prefer to maintain control over developments to ensure that these are covered by their intellectual property rights.

In this Section we collect data on the duty requirements and research publications related to the specific track components. First, in the remainder of this introduction, we give an overview of the components and the forces that they experience. Subsequent sections consider the individual components in more detail.

6.1.1 Sleepers, fasteners, and pads

The specified track components (apart from joints) feature in the load path that supports the rail on the ballast (see Figure 6.1 and Figure 3.14). As such they behave as part of the track support system that also includes the ballast, substrate, and the earth underneath. The primary support function is provided by the sleeper; without it the rail would sink into the ballast. The rail has to additionally be prevented from:

- moving laterally
- rotating about its longitudinal axis (rolling)
- moving longitudinally

The first two would result from the curving forces generated by a train whilst the latter would be caused by braking and traction forces. Lateral movement of the track from its design position would introduce the danger of striking objects adjacent to the track; rolling could lead to a derailment; and track that is not adequately restrained laterally and longitudinal could buckle when it expands in warm weather.

The simplest means of proving the necessary restraint is to use spikes driven into wooden sleepers that overlap the foot of the rail. The additional components and extra complexity shown in Figure 6.1 have been introduced to

- extend the life of the sleeper; replacing sleepers is an expensive operation (see Section 4.2.2.3)
- accommodate concrete sleepers (these are used throughout the Spanish route being studied in SustRail, and for the majority of the UK and Bulgarian route used in the project)
- reduce maintenance costs by making it easy to release rail
- reduce the sound and vibration caused by the passage of a train

- improve the restraint

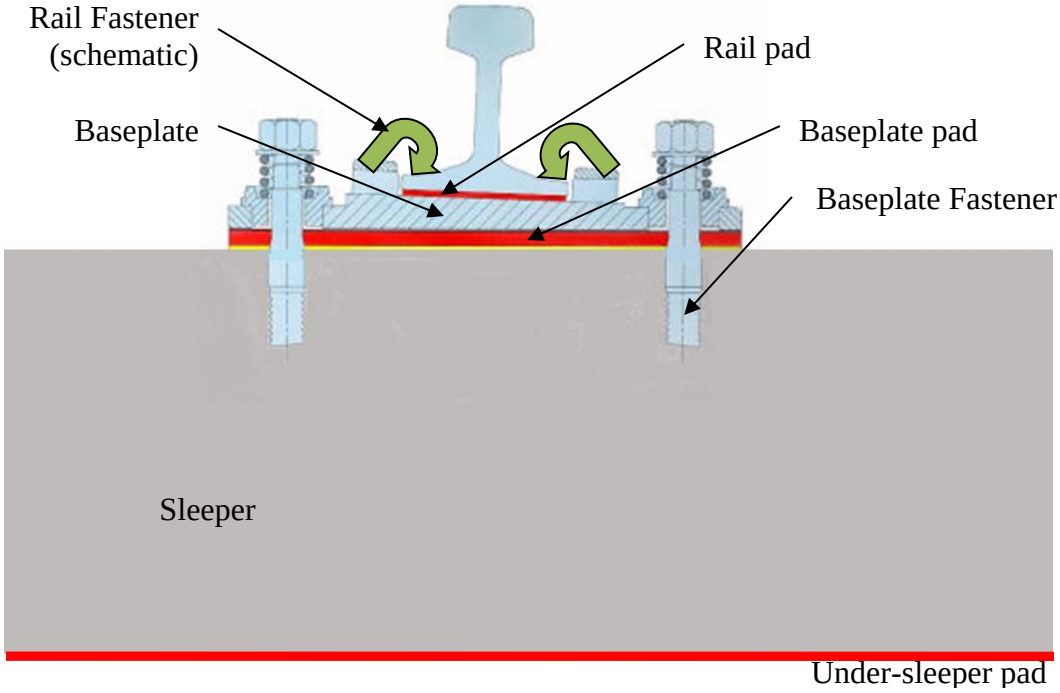


Figure 6.1: Track Components (Based on Image From [6.1])

As these components are part of the track support system their properties are inter-related so that, for example a failed pad can lead to a sleeper failing, or a failed sleeper can lead to a fastener failing. For this reason it is difficult to consider them separately.

6.1.2 Joints

The other component that is considered here is the rail joint. Nearly all of the track on the SustRail routes consists of continuously welded rail (CWR); the Bulgarian jointed track is being replaced by welded track. The rail joints that are considered are thus not those associated with jointed track but insulated block joints (IBJ's). These are used to provide electrically isolated sections of track; signalling systems can then determine the section that a train is in by measuring the electrical resistance between the two rails (there will a lower resistance when a train is in a section due to currents passing along its axles). A typical IBJ is shown in Figure 6.2. The "fishplates" (one on each side of the rails) are attached to the rails by six bolts (three in each piece of rail); lightly loaded tracks (but not on Network Rail infrastructure) may have only four bolts. The fishplates strengthen the joint.

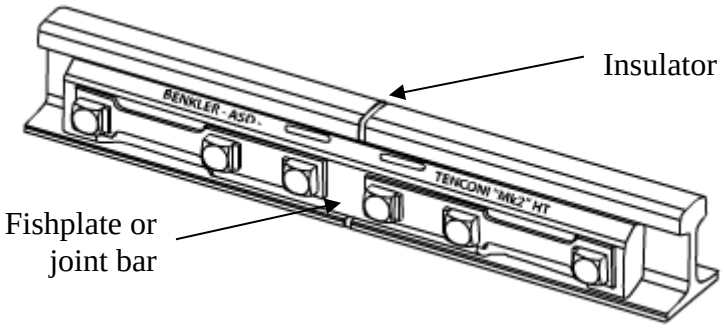


Figure 6.2: Rail Joint (Image From [6.2])

6.1.3 Forces

The forces that are experienced by the track are generated by the traffic that uses it. The components that are fitted on the SustRail routes have been chosen to cope with the planned traffic.

Network Rail (NR) has a requirement that track systems (unless they experience a very high annual loading) have a design life of 60 years [6.3] and that "*The track system shall be designed to have performance characteristics capable of sustaining the following forces:*

a) a maximum static axle load of 250 kN (25.5 tonnes);

b) a vertical dynamic force, generated by the static wheel load and the low frequency dynamic forces P2[1]*, of 350 kN per wheel and an occasional isolated vertical load of 500 kN per wheel;*

c) a lateral force generated by a train of 100 kN over a length of 2 m;

d) *be capable of resisting thermal forces which may be expected to occur over a rail temperature range of -14°C to +53°C, without distortion. Any track feature (e.g. insulated joint, S&C unit) to be incorporated into CWR shall therefore be capable of withstanding a longitudinal thermal tensile force in each rail of 700 kN (71 tonnes) and a longitudinal thermal compressive force in each rail of 620 kN (63 tonnes).*"

This standard does not specify which calculations are to be undertaken to prove that the design is adequate and we have not located any such calculation. However, during one month of Gotcha monitoring at Banbury the maximum recorded wheel force was 557kN with 25 trains (of the 3,125) recording a peak wheel force of over 350kN[2]. This suggests that the vertical dynamic force requirement is not conservative.

Data in [6.9] shows theoretical values of the P2 force of more than 400kN and that the highest values of this force are associated with locomotives and with vehicles travelling faster than 160kph. The highest value of this force for freight wagons travelling at speeds up to 120kph was 220kN. In this context, changing the axle load or speed of freight wagons (within the

[1] The P2 force is defined in many texts (e.g. [6.6.9]). It is the second of the two transient force peaks that are predicted to occur (using a simplified dynamic analysis) when a wheel travels across a dip in a rail. The "low frequency" refers to it occurring after the first peak (which is referred to as "P1") and it is associated with the spring-mass system in which the wheelset and a portion of the rail are supported by a "spring" defined by the stiffness of the substructure (pads/sleepers/ballast). It is odd that a value (350kN) is specified for a force that is a function of the properties of the system.

[2] There was some reservation about the calibration of the system for such high forces [6.100]; a Wheelchex system in a comparable location (Eastree) did not record any peak forces larger than 331kN. It may be that the systems' response to short duration events is different due to different sampling rates or filtering.

limits being considered by SustRail) would not affect the track system's compliance with the NR requirement.

The European bridge standard [6.4] includes the same static axle load of 250kN, with dynamic factors that depend on characteristics of the bridge, but do not result in values that are as large as those in the NR standard. This European standard also includes values for the braking and traction forces that are neglected in the NR standard [6.3] (but design of bridges for NR does include similar forces):

- Traction: F=33.L, F≤1000 (i.e. 33kN/m)
- Braking: F=20.L, F≤6000 (i.e. 20kN/m)

where F is force in kN and L is train length in metres (in the standard [6.4] this is the length of the relevant part of the bridge). The British "Track System Requirements" [6.5] requires that the track system can be capable of sustaining 1200kN along the rail to allow for train acceleration and braking, and thermal forces.

There are many suggested calculations for the vertical forces appropriate to use in the design of track components; see [6.6] for a review of these and [6.7] for a detailed exposition of equations used in design up to 1980. Some of these calculations include the properties of the track (e.g. [6.8]) so may need to be used iteratively if properties vary with load; see also [6.9].

6.2 Sleepers

6.2.1 Load Distribution

The load experienced by any one sleeper will be less than that applied to the rail by the wheel. This is because the rail transfers some of the load to adjoining sleepers. The amount that is transferred will depend on the relative values of the rail's bending stiffness and the stiffness of its supporting structure (sleeper, pads, ballast, etc.) and on the sleeper spacing. If the support is very soft compared to the rail stiffness the load will be shared between more sleepers, but if the rail is relatively flexible (e.g. adjacent to a joint) more load will be supported by the closest sleeper.

Similarly the stiffness of the support provided by the ballast will influence the stresses in the sleeper. Here the issue is the distribution of support along the underside of the sleeper. If the ballast has been removed from under the ends of a sleeper it will experience high tensile stresses at the top of its centre section ("hogging"), while if there is inadequate support under the section of a sleeper directly under the rail ("rail seat") it will experience high tensile stress at the underside of this section. The beneficial effects of under-sleeper pads are discussed in Section 6.4.

