Development of the Future Rail Freight System to Reduce the Occurrences and Impact of Derailment

D-RAIL

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Report on analysis of derailment causes, impact and prevention assessment

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	Name	Organisation
Leader of this deliverable:	Schöbel Andreas	VUT
Prepared by:	Schöbel Andreas	VUT
	Zarembski Allan	HARSCO
	Palese Joseph	HARSCO
	Maly Thomas	VUT
Verified by:	Mark Robinson	UNEW

Dissemination Level		
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D-RAIL consortium

1.	UNIVERSITY OF NEWCASTLE UPON TYNE	UNEW	United Kingdom
2.	UNION INTERNATIONALE DES CHEMINS DE FER	UIC	France
3.	RAIL SAFETY AND STANDARDS BOARD LIMITED	RSSB	United Kingdom
4.	TECHNISCHE UNIVERSITAET WIEN	VUT	Austria
5.	PANTEIA BV	PANTEIA	Netherlands
6.	CHALMERS TEKNISKA HOEGSKOLA AB	CHALM	Sweden
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9.	LUCCHINI RS SPA	LUCC	Italy
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20.	TRAFIKVERKET - TRV	TRV	Sweden

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Executive Summary

This document is an outcome of task 3.1 of the D-RAIL-Project and shall give an overview about the findings of several workshops on the investigation of the major derailment causes identified and listed in the Deliverable D1.1. The results of the workshops were put into an overall structure to identify all mitigation measures for the given major derailment causes in a systematic way. Thereby well-known and already introduced measures are considered as well as prototypes and technologies currently under development. Finally the potential for new measures is also indicated. This document shall be used as an input for WP 4 to analyse more in detail the here listed mitigation measures. The focus of all measures is primarily technology-oriented to gain the advantages of automated inspection. The cost benefit analysis of all suggested measures in detail will be up to WP 7 but this document already provides an approach to run a rough estimation for on-board and wayside monitoring systems.

Table of Contents

Glossary

ÖBB	Austrian Federal Railways (Österreichische Bundesbahnen)
SBB	Swiss Railways (Schweizerische Bundesbahnen SBB AG)
WP	Workpackage

1 Introduction

As mentioned before this document is an outcome of task 3.1 where in Vienna University of Technology and HARSCO were involved. HARSCO has a huge experience on previous derailment investigations which has been very useful to do this task in a proper way. Vienna University of Technology has done a national founded project in Austria with Austrian Railways (ÖBB) to structure well-known derailment mechanisms in a cause-consequence-matrix (chapter 3). This document takes into account the description of planned work from the proposal (chapter 4) and gives some comments on the updates required by the outcome of WP 1 (chapter 2.2). The findings of the workshops are presented in a structured way (chapter 4). This is the main work of task 3.1 where all given major derailment causes as identified by WP 1 mitigation measures were collected in a brain storming and finally sorted and harmonised for this document. To allow already in this early stage of the project a rough estimation of the cost benefit ratio an overall methodology for on-board and track-side systems is presented for all mentioned mitigation measures (chapter 5). The document closes with recommendations for further work in the project D-RAIL.

2 Organisation of work

2.1 Description of planned work

Derailment scenarios will be assessed based on existing benchmark analysis (WP1) to determine the extent of causal effects to support future improvements. A number of derailment mechanisms and influencing factors will be evaluated, undertaken for both vehicle and track based on an understanding of the 'total' integrated freight system.

The derailment mechanisms to be analysed as detailed in the tasks of WP3 are identified from the long-term experience of the D-RAIL partners and from the result of extensive data-mining of derailment reports. Significant existing research exists from previous investigation into freight derailments both within the EU and on a world–wide basis. The participants in the D-RAIL project have extensive knowledge and experience in this field and have been involved with many of the previous and current projects. The derailment investigation in D-RAIL will therefore set out from this existing state of the art position.

To investigate the origin of derailments (cause) and identify means of prevention, a 'top-down' approach is here taken for analysing derailment causes and impacts. An overall assessment is adopted to identify chains of events that lead to derailments (see Figure 2-1). The aim is to halt the chain of events before catastrophic failure occurs and to do so in a cost-efficient manner. Such an approach is suitable for the analysis of derailment caused e.g. by human errors or escalating technical failures.

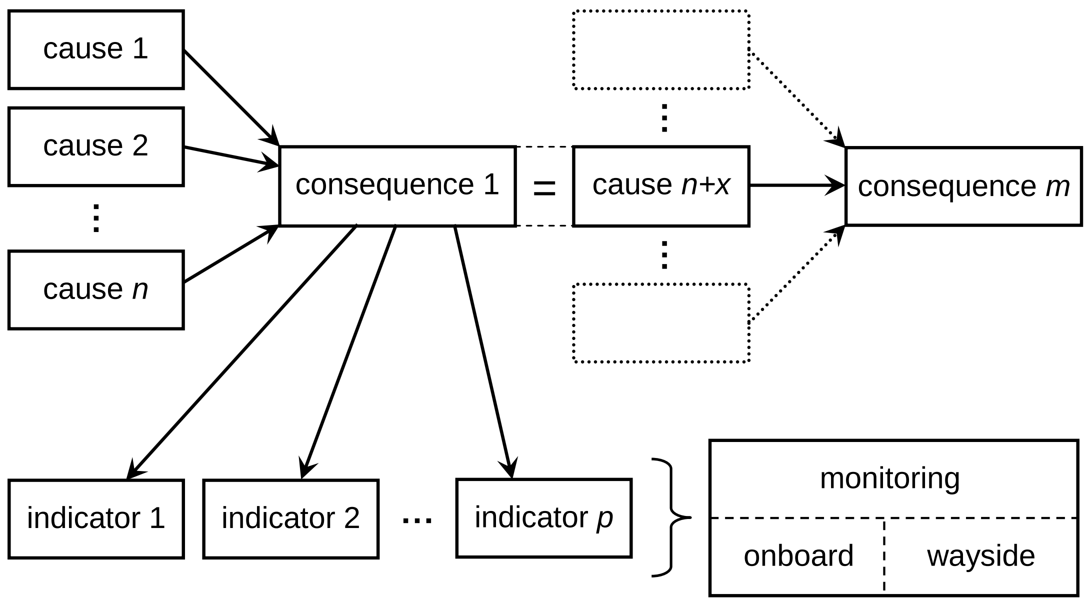

Figure 2-1: adopted approach of causes and consequences

In detail, task 3.1 starts from the overall assessment carried out in WP1 using existing data which has been analysed to provide valuable information on the root causes of freight derailments and subsequent severity. From this data detailed derailment analysis and the associated chain of events will be further examined in task 3.1 based on the following:

- Identification of highest priority derailment mechanisms
- Development of cause–consequence chains of events leading up to derailment
- Pertinent mitigation strategies and (when relevant) parameters to be monitored
- Review of existing modelling approaches
- Creation of a suitable best practice evaluation model
- First approximation of costs for proposed mitigating/preventative actions

The task will focus on mitigating strategies where identification can be related to existing and potential new monitoring or maintenance management activities of the freight and track system. It is recognised that human factors are an important element of cause–consequence in derailment events. Whilst these factors will be captured as part of WP1 assessment the research will only focus on the physical monitoring/prevention measures to prevent derailment and not on driver behaviour.

2.2 Input of findings of WP1

As there is no hierarchy for all elements of the railway system developed so far, the level of detailing and grouping of components is a very crucial aspect when analysing accident data bases. Thereby the grouping and splitting of accident causes (and especially derailment causes) is very sensitive to any ranking which might be done later on to argue priorities for different topics to be investigated in detail. As this problem is well known to the railway experts of the D-RAIL consortia, WP 1 decided to take into account expert's opinion when setting the major derailment causes which have to be analysed more in detail in the following WP.

Another important issue for task 3.1 is how to deal with operational measures (like speed reduction) to prevent derailments. Here the assumption was made that only solutions are acceptable which are not reducing the performance in daily operation. Moreover the focus of D-RAIL is strongly related to technology-oriented solutions by the design of the proposal. Thereby operational measures are seen as the last remaining opportunity to reduce a risk for derailment when no other measure is possible. One major finding from several accident reports was also that reducing the speed in front of a slow speed zone sometimes lead directly to the derailment. Therefore the existence of the slow speed zone can be also seen as a contributing factor for a derailment. This example shall only give an impression of the complexity of the railway system.

3 Cause consequence chains for major derailment causes

Different fault states of infrastructure and of wagons often show interdependencies. In the Austrian research project “SUParBahn – safety relevant monitoring-parameters for the railway system” these relations were systematically analysed and described by cause–consequence chains. Based on this, more detailed chains were developed, which focus on the major derailment causes. In the following the cause–consequence chains related to the eight major derailment causes identified in WP1, as well as further chains directly leading to a derailment are shown. Firstly, for common understanding some terminologies regarding the cause-consequence chains are clarified:

- *State*: property of track or vehicle with a (more or less) constant character over time.
- *Transition*: change of a state to another. Most of the transitions happen rapidly, but that is not a prerequisite for the definition of transitions.
- *Cause*: all states which may favour the occurrence of another state including the state (consequence).
- *Consequence*: all states including the derailment itself, which can arise due to other states. With the exception of the state ‘derailment’ consequences can be also causes, which can lead to another consequence, etc.
- *Mechanism*: a mechanism defines the whole process of getting from one state (cause) via a transition to another state (consequence). Thus, a cause-consequence chain with several states consists also of several mechanisms (as shown in Figure 3-1). Even if several causes lead to one consequence or if a cause can induce several consequences, the mechanisms of each cause-consequence relation have to be distinguished.

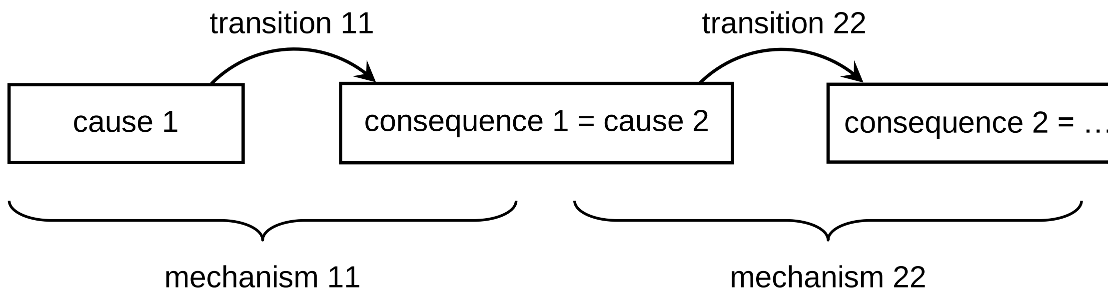

Figure 3-1: Definition of mechanism regarding to a simple cause-consequence chain

3.1 Axle rupture

breakage of stub shaft → derailment
Description: If the stub shaft breaks (structural failure), usually the affected axle box is not able to absorb and deflect vertical forces further on. Moreover as a consequence of a broken stub shaft the wheel may detach from the axle. Both probably lead to an abrupt derailment.

Suitable mitigation measures: The time between breakage of a stub shaft and a derailment is usually rather short. In general, a derailment is inevitable after the stub breaks while the train is moving. Thus it does not make much sense to recognise broken stub shafts.

broken axle ⟶ derailment
Description: If the axle breaks (structural failure), then there is no support for the individual wheels which always leads to an abrupt derailment.
Suitable mitigation measures: Similar to the breakage of a stub shaft, the time between breakage of an axle and a derailment is also usually rather short. In general, a derailment is inevitable after the axle breaks while the train is moving. Thus there is no demand to recognise broken axles.

3.1.1 Preceding causes

faulty bearing (before overheating) ⟶ faulty bearing (overheated) ⟶ breakage of stub shaft
Description: Material properties of bearings and axles are negatively influenced by the high thermal stress. If the temperature exceeds a critical value, overheating, thinning and fracture of the stub shaft might happen.
Suitable mitigation measures: Before an overheating of faulty bearings takes place, some types of bearings make a characteristic noise, which may be recognised by acoustic monitoring systems. Recognising the ongoing degradation of bearings condition in such an early stage allows the train to continue without any limitation to an operational suitable location (e.g. end of train run, shunting yard, etc.) and detaching the vehicle. If an overheating has already occurred, wayside hot box detection systems are able to measure the surface temperature of the bearing (housing) contactless and thereby recognise such defects while the vehicle is moving. In this case the train has to be stopped immediately to let the bearing(s) cool down. Afterwards the train has to proceed to the next maintenance point with reduced driving speed (to prevent further thermal stress on axle and on stub shafts).

faulty bearing (before overheating) ⟶ faulty bearing (overheated) ⟶ broken axle
Description: Material properties of bearings and axles are negatively influenced by the high thermal stress. If the temperature exceeds a critical value, overheating, thinning and fracture of the axle might happen.
Suitable mitigation measures: Because of the similar cause-consequence chain as above, the mitigation measures are identical.

faulty running surface / wheel spot ⟶ broken axle
Description: Faulty running surface leads to force peaks therefore causing higher vertical forces between wheel and rail. Due to the high stress, cracks on the axle may occur, which facilitate the breakage of the axle. Furthermore, the stress may damage axle boxes and cause additional failures.
Suitable mitigation measures: A faulty running surface or flat wheel spots are not directly monitorable during the vehicle's run. But the resulting force peaks may be measured and interpreted by axle load checkpoints. Furthermore with vehicle side stress measurements placed on particular locations at the bogie or frame, these peaks can also be recognised. If the peaks are too high, the vehicle has to be stopped at the next suitable location defined by an infrastructure manager and transferred to a maintenance centre. Independently, the running surface can be checked visually by staff or also supported by ultrasonic measurement in workshops (during regular inspection or after recognition of excessive force peaks).

faulty suspension ⟶ broken axle
Description: Components of a faulty suspension can slide on the axle. If the friction remains for a long period, the axle might break due to thermal stress. Furthermore, a faulty suspension may lead to a shifted load of a wheel. Due to the higher stress cracks on the axle may occur, which facilitate the breakage of the axle.
Suitable mitigation measures: In general, faulty suspension or faulty components of the suspension are not directly monitorable during the vehicle's run. But a possible shifting of wheel loads or axle loads can be measured and identified as a dangerous state by axle load checkpoints. In case of considerable defects of the suspension, the whole vehicle body can get an inclination, which is recognizable by a trackside vehicle profile measurement. If differences of axle or wheel loads are too high or the vehicle profile exceeds the allowed limits, the vehicle has to be stopped at the next suitable location defined by an infrastructure manager, checked if other reasons like displacement of cargo have caused the irregularity and (when indicated) transferred to a maintenance centre. Conspicuous differences of wheel loads or strains within components of the vehicle's frame or bogie can also monitored by onboard stress detectors. Similar to trackside monitoring, the train has to be stopped if there are irregularities detected. Furthermore, suspension defects are also recognizable by visual inspection in the yard or in the workshop.

faulty frame ⟶ broken axle
Description: If some elements of a faulty frame slide on an axle, the generation of thermal stress and/or material wear due to friction may lead to a breakage of

the axle. Furthermore, a faulty frame may lead to shifted load of wheels. Due to the higher stress cracks on the axle may occur, which facilitate the breakage of the axle.
Suitable mitigation measures: In general, a faulty frame is not directly monitorable during the vehicle's run. But a possible shifting of wheel loads or axle loads can be measured and identified as a dangerous state by axle load checkpoints. If there differences of axle or wheel loads are too high, the vehicle has to be stopped at the next suitable location defined by an infrastructure manager, checked if other reasons like displacement of cargo have caused the irregularity and (when indicated) transferred to a maintenance centre. Conspicuous differences of wheel loads or strains within components of the vehicle's frame can also monitored by onboard stress detectors. Similar to trackside monitoring, the train has to be stopped if irregularities are detected.

overload (continuous) ⟶ broken axle
Description: If one car is continuously overloaded, its components will be highly stressed and the wear of affected components will be increased. This might lead to the occurrence of cracks on the axle and/or the breakdown of the axle. In detail, the long term fatigue will manifest itself as a defect that will then propagate in a fracture mode. Thus time to fatigue defect initiation is long - time from initiation to failure is short.
Suitable mitigation measures: Too high axle or wheel loads can be detected by axle load checkpoints. If the loads are too high, the vehicle has to be stopped at the next suitable location defined by an infrastructure manager. Considerable overloading can also be monitored by onboard stress detectors. Similar to trackside monitoring, the train has to be stopped if there are irregularities.

3.1.2 Operational Examples

Broken Axle Derailment Canadian National Railways Quebec, Canada February 2001

On 15 February 2001, CN train No. G-894-31-14 derailed 25 cars at Mile 12.56 of the Drummondville Subdivision, near Trudel, Quebec. Twenty-four cars were destroyed, together with a main-track switch, the signal system, and 800 metres of track.

The derailment was caused by the fatigue fracture in an axle on car CNWX 107921. The fatigue failure occurred at a site where accumulation of moisture created corrosion pitting, which led to the initiation and development of fatigue fractures, and consequently, the axle failure. At the time of failure, the fatigue fracture covered over 65 percent of the fracture surface. Initiation occurred at sites with corrosion pitting in the axle journal fillet. While the fracture surfaces were highly oxidized, there were no signs of overheating on any of the components. The corrosion pitting on the axle journal fillets, as well as spalling on the bearing ring, cones and axle roller bearings, indicated that moisture penetrated and accumulated in the area.

Figure 3-2: Failed axle

Figure 3-3: Failure surface of axle

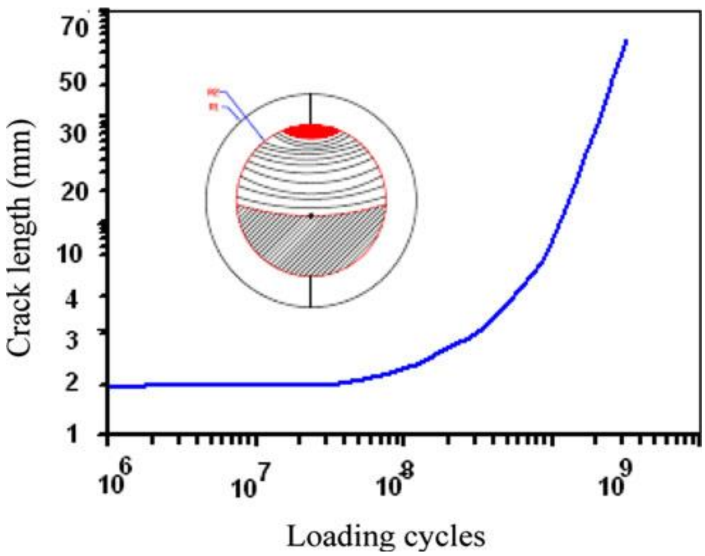

Figure 3-4: Crack growth behaviour

Burnt off Journal Bearing Derailment CN February 1999

On 06 February 1999, Canadian National eastward freight train No. M-304-41-05, travelling from Hornepayne, Ontario, to Toronto, Ontario, derailed 20 cars at Mile 248,5 of the Ruel Subdivision. The derailed cars (the 21st to the 40th behind the locomotives) included a loaded tank car of liquefied petroleum gas and two tank cars loaded with a flammable liquid mixture. One of the tank cars of the benzene mixture was punctured during the derailment resulting in a fire that burned for several days.