The load transfer effects discussed above are illustrated in Figure 6.3.

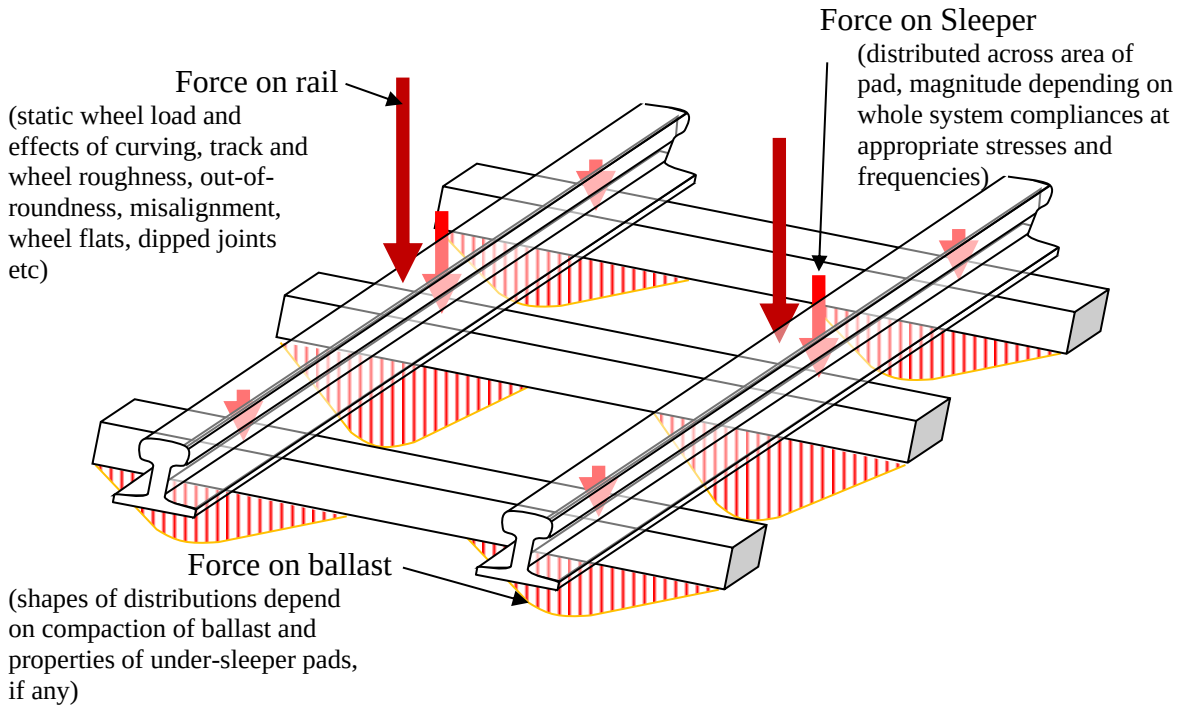


Figure 6.3: Track Section Illustrating Vertical Forces

6.2.2 Wooden Sleepers

Wooden sleepers continue to be used (on the SustRail routes, see Section 4.2.2, they feature in Bulgaria and Britain). They are more flexible than concrete ones and do not crack in the same way so need fewer absorbent pads. Their life is limited by the effects of decay so the quality of preservatives is important. Under high loads the rail can "dig in" to the seat area, so a baseplate is normally used to protect this region of the sleeper and to provide a connection for rail fasteners.

In America, where a sleeper is called a "tie" or "crosstie", the "Railway Tie Association" (RTA) promotes the 'economical and environmentally sound use of wood crossties' (http://www.rta.org/Default.aspx?tabid=115). They have made available publications that support these aims including: [6.6.10] that records strengths of wooden sleepers; and [6.11], an economic comparison with concrete sleepers that suggests that apart from in the most severe climates wooden sleepers have a cheaper life-time cost than concrete ones (modern treatments can extend the average life of wooden sleepers to 40 years [6.12]).

Unlike the case for concrete sleepers, neither the European standard [6.13] nor the Network Rail standard [6.14] specifies material properties or tests for wooden sleepers. The experience of wooden sleepers has been that if they are the correct species of tree, have no defects, and are adequately treated with preservative they will be adequate; thus these factors are specified. However, the fastenings (and thus the sleeper material supporting them) do need to satisfy certain tests, see [6.37].

The American "Fast Accelerated Service Testing" (FAST) "Heavy Axle Load" (HAL) Tie and Fastener Experiments [6.15] ran trains with axle loads of up to 35tonne at 64kph. These experiments included wooden sleepers that survived for 145 million tonnes of traffic.

6.2.3 Concrete Sleepers

A huge variety of different concrete sleepers are available [6.16]. They are designed to have different thicknesses, widths, lengths, and variations in details of their shape (from simple cuboids to complex geometries with reduced, even non-concrete, sections between the rail seats) and to have various ridges and protrusions on their sides and ends to provide better contact with the ballast. The properties of the concrete vary as does the type and proportions of fillers. Wires for strengthening also vary: their number, size, locations, materials, and tension (also whether stressed before or after the concrete sets).

The "International Federation for Structural Concrete" has published a state-of-the-art review of precast concrete railway track systems [6.17]. This includes details of calculation methods. Sleepers designed to the latest standards (that include the types of pads required to protect them from impacts) are expected to have a long life in service. Most sleepers on the SustRail routes are concrete (Section 4.2.2). European sleepers are expected to survive for 50 years (e.g. [6.18]). In Britain those installed recently are expected to survive for 60 years (Section 6.1.3); the shorter lives recorded in Table 4.7 reflect the sleeper types that were previously installed.

The European standard for sleepers [6.6.19] requires the concrete used for sleepers to have compressive strength of 45/55MPa (measured in test of 300mm cylinder / 150mm cube) whereas in the UK the concrete is required to have compressive strength of 50/60MPa [6.20]. If the concrete is inadequate then, even if the sleeper satisfies acceptance tests, the stress concentrations associated with holes drilled to accommodate fastenings can cause sleepers to fail [6.21].

For conditions in Britain, a track force limit of 340kN (vertical) was derived from tests [6.22] (reported in [6.9]). At higher forces concrete sleepers were predicted to crack (it was postulated that forces of this magnitude were associated with wheel flats). British sleepers for plain line are tested using standard test procedures [6.19] for positive and negative bending moments at the rail seat (27.8 and 12.5kNm respectively), but only a negative bending moment of 15kNm at the centre[3]. In the 1970's cracks at the top of rail seats were prevented by increasing the thickness of the centre section of sleepers and the pretension at the top of sleepers [6.23].

A study into cracking in concrete sleepers in Greece [6.18] reported that sleepers that satisfy the strength requirements calculated for the expected traffic (in this case cracking threshold of 125kN and failure load exceeding 140kN) can exhibit multiple failures (over 60% of sleepers in 15 years) if the rail pads are too hard. Changing to softer pads has dramatically reduced the numbers of failures despite vehicles with axle loads of 22.5tonne having their speeds increased to 140kph.

Sleeper developments have included the effect of changing the compressive strength of the concrete, the type of reinforcing, and the size of the pretension (see e.g. [6.24]). This study in common with many earlier ones used the methods in the design codes that do not include the influence of load rate on the properties of the materials, though [6.25] found that the loads at which cracks appeared were about the same for either static or impact loading and reported that the effect of an impact load in addition to a static load (as would be the case for a wheel flat impact) is less than the effect of an impact load in isolation. Other studies have included

[3] Despite a comment in a British Rail training course that "the centre of the sleeper does not (and should not) rest on the ballast" [6.6.101]. The test is to ensure that there are not cracks in the top of the centre of sleepers (from hogging). This type of cracking is a major cause of failures on the American railroad (reported in [6.6.16]).

impact loading tests; [6.26] reported tests and an approach to predict ultimate moment capacity of prestressed concrete sleepers under impact loading; [6.27] found that sleepers with severe impact damage could still support the design axle loads.

The rail seat area experiences the most severe impact damage, "Rail seat deterioration (RSD) is considered the most critical problem with concrete-tie performance on North American freight railroads" [6.28]. This study found that water, pressurised by the passage of a wheel, would produce RSD and suggested that a pad that did not seal in water would reduce the incidence of this damage mechanism (for more details see [6.29]). Using epoxy resin to protect the rail seat was found to be ineffective as after extended loading cycles it wore away [6.30].

If there are suitable rail pads to absorb impact forces then sleepers are expected to survive for over 50years; the American FAST/HAL Tie and Fastener Experiments [6.15] found that concrete sleepers could survive for 145 million tonnes of traffic (about 3% of the sleepers cracked during the early stages of the test, but none so severely that they didn't survive until the end of the test). This test also quantified the lateral resistance provided by larger sleepers [6.31].

6.2.4 Conclusions

The performance of appropriate sleepers that are properly installed is adequate for axle loads of up to 35tonne and for trains with 22.5tonne axle loads running at 140kph.

Concrete sleeper failures are generally caused by poor ballast providing inadequate support or by rail pads providing inadequate protection from impacts or the abrasive environment.

6.3 Fasteners

Two types of fasteners are shown in Figure 6.1: baseplate fasteners that attach the baseplate to the rail and rail fasteners that attach the rail to the baseplate. This report focusses on the latter.

6.3.1 Baseplate Fasteners

Modern concrete sleepers are often formed with the baseplate fastener already in place or with local reinforcing around fixing holes. These have been developed to cope with the anticipated service.

6.3.2 Rail Fasteners

Rail fastenings are required to prevent the rail from

- twisting due to lateral train forces
- moving relative to the sleepers

These items have been developed extensively over many years; there have been hundreds of patents issued for rail fastenings since the 1870's; they "have evolved in their design such that they are now anticipated to give a very long service life" [6.32]. From Section 4.2.3 the clips on the SustRail routes in Britain are nearly all made by Pandrol [6.33] and those in Spain by Vossloh [6.34] (the types listed in Table 4.8 are mainly different varieties of their fasteners). They are generally made of spring steel and either screwed to the sleeper (Vossloh) or pressed on similar to a large paper clip (Pandrol).