The cause of the derailment was a burnt-off axle journal bearing (BOJ - overheated bearing). The roller bearing at the L-3 (Axle 3 Left wheel) location on the south side of car CN 604697 overheated and seized, resulting in a burnt-off axle. The mode of failure BOJs is well known. As the roller bearing overheated and seized, the axle extruded, causing a reduction in the axle cross-sectional thickness. After sufficient thinning occurred, the overheated axle could no longer support the weight of the loaded car and complete axle fracture ensued. The nature of the failure that led to the overheating of the roller bearing could not be determined due to the amount of damage. However, the weight of the loaded car was within allowable limits, and the load was equally distributed over the length of the car body. The wheel had travelled less than half the number of miles expected before requiring replacement; the number of miles travelled by the wheel set was not considered to be a significant risk factor. The condition of the car as examined after the accident indicates that there were no obvious signs of the car having had a bearing problem that should have been identified during inspections performed by employees while car was en route.

Figure 3-5: Bearing Cap with Burnt Off and Fractured Axle

3.2 Excessive track width

variation of track gauge $\longrightarrow$ derailment
Description: Too large or too small track gauge might lead to a derailment. Excessive gauge can lead to hunting or high angle of attack, associated high lateral forces and Y/Q values and either wheel climb or rail overturning with

resulting gauge widening and risk of wheel-drop. Tight gauge can also result in high Y/Q and forcing of wheelset up and out of track gauge.
Suitable mitigation measures: A variation of track gauge, which includes an excessive track width, can be monitored by geometry measurements of a recording car. Especially in the US, for a generic evaluation approach of the measured data, simulations are used in addition. In detail, the recording car simultaneously calculates – in real time – the response of multiple rail vehicle types each at a wide range of travelling speeds. Furthermore, a track strength inspection system mounted on an inspection vehicle (also referred to as Gauge Restraint Measurement System - GRMS) which apply controlled Y and Q forces and measure the dynamic gauge widening can identify high risk gauge widening locations. This measurement is incorporated into US FRA track safety standards. In general, if sections are found which do not comply with the requirements, the track has to be maintained. In principle, high lateral forces (especially in curves or curve transitions) caused by the variation of track gauge can be recognized by onboard lateral acceleration/force measurements. In the US, the wheel set of the recording car is instrumented to monitor high dynamics of vehicle movements to reliably identify critical sections of the track. Similar to the procedure for geometry measurements, bad sections have to be reconditioned. The already mentioned high lateral forces can be also monitored trackside by axle load checkpoints, if they are able to measure Y-forces. But the detection of high force values on the measurement site only indicates problems of the track width, if they occur along the track especially at the measurement site. Locally restricted problems won't be detectable by axle load checkpoints.

3.2.1 Preceding causes

worn rail ⟶ variation of track gauge
Description: High abrasive lateral attrition leads to increased wear of the gauge face, which means increase of track gauge.
Suitable mitigation measures: The wear of rails can be measured by laser-based measurement on a recording car, which thereby also measures the track gauge. If the allowed limits are exceeded, the rails have to be reconditioned.

faulty rail pad ⟶ variation of track gauge
Description: If the rail pad of concrete sleepers is missing or faulty, the track gauge might be increased.
Suitable mitigation measures: There are no measurement based mitigation measures available for checking the condition of rail pads.

faulty rail fastening ⟶ variation of track gauge
Description: A faulty rail mounting implies a loose connection between rail and sleepers, which might lead to an increased track gauge (e.g. rail overturning).

Suitable mitigation measures: A loose connection between rail and sleepers can be recognized by a track strength inspection system mounted on an inspection vehicle (also referred to as Gauge Restraint Measurement System - GRMS) which apply controlled Y and Q forces and measure the dynamic gauge widening. If some irregularities have been identified, the reason for track weakness has to be identified. In case of faulty rail fastenings, they have to be renewed. Furthermore, with video inspection on a recording car even faulty rail fastening can be directly detected. Identified faulty fastenings have to be renewed.

Aged timber → variation of track gauge
Description: Old timber sleepers have reduced capability to deal with lateral track forces, which might generate an overturning moment and lead to an increased track gauge.
Suitable mitigation measures: Sleepers made of timber are typically used in shunting yards, but not on the open track of freight corridors. Due to the focus of D-RAIL, mitigation measures are not considered.

cracks in concrete sleeper → variation of track gauge
Description: Longitudinal or lateral cracks of concrete sleepers lead to a reduced capability to deal with lateral track forces, which might generate an overturning moment and lead to an increased track gauge.
Suitable mitigation measures: Track strength inspection system mounted on an inspection vehicle (also referred to as Gauge Restraint Measurement System - GRMS) which apply controlled Y and Q forces and measure the dynamic gauge widening can identify high risk gauge widening locations to include locations where sleeper shoulders are loose, where there is rail seat abrasion of concrete sleepers (and thus dynamic gauge widening). If some irregularities have been identified, the reason for track weakness has to be identified. In case of cracks in the concrete sleepers, they have to be renewed.

overload (continuous) → variation of track gauge
Description: If one car is overloaded continuously, its components will be highly stressed and the wear and material fatigue of affected components will be increased. As a consequence, the superstructure will be stressed.
Suitable mitigation measures: Too high axle or wheel loads can be detected by axle load checkpoints. If the loads are too high, the vehicle has to be stopped at the next suitable location defined by an infrastructure manager. Conspicuous overloading can also be monitored by onboard stress detectors. Similar to trackside monitoring, the train has to be stopped if there are irregularities.

3.2.2 Operational Examples

Timber sleeper: Canadian National Railways derailment of freight train on July 14, 2011

On 14 July 2011, Canadian National freight train Q10251-10, proceeding southward at 40 mph, derailed 11 multi-platform intermodal cars carrying 86 containers at Mile 243,10 of the Bala Subdivision near Waterfall, Ontario. Approximately 6800 feet of track was damaged or destroyed including the Waterfall south siding switch.

The cause of the derailment was dynamic gauge widening. Car DTTX 724638 derailed when the L3 and L4 wheels on the articulated C truck of DTTX 724638 dropped into gauge on a 3°-curve due to elevated track loading, localized low rail negative cant and inadequate rail-rollover resistance. A combination of non-conforming wheel/rail contacts, track-alignment variations and worn truck components, none requiring urgent in-service attention, produced increased lateral curving forces and a higher angle of attack on both the lead and trailing wheel sets at the point of derailment. At the same time, insufficient low rail fastening, low rail negative cant and wheel contact further to the field side of the low rail reduced the low rail resistance to rollover. The low rail canted out, enabling the L3 and then the L4 wheels to follow each other across the rail head and drop into gauge almost simultaneously.

The derailment conditions resulted from the combined effects of the weakened track structure, and high lateral loading (Y) due to worn truck component condition and the poor cornering behaviour of the double stack car. The weakened track structure would have been detected using a GRMS type track strength measurement system.

Figure 3-6: Bent and lifted gauge-side low rail spikes at the point of derailment

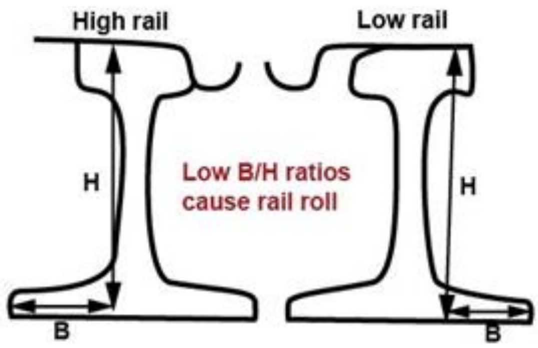

Figure 3-7: High Rail Roll: Y·H > Q·B

Concrete sleepers - Amtrak Derailment of April 3, 2005 on BNSF

On April 3, 2005, westbound Amtrak passenger train No. 27, consisting of a single locomotive unit and four passenger cars, derailed at milepost (MP) 58.562 on the BNSF Railway Company's (BNSF's) Northwest Division. The train was travelling 60 mph on single main line track when it derailed.

The cause of the derailment was dynamic gauge widening due to excessive concrete crosstie abrasion which allowed the outer rail to rotate outward and create a wide gauge track condition. At the derailment site there were 19 consecutive concrete crossties that exhibited rail seat abrasion, ranging in depth from 1/16 inch to 1 1/4 inches into concrete surface on the field side of the outside curve rail. These abrasions created voids between bottom of rail base and top of concrete crossties, which allowed the rail to deflect downward and rotate outward under load, resulting in gauge widening as trains passed over the area.

Rail seat abrasion occurs under tie pads, where the cement surface of the tie is abraded by repeated flexing of the rail under load, aided by the presence of moisture and gritting agents. As abrasion of the rail seat increases in depth; the rail head can rotate outward and allow the gauge to widen under train traffic. Once the pad area starts to deteriorate, the concrete abrasion process accelerates rapidly, rail cant is compromised and outer rail base corner (field side) rotated outward.

This would have been detected by a GRMS equipped track recording car.

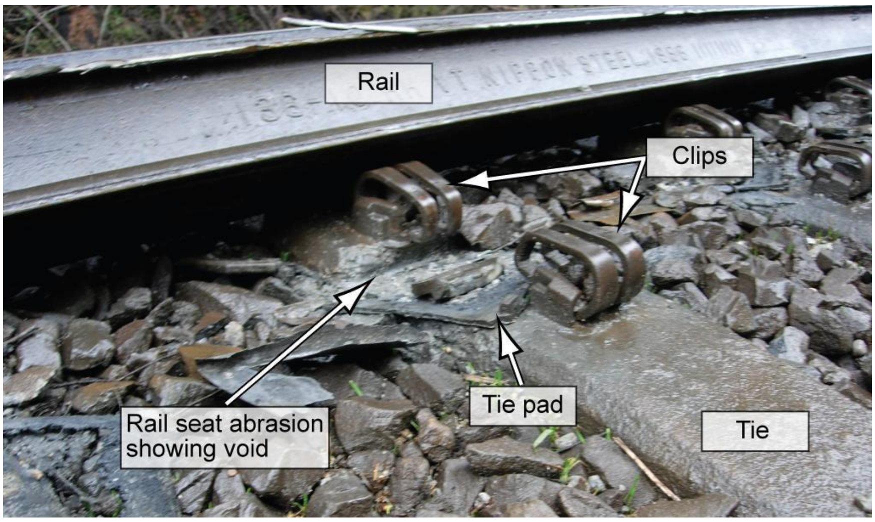

Figure 3-8: Rail seat abrasion and rolled over rail

Figure 3-9: Depth of abrasion approximately 25 mm

3.3 Wheel failure

broken wheel ⟶ derailment
Description: If a wheel breaks (structural failure), then it is not able to offer a guidance anymore. Therefore an abrupt derailment probably would take place.
Suitable mitigation measures: The time between breakage of a wheel and a derailment is usually rather short. In general, a derailment is inevitable after the wheel breaks while the train is moving. Thus there it does not make any sense to recognise broken wheels.

faulty flange of wheel ⟶ derailment
Description: An increased wear of the wheel flange and a resulting thin flange can result in the flange “picking the switch” and forcing itself in between the switch rail and stock rail of a closed switch point. Excessive wear also results in wide gauge and associated high dynamic loads due to high lateral play between rails and wheels. This may lead to a derailment by wheel climb under special operational conditions. Furthermore, if parts of the wheel flange are broken out (structural failure), the guidance will be missed completely and an abrupt derailment is most likely.
Suitable mitigation measures: A faulty flange (e.g. thin flange, irregular angle or profile of flange) can be detected by trackside laser based wear measurements. If the irregularity is too high, the vehicle has to be stopped at the next suitable location defined by an infrastructure manager and transferred to maintenance centre (with reduced speed). The condition of the wheel flange can also be checked in the workshop by visual inspection or laser based wear measurement systems. In case of high irregularities, the wheel has to be reconditioned or renewed.

High lateral forces due to mentioned high dynamic loads can be monitored trackside by axle load checkpoints, if they are able to measure Y-forces. In case of detected irregularities, the vehicle has to be stopped at the next suitable location defined by the infrastructure manager and transferred to maintenance centre (with reduced speed).

3.3.1 Preceding causes

blocked brake or wheel ⟶ overheated wheel ⟶ broken wheel
Description: tread brakes transform the moving energy due to friction into heat. As a result of the thermal stress on the running surface and the resulting formation of residual stresses during cooling a wheel breakage may happen.
Suitable mitigation measures: In general blocked brakes or blocked wheels are not directly detectable. But if an overheated wheel has already occurred, hot wheel detection systems are able to measure the surface temperature of the wheel contactless (infrared measurement). If the wheel is too hot, the train has to be stopped and/or the driving speed has to be reduced to prevent further thermal stress on the wheel.

faulty running surface / wheel spot ⟶ broken wheel
Description: Faulty running surface (e.g. shelling or cracks on the surface) leads to force peaks therefore causing higher stress for wheel and rail. This may cause the formation of subsurface initiated rolling contact fatigue.
Suitable mitigation measures: Force peaks induced to the rail can be recognised by axle load checkpoints. Moreover, a faulty surface usually creates additional noise with a characteristic pattern. Thus, such defects can be monitored by trackside acoustic inspection systems too. Furthermore, the occurrence of force peaks can also be monitored by onboard vertical acceleration or force measurement. If too high peaks or defects are recognised, the vehicle has to be stopped at the next suitable location defined by the infrastructure manager and transferred to maintenance centre (with reduced speed). The running surface can be checked either at the yard or in workshop by visual inspection. Especially in workshops, the surface quality can also be determined by ultrasonic inspection. If irregularities occur, the wheel has to be reconditioned or renewed.

overload (continuous) ⟶ broken wheel
Description: If one car is overloaded continuously, its components will be highly stressed and the wear as well as (thermomechanical) fatigue of affected components will be increased. This might lead to breakdown of elements like the wheel.

Suitable mitigation measures: Too high wheel loads can be detected by axle load checkpoints. If the loads are too high, the vehicle has to be stopped at the next suitable location defined by an infrastructure manager. Conspicuous overloading can also be monitored by onboard stress detectors. The vehicle has to be stopped at the next suitable location defined by the infrastructure manager if there is massive overloading.

defects on bogie ⟶ broken wheel
Description: If defects on a bogie results in a bad running quality with high lateral forces, the wheel is additionally stressed. This can lead to cold cracks (fatigue) and to a breakage of the wheel.
Suitable mitigation measures: The already mentioned high lateral forces can be monitored trackside by those axle load checkpoints, which are able to measure Y-forces. Furthermore, these forces can be recognized by onboard lateral acceleration/force measurements. If too high forces occur, the vehicle has to be stopped at the next suitable location defined by an infrastructure manager and transferred to maintenance centre (with reduced speed).

internal cracks ⟶ broken wheel
Description: Internal cracks in the wheel lower the toughness of the wheel. As a consequence, a wheel with internal cracks may break during operation (particularly in inappropriate loading situations).
Suitable mitigation measures: Internal cracks can only be recognized by ultrasonic inspection in the workshop. If there are such cracks, the wheel has to be exchanged.

3.3.2 Operational Examples

CN Broken Wheel Derailment February 2011

On 12 February 2011 CN Train C 751–51–11 travelling westward at 45 mph, derailed at Mile 93.45, near Fort Fraser/Encombe British Columbia. The train comprised 2 head–end locomotives and 104 loaded coal cars, weighed 9873 tons and was 10 678 feet in length. The train was a unit coal train that travelled from Tumbler Ridge, British Columbia, to Prince Rupert, British Columbia, a distance of approximately 611 miles. A total of 36 cars derailed, cars 43rd to 78th inclusive.

The wheel rim had fractured in four places. The hub of the fractured wheel was still on the axle, but it had been forced inboard off its seat. The tread of the fractured wheel exhibited a large number of shells extending all around the circumference of the wheel, approaching the AAR maximum allowable limit. Apart from the shelling, the treads of both wheels were otherwise undamaged and they did not exhibit thermal cracks. There was no evidence of wheel overheating.

Laboratory analysis of the L2 wheel on car BCNE 900534 determined that the wheel fractured due to Vertical Split Rim (VSR) that extended around ¼ of the wheel circumference. The VSR originated approximately ¼ inch below the tread surface along the bottom of a shell. Subsurface crack parallel to the tread that caused the shell was visible. The L2 wheel was shelled all around its circumference and exhibited multiple surface and subsurface cracks, indicating significant rolling contact fatigue crack growth activity; the VSR had originated at the base of such a shell. No metallurgical defects that would have led to the failure were observed at the origin. Wheel hardness, chemical composition, microstructure, rim wear, flange wear, and hollow tread wear met requirements of applicable AAR standards.

Vertical Wheel Impact Detector should have detected this wheel before failure.

Figure 3-10: Fractured Wheel

3.4 Skew loading

displacement of the load ⟶ unbalance (during vehicle's run) ⟶ derailment
Description: Displacement of load might cause unbalanced loads for axles and their respective wheels. Unloaded wheels do not provide lateral guidance. This might lead to a wheel climb derailment under bad conditions (curve, track twist, etc).
Suitable mitigation measures: Unbalanced wheel loads can be recognised by comparing wheel and axle loads measured by axle load checkpoints. Furthermore, the occurrence of high stress can also be monitored by onboard stress detectors. If the load differences or stress values exceed certain limits, the vehicle has to be stopped at the next suitable location defined by an infrastructure manager and has to be checked. If displaced cargo is the reason for the differences in wheel loads or for high stress, the balance has to be reestablished (e.g. rearrangement of cargo). Another monitoring approach focuses on the detection of the displacement itself by trackside optical measurements (note that this works only for open cargo cars). The procedure in case of recognised cargo displacement is the same as the mentioned procedure in case of detected unbalances.

3.4.1 Preceding causes

faulty load fixation and fastener → displacement of the load
Description: Faulty fixation or insufficient fixation might lead to movement of the cargo and therefore cause unbalanced loading conditions. Moreover cargo might fall off the car and extend into the clearance profile.
Suitable mitigation measures: Loose cargo fastenings are detectable by trackside optical measurements. If faulty load fixations are recognised, the vehicle has to be stopped at the next suitable location defined by the infrastructure manager and the balance has to be reestablished (e.g. rearrangement of cargo).

3.4.2 Operational Examples

CN Shifted Load derailment of 10 December 2000

Canadian National (CN) train M-309-21-09 (the train), powered by 2 locomotives, consisted of 51 loaded cars and 44 empty cars derailed on 10 December 2010. It was approximately 6600 feet long and weighed about 8300 tons. The train was restricted to a speed of 50 mph due to the presence of empty gondola cars and was proceeding at 49 mph, with the throttle in idle, and the air brakes released when it experienced a train-initiated emergency brake application.

The train speed was lower than the balance speed, generating lateral forces around several curves, causing the banding around the load of lumber on car DWC 605462 to dig into the corners of the lumber, gradually lessening the degree of securement and allowing even greater movement as the trip progressed.

One strip of banding broke several miles before the derailment as one of the recovered pieces of banding had been dragged for a period of time. At about Mile 210.0, the load had shifted enough to knock the north side guard rails off and more banding broke at this time. The already unstable load moved again in the curve at Mile 214.07. Just before the lumber began to fall off, the unbalanced load caused one or more wheels on the south side of the car to lift and derail to the south, destabilizing the trailing car which also derailed. Upon striking the roadbed, the remaining banding broke, allowing the lumber to scatter over the tracks.

3.5 Excessive track twist

Excessive track twist → derailment
Description: Excessive track twist might cause dynamic roll or rocking of the rail vehicle with unloading of the wheel during the roll process. Unloaded wheels reduce Y/Q particularly in curves where Y increases. This might lead to wheel climb derailment in a curve where Y increases during curving and Q decreases due to dynamic roll from excessive twist.

Suitable mitigation measures: Excessive track twist can be monitored by geometry measurements of a recording car. Especially in the US, for a generic evaluation approach of the measured data, simulations are used in addition. In detail, the recording car simultaneously simulates – in real time – the response of multiple rail vehicle types each at a wide range of travelling speeds. In principle, high vertical and lateral forces due to vehicle rolling (result of track twist) can be recognized by onboard lateral or vertical acceleration/force measurements. In the US, the wheel set of a recording car is instrumented to monitor high dynamics of vehicle movements to reliably identify critical sections of the track. If such track sections are found, which do not comply with the requirements, the track has to be reconditioned.

3.5.1 Preceding causes

Poor ballast or subgrade ⟶ Excessive track twist
Description: Poor or fouled ballast conditions or poor subgrade support with inadequate ballast can lead to excessive track twist.
Suitable mitigation measures: There are no measurement based mitigation measures available for checking ballast or subgrade strength quality. There might be only the opportunity to check the subgrade by ground penetration radar which needs a high demand of interpretation work. Mitigation measures for excessive track twist were already described above.

3.5.2 Operational Examples

Canadian National Derailment Lac Bouchette, Quebec, 15 May 2006

On 15 May 2006, CN freight train M-36921-15 derailed near Lac Bouchette, Quebec. The train was travelling at 30 mph and consisted of 3 locomotives and 75 cars (72 loads, 3 empties), weighed 8780 tons and was 4750 feet long. 16 loaded and 2 empty cars, the 39th, 46th, and 50th to 65th cars from the head end, derailed.

Derailed car CNA 405536 (first to derail) and cars CNA 406497 (next to derail), CNA 406135 were “high cube” box cars loaded with paper.

Derailment findings showed the 39th, 46th and 50th cars (high cube box cars) derailed while entering the exit spiral of the 5-degree 45-minute curve as a result of wheel lift; specifically track warp condition (excessive track twist) in spiral of left-hand curve caused the derailment. The design and loading of the first three derailed cars (high cube box cars with high center of gravity) made them more susceptible to wheel lift. Higher than usual snowfall and its melting in the spring affected sub grade and accelerated deterioration of track geometry.

Real time vehicle track dynamic analysis system could have identified the emerging series of defects as sufficient to cause a derailment.

3.6 Track height/cant failure

Improper cant/track height ⟶ derailment
Description: Improper cant height for operating can result in excessive centrifugal forces and high lateral loads on the outside of a curve. Alternately excessive cant can result in the vehicle overturning to low side of curve if speed is too low; e.g. train has to slow down or stop.
Suitable mitigation measures: The track height or cant can be monitored by geometry measurements of a recording car. Especially in the US, simulations are used in addition for a generic evaluation approach of the measured data. In detail, the recording car simultaneously calculates – in real time – the response of multiple rail vehicle types each at a wide range of travelling speeds. In principle, high vertical and lateral forces due to wrong cant or track height can also be recognized by onboard lateral or vertical acceleration/force measurements. In the US, the wheel set of the recording car is instrumented to monitor high dynamics of vehicle movements to reliably identify critical sections of the track. If such track sections are found, which do not comply with the requirements, the track has to be reconditioned.

3.6.1 Operational Examples

Excessive Track Elevation (Cant) - CN Shifted Load derailment of 10 December 2000

As noted in 3.4.2, for Canadian National (CN) train M-309-21-09 travelling at 49 mph due to equipment restrictions, the curves on the CN subdivision were designed for high speed, and a one-degree curve with a three-inch superelevation, such as the one at Mile 214,07, has a balance speed of 65,46 mph (the force of gravity to the inside of a curve will be balanced by the centrifugal [lateral] force to the outside of a curve). The operation of a train at any speed less than this, such as a maximum of 50 mph in this case, while not unsafe, results in a greater force being experienced to the inside of a curve. This force would be particularly strong on a bulkhead flatcar loaded with lumber as the centre of gravity would be quite high. Therefore, it is likely that the load had been encountering lateral forces, shifting the load from one side of the car to the other, all along the subdivision. These forces caused the banding to dig into the corners of the lumber, gradually lessening the degree of securement and allowing even greater movement as the trip progressed, resulting in the load shift derailment discussed in 3.4.2.

Excessive Track Elevation (Cant) - Cape Breton and Central Nova Scotia Railway derailment of 18 April 2004

On 18 April 2004, Cape Breton and Central Nova Scotia Railway (CBNS) freight train 301-18, proceeding westward on the Hopewell Subdivision, derailed 10 cars at Mile 51,7 near Linacy, Nova Scotia. Nine of the ten derailed cars were pressure tank cars loaded with liquefied petroleum gas, UN 1075. There were no injuries, and there was no release of dangerous goods. The train was travelling at 30 mph at the time of the emergency brake application.

There were many curves on the territory. The curve at the derailment location was a compound three- to four-degree curve, with five inches (125 mm) or more superelevation (track cant) at some points through the body of the curve. The superelevation corresponded to a balance speed (the speed at which the weight of a car would be equally distributed on both rails and no lateral force) of 45 mph. This superelevation was suitable for trains that were travelling over the subdivision at higher speed prior to 1993. The speed has since been reduced to 30 mph; however, the superelevation remained generally unchanged. With train operations at less than the balance speed, the low rail was subjected to increased lateral forces.

The likelihood of derailment is related to the ratio of lateral to vertical force (Y/Q) acting on the head of the rail. When a car is going around a curve at underbalanced speed, the low rail vertical force is larger than the vertical force applied on the high rail and the wheel flanges contact the low rail gauge face, resulting in large gauge spreading forces at the low rail. Wheels rolling on the high rail tend to have a lower vertical force and, therefore, a higher Y/Q ratio, making wheel climb or lift more likely. Entry spirals are the point where a car’s outer lead wheel of the lead truck forces the truck to swivel, increasing the lateral forces on the rail and that wheel’s L/V ratio. The point at which track destruction started was in the entry spiral of the curve; this is an area where tank cars, due to their rigid construction, are prone to derail in the presence of any track irregularities, such as the excessive elevation in combination with wide gauge and weak tie (sleeper) restraint.

The train derailed as a result of a combination of track conditions (excessive superelevation, wide gauge, and defective sleepers) when rigid pressure tank cars, which are prone to derailment in areas of track irregularities, were negotiating an entry spiral of a three- to four-degree compound curve at underbalanced speed.

3.7 Rail failures

broken rail $\longrightarrow$ derailment
Description: A breakage with a damaged rail head might cause a loss of guidance. If there is a vertical breakage of the rail, the rail will move laterally under load. Both might cause a derailment (e.g. wheel drop).
Suitable mitigation measures: Broken rails are detectable by track circuits of conventional signalling systems. Thereby, the current flow through the rails is disrupted, if a rail break leads to an electrical isolation. Furthermore, the loss of rail sections can be recognized by video inspection, by magnetic flux measurement or by eddy current measurement (in each case done by a special recording car). Independent of the monitoring approach, if a broken rail is detected, the traffic has to be stopped immediately by closing the track and the corresponding track section has to be reconditioned.

3.7.1 Preceding causes

overloading (dynamic) → faulty rail surface → broken rail
Description: Recurrent stress due to wheel loads, especially high loads resulting from overloaded vehicles, may damage the surface of rails (rail fatigue). As a general consequence of defects on the rail surface, there will be higher vertical and lateral force peaks at the rail-wheel-contact of subsequent traffic which cause higher stress for wheel and rail. This increased stress raises the risk for breakage of a rail (especially cold climate forces broken rails).
Suitable mitigation measures: For protection of the rail surface against mentioned damage, axle load checkpoints are able to detect overloaded vehicles. If the loads are too high, the vehicle has to be stopped at the next suitable location defined by an infrastructure manager. Considerable forces due to overloading as well as force peaks due to surface defects can be monitored by onboard vertical acceleration or force measurement. Similar to trackside monitoring, the train has to be stopped if irregularities are recognised. Defects on the rail surface can be detected by ultrasonic inspection, by magnetic flux measurement or by eddy current measurement (in each case done by a special recording car). If some irregularities have been identified, the corresponding track section has to be reconditioned.

faults inside rail → broken rail
Description: Material fatigue induces cracks on the surface that propagate in the rail (see previous chain with faulty rail surface) as well as internal cracks, which reduce the toughness of a rail. Thus, such faults inside the rail raise the risk for breakage of a rail (especially cold climate forces broken rails).
Suitable mitigation measures: Internal rail defects (cracks, etc.) can be detected by ultrasonic inspection, by magnetic flux measurement or by eddy current measurement (in each case done by a special recording car). If some irregularities have been identified, the corresponding rail section has to be renewed.

worn rail → broken rail
Description: High lateral and longitudinal wear cause higher stress for rails. This might lead to a breakage of a rail.
Suitable mitigation measures: Excessive wear of the rail can be recognized by laser-based wear measurement done by a special recording car. If some irregularities have been identified, the corresponding track section has to be reconditioned.

3.7.2 Operational Examples

Derailment of CSX freight Train derailment March 12, 2007 near Oneida, New York

The train consisted of 3 locomotives and 78 cars, travelling at 47 mph. Twenty-nine cars derailed (cars 25-54), six tank cars were breached, including four carrying liquefied petroleum gas, one carrying toluene, and one carrying ferric chloride. An explosion and fire followed that led local emergency response officials to close two elementary schools and evacuate a 1-mile area around the derailment site. Estimated damages and environmental cleanup costs were $ 6,73 million.

Cause of derailment was rail fracture under the wheel of the 25th car in the train. The fracture was a large detail fracture in the rail head that most likely was a primary fracture. The detail fracture originated from a longitudinal shelling crack that propagated below the running surface of the rail and turned downward to form the detail fracture. This fracture propagated in fatigue until it penetrated more than 70 percent of the existing head cross section. The detail fracture measured 55 mm (2,2 inches) wide and 50 mm (2 inches) deep and extended into the web of the rail.

Proper management of the ultrasonic testing using risk based UT scheduled could have found the defect and detected the defect before the derailment.

Figure 3-11: Rail Defect – Detail Fracture from Shell

Figure 3-12: Detail Fracture from Shell

3.8 Spring and suspension failure

faulty suspension → derailment
Description: A faulty suspension can be for instance a cracked or twisted bogie frame, cracked springs, etc. In general defects of the suspension may cause a loss of contact between wheel and rail. Furthermore, the vehicle body may get an inclination. In addition, due to the reduced absorption capability of faulty suspensions the vehicle body may oscillate. Both might lead to a derailment by wheel climb. Furthermore, mentioned oscillations may lead to extensive Y and Q forces. Thus, a faulty suspension may also result in fatigue and structural failures of the bogie elements and lead to an abrupt derailment.
Suitable mitigation measures: The mentioned load rejection is detectable by axle load checkpoints. Moreover, these checkpoints are able to detect the load oscillations due to the described body motions. A considerable inclination of the vehicle body is recognizable by a trackside vehicle profile measurement. In the case of conspicuous unbalances, inclinations or oscillations, the vehicle has to be stopped at the next suitable location defined by an infrastructure manager, where it has to be checked, if a suspension failure is the reason for the detected irregularity. When indicated, the vehicle has to be transferred to a maintenance centre. Conspicuous differences or oscillations of wheel loads or strains within components of the vehicle’s frame or bogie can also monitored by onboard stress detectors. Similar to trackside monitoring, the train has to be stopped and checked if there are irregularities detected. The suspension can be visually checked against faults by staff in yards or in a workshop.

3.8.1 Preceding causes

overload (continuous) → faulty suspension	
Description: If one car is overloaded continuously, its components will be highly stressed and the wear of affected components will be increased. This might lead to a breakdown of suspension elements.	
Suitable mitigation measures: Too high axle or wheel loads can be detected by axle load checkpoints. If the loads are too high, the vehicle has to be stopped at the next suitable location defined by an infrastructure manager. Considerable overloading can also be monitored by onboard stress detectors. Similar to trackside monitoring, the train has to be stopped if there are irregularities.	

3.8.2 Operational Examples

Suspension Failure Derailment of 29 August 1996

On 29 August 1996, St. Lawrence & Hudson Railway (StL&H) freight train No. 902-29, proceeding eastward on the south track of the StL&H Winchester Subdivision, derailed 36 cars at Mile 42.7. One of the derailed cars, GATX 73738, turned on its side and released up to 1,900 litres (500 U.S. gallons) of hydrogen peroxide, a dangerous commodity. Two other cars caught fire.

Analysis of the derailment showed that the suspension damping components on car MSDR 81026 were worn to the extent that their ability to resist car body roll was reduced. It was determined that the empty, open-top hopper car MSDR 81026 experienced a wheel climb derailment due to excessive car body roll and speed-induced truck hunting. The excessive car body roll and susceptibility to truck hunting were attributable to the fact that worn truck components are not recognized as safety defects.

3.9 Any other causes

blocked brake or wheel → derailment
Description: Continuous braking may lead under bad situations (acceleration, curve movement, bad combination of cars regarding their weight) due to additional longitudinal forces to a derailment of one axle. Moreover the thermal stress of wheel and axle may lead to a displacement of a wheel on the axle and thus to a reduced distance between the wheels. Therefore the risk of a derailment is rising caused by a play between rails and wheels.

violation of clearance gauge → derailment
Description: If the clearance profile is exceeded by massive objects, a crash with applications might lead to a derailment.

faulty buffer → derailment
Description: If there are cracks on the buffer disc, the sliding of discs will be handicapped. Derailments or overriding buffers might be the consequence.

overriding of buffers → derailment
Description: Due to an overriding of buffers it is not possible for buffer discs to slide and therefore an axle can be pressed out of the track.

objects within the clearance gauge → derailment
Description: If objects extend into the clearance profile, a crash with parts of a moving vehicle might occur. If the object is massive then such an event might lead to a derailment. Also objects laying in the superstructure might cause a derailment.

3.10 Clustering of causes

Following the expert's opinion and their naming, Table 3-1 shows the separation of derailments into:

- wheel climb related derailments: happen typically due to dynamics in wheel rail interaction
- abrupt derailments due to a structural failure: caused by structural failures of any material involved
- wheel drop derailments: one wheel of an axle drops off the rails without wheel climb of the other wheel
- derailments due to crash: the application of a force during a crash with external objects induces a derailment

Of course there are several cause-consequence chains where more than one of these derailment types are possible. Those have also been indicated in this table.

Table 3-1: causes of the cause-consequence chains, which may lead directly to the state 'derailment' and corresponding type of derailment

causes	type of derailment
broken axle	abrupt derailment (structural failure)
breakage of stub shaft	abrupt derailment (structural failure)
broken wheel	abrupt derailment (structural failure)
faulty flange of wheel	dynamic derailment (wheel climb) or abrupt derailment (structural failure)

faulty suspension	dynamic derailment (wheel climb) or abrupt derailment (structural failure)
unbalance	dynamic derailment (wheel climb)
variation of width of track gauge	dynamic derailment (wheel climb) or wheel drop
broken rail	wheel drop
blocked brake or wheel	dynamic derailment (wheel climb) or abrupt derailment (structural failure)
violation of clearance gauge	derailment due to crash
faulty buffer	dynamic derailment (wheel climb)
overriding of buffers	dynamic derailment (wheel climb)
objects within the clearance gauge	derailment due to crash

4 Mitigation measures for selected derailment causes

Strategies for mitigation of derailments and their consequences have two major targets:

- lower the probability of occurrence of operational scenarios that may impose a high risk of derailments
- lower the probability of derailments by reducing the time of scenarios that may impose a high risk of derailments in operations

To fulfil these targets, in general such strategies aim to identify either existing derailment causes or preceding conditions which raise the probability of the occurrence of derailment causes. Furthermore, derailment causes are often not directly recognizable, but their effects can be monitored. Thus, mitigation measures can be roughly divided into:

- recognition of causes, which may lead to a major derailment cause
- recognition of existing derailment causes
- recognition of possible consequences of derailment causes

In the following, for each of the eight major derailment causes in Europe, which were identified in WP1, and for reasonable subcategories of these causes such a distinction is carried out. Based on this, mitigation measures in terms of systems or technologies, which allow monitoring of these subcategories of derailment causes, are presented. Thereby not only systems available on the market are considered but also well known developments (prototypes, etc) as well as future monitoring approaches, which seem to be promising from a present-day perspective.

In comparison to the cause-consequence analysis of chapter 3, the mitigation measures are mainly based on the US experience where higher axle loads are applied than in Europe and additionally double decker container trains. Therefore the identified root causes vary slightly, but on the other hand they already include a ranking of priorities for derailment mechanisms and suitable allocated mitigation measures. The mitigation measures from DNV report A1 “Assessment of freight train derailment risk reduction measures - Existing measures” [1] have been considered as a backbone for this chapter.

4.1 Axle rupture

Axle rupture is a structural failure of the axle which results in complete fracture of the axle component and the inability of the wheels to support the bogies or vehicle. Axle rupture includes fatigue failure of the axle due to repeated overloads, static and/or dynamic, and thermal failure of the axles, usually in conjunction with an overheated bearing and bearing/axle burn-off.

Table 4-1 Mitigation measures for derailment cause “axle rupture”

				T	T	T	T	T	T	V	V	Y	W	W	W
number of subcategory	subcategories of derailment causes	monitoring target	monitoring target type	axle load checkpoint (Q)	axle load checkpoint (Y and Q, resp. Y/Q)	wayside crack detection	hot box detection (infrared-based)	acoustic bearing detection	vehicle profile measurement	acceleration/force measurement (vertical)	stress detector	visual inspection	visual inspection	ultrasonic inspection	magnetic particle inspection
1	axle rupture (in general)	cracks on axle	preceding causes			c							a	b	a
2	axle rupture (in general)	faulty running surface	preceding causes	a	b					c		a	a		a
3	axle rupture (in general)	faulty suspension	preceding causes	a	b				b		c	a	a		
4	axle rupture (in general)	faulty frame	preceding causes	a	b						c				
5	axle fatigue	overloading	preceding causes	a	b						c				
6	axle fracture	overloading	preceding causes	a	b						c				
7	axle rupture due to thermal stress	faulty bearings (before overheating)	preceding causes					b							
8	axle rupture due to thermal stress	faulty bearings (overheated bearings)	preceding causes				a								

Legend:

T - track side
V - vehicle side (in general)
R - vehicle side (recording car)
Y - (shunting) yard
W - workshop

a - measures, which are well known and widely used
b - measures, which are already known but not widely applied (prototypes, etc)
c - measures, which might be relevant for the future

4.2 Excessive track width

Excessive track width is a failure mode in which the gauge of the track is widened in either a loaded or unloaded state. This widening can be due to degradation or improper installation of the rail fastener/sleeper system, loss of or inadequate strength of the fastening system (which will result in widening under load), excessive rail wear, excessive widening on curves, or transitions, or excessive bending of the sleepers under load usually with improper ballast support.