Four Vossloh (SKL) fastenings were tested for the upgrade of the Spanish high-speed line [6.35]. It was found that the properties depended on the associated pads and anchors, that

protective surface treating made a small difference, and that the thinner SKL14 clip (see Figure 6.4) did not generate sufficient clamping force.



A selection of Pandrol clips



HM fastening (clip SKL1)



Clip SKL14

Figure 6.4: Rail Fastenings (Pandrol Clips From [6.6.36], Vossloh's SKL Clips From [6.35])

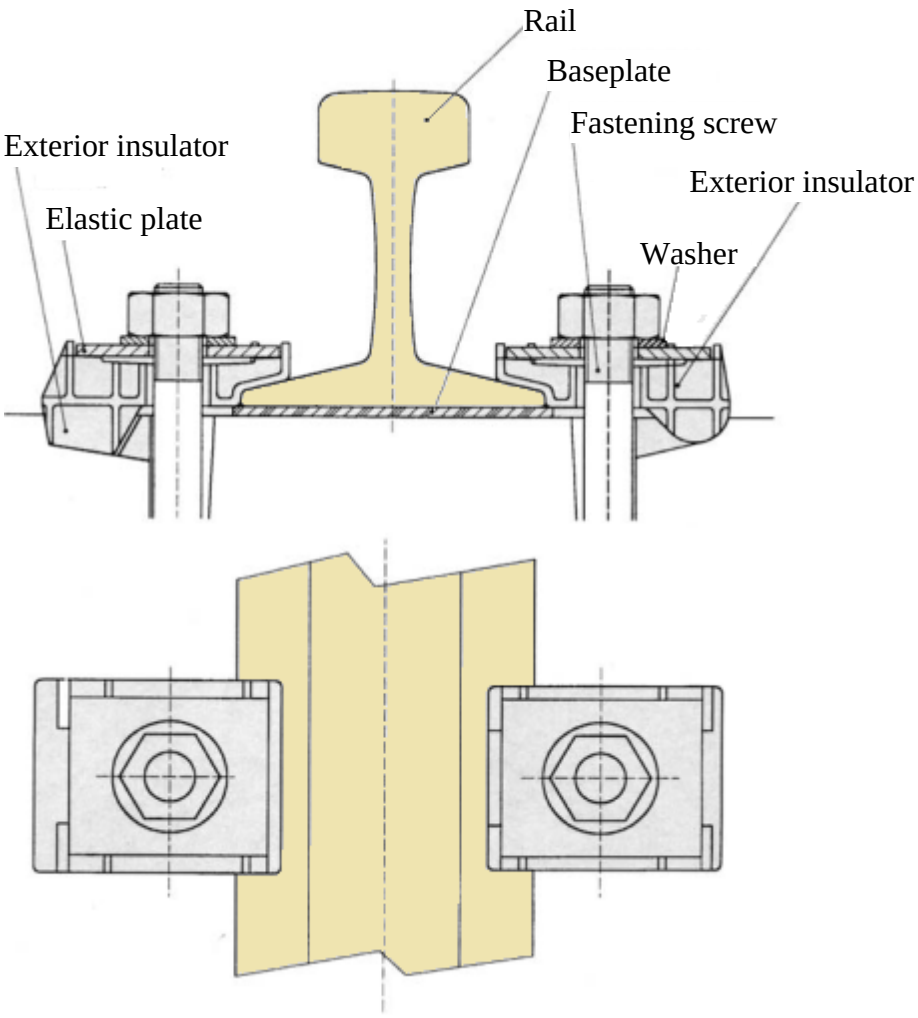


Figure 6.5: Rail Fastening J-2, Used on Spanish SustRail Route (From [6.35])

The material of the clips experience extremely high stresses. This has been shown by an analysis of a Pandrol clip being pressed onto a rail foot and thus bending the central portion upward by 13mm (an angle of about 8° and a force of 11kN). The resulting dominant principal stress (major principal stress if it is larger than the absolute value of the minor principal stress, otherwise minor principal stress) is shown in Figure 6.6. Note that the classical torsion calculation for 20mm long, 12mm diameter, steel rod twisted through 8° predicts a torsional stress of about 1700MPa so the high stresses are (theoretically) reasonable.

As would be expected from such a high stress level, clips only survive for a very short period once a crack initiates [6.21] so fracture mechanics is not appropriate to model service lives (this is similar to bolts; if a crack initiates in the highly-stressed material in a bolt thread the bolt will rapidly break yet if there is no crack the extreme stress levels are not a concern).

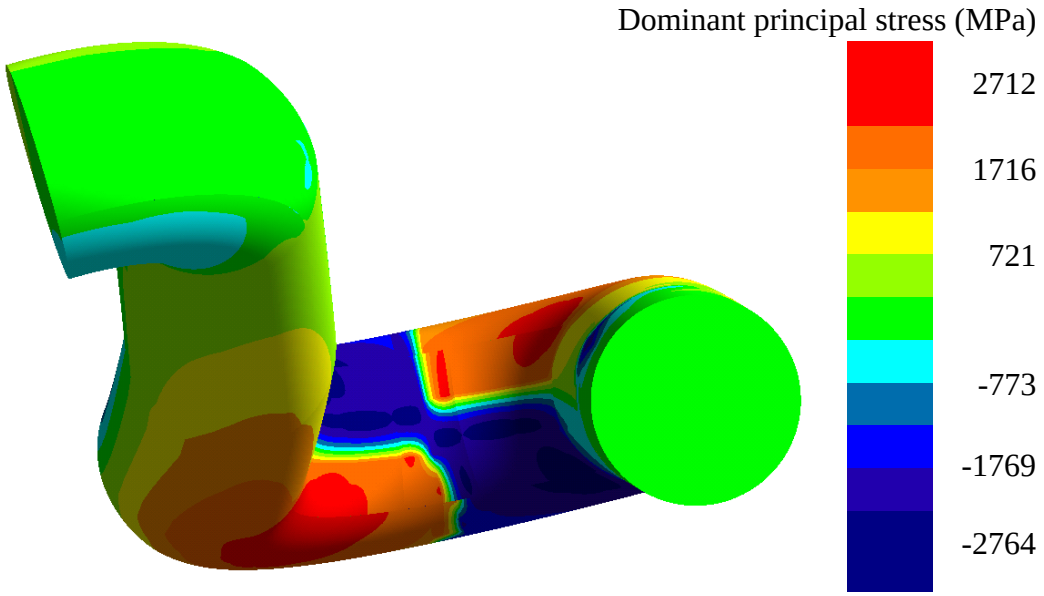


Figure 6.6: Boundary Element Analysis of a Pandrol clip (Deformation Magnified)

The European standards for fastenings ([6.37], [6.38], and [6.39]) were developed by a committee including representatives of Pandrol and Vossloh. These standards specify which tests should be satisfied and how the tests should be carried out. The work was informed by track measurements (e.g. [6.40, 6.41]) of the forces generated by particular vehicles. The standard for heavy-haul lines (with axle loads between 26 and 35tonne) [6.38] was based on simulations of freight vehicles traversing curves with large cant excess [6.42]. This situation occurs when freight vehicles use track designed to also accommodate fast passenger vehicles. Note that both Pandrol and Vossloh provide fastenings that satisfy this standard, so the SustRail axle loads of up to 25tonne will not be near the limit of their capabilities.

The clamping force is considered in [6.43]; too large and the rail will not accommodate local temperature differences or may cause sleepers to move; too small and the rail will buckle when a train brakes. The European (EN) [6.39] and American (AREMA) [6.44] standards are also compared (see also [6.45]): AREMA allows limited slip for a longitudinal force of 10.7kN ("sufficient for general service"), while the EN requires the force at which slip initiates to be recorded and to be at least 9kN; after 3 million cycles of loading the slip tests are repeated; AREMA has the same requirement, but EN requires the slip force to be larger than 9kN and within 20% of the first test's value. The paper [6.43] also mentions the increased longitudinal restraint provided by rail pads that are more rigid so are not as good at absorbing energy from impacts.

In America fastenings have been tested at up to 35tonne with only a few failures of low strength fastenings [6.31].

6.4 Pads

Three types of pad are shown in Figure 6.1: rail pad, baseplate pad, and under-sleeper pad. These add a defined stiffness and damping into the track system for the attenuation of impacts and the reduction of noise and vibration; if correctly "tuned" they can reduce the rate of degradation of a track.

There is on-going research into pad materials: [6.46] studied the effects of changing various factors on the performance of rubber pads: ash content, tensile strength, elongation at break, and the difference between "grooved" and "dimpled" pads. The manufacturers of pads (Getzner [6.47], Edilon)(sedra [6.48] (Tiflex [6.1])) all develop products to suit specific

requirements and fastening producers develop pads that work well with their products (the degradation of rail pads can cause fastenings to come loose or fail).