Table 4-2 Mitigation measures for derailment cause "excessive track width"

				T	T	V	V	R	R	R	R	R
number of subcategory	subcategories of derailment causes	monitoring target	monitoring target type	axle load checkpoint (Q)	axle load checkpoint (Y and Q, resp. Y/Q)	acceleration/force measurement (lateral)	stress detector	track strength testing	acceleration/force measurements on wheel sets	geometry measurements	simulation based evaluation of geometry measurements	video inspection of rail, sleepers and fastenings
9	excessive track width (in general)	poor fastenings of rails or sleepers	preceding causes					b				b
10	excessive track width (in general)	overloading	preceding causes	a	b		c					
11	excessive track width (in general)	track width	derailment causes							a	b	
12	excessive track width (in general)	high dynamics of vehicle movements	consequences						b			
13	curve and curve transitions	track width	derailment causes								b	
14	curve and curve transitions	high lateral forces	consequences		b	c						
15	rail overturning	rail overturning	derailment causes					b		a		b

Legend:
T - track side
V - vehicle side (in general)
R - vehicle side (recording car)
Y - (shunting) yard
W - workshop

a - measures, which are well known and widely used
b - measures, which are already known but not widely applied (prototypes, etc)
c - measures, which might be relevant for the future

4.3 Wheel failure

Wheel failure is a failure of the wheel to properly operate in the wagon/bogie/track system. It includes excessive wear of the wheel tread, flange or profile, cracking and resulting structural failure of the wheel to include both fatigue cracking and thermal cracking, and circumferential degradation (spalling, flat spots, “out-of-round”) which results in the development of excessive dynamic forces. It also includes catastrophic fracture of the wheel, usually due to fatigue or thermally initiated cracks which propagate to failure often under high dynamic load conditions.

Table 4-3 Mitigation measures for derailment cause “wheel failure”

				T	T	T	T	T	V	V	V	Y	W	W	W	W
number of subcategory	subcategories of derailment causes	monitoring target	monitoring target type	axle load checkpoint (Q)	axle load checkpoint (Y and Q, resp. Y/Q)	hot wheel detection	acoustic inspection	laser-based wear measurement	acceleration/force measurement (lateral)	acceleration/force measurement (vertical)	stress detector	visual inspection	visual inspection	ultrasonic inspection	laser-based wear measurement	magnetic particle inspection
16	cracks on running surface	cracks on running surface	derailment causes				c			c		a	a	a		a
17	internal cracks	internal cracks	derailment causes											a		
18	cold cracks (fatigue)	overloading	preceding causes	a	b						c					
19	cold cracks (fatigue)	poor performing bogie	preceding causes		b				c							
20	shelling (fatigue)	defects on running surface	derailment causes	a	b		c			c		a	a	a		a
21	hot cracks (thermal cracking)	overheated wheels	preceding causes			a										
22	excessive wear	thin flanges	derailment causes					a					a		a	
23	excessive wear	wide gauge dynamics	consequences		b											
24	excessive wear	flange angle/profile	derailment causes					a					a		a	

Legend:

T - track side
V - vehicle side (in general)
R - vehicle side (recording car)
Y - (shunting) yard
W - workshop

a - measures, which are well known and widely used
b - measures, which are already known but not widely applied (prototypes, etc)
c - measures, which might be relevant for the future

4.4 Skew loading

Skew loading is the development of excessive or unusually dynamic wheel/rail loads, to include vertical, lateral and/or longitudinal usually associated with improper loading of the wagon or fastening of the cargo. This includes non-uniform loading of the wagons which can generate excessive dynamic loadings at one side or end of the wagon, and shifting of the cargo which can result in poor wagon dynamic performance, load unbalance, and excessive dynamic loading at the wheel/rail interface.

Table 4-4 Mitigation measures for derailment cause "skew loading"

				T	T	T	V
number of subcategory	subcategories of derailment causes	monitoring target	monitoring target type	axle load checkpoint (Q)	axle load checkpoint (Y and Q, resp. Y/Q)	optical monitoring of loading	stress detector
25	skew loading (in general)	unbalanced vehicle	consequences	a	b		c
26	skew loading due to improperly fastenings	improperly fastened	preceding causes			c	
27	skew loading due to improperly fastenings	displacement of cargo	derailment causes			b	

Legend:
T - track side
V - vehicle side (in general)
R - vehicle side (recording car)
Y - (shunting) yard
W - workshop

a - measures, which are well known and widely used
b - measures, which are already known but not widely applied (prototypes, etc)
c - measures, which might be relevant for the future

4.5 Excessive track twist

Excessive track twist is a condition in which there is a repeated condition of excessive cross-level or cant of the track (i.e. the height of one rail over the other) along the length of the track, usually over a relatively short interval corresponding to one or two wagon lengths. Repeated here means there is a series of cross-level or cant defects in the track, over a length of the track, which generate adverse dynamic behaviour in certain classes of vehicles based on axle spacing, defect spacing-wavelength etc. This repeated cant condition, usually out of phase, generates a dynamic rolling or rocking response in rail vehicles which in turns generates excessive dynamic loading and/or excessive and unsafe dynamic movement. This condition can be due to non-uniform and uncorrected degradation of the track geometry, usually in the ballast or subgrade areas, or non-uniform track support conditions to include the fastener/sleeper/ballast/subgrade areas of the track.

Table 4-5 Mitigation measures for derailment cause "excessive track twist"

				V	V	R	R	R
number of subcategory	subcategories of derailment causes	monitoring target	monitoring target type	acceleration/force measurement (lateral)	acceleration/force measurement (vertical)	Acceleration/force measurements on wheel sets	geometry measurements	simulation based evaluation of geometry measurements
28	general excessive track twist	track twist	derailment causes			b	a	b
29	general excessive track twist	excessive vehicle rolling	consequences	c	c			

Legend:
T - track side
V - vehicle side (in general)
R - vehicle side (recording car)
Y - (shunting) yard
W - workshop

a - measures, which are well known and widely used
b - measures, which are already known but not widely applied (prototypes, etc)
c - measures, which might be relevant for the future

4.6 Track height / cant failure

Excessive track height/cant failure is a condition of excessive cross-level or cant of the track (i.e. the height of one rail over the other) along the length of the track, to include tangent (straight) track where one rail is excessively higher than the other rail or curve and transition track, where the cant is significantly higher (or lower) than the amount required for the speed and curvature of the track at that location. This cant condition leads to poor steering of the trains and generates a dynamic response that includes impact loading and excessive dynamic vehicle response. This condition can be due to non-uniform and uncorrected degradation of the track geometry, usually in the ballast or subgrade areas, or non-uniform track support conditions to include the fastener/sleeper/ballast/subgrade areas of the track.

Table 4-6 Mitigation measures for derailment cause "track height/cant failure"

				V	V	R	R
number of subcategory	subcategories of derailment causes	monitoring target	monitoring target type	acceleration/force measurement (lateral)	acceleration/force measurement (vertical)	geometry measurements	simulation based evaluation of geometry measurements
30	excessive cant / track height	excessive cant / track height	derailment causes	c	c	a	b

Legend:
T - track side
V - vehicle side (in general)
R - vehicle side (recording car)
Y - (shunting) yard
W - workshop

a - measures, which are well known and widely used
b - measures, which are already known but not widely applied (prototypes, etc)
c - measures, which might be relevant for the future

4.7 Rail failure

Rail failure is a failure mode that includes excessive wear of the rail head (top), gauge face (side), or profile, development of internal defects or cracks which will grow under traffic and result in structural failure of the rail, or surface degradation (surface spalling, shelling, rolling contact fatigue, etc) which results in the development of excessive dynamic wheel/rail forces. It includes catastrophic fracture of the rail, usually due to fatigue initiated cracks which propagate to failure.

Table 4-7 Mitigation measures for derailment cause “rail failure”

				T	T	T	V	R	R	R	R
number of subcategory	subcategories of derailment causes	monitoring target	monitoring target type	axle load checkpoint (Q)	axle load checkpoint (Y and Q, resp. Y/Q)	broken rail detector (signalling system)	acceleration/force measurement (vertical)	video inspection of rail, sleepers and fastenings	laser-based wear measurement	ultrasonic rail inspection	magnetic flux or eddy current
31	rail surface defects	(dynamic) overloading	preceding causes	a	b		c				
32	rail surface defects	rail surface defects	derailment causes					b			b
33	rail surface defects	force peaks	consequences				b				
34	rail fatigue	rail surface defects	derailment causes					b			b
35	rail fatigue	internal, crack propagation	derailment causes							a	b
36	loss of rail section	wear of rail	preceding causes						a		
37	loss of rail section	internal fatigue	preceding causes							a	b
38	rail break	rail break	derailment causes			a					

Legend:

T - track side
V - vehicle side (in general)
R - vehicle side (recording car)
Y - (shunting) yard
W - workshop

a - measures, which are well known and widely used
b - measures, which are already known but not widely applied (prototypes, etc)
c - measures, which might be relevant for the future

4.8 Spring and suspension failure

Spring and suspension failure is a failure of the suspension elements of the wagon bogie (or for single axle wagons, the suspension element of the axle). This failure of the suspension elements, which for freight wagons is usually a set of springs, includes failure of the springs such as due to cracking of the spring elements, movement of the springs out of position, failure of the bogie elements that support the springs, etc. This set of failure modes results in the development of excessive and unsafe levels of dynamic forces and/or movement of the bogies and wagons.

Table 4-8 Mitigation measures for derailment cause “spring and suspension failure”

				T	T	T	V	Y	W
number of subcategory	subcategories of derailment causes	monitoring target	monitoring target type	axle load checkpoint (Q)	axle load checkpoint (Y and Q, resp. Y/Q)	vehicle profile measurement	stress detector	visual inspection	visual inspection
39	crack bogie frame	crack bogie frame	derailment causes	a			c		a
40	twisted bogie frame (deformation, etc)	twisted bogie frame	derailment causes	a	b		c		a
41	faulty suspension (springs)	faulty suspension	derailment causes	a	b	b	c	a	a
42	faulty suspension (in general)	overloading	preceding causes	a	b		c		

Legend:
T - track side
V - vehicle side (in general)
R - vehicle side (recording car)
Y - (shunting) yard
W - workshop

a - measures, which are well known and widely used
b - measures, which are already known but not widely applied (prototypes, etc)
c - measures, which might be relevant for the future

4.9 Description of mitigation measures

4.9.1 Track side measures

In this section possible track side measures are mentioned. Certain mitigation measures were already investigated in the former project INNOTRACK (www.innotrack.eu).

- Axle load checkpoint (Q)

  Track side (track based) measurement system for measuring the vertical wheel/rail force Q of each wheel or each wagon passing over the checkpoint.

- Axle load checkpoint (Y and Q, resp. Y/Q)

  Track side measurement system for measuring the lateral wheel/rail force Y, the vertical wheel/rail force Q, and the ratio of Y/Q of each wheel or each wagon passing over the checkpoint.

- Trackside crack detection

  Track side measurement system to detect cracks in the wheels and/or axles of each wagon passing over the measurement system site.

- Hot box detection (infrared-based)

  Track side measurement system for measuring the temperature of each bearing (for each wheel) as the wagon passes over the measurement site. Infrared systems use non-contact infrared temperature measurement technology to measure this temperature.

- Hot wheel detection

  Track side measurement system for measuring the temperature of each wheel as the wagon passes over the measurement site. Infrared systems use non-contact infrared temperature measurement technology to measure this temperature.

- Acoustic bearing detection

  Track side measurement system for measuring the condition of each bearing (for each wheel) as the wagon passes over the measurement site. Non-contact acoustic measurement techniques coupled with acoustic signature analysis is used to detect acoustic signatures which represent bearings approaching failure, but before they generate sufficient heat to trigger the hot-box detectors.

- Vehicle profile measurement

  Track side measurement system for measuring the profile and condition of each wagon as it passes over the measurement site. Laser or other non-contact optical technology measures the width, height, and rotation (angle or tilt) of the wagon, to determine if the wagon has excessive movement or rotation (tilt).

- Acoustic inspection

  Track side measurement system for measuring the condition of each axle, bogie and wagon as it passes over the measurement site. Non-contact acoustic measurement techniques coupled with acoustic signature analysis is used to detect acoustic signatures which represent components approaching failure, but before they are visible or otherwise detectable.

- Optical monitoring of loading

  Track side measurement system for measuring the load distribution and condition of each wagon as it passes over the measurement site. Non-contact optical measurement techniques are used to detect improper load conditions or conditions of shifted load.

- Broken rail detector (signalling system)

  Track side measurement system for monitoring continuity of the rail usually by sending an electrical signal through the rail. In the event of a rail break, the continuity of the rail is disrupted and the signal detects the presence of the break, providing an indication of the rail break. Used when traditional, track (rail) based signal systems are not present in the track.

- Laser-based wear measurement

  Track side measurement system for measuring the profile and wear condition of each wheel as the wagon passes over the measurement site. Laser or other non-contact optical technology measures the width and height of the wheel flange, and the depth and profile of the wheel tread.

4.9.2 General vehicle side measures

- Acceleration/force measurement (lateral)

  Wagon based measurement of acceleration and/or force to determine if, for each wagon, excessive lateral dynamic forces or excessive movement of the vehicle is being generated.

- Acceleration/force measurement (vertical)

  Wagon based measurement of acceleration and/or force to determine if, for each wagon, excessive vertical dynamic forces or excessive movement of the vehicle is being generated.

- Stress detector

  Wagon based measurement of stress in key wagon components (e.g. wagon body, bogie structural elements, axles, etc.) for each wagon, to determine if excessive stress of the wagon components is being generated.

4.9.3 Vehicle side measures on recording car

- Track strength testing

  Measurement of the gauge widening resistance (gauge holding strength) of the track using an inspection vehicle that applies a controlled lateral (Y) and vertical (Q) load to the track and measures the gauge widening of the track under this known load (together with the unloaded gauge of the track).

- Acceleration/force measurements on wheel sets

  Instrumented wheel sets on an inspection vehicle that measure wheel rail forces (using strain gauged wheel sets or alternate technologies) and/or accelerations (using vertical/lateral/longitudinal accelerometers mounted on the axles or bogies) to detect track locations that generate these high levels of force or acceleration.

- Geometry measurements

  Inspection based measurement of the geometry of the track to include measurement of all of the key track geometry parameters of gauge, alignment (lateral), profile or vertical alignment, cant or cross-level, twist, curvature, etc. Usually using non-contact based systems to generate a space curve or chord offset measurement or a direct measurement of the parameter as appropriate. Also used to measure an integrated value of each parameter over a defined length of track to provide a condition index for each section of track.

- Simulation based evaluation of geometry measurements

  Dynamic simulation model that is used to perform a real-time analysis using a continuous input stream of track geometry data (on the track geometry car). The model generates response predictions for the car body bounce, roll angle, pitch angle, vertical acceleration, and vertical wheel. These values are determined on a foot-by-foot basis for every foot for which input geometry data is supplied. Using established thresholds for these values, response predictions are assessed to determine if the rail vehicle is well behaved, or if it exhibits adverse dynamic behaviour and derailment potential. The answer can be used to identify locations producing unsafe vehicle performance in the field and provide the railroad with a defect report that will allow fast corrective action to be taken.

- Video inspection of rail, sleepers and fastenings

  Inspection based system using video camera and related optical imaging technologies to record the condition of the track and its key elements, which are visible to an inspection vehicle. This includes rail surface condition, fastener and sleeper condition, ballast surface condition, etc. The inspection also includes the use of detection algorithms to aid in the detection of track and track component anomalies.

- Laser-based wear measurement

  Inspection vehicle based measurement system for measuring the profile and wear condition of rail at a predefined interval. Laser or other non-contact optical technologies are used to measure the width, height and profile of the rail.

- Magnetic flux or eddy current

  Vehicle based testing of the internal condition of the rail using magnetic field technology introduced into the surface of the rail to detect the presence of internal defects in the rail. Usually used as a complement or supplement to ultrasonic technology.

- Ultrasonic rail inspection

  Vehicle based testing of the internal condition of the rail using ultrasonic wave technology introduced into the surface of the rail (from ultrasonic crystals embedded in a fluid filled wheel or sliding shoe via a couplant medium). The reflected ultrasonic waves are used to detect the presence of internal defects in the rail.

4.9.4 Measures in shunting yards

- Visual inspection

  Inspectors perform visual inspection of both wagons and track in the shunt yard to detect defects or unsafe conditions.

4.9.5 Measures in workshop

- Visual inspection

  Inspectors perform visual inspection of wagons in workshop to detect defects or unsafe conditions.

- Ultrasonic inspection

  Use of fixed ultrasonic measurement techniques to measure the integrity of key wagon components such as axles and bogie frames in the workshop. Wagons or individual components are brought to the inspection system located in the workshop for testing.

- Magnetic particle inspection

  Magnetic particle inspections are typically carried out at axles and solid wheels in workshops. Thereby axles or wheels are magnetized. Metal discontinuities (cracks, etc.) cause a magnetic flux leakage, which can be made visible by the means of ferrous iron particles. Therefore this technique helps to detect fatigue cracks and other defects at an early stage of their development (surface micro cracks with width from 0,001 mm and more, depth from 0,01-0,03 mm).

4.9.6 Ranking of measures according to costs

In the following the costs of the acquisition of mitigation measures are roughly estimated and categorized into:

- High: > 500.000 $
- Medium: 100.000 $ - 500.000 $
- Low: < 100.000 $

This estimated cost represents the cost of acquisition of these mitigation /monitoring systems. In addition, there will be annual operating and maintenance costs as well as amortization of the acquisition costs over a defined life cycle.

Table 4-9: Ranking of mitigation measures according to estimated costs

Mitigation measure	Mitigation measure type	Estimated costs
Trackside crack detection	Track side	High
Vehicle profile measurement	Track side	High
Acoustic inspection	Track side	High

Optical monitoring of loading	Track side	High
Stress detector	Vehicle side	High
Track strength testing	Recording car	High
Acceleration/force measurements on wheel sets	Recording car	High
Geometry measurements	Recording car	High
Video inspection of rail, sleepers and fastenings	Recording car	High
Magnetic flux or eddy current	Recording car	High
Ultrasonic inspection	Workshop	High
Axle load checkpoint (Q)	Track side	Medium
Axle load checkpoint (Y and Q, resp. Y/Q)	Track side	Medium
Hot box detection (infrared-based)	Track side	Medium
Hot wheel detection	Track side	Medium
Acoustic bearing detection	Track side	Medium
Laser-based wear measurement	Track side	Medium
Simulation based evaluation of geometry measurements	Recording car	Medium
Laser-based wear measurement	Recording car	Medium
Ultrasonic rail inspection	Recording car	Medium
Acceleration/force measurement (lateral)	Vehicle side	Medium
Acceleration/force measurement (vertical)	Vehicle side	Medium
Broken rail detector (signalling system)	Track side	Low
Visual Inspection	Shunting yards	Low
Visual Inspection	Workshop	Low

4.10 Showcases

The rough estimation of the application level of mitigation measures (Table 4-1 to Table 4-8) was based on experts directly involved in T3.1. This estimation has been more detailed for some countries, following the established standard for Technology Readiness Assessment (TRA, [2]). Thereby the readiness of technologies is classified to 9 different categories, shown in Table 4-10.

Table 4-10: Definition of Technology Readiness Levels (TRL), Descriptions, and Supporting Information

TRL	Definition	Description	Supporting Information
1	Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.	Published research that identifies the principles that underlie this technology. References to who, where, when.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Publications or other references that outline the application being considered and that provide analysis to support the concept.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed.
4	Component and/or breadboard validation in a laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.	System concepts that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.
5	Component and/or breadboard validation in a relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.	Results from testing laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?
6	System/subsystem model or	Representative model or prototype system, which is well	Results from laboratory testing of a prototype

	prototype demonstration in a relevant environment.	beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
7	System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space).	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design?
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.	OT&E reports.

4.10.1 Comparison between experts opinion, OeBB, SBB and SNCF

The following matrices (Table 4-11 to Table 4-18) show the previously shown rough estimation of implementation of the mitigation measures as well as the estimation of OeBB, SBB and SNCF according to the TRA (technology readiness level 1 to 9). A hyphen indicates that a mitigation measure is not used in the country. A greyed cell symbolises that no evaluation was carried out (lack of information, etc.).

Axle rupture

Table 4-11: Axle rupture - comparison (meaning of fields from top to bottom: experts opinion, OeBB, SBB and SNCF)

number of subcategory	subcategories of derailment causes	monitoring target	monitoring target type	axle load checkpoint (Q)	axle load checkpoint (Y and Q, resp. Y/Q)	wayside crack detection	hot box detection (infrared-based)	acoustic bearing detection	vehicle profile measurement	acceleration/force measurement (vertical)	stress detector	visual inspection	visual inspection	ultrasonic inspection	magnetic particle inspection
				T	T	T	T	T	T	V	V	Y	W	W	W
1	axle rupture (in general)	cracks on axle	preceding causes			c - - 2							a 9 9	b 9 9	a
2	axle rupture (in general)	faulty running surface	preceding causes	a 8 7 5	b 8 - 1					c - 2		a 9 9	a 9 9		a
3	axle rupture (in general)	faulty suspension	preceding causes	a 8 9 5	b 8 - 1				b 6 9 1		c - 2	a 9 9	a 9 9		
4	axle rupture (in general)	faulty frame	preceding causes	a - 9 5	b - - 1						c - 2				
5	axle fatigue	overloading	preceding causes	a 9 9 5	b 9 - 1						c - 2				
6	axle fracture	overloading	preceding causes	a 9 9 5	b 9 - 1						c - 2				
7	axle rupture due to thermal stress	faulty bearings (before overheating)	preceding causes					b - - 5							
8	axle rupture due to thermal stress	faulty bearings (overheated bearings)	preceding causes				a 9 9 9								

Legend:
T - track side
V - vehicle side (in general)
R - vehicle side (recording car)
Y - (shunting) yard
W - workshop

a - measures, which are well known and widely used
b - measures, which are already known but not widely applied (prototypes, etc)
c - measures, which might be relevant for the future
1…9 - technology readiness level (TRL)

Excessive track width

Table 4-12: Excessive track width - comparison (meaning of fields from top to bottom: experts opinion, OeBB, SBB and SNCF)

				T	T	V	V	R	R	R	R	R
number of subcategory	subcategories of derailment causes	monitoring target	monitoring target type	axle load checkpoint (Q)	axle load checkpoint (Y and Q, resp. Y/Q)	acceleration/force measurement (lateral)	stress detector	track strength testing	acceleration/force measurements on wheel sets	geometry measurements	simulation based evaluation of geometry measurements	video inspection of rail, sleepers and fastenings
9	excessive track width (in general)	poor fastenings of rails or sleepers	preceding causes					b - 1				b 9 1
10	excessive track width (in general)	overloading	preceding causes	a 9 9 5	b 9 - 1		c - 2					
11	excessive track width (in general)	track width	derailment causes							a 9 9	b - 1	
12	excessive track width (in general)	high dynamics of vehicle movements	consequences						b 9 4			
13	curve and curve transitions	track width	derailment causes								b 9 1	
14	curve and curve transitions	high lateral forces	consequences		b 8 - 1	c - 4						
15	rail overturning	rail overturning	derailment causes					b - 1		a 9 9		b 9 1

Legend:
T - track side
V - vehicle side (in general)
R - vehicle side (recording car)
Y - (shunting) yard
W - workshop

a - measures, which are well known and widely used
b - measures, which are already known but not widely applied (prototypes, etc)
c - measures, which might be relevant for the future
1…9 - technology readiness level (TRL)

Wheel failure

Table 4-13: Wheel failure – comparison (meaning of fields from top to bottom: experts opinion, OeBB, SBB and SNCF)

				T	T	T	T	T	V	V	V	Y	W	W	W	W
number of subcategory	subcategories of derailment causes	monitoring target	monitoring target type	axle load checkpoint (Q)	axle load checkpoint (Y and Q, resp. Y/Q)	hot wheel detection	acoustic inspection	laser-based wear measurement	acceleration/force measurement (lateral)	acceleration/force measurement (vertical)	stress detector	visual inspection	visual inspection	ultrasonic inspection	laser-based wear measurement	magnetic particle inspection
16	cracks on running surface	cracks on running surface	derailment causes				c - - 4			c - 4		a 9 9	a 9 9	a 9 9		a
17	internal cracks	internal cracks	derailment causes											a - 9		
18	cold cracks (fatigue)	overloading	preceding causes	a 9 9 5	b 9 - 1						c - 4					
19	cold cracks (fatigue)	poor performing bogie	preceding causes		b - - 1				c - 4							
20	shelling (fatigue)	defects on running surface	derailment causes	a 8 8 5	b 8 - 1		c - - 4			c - 4		a 9 9	a 9 9	a 9 9		a
21	hot cracks (thermal cracking)	overheated wheels	preceding causes			a 9 9 9										
22	excessive wear	thin flanges	derailment causes					a - - 2					a 9 9		a 9 	
23	excessive wear	wide gauge dynamics	consequences		b 8 - 1											
24	excessive wear	flange angle/profile	derailment causes					a - - 2					a 9 9		a 9 	

Legend:
T - track side
V - vehicle side (in general)
R - vehicle side (recording car)
Y - (shunting) yard
W - workshop

a - measures, which are well known and widely used
b - measures, which are already known but not widely applied (prototypes, etc)
c - measures, which might be relevant for the future
1…9 - technology readiness level (TRL)

Skew loading

Table 4-14: Skew loading - comparison (meaning of fields from top to bottom: experts opinion, OeBB, SBB and SNCF)

				T	T	T	V
number of subcategory	subcategories of derailment causes	monitoring target	monitoring target type	axle load checkpoint (Q)	axle load checkpoint (Y and Q, resp. Y/Q)	optical monitoring of loading	stress detector
25	skew loading (in general)	unbalanced vehicle	consequences	a 8 9 9	b 8 - 1		c - 1
26	skew loading due to improperly fastenings	improperly fastened	preceding causes			c - - 1	
27	skew loading due to improperly fastenings	displacement of cargo	derailment causes			b - 9 1	

Legend:

T - track side
V - vehicle side (in general)
R - vehicle side (recording car)
Y - (shunting) yard
W - workshop

a - measures, which are well known and widely used
b - measures, which are already known but not widely applied (prototypes, etc)
c - measures, which might be relevant for the future
1…9 - technology readiness level (TRL)

Excessive track twist

Table 4-15: Excessive track twist - comparison (meaning of fields from top to bottom: experts opinion, OeBB, SBB and SNCF)

				V	V	R	R	R
number of subcategory	subcategories of derailment causes	monitoring target	monitoring target type	acceleration/force measurement (lateral)	acceleration/force measurement (vertical)	Acceleration/force measurements on wheel sets	geometry measurements	simulation based evaluation of geometry measurements
28	general excessive track twist	track twist	derailment causes			b 9 6	a 9 9	b 9 1
29	general excessive track twist	excessive vehicle rolling	consequences	c - 4	c - 4			

Legend:
T - track side
V - vehicle side (in general)
R - vehicle side (recording car)
Y - (shunting) yard
W - workshop

a - measures, which are well known and widely used
b - measures, which are already known but not widely applied (prototypes, etc)
c - measures, which might be relevant for the future
1…9 - technology readiness level (TRL)

Track height / cant failure

Table 4-16: Track height / cant failure - comparison (meaning of fields from top to bottom: experts opinion, OeBB, SBB and SNCF)

				V	V	R	R
number of subcategory	subcategories of derailment causes	monitoring target	monitoring target type	acceleration/force measurement (lateral)	acceleration/force measurement (vertical)	geometry measurements	simulation based evaluation of geometry measurements
30	excessive cant / track height	excessive cant / track height	derailment causes	c	c	a	b
				-	-	9	9
				4	4	9	1

Legend:

T - track side
V - vehicle side (in general)
R - vehicle side (recording car)
Y - (shunting) yard
W - workshop

a - measures, which are well known and widely used
b - measures, which are already known but not widely applied (prototypes, etc)
c - measures, which might be relevant for the future
1…9 - technology readiness level (TRL)

Rail failure

Table 4-17: Rail failure - comparison (meaning of fields from top to bottom: experts opinion, OeBB, SBB and SNCF)

				T	T	T	V	R	R	R	R
number of subcategory	subcategories of derailment causes	monitoring target	monitoring target type	axle load checkpoint (Q)	axle load checkpoint (Y and Q, resp. Y/Q)	broken rail detector (signalling system)	acceleration/force measurement (vertical)	video inspection of rail, sleepers and fastenings	laser-based wear measurement	ultrasonic rail inspection	magnetic flux or eddy current
31	rail surface defects	(dynamic) overloading	preceding causes	a 9 9 4	b 9 - 1		c - 4				
32	rail surface defects	rail surface defects	derailment causes					b 9 1			b 7 1
33	rail surface defects	force peaks	consequences				b - 4				
34	rail fatigue	rail surface defects	derailment causes					b 9 1			b 7 1
35	rail fatigue	internal, crack propagation	derailment causes							a 9 9	b 7 1
36	loss of rail section	wear of rail	preceding causes						a 9 9		
37	loss of rail section	internal fatigue	preceding causes							a 9 9	b 7 1
38	rail break	rail break	derailment causes			a - - 9					

Legend:
T - track side
V - vehicle side (in general)
R - vehicle side (recording car)
Y - (shunting) yard
W - workshop

a - measures, which are well known and widely used
b - measures, which are already known but not widely applied (prototypes, etc)
c - measures, which might be relevant for the future
1…9 - technology readiness level (TRL)

Spring and suspension failure

Table 4-18: Spring and suspension - comparison (meaning of fields from top to bottom: experts opinion, OeBB, SBB and SNCF)

				T	T	T	V	Y	W
number of subcategory	subcategories of derailment causes	monitoring target	monitoring target type	axle load checkpoint (Q)	axle load checkpoint (Y and Q, resp. Y/Q)	vehicle profile measurement	stress detector	visual inspection	visual inspection
39	crack bogie frame	crack bogie frame	derailment causes	a			c		a
				9			-		9
				4			1		9
40	twisted bogie frame (deformation, etc)	twisted bogie frame	derailment causes	a	b		c		a
				-	-				
				9	-		-		9
				4	1		1		9
41	faulty suspension (springs)	faulty suspension	derailment causes	a	b	b	c	a	a
				-	-	6			
				9	-	9	-	9	9
				4	1	1	1	9	9
42	faulty suspension (in general)	overloading	preceding causes	a	b		c		
				9	9				
				9	-		-		
				5	1		2		

Legend:
T - track side
V - vehicle side (in general)
R - vehicle side (recording car)
Y - (shunting) yard
W - workshop

a - measures, which are well known and widely used
b - measures, which are already known but not widely applied (prototypes, etc)
c - measures, which might be relevant for the future
1…9 - technology readiness level (TRL)

4.10.2 Conclusion

Finally the two showcases have shown that the first estimation carried out by the task partners closely matches the overall situation in Europe. It should be noted that the spread over Europe might vary a little more when looking into the fine scaling. Additional work will be carried out in WP4 to assess all mitigation measures in member countries of the EU.

5 Available risk assessment

Risk management includes the development of risk based tools to identify high risk locations in the track and provide guidance for improved inspection and/or preventive maintenance to reduce that level of risk. This is particularly the case for major derailment cause categories in the area of track or vehicle/track interaction failure, where failure or degradation can result in a derailment.

Several new generation risk management models that deal directly with track safety in several key track failure (and derailment) areas have been implemented on railways in the US. These risk management models include:

- Broken rail risk model which quantifies the risk of occurrence of a broken rail (and associated broken rail derailment) and allows railways to adjust their UT test schedules to reduce that risk.
- Track buckling risk model which identifies and prioritizes locations of high potential buckling risk and directs railway engineers to them for appropriate action.
- Vehicle/track geometry risk model which identifies and prioritizes locations of high potential for vehicle/track geometry related derailments.
- Track geometry defect risk model which quantifies the risk of occurrence of a critical geometry defect (FRA violation) and allows railways to adjust their track geometry car test schedules to reduce that risk.
- Switch inspection system and associated risk prioritization model that quantifies the condition of a switch (turnout) and provides prioritized ranking to the railroad for maintenance and safety intervention.

All these models described in the following rely on research that has been developed over the last several decades, and the resulting body of knowledge on the theory behind these track failure modes.

Additionally, in case of usage of systems for monitoring safety-related parameters of trains or of the track to prevent or to mitigate derailments, the requirements on system safety have to be considered. If such systems do not recognize hazardous states, the probability of a derailment can increase significantly. Thus, a best-practice risk assessment for estimation of the safety requirements for such systems is presented at the end of this chapter.

5.1 Broken rail risk management

Broken rail derailments represent one of the most expensive and dangerous derailment categories with a high potential for injury, death and damage due to the sudden and potentially catastrophic nature of this failure. Control of rail service defects by improved inspection efficiencies has the potential for controlling the risk of broken rail derailments by reducing the percentage of service defects and the associated service defect rate [3] [4] [5].

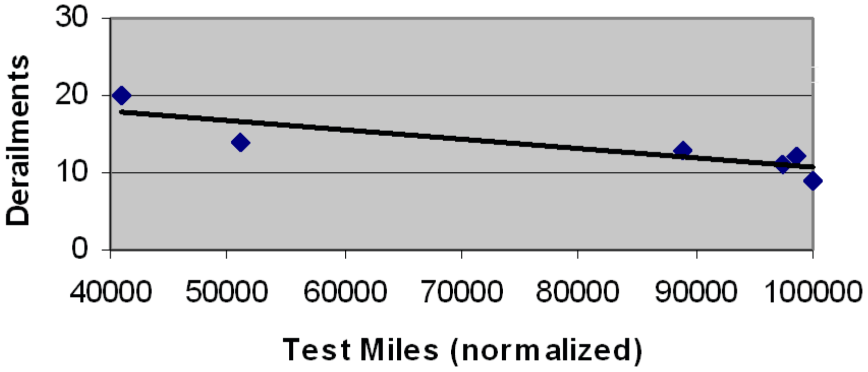

Figure 5-1: Derailment rate vs. test miles between 1995 – 2003

Increased testing has a direct effect on this behaviour, as shown in Figure 5-1 [3], where the number of derailments decrease with increased testing. However, increased testing is expensive and as such must be optimized. Rather, targeted increased inspection, focusing on “high risk” locations, offers a more cost effective alternative.

Quantification of the risk of broken rails, and using this quantification to focus rail testing resources, represents a recently introduced approach to fine tuning testing with a focus on reducing service defects, and thus broken rail caused derailments.

The objective of this analysis methodology is to schedule ultrasonic testing (UT) so that a defined level of risk (of rail failure) is held constant, even as rail ages. Risk is defined as the number of service defects (e.g. rail breaks) per mile per year, which, as shown above, is related to the occurrence of broken rail derailments. Table 5-1 presents risk guidelines developed through application of this broken rail risk methodology on a broad range of freight and passenger railways in North America and Europe [3] [5]. Analysis of defect records on thousands of track segments has shown that many locations of higher than acceptable risk do occur and that these locations have a higher probability of experiencing a broken rail. These high risk track segments must be addressed by improved UT inspection, either through the use of better equipment or through improved test scheduling.

Table 5-1: Broken rail risk guidelines

Risk - service defects (rail breaks)/mile/year	Traffic Type
0,09 to 0,10	General freight route (no passenger or hazardous materials)
0,07 to 0,08	Key freight line
0,06 to 0,07	Freight route with Hazmat but no passenger traffic
0,04 to 0,06	Freight with limited passenger traffic
0,01 to 0,03	Low-speed passenger route (less than 90 mph)
0,005 to 0,01	Moderate-speed Passenger route (90 to 125 mph)

0,001	High speed passenger line route (125 mph and higher)

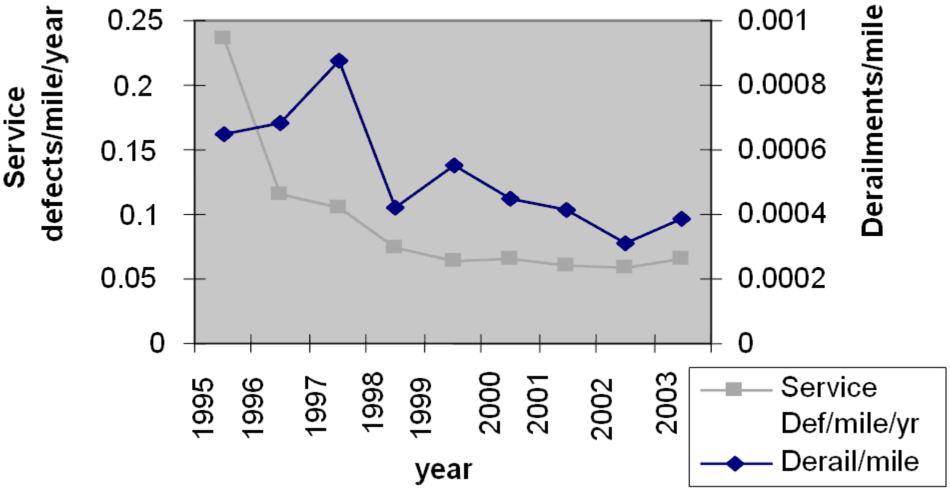

Figure 5-2: Derailment Rate vs. Service Defect Rate, US Class 1 RR (1995 – 2003)

Improved test scheduling has been achieved on several major rail systems in the US and Europe through application of this risk based approach with documented reduction in both service defects and in rail related derailments. This is illustrated in Figure 5-2, which shows service defect and derailment rate for a major US Class 1 railroad over a nine-year period from 1985 through 2003, with a well-defined reduction in service defect rate and in broken rail derailments from time of application of risk based ultrasonic testing in 1988.

5.2 Track geometry based risk management

Track geometry represents another major area of failure caused where the interaction between the vehicle and track is such that a combination of geometric parameters or repeated geometric anomalies can lead to unsafe vehicle dynamic response and subsequent derailment.

In order to address this derailment category, two risk management tools have been developed and implemented. The first is a track geometry defect risk model which quantifies the risk of occurrence of a critical geometry defect (FRA violation) and, in a manner similar to the broken rail risk management approach discussed previously, allows the railways to adjust their track geometry car test schedules to reduce that risk. The second is a vehicle/track geometry risk model which identifies and prioritizes locations with track geometry conditions that have a high potential for vehicle/track geometry related derailments.