6.4.1 Rail Pads

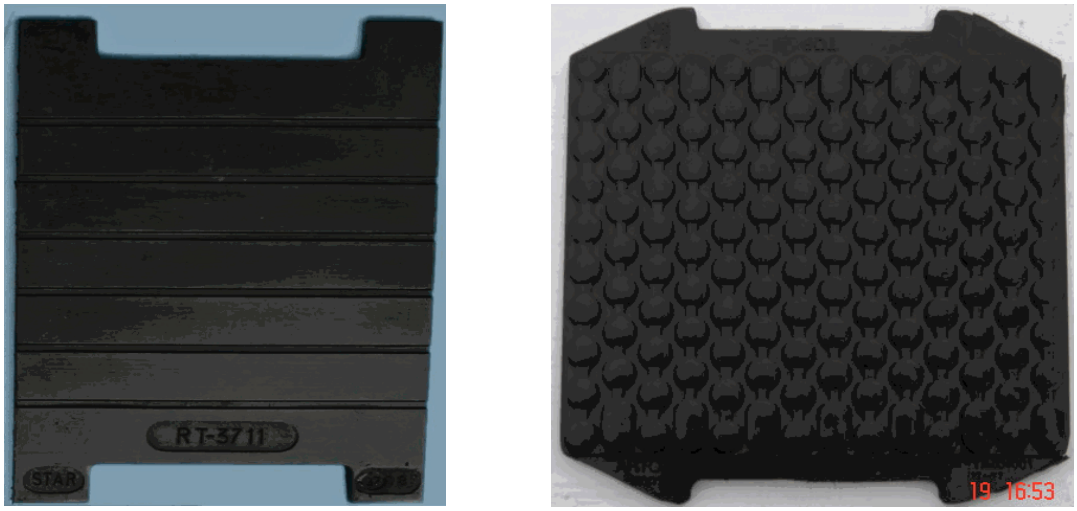


Figure 6.7: Rail Pads, Ridged and Dimpled (From [6.46])

Edilon)(sedra's product brochure [6.48] lists static and dynamic stiffnesses of different materials for a linear response with load. However, it is well known (e.g. see plots of load-deflection curves in [6.49] and [6.29]) that the response of pads is not linear. The surface geometry has a significant influence on the shape of the load-deflection curves and is designed to provide the desired response.

Fitting softer rail pads will reduce the impacts on the sleeper, thus extending life [6.50][4]. This summary also mentioned that there may be an optimum stiffness for the whole track-support system, but the value varies with the specifics of the traffic and the infrastructure manager's priorities.

A rail pad tester that allows preloads to be applied is described in [6.51]. The dynamic stiffness and damping are calculated using the measured response to the blow of an instrumented hammer.

Four pad materials and three designs (different dimples) were tested for the upgrade of the Spanish high-speed line [6.35]. The softest pad was found to be inadequate, particular materials (Hytrel® and Arnitel®) were found to perform best.

The Australian specification for rail pads [6.52] specifies that they must be able to withstand train speeds up to 160kph and axle loads up to 25tonnes so there are pads available that would be able to sustain the forces generated by the SustRail vehicles.

Rail pads are an integral part of the fastening system and they are surviving on lines that experience higher loads and speeds than the SustRail targets.

6.4.2 Under-sleeper Pads

[4]In this report soft pads have a vertical stiffness of about 75MN/m, typical pads 150MN/m, and stiff pads 500MN/m. In the EN standard for fastenings [6.6.37] soft pads have a dynamic vertical stiffness less than 100MN/m, medium pads between 100 and 200MN/m and hard pads have a dynamic vertical stiffness more than 200MN/m

A manufacturer of under-sleeper pads (USPs) has reviewed their benefits [6.53]; mainly reduced track maintenance costs resulting from the increased impact resistance and a reduction in rail corrugations. Vibrations are reduced. The effect the pads have on lateral stability is uncertain; a study in Switzerland [6.54] concluded that "the use of USPs generates higher rail and sleeper accelerations but lower sleeper strains due to bending. The degradation of track geometry appears to slow down when USPs are used". In Austria on track tests [6.55] found that "If the stiffness of the under sleeper pad has the right dimension, it leads to a reduction of ballast forces, sleeper bending forces, track settlement, corrugations' growth, rail pad wear and vibrations".

6.5 Joints

Of the infrastructure managers contacted by Innotrack ([6.56], see Section 2.1) half reported that insulating rail joint failures were a major problem, more important than rail corrugation or wear. The harm[5] attributable to joint bar defects in America is similar; [6.57] presents statistics that show that joints are associated with over 35%[6] of harm, though [6.58] reports that "40% of the maintenance cost on rail is associated with rail joints" and his damage model attributed the highest exponent (10/3) of axle load to joint damage (so it is expected to become more significant as axle loads increase). Dynamic forces of up to five times the static axle load were measured in China (reported in [6.59]). The review in [6.60] notes that the stiffness variation associated with joints will lead to a reduced quality of ride for trains and hence a more rapid degradation of the track; using tuned stiffness of associated pads is suggested to remedy this.

Comprehensive reviews of joint properties and research ([6.61], [6.62], [6.63]) have been undertaken for the Australian heavy-haul railway. These include views of types of joints and of joint failures. The former ([6.61]) states that joints (recall that we are only considering insulated joints) have lives of only 20% that of rail and the large statistical variability in these lives means that maintenance cannot readily be planned.

6.5.1 Examples of Joints

The Elektro-Thermit "MT" joint is widely used throughout the world (including Spain). It consists of a pair of insulated fishplates that are assembled onto drilled track using bolts and a "synthetic mortar", see Figure 6.8. It is described in [6.64]. The same company produces a factory-assembled pre-glued joint.

[5] This term is not defined in the report, but is related to consequences of accidents due to loss of rail integrity.

[6] The sum is: 15.13% "Other rail and joint bar defects" +7.86% "Head and web separation (within joint bar limits)" +6.05% "Joint bar broken (noninsulated, insulated or compromise)" +5.48% "Bolt hole crack or break" +0.72% "Joint bolts, broken, or missing" = 35.24%

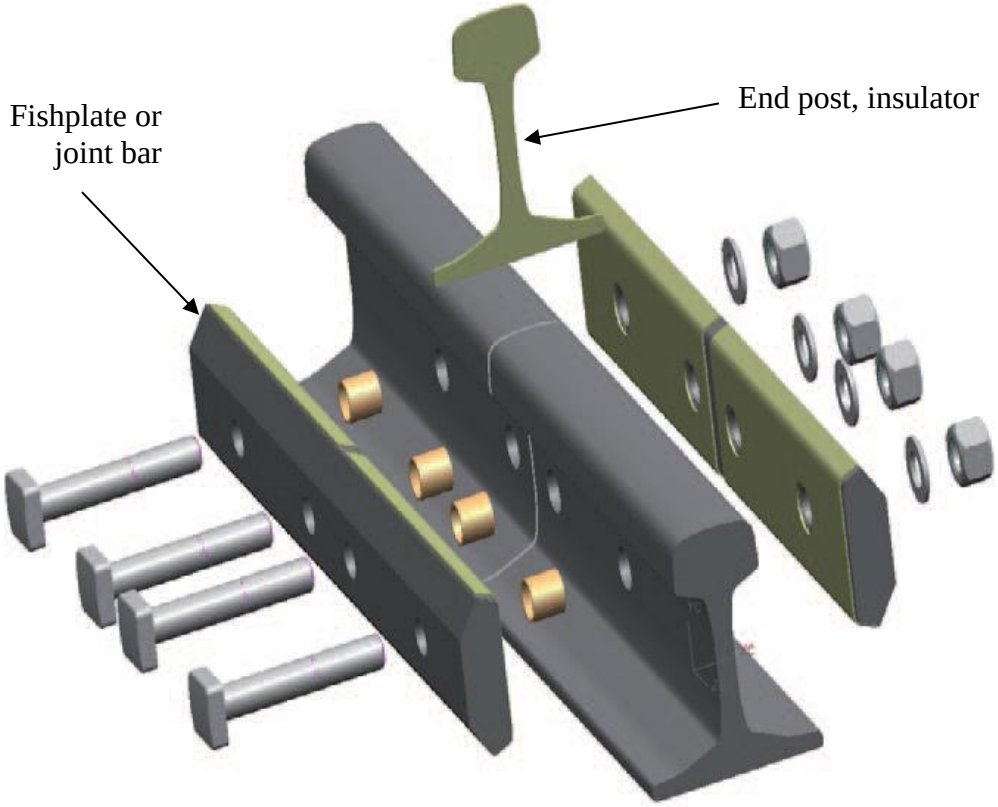


Figure 6.8: Elektro-Thermit "MT" Joint (From [6.65])

The company LBFoster includes Allegheny Rail Products. They manufacture a range of joints that are mainly used in America [6.66]. LBFoster's UK business, Portec, manufactures joints for European infrastructure [6.67]. Vossloh also manufacture insulated joints; they market a joint with a 45º railhead end and a 90º rail-foot end (see Figure 6.9).

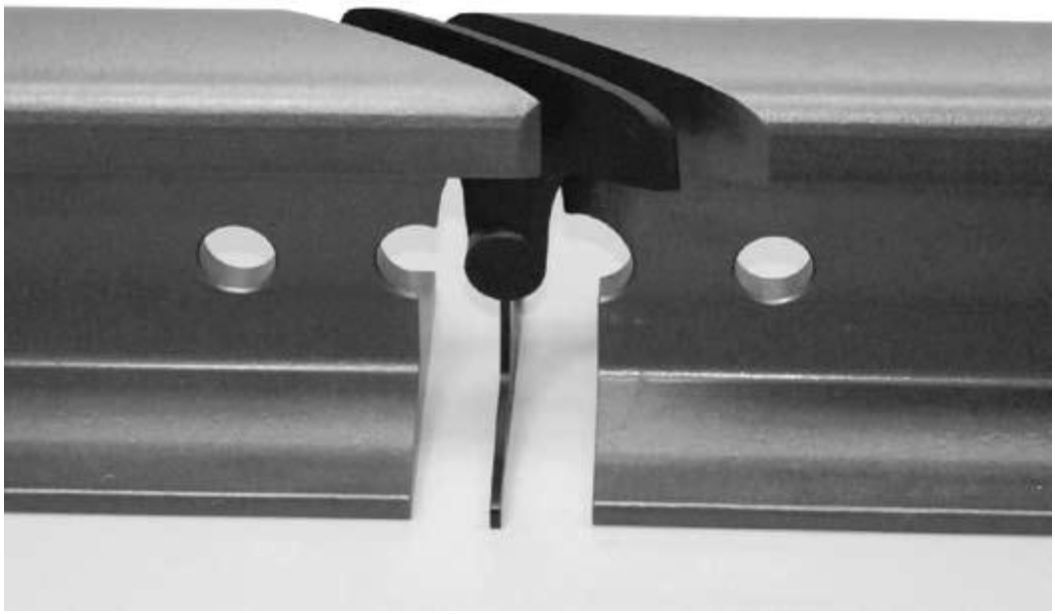


Figure 6.9: Vossloh's IVB 30 Glued Insulated Joint (From [6.68])

6.5.2 Tests

The Network Rail standard for joints [6.69] specifies a testing regime that commences with a 700kN force along the rail for an hour. This force is reduced to 460kN and 2 million cycles of vertical loading from 5 to 205kN through two actuators placed either side of the joint (to represent wheels passing over the joint) are applied. After this loading the joint should have minimal damage (limits are specified) and pass an electrical insulation test.

The American standard [6.44] specifies separate compression, bending (rolling load), and electrical tests. The compression test requires no slippage of the rail joint for a load of 650,000lbf (2.9MN). The rolling test requires 2 million passes of a 44,000lbf (196kN) wheel, so is similar to the NR standard.

The Australian standard [6.70] specifies separate electrical, pull-apart, load deflection, repeated load deflection, and straightness tests. The loads have different values depending on the rail section; the 60kg/m values are given as these would apply to UIC60 rail. The pull-apart test requires that the joint withstand a longitudinal force of 1,130kN for three minutes during which time a vertical force of 210kN is applied to the endpost for two periods of 15seconds. The load deflection test requires a deflection of less than 20mm for a 1,100kN vertical force and a test to destruction or 1,900kN vertical load. The repeated load test is for 3 million cycles of 245kN, so more onerous than the British or American tests.

The INNOTRACK project [6.71] included observations of the degradation of joints in track. It was found that after only two months in traffic the insulating layer was detached from the ends of the rail.

On heavily used coal routes in the U.S. joints may only last for 180 million gross tonnes of traffic (180MGT) [6.72]; this is about a tenth of the life of the rail. The American “Transportation Technology Center, Inc” (TTCI) has been testing a range of modified joints [6.73]. These included a tapered transition ([6.74], see Figure 6.10) which when produced from hardened steel lasted for about 180MGT. This joint puts far lower loads into the larger insulator and larger area of glue than a conventional joint, yet appears to fail in the same manner. Using Kevlar™ as a high strength insulating material was also studied; it lasted for about 540MGT. A similar tonnage was recorded for joints with stiffer insulators than those currently used.

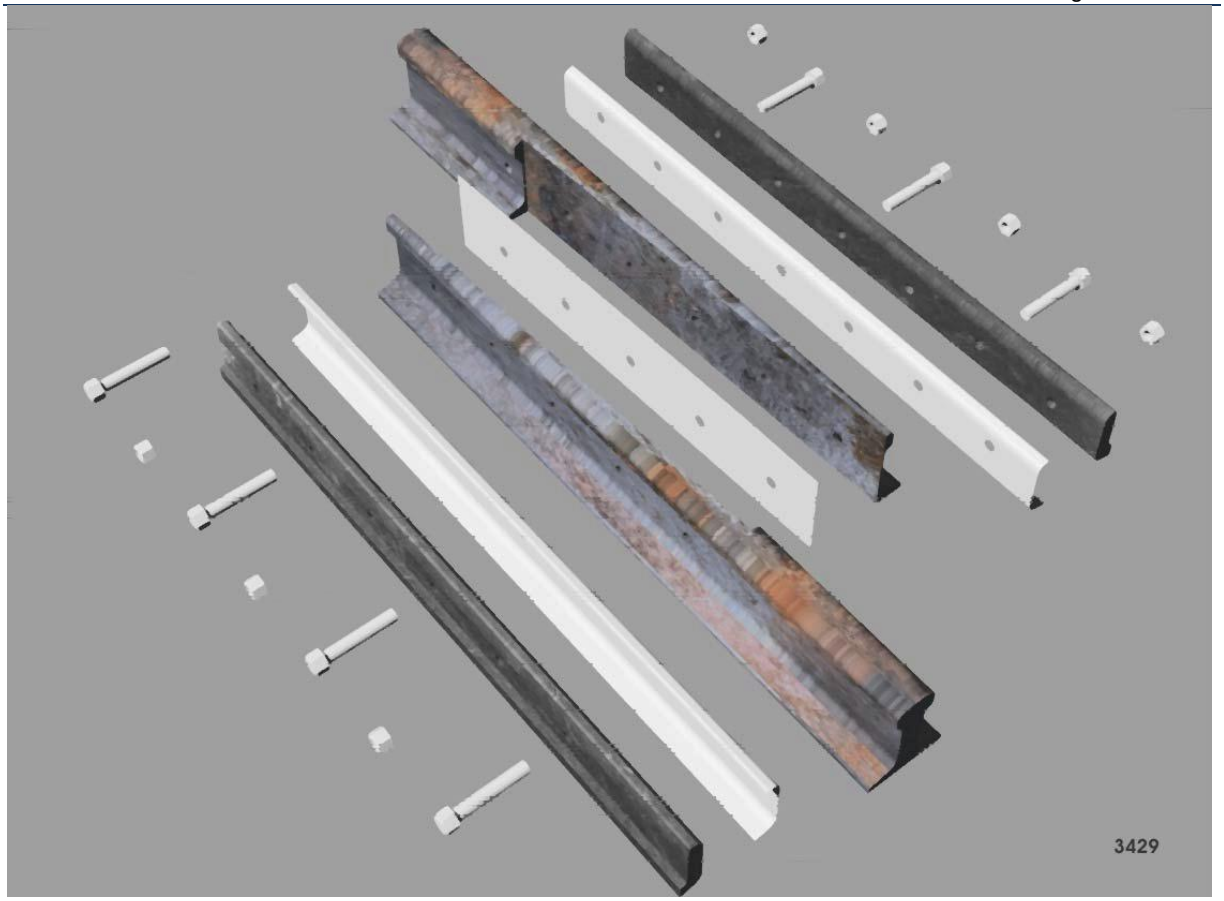


Figure 6.10: Tapered Joint (From [6.73])

The effect of poor support on the life of joints was also investigated. The worst "foundation condition" of the three categories was associated with two thirds of the failures during their trial while no joint failures occurred when there was a good foundation. This motivated improvements in support (adding additional sleepers, renewing ballast etc.) that resulted in lives of about 360MGT. In service tests of joints supported on plates that extend over three sleepers were commissioned [6.75]. It was found that these joints survived at least three times as long as the conventional design [6.76].



Figure 6.11: Supported Joint (From [6.77])

Another report [6.78] gives results of tests on different geometries of joint bars. These tests did not assess lives, but measured service stresses and calculated the growth of artificial cracks in joint bars. It was reported that, during track inspections, cracked bars were not identified as often as would be expected given the number of broken bars that were found and the expected crack growth rate; this may have been due to misreporting of defects or inadequate inspection. Joint bars are fitted in pairs so total failure of joints is rare.

A comparison of a square (90º) and inclined (75º) cut (see Figure 6.12) on the strains and loads experienced in service was undertaken in Australia [6.79]. It was found that

- the square joint exhibited better resistance to web shear than the inclined ones
- initially the vertical impact strains (VIS) measured at the inclined joint had a smaller average than those at the square joint, but the inclined joint's VIS had higher statistical variability
- by the end of the test VIS had increased for both joints but the increase for the inclined joint was larger so that it had larger average VIS

It was noted that only one sample of each joint had been tested.

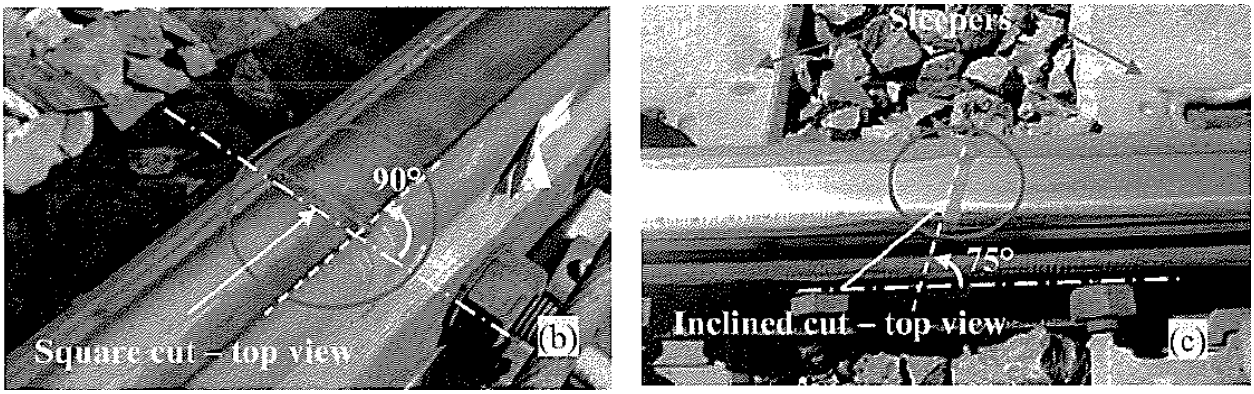


Figure 6.12: Square and Inclined Joints Tested in Australia (From [6.79])

Replacing the epoxy resin in bonded insulated joints by a different material was investigated in [6.80]. The work focussed on fibre-reinforced polymers or ceramics and developed a design that incorporated ceramic spindles; this was installed in the FAST test track in Colorado, U.S.A. The work includes a design study with supporting static finite element analyses of components.

The deterioration of the epoxy resin between the rail and joint bars was studied in [6.81]. It was found that debonding commences at the centre of the joint and toward the upper and lower edges; the extent is approximately symmetric across the rail but not along the rail. A study of different materials for joint insulators was reported in [6.82]. The results of these laboratory tests highlighted several possible combinations that may warrant further study as actual IJ prototypes.

6.5.3 Modelling

A spring/mass model of a joint is described in [6.83]. This simple analytical/empirical model produced results for strain and deflection that agreed well with laboratory testing.