Both approaches make use of the data provided by track geometry inspection cars which represent the primary method used by railways to inspect track for geometry and identify those locations where track geometry defects exist.

5.3 Risk based geometry car scheduling

The risk based track geometry inspection scheduling methodology focuses on the frequency of inspection itself and builds on the extensive work done in the area of rail testing, and uses a similar risk based approach for the identification of geometry based high-risk locations and the adjustment of the testing schedules based on that risk.

As such, this methodology includes:

- Definition of risk in terms of critical (FRA) track geometry defects.
- Use of both critical (FRA) defects and priority (next FRA class) defects as recorded by the track geometry car.
- Rate of track geometry defect development with tonnage.
- Track geometry car measurement reliability.
- Track geometry defect growth behaviour as a function of track and support conditions.
- This risk-based theory evaluates track geometry defects and traffic conditions, along with historic testing frequencies, to determine the optimal testing frequency [6]. The track being analysed is segmented based on track and operating continuity, and, for each segment, the risk-based approach is applied and an optimal test frequency developed.

Risk is defined as the number of critical defects per mile; where a critical defect corresponds to an FRA track geometry defect. Defining risk in this manner results in a critical defect rate such that the incidence of FRA exceptions (and potential derailments) is minimized. As in the case of rail test scheduling, the acceptable level of risk must be defined in terms of a number of key parameters to include presence of passenger trains or hazardous materials, importance of the route, speed and density of traffic, etc.

Application of this class of models (such as ZETA-TECH's *GeoTest* model) to several thousand miles of track geometry car data over several different US Class 1 railroads showed that numerous segments were identified where increased inspection was required, with frequency increasing between 6% and 50%. Other segments showed decreased inspection frequency allowed, with reductions of between 20% and 100%.

5.4 Real time vehicle-track interaction

Real time track geometry interaction assesses track geometry based, not only on static geometry standards, but also on the interaction between the track and vehicle and then using this to identify high risk locations for follow up maintenance action. Specifically, this has led to the development of dynamic simulation models (Among the models that do this real-time analysis of track geometry defects are ZETA-TECH's *TrackSafe* model, TTCI's Performance Based Track Geometry (PBTG) model and AEA's Real-Time Vampire model.) to perform this analysis in either real time or off-line, using a continuous input stream of track geometry data (e.g. on the track geometry car). The objective is to identify locations producing unsafe vehicle performance in the field and provide the railroad with an immediate defect report that will allow them to take fast corrective action.

In order to be a practical and effective system, any such real time analysis tool must identify locations in track likely to result in dynamically unsafe vehicle performance from a range of different vehicle types and speeds [7] [8] [9]. The need to assess track safety for a range of simulated speeds and vehicle types stems from the fact that not all derailments occur precisely at track speed; many occur during operations well below posted speed limits. Likewise different vehicles react differently to the same geometry conditions.

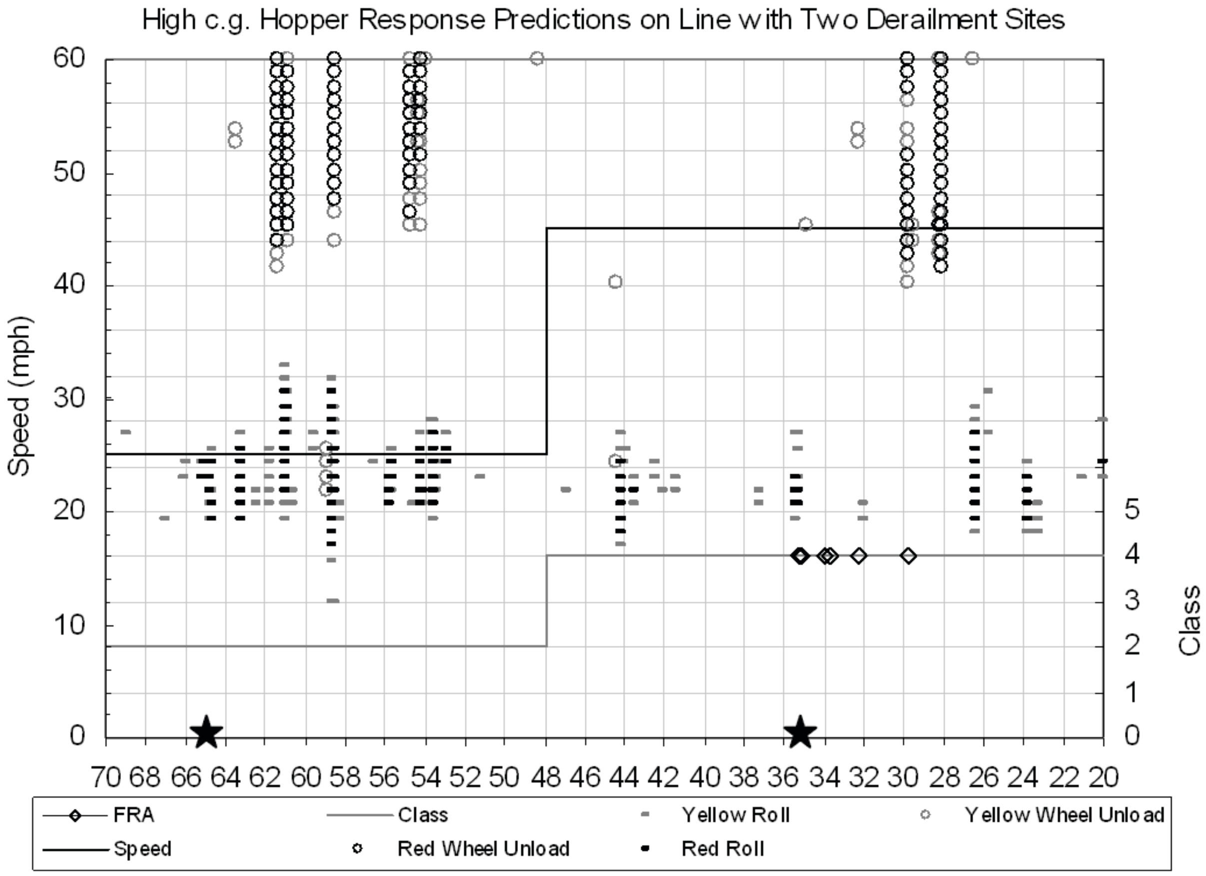

Figure 5-3: Derailment investigation predictions for high c.g. hopper car

A recent analysis of a rail line which had experienced several geometry related derailments is illustrated in Figure 5-3, which shows results from a recent derailment investigation. In this analysis, two derailment sites were both flagged with “red” and represent dynamic roll violations over a range of speeds. This result showed the importance of testing at a wide range of operating speeds since only in the small range of speeds from 20 to 25 miles per hour were red level roll warnings predicted.

5.5 Roadbed: track buckling risk management

Another high-risk area, which falls under the more general track caused derailment category of Roadbed, is that of track buckling. Track buckling, the sudden lateral movement of the track due to thermally generated longitudinal rail forces, remains a major track failure mode both in North America and worldwide.

A risk based methodology for the assessment of track buckling potential has been developed using track buckling theory and the newest generation of track buckling analysis models [10]. This methodology has been implemented into a production analysis model, (*BuckleRisk* model) which allows for large-scale application on large railway networks. This model is designed to identify high-risk track buckling sites using site-specific risk factors to develop a site “risk” value. Based on the magnitude of this value, the potential for a track buckle occurring at the site is defined and the need for any follow up action identified.

In this methodology the railway is divided into small homogeneous analysis segments, of the order of 0,1 to 0,2 mile in length, and, for each segment, a buckling risk value or “risk factor” is calculated based on track, traffic and environmental conditions present at that segment. These risk factor values are based on track buckling theory which relates the potential for track buckling to the increase in rail temperature above the neutral or force free temperature of the rail and to the buckling resistance of the track structure (see Table 5-2).

Table 5-2: Track Buckling Risk Parameters

Curvature
Track Grade
Train Braking/Acceleration
Tonnage
Presence of “Hard Spot” in Track
Track Characteristics • Rail size • Tie type • Fastener type • Anchoring • Tie spacing (in.) • Ballast type /condition • Track consolidation (MGT) • Shoulder width (in.) • Ballast crib condition • Track Class
Recent Maintenance Activity
Track /Rail Movement
History of Track Buckles
Time Since Last Adjustment
Rail Repair • Cold weather plug • Weld repair

The higher this risk value the greater the potential for track buckling at that site.

In a recent full system application on a US [10] Class 1 railroad, 24,200 track miles were analyzed, divided into 133,012 segments, with an average segment length of 0.18 mile. The resulting risk analysis identified 30 segments (0.02% of system) considered very high risk with index values greater than 80 (and an additional 961 segments (0.72% of system) considered high buckling risk with index values of between 70 and 79. The 30 very high-risk segments underwent immediate inspection by local forces. As a result of these follow up inspections, 9 of the 30 segments (30%) were destressed (rail removed) immediately (see Table 5-3). Overall, the application of the risk based buckling model identified over 100 very high risk sites during one buckling season.

Table 5-3: High Risk Segment Report of February 2004 and Follow up Action

Risk Factor	Sub Division Name	Line Segment	BMP	EMP	Action Taken	Notes
82	AURORA	3	98.23	98.38	Y	Destressed 04/12/04, 1" out
80	AURORA	3	180.93	181.11	Y	Destressed 04/16/04, 0.5" out
84	VALLEY	5	0	0.15	No	Field inspected, nothing found, discrepancies w / data
80	KOOTENAI RIVER	36	1,402.22	1,402.42	Y	Destressed 4 locations, 8.5" out
80	SEATTLE	51	10.39	10.51	No	Destressed 09/24/03, 1" out
80	SEATTLE	51	10.4	10.51	No	Destressed 12/02/03, 3.5" out
82	SIOUX CITY	144	108.09	108.11	No	Destressed on 7/29/03
80	SIOUX CITY	144	105.31	105.62	No	Notes stating reason for no destress
81	MARSHALL	197	144.53	144.67	Y	Destressed TNT 04/22/04
83	RED RIVER VALLEY	485	147.39	147.54	Y	Destressed but no date, 2" out
83	RED RIVER VALLEY	485	236.3	236.65	Y	Destressed but no date, 2" out
81	RED RIVER VALLEY	485	139.74	140.07	No	Destressed but no date, 1.5" out
81	RED RIVER VALLEY	485	144.55	144.83	No	Destressed but no date, 2" out
80	THAYER SOUTH	1,001	495.81	496.06	No	Still need to w ork on 1 Work Order, 6.5" out
82	CHICKASHA	1,003	721.69	721.95	No	Destressed but no date.
81	CHICKASHA	1,003	720.87	721.22	No	Destressed but no date.
80	ST JOSEPH	3,000	205.91	206.1	No	Is 0'45" curve not 5 degree curve
80	CHILLICOTHE	7,000	36.29	36.41	No	retied in 2003 w ith new ins jt cut in and 0" rail added
80	CHILLICOTHE	7,000	37.06	37.2	No	retied in 2003 w ith new ins jt cut in and 0" rail added
80	MARCELINE	7,000	264.47	264.69	Y	Destressed 4/16/04, 2.5" out
83	PANHANDLE	7,100	497.34	497.39	No	Gave 2 Work order numbers. No dates of action
83	PANHANDLE	7,100	489.8	490.02	No	Gave 2 Work order numbers, 4.5" rmvd. On 1 WO.
83	SLATON	7,107	38.65	38.83	No	Mail Note: Location of TO not in res. area. (?)
85	ARKANSAS CITY	7,400	261.05	261.25	No	Note: no rail added locations remaining
81	RED ROCK	7,400	416.56	416.74	Y	Removed 2" w hen w elding joint
85	GALVESTON	7,500	24.24	24.57	No	Destressed 11/19/03
80	GALVESTON	7,500	125.95	126.16	No	Destressed 11/25/03
83	LAMPASAS	7,508	218.72	218.89	Y	Destressed 03/31/04, 0.5" out
81	LAMPASAS	7,508	272.2	272.34	No	Destressed 07/02/03, 2.25" out
81	LAMPASAS	7,508	394.25	394.41	No	Destressed 11/12/03
30 High Risk Sites Reported: Action Taken on 9 sites (30%)						

5.6 Turnout condition assessment and risk management

Another major focus area for track caused derailments is the category of Switches. This category, with approximately 200 to 250 reported derailments per year, is particularly focused on turnouts and turnout condition related issues. New state of the art switch inspection systems and associated risk prioritization models that quantify the inspection based condition of a switch (turnout) that calculate a level of risk, can provide prioritized ranking to the railroad for maintenance and safety intervention.

Using the new generation inspection tools such as ZETA-TECH's *Automated Switch Inspection Vehicle* (ASIV) it is possible to quantify the condition of the turnout using condition measurements made in the field by this new generation inspection system. This Automated Switch Inspection Vehicle (ASIV) allows for automated inspection of the rail portions of turnouts to include switch point, frog, stock rail and closure rails on both the open and closed sides of the switch. The inspection vehicle uses a new generation high speed rail profile measurement system to measure the switch and frog profiles (see Figure 5-4) and then analyzes these profiles using newly developed state of the art switch analysis software (*SwitchWear*). The software analyzes all of the key measurement areas of the switch and frog to include such key safety parameters as the gap width between switch point and stock rail, vertical and side wear on the stock rail, relative height of the switch point and stock rail, gauge face angle and corner radius of the switch point, relative height and angle of the frog nose and wing rails, etc.

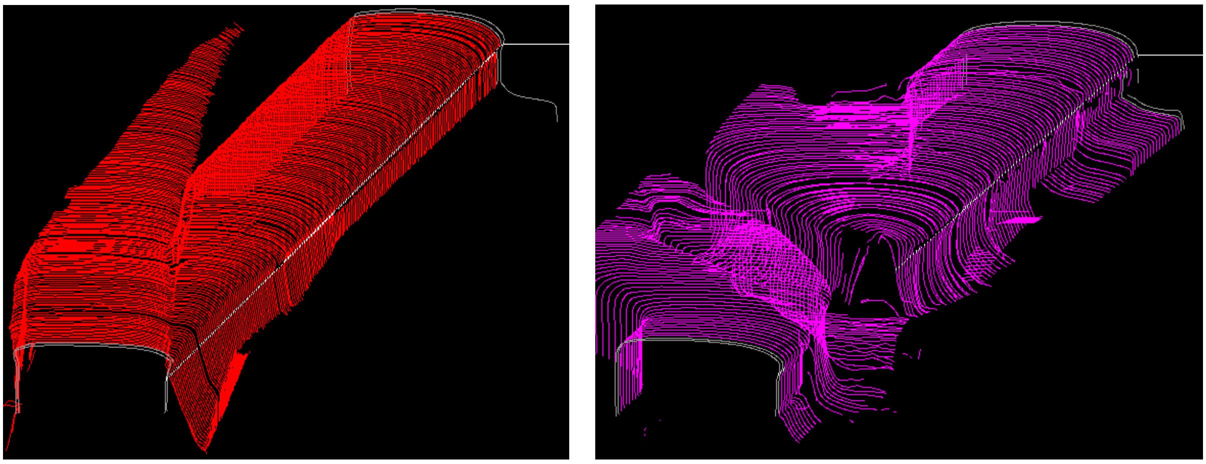

Figure 5-4: Three dimensional images: closed side of switch point and stock rail (left) and frog and wing rail (right)

In addition to the direct measurements of the switch and stock rails, the safety condition of the switch points, stock rails and frogs were checked against railroad and government standards to see if the conditions violated railway safety standards. These standards included checks to ensure there was no switch point damage, excessive wear or wear angle on the switch point or stock rail, unacceptable contact between wheel flange and the switch rail, sharp gauge corner profiles, etc. In addition the potential for a wheel to climb the switch point can be examined as shown in Figure 5-5. Results of field testing showed that the automated switch inspection vehicle has the ability to measure key switch point and stock rail wear and geometry parameters, and identify potential derailment sites,. The system also provides accurate data on switch and stock rail condition which allows for the monitoring of degradation over time.

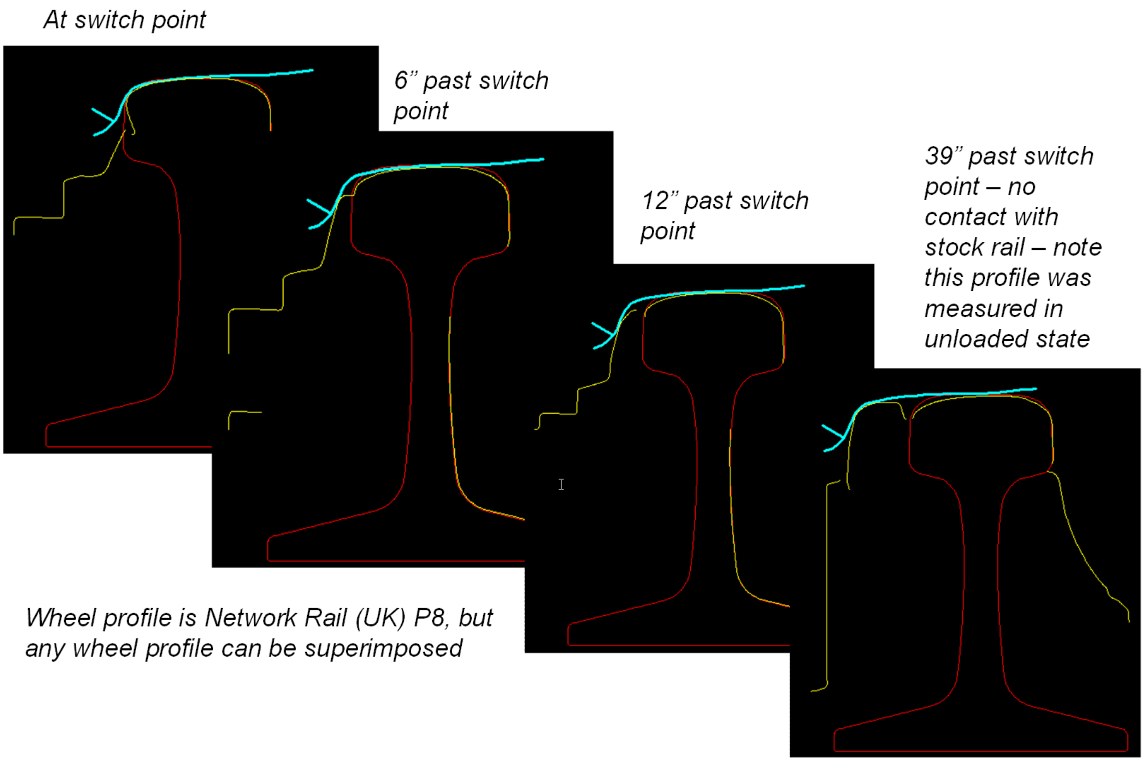

Figure 5-5: Wheel/Rail Contact Through Switch for Wheel Climb Safety Analysis

5.7 Best practice risk assessment

BP-Risk is a semi-quantitative approach for railway risk assessments, which has been published [11] and validated [12].

Semi-quantitative methods are a combination of qualitative and quantitative approaches. In [13], they are defined as "qualitative, model-based" risk assessment methods. This means, that for semi-quantitative risk assessment methods, numerical (quantitative) values are assigned to qualitative scales. Examples for semi-quantitative risk methods can be found in the automobile industry and in the IEC 62061 [14] standard "Safety of machinery".