Three-dimensional finite element modelling of a simplified joint geometry (cuboids and cylinders) was undertaken ([6.84]). This study considered contact between the bolts and the joint and focussed on the effect of changing bolt tension on stresses resulting from vertical bending; it suggested that the simple theory of bending is not applicable and that bolt tension does not affect bending stress (but the effects of changing from bolts to Huck® fasteners, that do not loosen when vibrated, is the subject of tests in America [6.77]).

A three-dimensional static elastic model of wheel-rail contact with a glued insulator but no joint bars was used in [6.85]. The results indicated that the closer the insulator's elastic modulus approached that of steel the lower the stress concentration in the railhead but the higher the stress in the insulator. A series of parametric finite element models are described in [6.86].

A three-dimensional finite element model of a joint in the centre of a 15.24m long section of rail and sleepers was modelled in [6.87] (see [6.88] for more details). The model was symmetric about the centre of the rail and a Hertzian semi-elliptic pressure distribution (not reflecting the stiffness of the joint) was applied. This loading was applied (statically) both central to the joint and offset by half a sleeper width. The model was used to investigate the effect on stresses in the adhesive of (a) larger ties, (b) longer joint bars, and (c) increased widths of the joint bars.

Three-dimensional dynamic finite element modelling of two wheels passing over a joint in 4.5m of rail was reported [6.89]. Steel, plastic, and glue were all modelled using a Johnson-Cook[7] material model with appropriate parameters. The results were said to correlate well with measured data and are to be used to improve joint design.

The effect of changing joint bar thickness was considered in [6.62]. Simplified three-dimensional finite element analyses were used (rails fixed at sleeper locations, no flexibility in joints, uniform rectangular load area, etc.). The effect of thickness was not found to be significant, whereas a more comprehensive shape optimisation [6.90] predicted that an 18% reduction in equivalent stress could be achieved.

Three-dimensional elastic models of rail joints including a 12.19m length of rail were reported in [6.91]. A vertical point load (representing wheel load) was applied at one side of the joint and a tensile force (representing contraction of rail in winter) was applied to the ends of the rail. Contact between joint elements was included and sleepers were represented as linear springs with different stiffnesses for summer or winter conditions. This study reported stress levels commensurate with material failure (equivalent stress exceeding yield); increasing the stiffness of the joint provided stresses similar to those in a well-supported joint [6.92].

Three-dimensional quasi-static finite element modelling including the contact between wheel and rail (but with no friction) and three different insulating materials (epoxy-fibreglass, polytetrafluoroethylene (PTFE) and Nylon-66) were reported in [6.93]. The same investigation continued [6.94] and reported a good comparison between the contact pressure results from the previous model and those from a two-dimensional model. This latter model was used with a friction coefficient of 0.3 to investigate the effect of traction and braking on the tangential stresses.

A two-dimensional model was also used (with wheel loading calculated from cylinder-on-cylinder Hertzian calculations) in [6.95]. The results were found to have a satisfactory agreement with measurements on a strain-gauged joint in traffic.

The group at the Southwest Jiaotong University in China developed a dynamic elastic-plastic (bilinear isotropic kinematic hardening) finite element model of a wheel rolling over a joint (one rail modelled on a spring damper system to represent the sleepers etc.). In [6.96] they report that the impact load is not affected by train speed (30 to 90kph). In [6.59] they investigated the effects of train speed, axle load, and height difference between the two sides of a joint on the contact forces, stresses, and strains at the railhead. They found that:

- for a height difference of 2mm

[7] This model is an elastic-plastic model with isotropic hardening. The yield stress depends on strain, strain rate, and temperature. It is said to be suited to the modelling of high strain rate deformation of metals [6.6.102].

  - when speed is increased from 100 to 160kph at an axle load of 18tonne the equivalent plastic strain increases by about 10%
  - when axle load is increased from 16 to 20tonne at a speed of 120kph the equivalent plastic strain increases by about 1.3%
- for a speed of 120kph and an axle load of 18tonne, when the height difference increases from 1 to 3mm the equivalent plastic strain increases by over 200%

There appeared to be little non-linearity in any of the results. Clearly the most important factor to control is the height difference across the joint.

The INNOTRACK project included analyses of joints ([6.71] with more details in [6.97], building on [6.98]). Four passes of a wheel were simulated using a quasi-static three-dimensional finite element model with a sophisticated material model to simulate non-linear cyclic hardening. It was found that effective strain was a "more conclusive measure" of the fatigue impact (damage) than a multi-axial fatigue damage parameter that had been validated in rolling contact fatigue studies ([6.99] but with a different material model). It was found that the damage predicted with a friction coefficient of 0.25 was about 10% less than that predicted with a friction coefficient of 0.5; the former value was used for the remainder of the simulations. It was found that increasing the insulating gap from 4 to 6mm gave roughly the same effect as an increase of the vertical load from 150 to 200kN. In addition, a very detrimental effect of traction and braking was found: Increasing the longitudinal load from 0 to 45kN caused the predicted damage to almost double.

A three-dimensional dynamic elastic-plastic finite element model of a 12m length of rail contacted by a conical wheel was considered in [6.63]. The central 2.4m was modelled with solid elements with a pair of beam elements, appropriately connected, modelling the outer lengths. Interfaces of the joint were not allowed to slide or separate. The sleepers were modelled by constraining relevant nodes on the base of the rail to only move vertically and for each sleeper the vertical movement of each relevant node was controlled by one spring and damper in parallel. The simulation had two phases: the wheel resting on the rail and rolling across the joint. It was found that the peak contact force (assumed to govern damage) increased by:

- 13% if the wheel was sliding instead of braking
- up to 8% if the end-post was not glued to the rails
- 6.7% if the gap between rails increases from 5 to 10mm
- 18% if the foundation is infinitely stiff instead of having typical compliance
- 10% if the joint is directly above a sleeper instead of between two sleepers

It was also found that the length of the joint bar did not affect the peak contact force and an epoxy-fibreglass end-post would reduce the peak contact force by 3.4%. The model was validated by comparison with strain-gauged joints loaded both in the lab and in track.

6.6 Conclusions

Of the track components that have been studied the fasteners, pads, and sleepers all have versions available that will survive the loads envisaged in the SustRail project.

A rail system designed to satisfy Network Rail's track requirement would still satisfy this requirement if the freight wagon's load or speed were increased to the maximum values being considered by the SustRail project.

Insulated rail joints are the most critical component and improvements to these would be a benefit to the industry through reduced maintenance and fewer unexpected delays to traffic.

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7. CONCLUSIONS

Deliverable D2.3 is mainly oriented to the specification of required track performance and to infrastructure managers' requirements. Each chapter contains a wide range of information about the duty requirements, obtained from:

- a deep study of the literature,
- data gathered from the infrastructure managers,
- contributions of companies like TATA Steel,
- studies made by expert researchers.

UPM has conducted the research and data compilation supplied by the infrastructure managers on the track duty requirements in terms of environmental performance, maintenance needs, renewal frequency, etc. USFD and KTH also contributed to the enhancement of this deliverable.

The data gathered from the Infrastructure Managers and from technical and scientific literature, is a worthy input for the development of the upcoming tasks of the SustRail project. There are significant differences between the three infrastructure managers considered, due to the differences in traffic occupancy, and climate conditions.

Also the impact of climate change on rail maintenance and the constraints that may be imposed by carbon targets should be taken into account for the development of the work packages WP4 and WP5. Although infrastructure is not yet regulated in terms of climate change impact, a European objective should be to include infrastructure in legislation in the future, and the deliverable contains some recommendations that could help legislation in the near future.

Main track components and infrastructure duty requirements have been defined in terms of fatigue, wear, life cycle cost, etc. There are data of:

- estimated life, measurements to increase the life of the main track components,
- most common maintenance operations and their costs,
- the conditions that apply to the bridges and civil engineering structures, etc.

It is difficult to define a life cycle cost for each track component individually, because in most cases, the renewal of one of the main components (for example the rails) is used to make renewals in the whole track elements, including sleepers, fastenings, ballast, etc.

The deliverable used the data gathered on duty requirements to make a study about track forces and energy dissipation, i.e. key elements with respect to system performance and maintenance cost. The study shows that the axle-load is the most decisive parameter for the total wheel force, so an enhanced suspension system should deliver a substantial reduction of the track forces.

Also in order to finish this deliverable, current performance (cyclic loading and overload limits) for track components have been defined. Fasteners, pads, and sleepers have versions available that will survive the loads envisaged in the SustRail project. The study also shows that insulated rail joints are the most critical component and improvements to these would be a benefit to the industry through reduced maintenance.

The objectives of this deliverable have been completely achieved, and the track duty requirements, to improve freight sustainability and competiveness during the SUSTRAIL project, have been defined. This deliverable is an input for future task developments.

APPENDIX A – MAINTENANCE QUESTIONNAIRE

The following questionnaire has been elaborated to support the deliverable D2.3 Track design requirements for reduced maintenance in gathering input from IMs to define track duty requirements.

According to the DoW task 2.3.1 : the duty requirements are: maintenance intervals and intervention levels, requirement for and availability of personnel (including consideration of the impacts of an ageing population), requirement for plant, extension of existing track life, options for designs of replacement track (conventional and novel options).

The objectives of this task can be summarized in two main points:

- To define the requirements of track maintenance and replacement.
- To support sustainable achievements of the requirement to "potentially double the life of track components when combined with low impact vehicles",

The most important features of the analysis are:

1. Standards or routines, the examination / maintenance / operation / renovation of which, the railway administrator has to perform:
2. Type, availability and amount of equipment and depot or base those are available to perform examination / maintenance / renovation operations.
3. Index of availability of the track section in the selected line in the last 5 years (2006-2010).
4. Track quality index of the section, in percentage over the total length of it, in the last 5 years (2006-2010).
5. Number of examinations and monitoring or prevention operations done over the past 5 years (2006-2010).
6. Number of maintenance operations done over the past 5 years (2006-2010).
7. Number of track renovation operations done over the past 5 years (2006-2010).
8. General information of annual maintenance performed in the last 5 years (2006-2010) in the selected line.
9. Annual maintenance cost, and replacement expenses, relative to the selected line in the last 5 years (2006-2010). The resources and the subcontract works should be taken into account.
10. Future Project Plan of maintenance and renovation. Take into account the current and the next year planning.

Starting from the data gathered, a study will be performed in order to show the actual situation in the selected routes, and trying to define the requirements of track maintenance and replacement.

Some of the data regarding the selected routes has been (it has already, or it will have been collected when the tasks are done?) collected in tasks 1.2: Route Characteristics and 1.4.

Infrastructure, and could prove very necessary to complete this questionnaire and very useful in drawing conclusions.

The questionnaire is divided into 10 questions:

- Questions 1, 2 and 10 are open questions and must be complete with as short and precise answers as possible.
- Questions 3 to 9 must be completed in the next tables:

QUESTION 1:

SUMMARY:

Standards or routines, the examination / maintenance / operation / renovation of which, the railway administrator has to perform.

INSTRUCTIONS:

Answer each question as short and precisely as possible with the criteria, standards or rules that are regularly used in the following operations, about the line selected examination, maintenance and renovation.

1.1. Geometry and dynamics track examination with track inspection coach or handheld inspection devices (maybe it is regular in time or at certain tonnage of circulation).

1.2. Catenary, contact wire, and the electrification equipment (substation, neutral zone, catenary supports, etc.) inspection or examination.

1.3. Planned or routine interventions on the track superstructure, or track maintenance operation non-urgent.

1.4. Planned or routine interventions on the catenary and electrical supply equipment, or maintenance operation non-urgent.

1.5. Urgent maintenance operation to correct track superstructure defect.

1.6. Urgent maintenance operation to correct defects on the catenary and electrical supply equipment

1.7. Track superstructure renovation.

1.8. Catenary and electrical supply equipment renovation.

1.9. Implementation of limited traffic, or speed restrictions, in a line (caused by line defects and not for meteorological conditions).

QUESTION 2:

SUMMARY:

Type, availability and amount of equipment and depots or bases those are available to perform examination / maintenance / renovation operations.

INSTRUCTIONS:

Answer each question as short and precisely as possible with the types of equipment you have, and your number and availability of it, to perform the following activities about the examination, maintenance and renewal of the railway line selected.

2.1. For examination of the track state and running order (track inspection coach, electronic track tester, handheld inspection devices or others

a. Own resources.

b. External or subcontracts resources.

c. Technical staff.

2.2. For examination of the catenary state (catenary inspection coach or others).

a. Own resources.

b. External or subcontracts resources.

c. Technical staff.

2.3. For track superstructure or catenary maintenance operations.

a. Own resources.

b. External or subcontracts resources.

c. Technical staff.

2.4. For track superstructure or catenary renovation.

a. Own resources.

b. External or subcontracts resources.

c. Technical staff.

2.5. Finally, indicate:

a. How many technical staff are employed for the maintenance of the selected line?

b. How many maintenance depots or stations are on the selected line?

QUESTION 3:

SUMMARY:

Index of availability of the track section in the selected line in the last 5 years (2006-2010).

INSTRUCTIONS:

Fill in the following table with the track section availability in the semester column; take into account the following levels of availability:

a. Full availability of track section.

b. Implementation of limited traffic, or speed restrictions in the track section (more than two days).

c. Track section partially, or not available, due to maintenance operations (more than two days).

d. Track section not available due to renovation works (more than two days).

Track section	**1st sem 2006**	**2nd sem 2006**	**1st sem 2007**	**2nd sem 2007**	**1st sem 2008**	**2nd sem 2008**	**1st sem 2009**	**2nd sem 2009**	**1st sem 2010**	**2nd sem 2010**
Sect. 1										
Sect. 2										
Sect. 3										
Sect. 4										
(…)										

QUESTION 4:

SUMMARY:

Track quality index of the section, in percentage over the total length of it, in the last 5 years (2006-2010).

INSTRUCTIONS:

Fill in the following table with the track quality index of the section in the semester column. It should be a mean of the track quality over the indicated semester. Take into account the following quality levels:

a. Excellent
b. Good (limit value punctually exceeded in less than 5% of the total section length)
c. Fair (limit value near to exceeded, or exceeded in less than 20% of the section total section length)
d. Poor (limit value exceeded in more than 20% of the section or unacceptable variation in track geometric quality.).

Track section	**1st sem 2006**	**2nd sem 2006**	**1st sem 2007**	**2nd sem 2007**	**1st sem 2008**	**2nd sem 2008**	**1st sem 2009**	**2nd sem 2009**	**1st sem 2010**	**2nd sem 2010**
Sect. 1										
Sect. 2										
Sect. 3										
Sect. 4										
(…)										

QUESTION 5:

SUMMARY:

Number of examinations and monitoring or prevention operations done over the past 5 years (2006-2010).

INSTRUCTIONS:

Fill in the following table with the numbers of examinations done in the year column. Indicate its number and its type, taking into account the following types of operations:

a. To test several geometric parameters of the track (vertical and lateral alignment, levelling, twist and track gauge) and parameters related to the track (curve radius, superelevation (cant) of the track, gradient, and profile).without obstructing normal railroad operations.
b. To inspect the track dynamic (Lateral and vertical accelerations at body, lateral accelerations on each bogie frame, at the position of each outer wheelset).
c. Ultrasonic testing of rails.
d. To gauge the rail wear
e. To monitor the state of the ballast and the ballast subbase(track ballasting, inspection of the setting bed, ballast thickness, ballast limestone, uses of ground-penetrating radar, etc.).
f. To examine the catenary, the contact wire, or the electrification equipment.
g. To check and verify the other track equipment, switch gears, etc.
h. Other (Mark with an index and explain briefly below)

Track section	**2006**	**2007**	**2008**	**2009**	**2010**
Sect. 1					
Sect. 2					
Sect. 3					
Sect. 4					
(…)					

QUESTION 6:

SUMMARY:

Number of maintenance operations done over the past 5 years (2006-2010).

INSTRUCTIONS:

Fill in the following table with the numbers of maintenance operation done in the year column. Indicate its number and its type, taking into account the following types of operations:

a. To reduce the track geometric defects by non-machining methods.
b. To tamper the ballast, or something similar.
c. Mechanical track stabilization.
d. To grind and to reprofile the rails.
e. To tighten the track fastenings.
f. To repair the catenary, the contact wire, or the electrification equipment.
g. To repair the track equipment (switch gears, etc.), or the signalling and safe equipment, due to track deterioration and maintenance needs.
h. Other (Mark with an index and explain briefly below)

Track section	**2006**	**2007**	**2008**	**2009**	**2010**
Sect. 1					
Sect. 2					
Sect. 3					
Sect. 4					
(…)					

QUESTION 7:

SUMMARY:

Number of track renovation operations done over the past 5 years (2006-2010).

INSTRUCTIONS:

Fill in the following table with the numbers of track renovation operation done in the year column. Indicate its number and its type, taking into account the following types of operations:

a. To renovate completely the track.
b. To renovate the track bed, the subbase or the track formation (please include if have installed a special solution like textile protective layer).
c. To clear or remove the ballast and/or subballast.
d. To remove the sleepers or the rail fastening.
e. To remove the rails.
f. To remove catenary, the contact wire, or the electrification equipment.
g. To remove the track equipment (switch gears, etc.), or the signalling and safe equipment, due to track deterioration and maintenance needs.
h. Other (Mark with an index and explain briefly below)

Track section	**2006**	**2007**	**2008**	**2009**	**2010**
Sect. 1					
Sect. 2					
Sect. 3					
Sect. 4					
(…)					

QUESTION 8:

SUMMARY:

General information of annual maintenance performed in the last 5 years (2006-2010) in the selected line.

INSTRUCTIONS

Fill in the following table with the kilometres done of each task.

TASK	2006	2007	2008	2009	2010
Length of the line (km) over which the track have been examined in order to know the state or prevent future defect.					
Length of the line (km) over which the catenary have been examined in order to know the state or prevent future defect.					
Length of the line (km) over which have been done track maintenance operation.					
Length of the line (km) over which have been done catenary maintenance operation.					
Length of the line (km) over which the track have been renewal.					
Length of the line (km) over which the catenary have been renewal.					

QUESTION 9:

SUMMARY:

Annual maintenance cost, and replacement expenses, relative to the selected line in the last 5 years (2006-2010). The resources and the subcontract works should be taken into account.

INSTRUCTIONS

Fill in the following table with the costs, and the total amount of uninterrupted labour, required to perform the task (euro and man month) divided by annual.

TASK	2006		2007		2008		2009		2010	
Cost of track examination equipment purchases to be used for the selected line (Own resources).										
Cost of track maintenance equipment purchases to be used for the selected line (Own resources).										
	€	**Mm**	**€**	**Mm**	**€**	**Mm**	**€**	**Mm**	**€**	**Mm**
Cost of track examination or prevention (includes cost of subcontract works).										
Cost of track maintenance (includes cost of subcontract works).										
Cost of track renovation (includes cost of subcontract works).										

QUESTION 10:

SUMMARY:

Future Project Plan of maintenance and renovation. Take into account the current and the next year planning.

INSTRUCTIONS

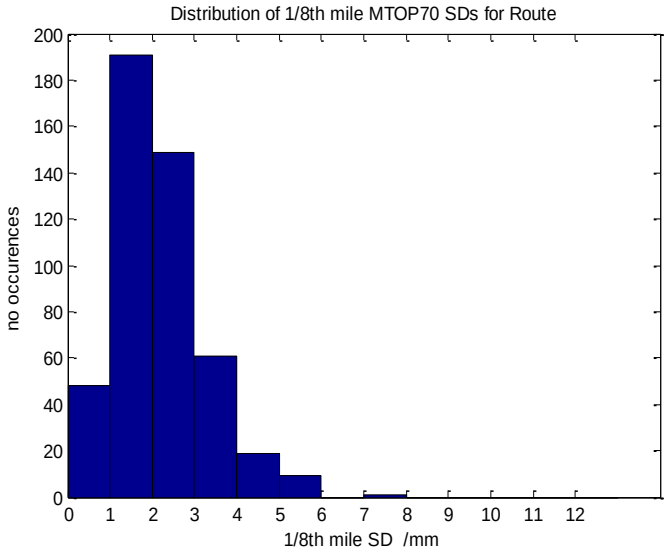
There are two questions about the current and the next year planning. Answer each question as precisely as possible.