For BP-Risk, semi-quantitative implies that on the outside, the risk analyst uses the front-end tables, provided by BP-Risk to assess the risk parameters. On the inside, there exists a risk model, which is implemented in the tables and actually uses numerical input values. Therefore BP-Risk uses the following risk model:

$R = f \cdot g \cdot s$,

where f is the hazard frequency - expressed as a Tolerable Hazard Rate (THR), g is the probability, that the considered hazard leads to an accident, and s represents the potential damage. The two risk parameters g and s are divided into sub parameters to ease their assessment.

The general approach for risk assessments with the help of BP-Risk includes the common aspects (as required by standards and regulations):

- System definition
- Hazard identification
- Consequence analysis with BP-Risk tables

- THR derivation with BP-Risk table

These steps are described in the following for the application of BP-Risk for the safety requirements of hot box detection systems.

5.7.1 Application example: safety requirements of a hot box detection system

Hot box detectors can be interpreted as monitoring devices to ensure the track guiding by measuring temperature as an indicator for failures at boxes or brakes. Thus the hot box detectors have to recognize if the temperature is exceeding a specified threshold. The considered function could be called: “hot box detection”.

For this example, the following assumptions were made:

- As 90 to 95% of all hot boxes are observed on freight trains, only freight traffic is considered for this analysis. The average speed limit for most European freight trains is 100 km/h.
- With the assumption that an on-site staff (e.g. station inspector) watches the trains and thus is able to discover possible hot boxes, it might be possible to prevent a hazard or even an accident through human mitigation.
- Experts estimate that every fifth to tenth hot box eventually leads to a derailment.

Hazard identification

If the hot box detection fails unnoticed and a hot box occurs, the resulting event could be called “track guidance not ensured”. One possible consequence could be a derailment caused by a broken axle stub. Thus, the considered hazard is the “failure of the hot box detection” (the hazard scenario assumes that a hot box already exists).

Another possible consequence of a hot box could be a fire in the vehicle. In the following this accident type is excluded within this analysis to reduce complexity.

Consequence analysis

To assess the potential mitigation of an accident and the possible consequences of an accident, the BP-Risk parameters are used for the risk analysis.

To assess parameter *G*, which assesses possible mitigation factors, two sub parameters are used: parameter *B* and *M*.

Subparameter *B* was previously called “operating density”, because it considers the possibility of a train entering an occupied track. For hot box detection and in particular for derailments, this aspect is not crucial. Thus, the original meaning of the quantitative parameter *B* was used in this case, which is the “confrontation probability of disadvantageous circumstances”, defined by [15]. This confrontation probability implies a situation in which at least one counter measure exists that can prevent the impending loss. Here, this probability is considered as how likely a hot box leads to a derailment. The experts judgment of every fifth to tenth hot box leading to a derailment is interpreted unlikely. Thus, for parameter *B*, value 2 is chosen (refer to Table 5-4). The mitigation factor of not having a hot box, when the hot box detection fails is not considered here and has to be included in a following causal analysis.

Table 5-4: Probability of confrontation (Parameter *B*)

B	probability of confrontation	explanation
1	low	hardly ever does the hazard lead to an accident
2	regular	rarely does the hazard lead to an accident
3	high	frequently does the hazard lead to an accident

Subparameter *M* assesses if human mitigation is possible. Thus, it assesses a situation where the hazard already exists and where only human intervention can prevent an accident. For hot box detection this could be the train driver or an on-site staff member (e.g. a station inspector). The train driver has no possibility to detect a hot box by himself – sometimes he doesn't even recognize a derailment when only one wheel derails and the air pipe is still working well. Therefore the only potential intervention can be carried out by an on-site staff member who could observe a hot box and then prevent the train from driving on (e.g. by immediate stopping of the train in terms of interlocking system). In the following the assumption is made, that this can be considered as a rule-based action, because it is not daily routine, but still possible. Hence, the *M* value is determined to be 3 for the on-site staff member and 5 for the train driver, if you refer to Table 5-5. Therefore we can take 4 the value for parameter *M*.

Table 5-5: Human prevention (Parameter *M*)

M	human prevention	explanation
1	often possible	"skill-based" action under disadvantageous circumstances
3	seldom possible	"rule-based" action under disadvantageous circumstances
5	almost never possible	random human intervention

Accordingly, parameter *G* has the following value: $G = B + M = 2 + 4 = 6$

To assess the potential damage *S*, three sub parameters are used: parameter *T*, *V* and *A*.

Subparameter *T* considers the mass of the trains, because parameter *S* takes the kinetic energy into account. As Table 5-6 illustrated, the more mass the trains have, the higher is the *T*-value and thus the higher will be the risk value afterwards. It can be assumed that the mass of the trains doesn't really play a role for this accident type. It can even be advantageous to prevent a derailment, if the train is heavier because of the higher Q-force in relation to the Y-force (in accordance with the derailment criteria defined by NADAL). Therefore, the subparameter *T* won't be considered and thus we assign it the value 0.

Table 5-6: Train category (Parameter *T*)

T	train category	example

1	short-distance passenger traffic	local train, rapid-transit, commuter rail
2	long-distance passenger traffic + high speed traffic	trainset, passenger train, night train, motorail train
3	freight traffic	freight trains

The decisive speed *V* is estimated to be around 100 km/h for our considered freight trains. This would correspond to a high speed when referring to Table 5-7. Thus, the value for *V* is chosen to be 3.

Table 5-7: Decisive speed (Parameter *V*)

V	decisive speed	example
1	minor	shunting, running at sight, freight corridor
2	medium	line with limited traffic
3	high	local line, regional service
4	very high	long distance or high speed line

Subparameter *A* assesses how many people might be affected by the potential accident. In this example, a derailment is considered as the typical accident type. But also freight trains are considered, where no passengers are on board the train.

Usually derailments of a freight train don’t lead to harm of persons but only to damage to property. Hence, the number of affected people can be estimated to be no person but only damage to property, which is not considered by BP-Risk at this stage. That corresponds to *A* having the value of 0.

But it has to be noted, that follow up events like collisions or even fire of dangerous goods are not considered here, because those would be worst case scenarios which have a very low frequency of occurrence. BP-Risk uses typical scenarios, which lead to typical consequences. If worst case scenarios would be assessed, there is no need for a method like BP-Risk, because one would have to derive the highest safety requirements anyway which lead to unnecessary high costs for the components.

Table 5-8: Number of affected persons (Parameter *A*)

A	number of affected persons	example
1	single person	collision with obstacle (not other train)
2	few persons	collision at level crossing
3	several persons	derailment
4	many persons	severe derailment
5	very many persons	head-on or end-on collision (of trains)

Parameter *S* can then be calculated by adding the three subparameters: $S = T + V + A = 0 + 3 + 0 = 3$. Altogether the sum of *G* and *S* is 6 + 3 = 9.

THR Derivation

To derive the THR for the considered function, Table 5-9 is used. The sum of *G* and *S* corresponds to a certain tolerable hazard rate (THR). For considered example, this would be THR = $3 \cdot 10^{-5}$/h. Thereby BP-Risk uses RAC-TS as a risk acceptance criterion which was implemented in Table 5-9.

It is important to note that the hot box detection is not determined by a technical component only at this stage. The function itself can be carried out by on-site staff only or by technical components or a combination of the two although there would be differences in reliability and availability. Moreover networked technical components would allow trend analysis and therefore a higher level of operational safety and performance. In case of networked components, an in-depth analysis would have to take into account that the devices are “connected” with each other.

Also an in-depth analysis would have to consider the aspect of having only technical wayside components. For this example, it can be assumed as a simplification, that the devices are independent from each other and don’t belong to a network.

Table 5-9: Table for deriving a tolerable hazard rate (THR)

THR = $(\sqrt{10})^F$ (per function)	*G* + *S*	Description
$3 \cdot 10^{-5}$ / h	9	once in 3 years
10^{-5} / h	10	once in 10 years
$3 \cdot 10^{-6}$ / h	11	once in 30 years
10^{-6} / h	12	once in 100 years
$3 \cdot 10^{-7}$ / h	13	once in 300 years
10^{-7} / h	14	once in 1,000 years
$3 \cdot 10^{-8}$ / h	15	once in 3,000 years
10^{-8} / h	16	once in 10,000 years

6 Evaluation approach for mitigation measures

The following approach allows making a cost-benefit-analysis for the implementation of on-board or wayside train monitoring systems as well as recording cars based upon prevented damages of superstructure, vehicles, etc.

6.1 Trackside monitoring systems

The occurrence probability of a derailment is the first input parameter of a cost-benefit-analysis and can be estimated from the accident data base of an infrastructure manager. Thereby, from the total quantity of derailments only those derailments which can be avoided by trackside monitoring system are relevant.

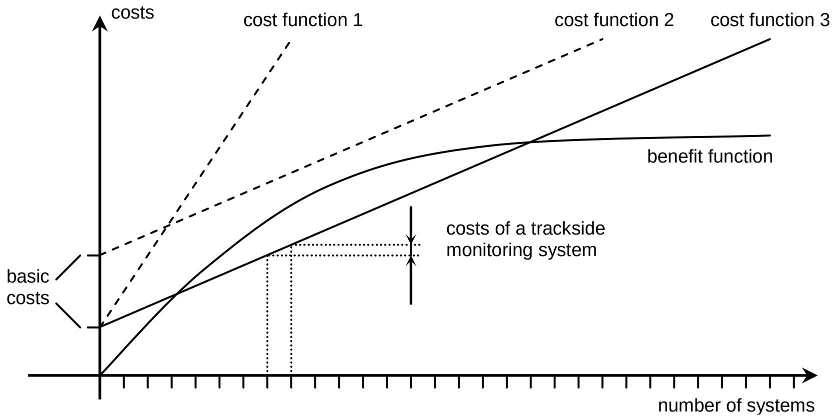

Figure 6-1: Cost-benefit-analysis for damage reducing strategy for trackside monitoring

The benefit of using monitoring systems results from the saving of costs for reparation of infrastructure and vehicles. By using the occurrence probability of derailments, the probability of prevention due to monitoring with a certain number of systems and the average costs of a derailment, the total saving of cost can be determined. Afterwards, with variation of the number of used detectors, a similar calculation has to be done which considers the variation of probability for detection of fault states before derailments happen. Figure 6-1 shows the resulting benefit function quantitatively.

The cost-analysis focuses on the investments of trackside monitoring systems, which increase linearly with the number of installed sensors. Before the first installation of a monitoring system it is also necessary to ensure an operational integration of all collected data. Thus basic costs must be also taken into account.

Figure 6-1 shows three different cost functions. Function 1 illustrates low basic costs but high costs per system, which leads to a comparatively fast increase of the total costs. In contrast, function 2 represents high basic costs and low detector prices per system. Due to these constrains both functions are located above the benefit function. Thus, in both these scenarios the costs will be always higher than the investments and therefore the introduction of a system is not economically feasible.

Cost function 3 shows the combination of low basic costs and low unit costs. Here an economical feasible zone can be found, which should be reached with an implementation of trackside monitoring systems. As suggested in Figure 6-1 there will be a significant area of optimal benefit where the difference of costs and benefit has a global maximum. From an economical point of view an infrastructure manager should ensure that the number of installed detectors is in this range.

6.1.1 Example of hot box detection in Austria

Based upon the Austrian experience with derailments caused by faulty bearings (overheated), the average costs are about 1.000.000 €. Taking this into consideration, the required network coverage is to have installations every 30 km on main lines and every 50 km on secondary lines at approximately 200 locations. The installation costs for one location on a double track line are approximately 150.000 €. This leads to an overall investment of approximately 30.000.000 € for the whole network. Assuming a life cycle of 15 years for each hot box detection system, the annual investment is 2.000.000 €. The basic costs in this showcase are allocated to the maintenance centre, which is required to guarantee the performance of the system in daily operation. To build up a maintenance centre, basic costs of 100.000 € are incurred.

Without the implementation of hot box detection systems, there would be about 10 derailments per year, which would lead to costs of 10.000.000 €. If there are fewer systems located in the network, the benefit would be significantly reduced due to the fact that not every faulty bearing would be recognised in proper time.

6.1.2 Example of Vertical Load (Q) Wayside Detector (Wheel Impact Load Detector-WILD)

Vertical load detectors have been in use in the US railroad industry since the 1980s when they were introduced in the Northeast Corridor to address the issue of excessive vertical loads causing cracking of concrete ties. Vertical load detectors are designed to measure the vertical dynamic wheel/rail forces generated by passing equipment and to identify those wheels (and corresponding freight cars) which generate loads that exceed predefined thresholds. Benefits from the vertical load detectors include:

- Derailment reduction resulting from the reduction in failure of track or equipment components under high impact loads
- Reduced damage to track and equipment due to elimination of high impact loads resulting from flat or “out of round” wheels
- Reduction in lading damage for high value commodities

In the US, with its large number of wheel and rail related derailments (there are approximately 60 wheel caused derailments a year with a total annual cost of approximately $15.000.000[1]) and over 300 rail caused derailments a year with an annual cost of over $75.000.000) there is a significant potential benefit associated with wheel impact load related derailment reduction, provided that sufficient numbers

[1] This is the FRA reported cost. Actual cost is estimated to be approximately twice this cost.

of impact detectors are placed in service to cover the 300.000+ km of railroad track in the US.

An economic analysis of the costs and benefits associated with vertical wheel impact detectors indicated that while the reduction in derailments is significant, additional supplemental benefits such as reduction in track maintenance due to elimination of high impact wheels as presented in Table 6-1 [17] supplement these derailment benefits and provide a strong economic case for the implementation of wheel impact detectors.

Table 6-1: Savings/Cost Summary for Vertical Load Wayside Detectors Analysis (WILD)

Savings/Cost Category	**Annual Savings/Costs per detector**
Annual Savings	
Derailments	$ 2.692
Track Maintenance	$ 58.590
Equipment Maintenance	$16.152
Fuel	$ 776
Lading Damage	$ 1.101
Inspection	$ 8
Total Annual Savings	**$ 79.319**
Annual Costs	
Equivalent (annual) Purchase and Installation Cost	$ 9.439
Maintenance Cost	$10.000
Train Delay-Setout Cost- Non-Emergency Basis	$ 7.741
Total Cost (-without Emergency Setout)	$ 27.181
Net Benefit (-without Emergency Setout)	**$ 52.139**

Furthermore, the study [17] showed that the vertical load detector is economic over a wide range of conditions, and the economics appear robust.

6.1.3 Example of Lateral Load (Y, Y/Q) Wayside Detector (Truck performance Detectors-TPD)

Truck (Bogie) Performance Detectors, which focus on lateral loads, have been in service for only a few years and are still the subject of research by the railroad industry. The Lateral load detector attempts to detect excessive lateral forces when a train moves through a curve. Thus they must be installed in curves of at least three degrees (less than 600 meter radius), to ensure wheel flanging. Many factors, including speed and train forces, can affect lateral forces, so the sorting out of excessive readings is more complex for a Lateral load detector than for a Vertical load detector. Still, there is considerable interest in the US railroad industry in TPDs, since it is suspected that “stiff” trucks (bogies) may be responsible for a significant number of derailments, and that these trucks, which may flange continuously on the rail, can also increase fuel consumption.

An economic analysis of the costs and benefits associated with lateral wheel impact detectors indicated that while the reduction in derailments is potentially significant, additional supplemental benefits such as reduction in track maintenance due to elimination of high impact wheels as presented in Table 6-2 [17] supplement these derailment benefits and provide a better, though still marginal, economic case for the implementation of lateral load detectors.

Table 6-2: Savings/Cost Summary for Lateral Load Wayside Detectors Analysis (TPD)

Savings/Cost Category	Annual Savings/Costs
Annual Savings	
Derailments	$ 4.434
Track Maintenance	$ 6.262
Equipment Maintenance	$ 919
Fuel	$ 242
Lading Damage	$ 368
Inspection	$ 8
Total Annual Savings	**$ 12.234**
Annual Costs	
Equivalent (annual) Purchase and Installation Cost	$ 9.439
Maintenance Cost	$10.000
Train Delay-Setout Cost-Non-Emergency Basis	$ 691
Total Cost (without Emergency Setout)	$ 20.130
Net Benefit (without Emergency Setout)	**($ 7.896)**

6.2 On-board monitoring systems

Similar to trackside monitoring systems, the approach is based upon the estimation of cost and benefit functions. Depending on the type, for application of on-board monitoring systems basic costs may arise (e.g. for power supply on freight vehicles or communication link to the driver), shown in Figure 6-2 for cost function 2 and 3. In the future, self-sustaining systems with radio communication are conceivable; these do not require basic installations and thereby impose no basic costs. On the other hand such systems will be more sophisticated and thus will have higher piece costs (see cost function 1 in Figure 6-2).

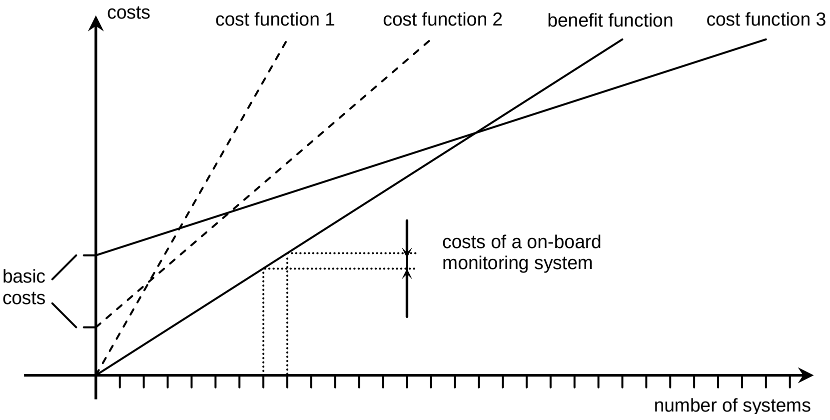

Figure 6-2: Cost-benefit-analysis for damage reducing strategy for on-board monitoring systems

The benefit function can be derived as for trackside monitoring vehicles. In contrast, using on-board systems affects only the vehicle on which the system is installed. As a consequence, the benefit function will be (more or less) linear if considered systems are applied arbitrarily on different types of vehicles. Only if the systems were used on specific types of vehicles (e.g. vehicles with higher risk of derailing or higher potential of loss) the benefit function will be appropriate.

With these functions, systems which are economically attractive can be identified. In the case of linear benefit functions, the highest benefit can be achieved by equipping all vehicles with on-board monitoring systems.