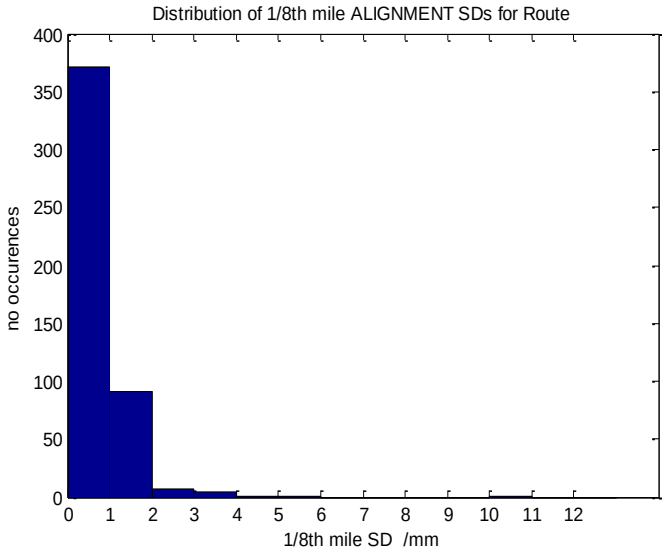
10.1. Average annual budget for the future renewal of the selected track in the current and next year. (If exact budget value is unknown, you should give an estimate based on the budgets of the last 5 years and the growth forecast).

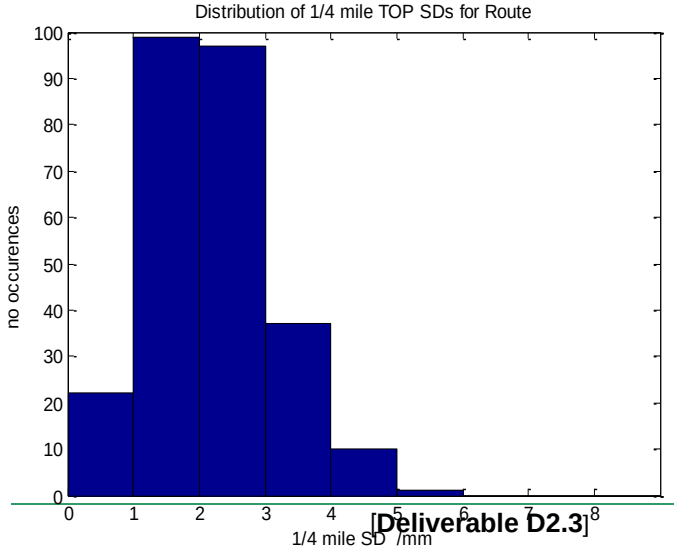
10.2. Estimated averaged life span (in tonnes or time) for installed:

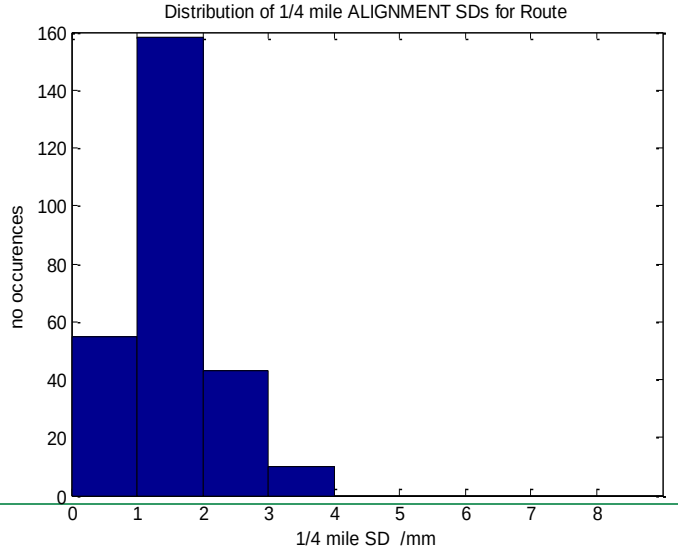
a. Rail
b. rail fastening
c. sleepers
d. ballast
e. catenary

APPENDIX B1: TRACK SDS



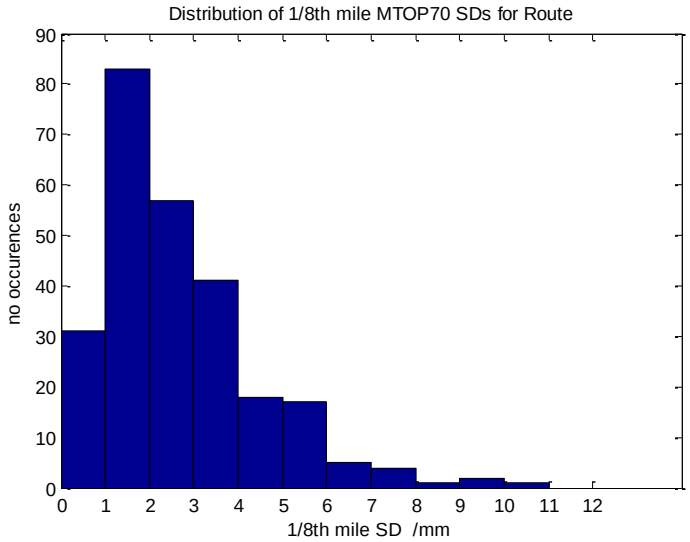


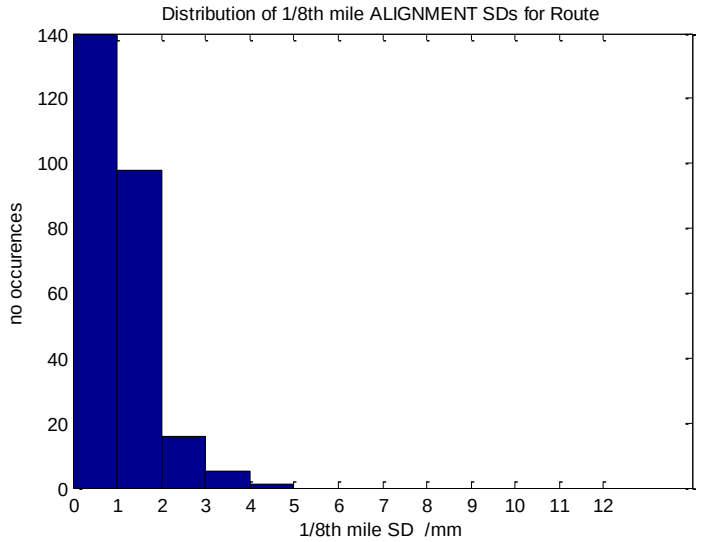


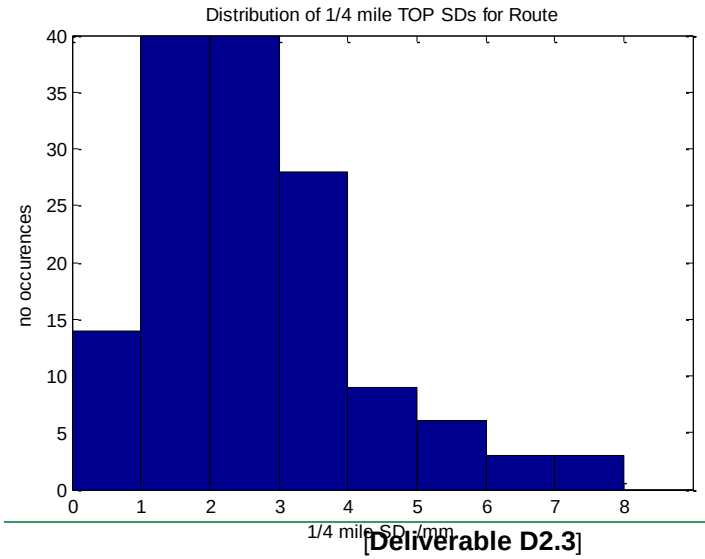


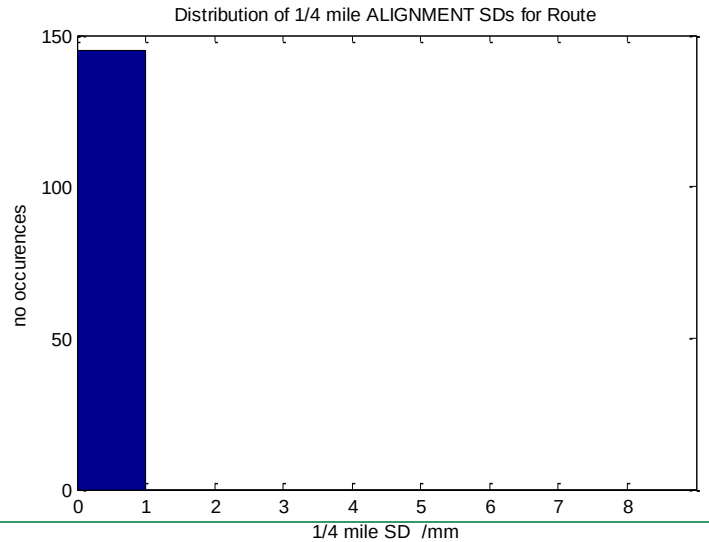
APPENDIX B1: TRACK SDS
- 1/8 MILE AND 1/4 MILE – SECTION 1:
CHESTER LINE JN DCL 2100 53MI 12CH TO LEAMINGTON SPA JN DCL 2100 106MI 25CH

APPENDIX B2: TRACK SDS









APPENDIX B2: TRACK SDS
- 1/8 MILE AND 1/4 MILE – SECTION 2:
ELY NORTH EMP 2100 71MI 63CH TO PETERBOROUGH JUNCTION EMP 2100 100MI 2CH