6.2.1 Example of onboard derailment detection for dangerous goods

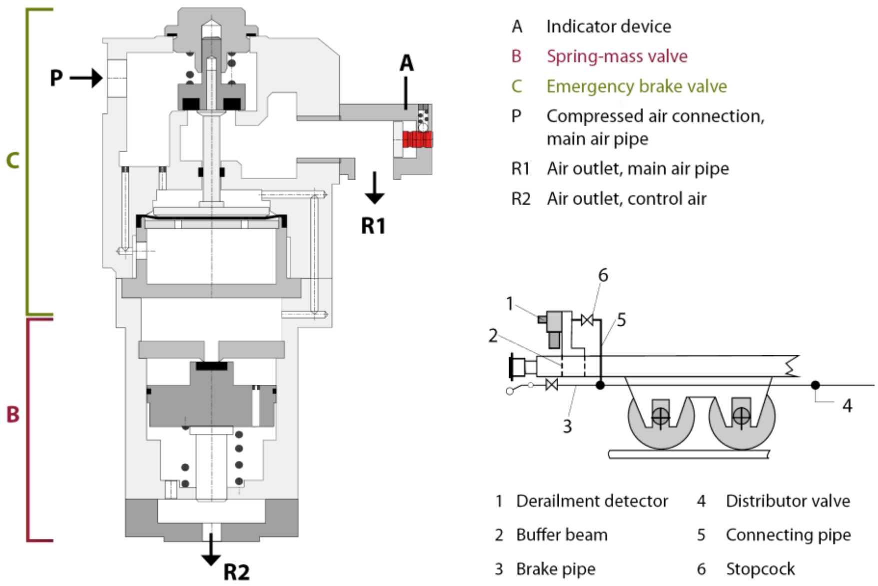

Figure 6-3: Derailment detector EDT101 (Knorr-Bremse [16])

Especially for tank wagons (and other wagons transporting dangerous goods) the vehicle side derailment detector has been developed to immediately brake an already derailed wagon. The business case is also rather simple to estimate, as a derailment of a wagon with dangerous goods can be really expensive. Of course, it is cheaper to include the derailment detector when purchasing the wagon instead of additionally equipping existing cars. Since 2011 it is obligatory for new tank wagons to be equipped with a vehicle side derailment detector.

6.2.2 Example of Automated Switch Inspection (Automated Switch Inspection Vehicle-ASIV)

The Automated Switch Inspection Vehicle (ASIV) consists of a hy-rail truck with specially designed high-image-acquisition-rate laser rail profile measuring systems (Figure 6-4) together with new generation analysis software that analyses key turnout rail information. This analysis addresses key safety and maintenance related switch rail information to include shape dimensions and condition of switch rail and frog, relative height of switch and stock rail, gap between switch and stock rail, gauge face angle and surface damage (see Figure 6-5), etc. Field testing showed that this inspection system has the ability to measure turnout rail safety and maintenance parameters and identify problems to include potential derailment locations and damage sites on turnouts [18]. Current testing speed is of the order of 20 kph.

Figure 6-4: Automated Switch Inspection vehicle

Figure 6-5: ASIV Image (left) and Photo (right) of Frog Defects

A recent study showed there are as many as 150 switch related safety and maintenance parameters to be measured with ASIV type technology being able to measure more than 75% of these. Costs for this type of inspection vehicle are of the order $1 Million to $1,5 Million. It should be noted that in the US there are approximately 180 turnout related derailments a year at an annual FRA reported cost of approximately $12.000.000. An economic analysis of the costs and benefits associated with automated switch inspection indicated that while the reduction in derailments is significant, additional supplemental benefits such as extension of asset life of the very expensive switch assets as presented in Table 6-3 supplement these derailment benefits and provide a strong economic case for the implementation of automated switch inspection systems such as the ASIV.

Table 6-3: Economic Example for ASIV Cost-Benefits

Yards	12
TO/Yard	300
TOs	3600
Cost/TO	$ 45.000
Asset Value	$ 162.000.000
Avg Life (years)	20
Life Ext	10%
Rev Life (years)	22
Annual cost w/o ASIV	$ 8.100.000
Annual cost with ASIV	$ 7.363.636
Annual benefit	$ 736.364
FRA Derailments - FRA DB	9
Cost/Derailment	$ 61.2639
Derailment Savings	10%
Annual Savings	$ 55.137
Non FRA Derailments	90
Cost/Derailment	$ 4.000
Derailment Savings	20%
Annual Savings	$ 72.000
Overall Savings	$ 863.500
Derailment Savings-Annual	$ 127.137
Cost/Year – ASIV[2]	$ 400.000
Annual Savings- ASIV	$ 463.500

[2] Annualized Capital plus maintenance cost

6.2.3 Onboard Vehicle Sensors

Onboard sensors and remote monitoring have also been assessed for freight train monitoring in the US since 1999 [19]. On-board condition monitoring system incorporates sensors to monitor the bearings, wheels, trucks and brakes using a vehicle-mounted supervisory computer which communicates within the train using a wireless LAN technology and with remote computers over the internet via cell phone technology. Figure 6-6 depicts the monitoring sensor configuration installed on each car. Accelerometers are mounted on each bearing adapter to measure vertical accelerations which are then digitally processed to identify signal characteristics typical of bearing damage, wheel defects and derailed wheels dragging along the ties and ballast. Thermocouples are installed on the inboard and outboard bearings of each axle to sense bearing temperature. A tri-axial accelerometer – one that measures accelerations in the vertical, lateral and longitudinal directions – is installed on the centre sill above the bolster of each truck. Lateral accelerations are processed to detect truck hunting, vertical accelerations provide an indication of track quality and large longitudinal accelerations indicate undesirable train action during braking. The electronics systems on each freight car are powered using 10 year batteries (current designs) or generator built into the bearings (future design - prototype only).

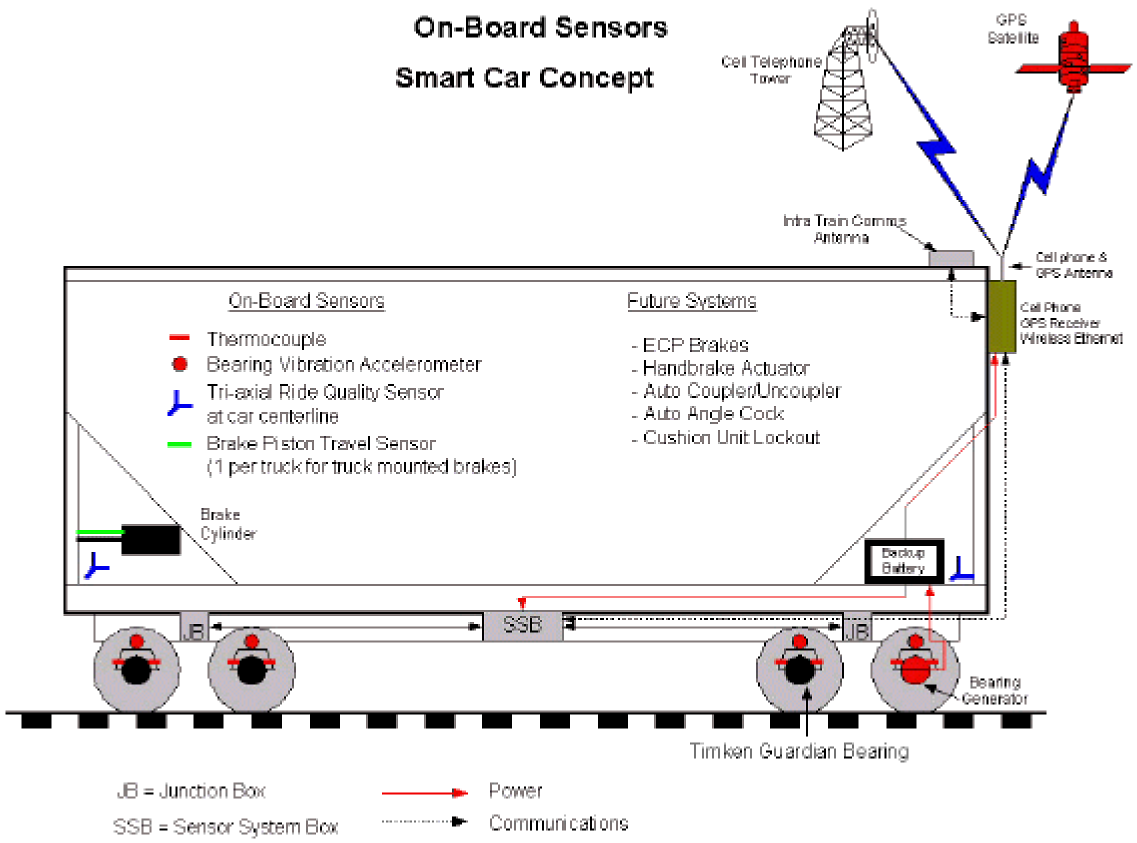

Figure 6-6: Onboard Sensors on Freight Vehicle

6.3 Recording car

Use of track recording cars has been active in the railroad industry for many decades and has proven to be invaluable in reduction of track geometry related defects as well as for improved track maintenance. Traditional Track Recording Cars (also referred to as Track Geometry Cars), measure the following parameters:

- Gauge
- Curvature
- Crosslevel
- Track cant (Superelevation)
- Alignment
- Surface (or Profile)
- Twist/warp
- Maximum Safe Curving Speeds

However, track geometry derailments still remain a major category of defects with approximately 350 geometry defect related derailments in the US with an annual reported cost of over $45 Million. Overall track caused derailments, which also include rail, sleeper, switch, and other track caused derailments, represent almost 800 derailments per year.

As a result, considerable work is being performed to provide supplemental technology to track recording cars to improve their ability to locate derailment causing defects. These technologies include:

- Gauge Restraint Measurement System (GRMS) to apply a controlled lateral and vertical load to the railhead, and measure the change in gauge under load. US testing vehicles utilize a Split Load-Axle system which applies constant and consistent vertical and lateral loads. This system has been proven effective in the US to measure sleeper, fastener and wide gauge conditions, another major failure category (with approximately 100 derailments per year). Figure 6-7 shows a schematic of the gauge loading mechanism, which is mounted under the FRA Track Recording Car shown in Figure 6-8. The effectiveness of this system is such that the US Federal Railroad Administration Track Safety Standards were amended several years ago to permit sleeper condition inspection using GMRS instead of traditional visual inspections of poor sleepers. This system is mounted on track recording vehicles on several major US railroads to include CSX, CP, and the FRA's own inspection vehicles
- Rail Profile Measurement System to measure the profile of the rail head and calculate amount of rail wear (both head and side wear). Such systems are standard in the US and are mounted on virtually all track geometry (recording) vehicles used by major US railways.
- Real time vehicle/track dynamic analysis models for analysis of track geometry defects. These systems identify locations producing unsafe vehicle dynamic performance to include excessive vehicle roll, wheel unloading, etc. and provide an immediate defect report to allow fast corrective action. These models look at actual track geometry data from the track recording car and analyze multiple vehicles at multiple speeds to identify unsafe dynamic performance.
- Machine Vision Systems to inspect the track visually and introduce machine logic to detect faulty or missing components such as fasteners.

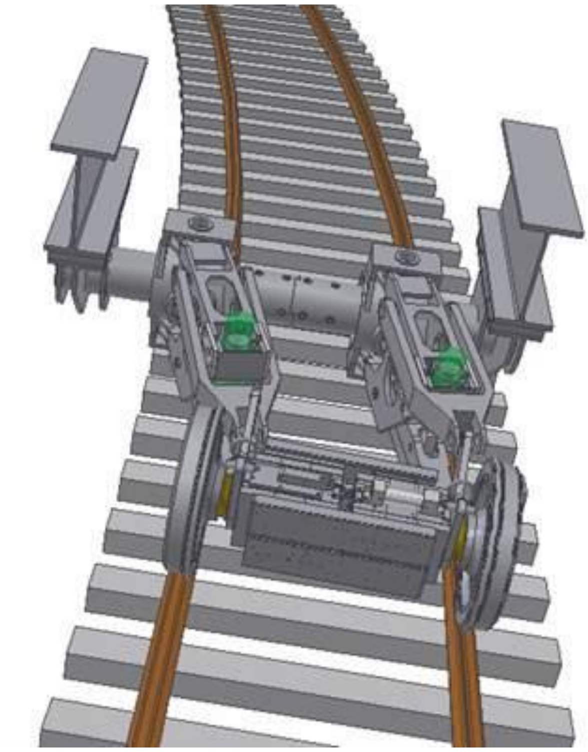

Figure 6-7: Schematic of Gauge Restraint Measurement System (GRMS)

Figure 6-8: US FRA Track Recording Car with Supplemental Inspection Systems (to include GRMS)

7 Recommendations for further work

This section of the report contains recommendations for further work in the project D-RAIL in other WPs, but also general remarks for other European activities. As mentioned previously a major weakness of monitoring derailment causes is that they often cannot be monitored directly and only pre-causes or consequences of a derailment can be monitored. Today's reporting style in accident databases does not allow calculating the probability for transition of one pre-derailment parameter into an immediate derailment root cause. Sometimes it is even hard to identify after an accident which failure has been the root cause and which is only a consequence of the derailment. Here expert knowledge is required to judge causes and consequences in the right way. From a scientific point of view it would be convenient to have at least a two-level approach of expert judgement to make it more objective. Only if this level of detailed information on every derailment in Europe were available in a database would it be possible to run systematic evaluations. Additionally this should also include a more structured way of reporting technical details as suggested in WP1. Also networking sensor systems would allow improving the level of details during investigations. This issue should be addressed also in WP 5 which is already dedicated to deal with cross border operations on the European freight corridors.

This document contains a rough estimation to be able to run a cost benefit analysis to identify economically feasible mitigation measures for major derailment causes identified by WP1. More detailed analyses are the objective of WP7 where more detailed information on the systems mentioned in this document will be required. WP4 will have to deliver this input to bring WP7 in the position to do the LCC engineering.

The matrices of mitigation measures for major derailment causes identified by WP1 which are described in this document cover at least the state-of-the-art perspective. The future potential shall be analysed in more depth by WP4 where it should be noted that many existing mitigation measures might also have the potential with some minor adoptions to be used for other purposes. Therefore WP4 should adopt this document as a starting point to have a structure of well-known mitigation measures. Later on an update of the matrices in this document might be required to keep the information gained in the project consistent. As the project D-RAIL has been set up during the creation of the proposal as a technology-oriented project, human factors and human inspections are not directly addressed by this document. This also has the benefit of removing the need to identify the (sometimes very fuzzy) boundary between technology and human factor causes.

During the work in this task, some practical recommendations were found which cannot be structured in an overall manner, but that seem to be important enough to be documented to make sure that they are considered during the project. One of these practical examples is the ability of track circuits (which are primarily used for checking the route occupation) to act also for detection of broken rail. During replacement of track circuit to axle counting systems this functionality gets lost and has to be overtaken by some other type of inspection.

Another topic for further work would be to analyse the potential for x-ray inspection of rail failures by recording cars.

Finally the question arises if there are still any missing inspection and technology areas which are not covered by today's state-of-the-art. This question might be answered during WP4 when looking in more detail at the major derailment causes and ways of mitigation.

For all the long term mechanisms it might be interesting from an economical point of view to have the capability to predict the right time for intervention. This issue is strongly related to the models applied and of course on their accuracy. Automated inspection might offer some potential to reduce costs and increase the level of available information on actual conditions of components used in daily operation.

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Appendices

				T	T	T	T	T	T	T	T	T	T	T	V	V	V	R	R	R	R	R	R	R	R	Y	W	W	W	W
number of subcategory	categories and subcategories of derailment causes	monitoring target type	monitoring target	axle load checkpoint (Q)	axle load checkpoint (Y and Q, resp. Y/Q)	wayside crack detection	hot box detection (infrared-based)	hot wheel detection	acoustic bearing detection	vehicle profile measurement	acoustic inspection	optical monitoring of loading	broken rail detector (signalling system)	laser-based wear measurement	acceleration/force measurement (lateral)	acceleration/force measurement (vertical)	stress detector	track strength testing	acceleration/force measurements on wheel sets	geometry measurements	simulation based evaluation of geometry measurements	video inspection of rail, sleepers and fastenings	laser-based wear measurement	ultrasonic rail inspection	magnetic flux or eddy current	visual inspection	visual inspection	ultrasonic inspection	laser based wear measurement	magnetic particle inspection
	Axle rupture																													
1	axle rupture (in general)	preceding causes	cracks on axle			c																					a	c	c	a
2	axle rupture (in general)	preceding causes	faulty running surface	a	b											c										a	a			a
3	axle rupture (in general)	preceding causes	faulty suspension	a	b					b							c									a	a			
4	axle rupture (in general)	preceding causes	faulty frame	a	b												c													
5	axle fatigue	preceding causes	overloading	a	b												c													
6	axle fracture	preceding causes	overloading	a	b												c													
7	axle rupture due to thermal stress	preceding causes	faulty bearings (before overheating)						b																					
8	axle rupture due to thermal stress	preceding causes	faulty bearings (overheated bearings)				a																							
	Excessive track width																													
9	excessive track width (in general)	preceding causes	poor fastenings of rails or sleepers															b				b								
10	excessive track width (in general)	preceding causes	overloading	a	b												c													
11	excessive track width (in general)	derailment causes	track width																	a	b									
12	excessive track width (in general)	consequences	high dynamics of vehicle movements																b											
13	curve and curve transitions	derailment causes	track width																		b									
14	curve and curve transitions	consequences	high lateral forces		b										c															
15	rail overturning	derailment causes	rail overturning															b		a		b								
	Wheel failure																													
16	cracks on running surface	derailment causes	cracks on running surface								c					c										a	a	a		a
17	internal cracks	derailment causes	internal cracks																									a		
18	cold cracks (fatigue)	preceding causes	overloading	a	b												c													
19	cold cracks (fatigue)	preceding causes	poor performing bogie		b										c															
20	shelling (fatigue)	derailment causes	defects on running surface	a	b						c					c										a	a	a		a
21	hot cracks (thermal cracking)	preceding causes	overheated wheels					a																						
22	excessive wear	derailment causes	thin flanges											a													a		a	
23	excessive wear	consequences	wide gauge dynamics		b																									
24	excessive wear	derailment causes	flange angle/profile											a													a		a	
	Skew loading																													
25	skew loading (in general)	consequences	unbalanced vehicle	a	b												c													
26	skew loading due to improperly fastenings	preceding causes	improperly fastened									c																		
27	skew loading due to improperly fastenings	derailment causes	displacement of cargo									c																		
	Excessive track twist																													
28	general excessive track twist	derailment causes	track twist																b	a	b									
29	general excessive track twist	consequences	excessive vehicle rolling												c	c														
	Track height / cant failure																													
30	excessive cant / track height	derailment causes	excessive cant / track height												c	c				a	b									
	Rail failure																													
31	rail surface defects	preceding causes	overloading	a	b											c														
32	rail surface defects	derailment causes	rail surface defects																			c			b					
33	rail surface defects	consequences	force peaks													b														
34	rail fatigue	derailment causes	rail surface defects																			c			b					
35	rail fatigue	derailment causes	internal, crack propagation																					a	b					
36	loss of rail section	preceding causes	wear of rail																				a							
37	loss of rail section	preceding causes	internal fatigue																					a	b					
38	rail break	derailment causes	rail break										a																	
	Spring & suspension failure																													
39	crack bogie frame	derailment causes	crack bogie frame														c										a			
40	twisted bogie frame (deformation, etc.)	derailment causes	twisted bogie frame	a	b												c										a			
41	faulty suspension (springs)	derailment causes	faulty suspension	a	b					b							c									a	a			
42	faulty suspension (in general)	preceding causes	overloading	a	b												c													

T - track side
V - vehicle side (in general)
R - vehicle side (recording car)
Y - (shunting) yard
W - workshop

a - measures, which are well known and widely used
b - measures, which are already known but not widely applied (prototypes, etc)
c - measures, which might be relevant for the future