

Proceedings of 7th Transport Research Arena TRA 2018, April 16-19, 2018, Vienna, Austria

Design of a novel, low impact bogie for a freight locomotive

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Abstract

This paper reports on the work being carried out in the Shift2Rail ‘DYNAREIGHT’ project to develop a novel freight locomotive bogie which will reduce wheel and track wear and run with lower noise than current locomotive bogie designs. This is being achieved by developments in several areas including the use of advanced materials and manufacturing processes and the adoption of passive and mechatronic systems for radial steering of bogies, which will allow improved running performance compared to conventional bogies. In particular, significant reduction of wheel wear and damage, improved traction in curves and reduced resistance to motion in sharp curves will be achieved. The use of noise optimized wheelsets and noise absorbing structure in order to reduce the running gear related noise is also being considered. Monitoring of the most maintenance cost-intensive bogie elements is also being considered in order to contribute to lower life cycle costs and to improve the reliability and availability of the locomotive.

Keywords: Railway locomotive; Materials; Steering; Condition monitoring; DYNAREIGHT

1. Introduction

DYNAREIGHT (Innovative technical solutions for improved train DYNAMics and operation of longer FREIGHT Trains) is a 20-month Shift2Rail project coordinated by UNIFE and gathering ten partners coming from Academia (Huddersfield, KTH, TUBerlin), the Railway Industry (Stadler Rail Valencia, Lucchini RS, Laird), Infrastructure Managers (ADIF) and consultancy (FIT Consulting).

The Shift2Rail Joint Undertaking (S2R JU) is a public-private partnership in the rail sector, providing a platform for Cooperation that will drive innovation in the years to come. The S2R JU will pursue research and innovation activities in support of the achievement of a Single European Railway Area and improve the attractiveness and competitiveness of the European rail system. S2R includes five Innovation Programs (IPs) including IP5 the Innovation Program dealing with Technologies for Sustainable & Attractive European Rail Freight in which the DYNAREIGHT project sits. More information is available at <https://shift2rail.org/>

The vision of DYNAREIGHT is to contribute to the objectives of the EU White Paper on Transport 2011, which states that by 2030 a shift of 30% of road freight over 300km to rail, or a doubling of the freight transport by rail compared to 2005, should be achieved. Future models of locomotives will strongly contribute to the achievement of this challenge, supporting the realisation of the goal by providing more attractive rail freight services to the final customer, with competitive rail solutions, maximizing flexibility and efficiency while reducing the operating and maintenance costs. DYNAREIGHT will contribute to this vision and overall concept of the EU rail freight transport by focusing on the next generation freight bogie locomotives and on preparing the path for regular operations of long freight trains (up to 1,500m), providing the first steps for the development of New Freight Propulsion Concepts Technical Demonstrator within Shift2Rail IP5. The innovations to be achieved in the two

technical work packages proposed in DYNAREIGHT are linked in the sense that the outcomes will be combined within Shift2Rail IP5 to bring a benefit at rail freight system level.

In technical terms, the final goal of DYNAREIGHT is to provide the necessary inputs for the development of the next railway freight propulsion concepts, contributing to overcoming the problems of operational and technical nature that have been negatively affecting the overall capacity, performance and competitiveness of the EU rail freight industry. The project will address two main areas: freight running gear for locomotives and operation of long freight trains, with the following technical objectives:

a) To specify, design and develop new concepts to be applied on future freight locomotive bogies via identification and evaluation of lighter materials to be used in a freight environment for bogie components; study and development of noise concepts to reduce the overall noise level caused by freight running gear; analysis of passive steering and active mechatronic systems for improved curve negotiation and running performances achieving significant reduction of wheel / rail forces; and monitoring of the most maintenance-costly bogie elements, in order to reduce LCC by smarter maintenance policies and selection of more cost-effective components.

b) To prepare the path for regular operations of long freight trains (up to 1,500m), following the outcomes of MARATHON EU project. This will be achieved by a number of activities including the definition and implementation of functional, technical and homologation requirements for a radio remote controlled traction and braking system, in order to be ready for certification; the proposition of safety precautions in train configuration and brake application by analysing and simulating the longitudinal forces and the derailment risk of long freight trains; and the identification of adaptations needed in the infrastructure for the operation of long freight trains up to 1,500m, which will be operated as double trains.

2. Use of advanced materials

Many high performance freight locomotives have three axle bogies in order to allow greater traction but these bogies can be more track damaging than two axle bogies. This study has looked at the potential for reduction in track damage and noise by improved bogie design to reduce mass and optimise running gear design. For mass reduction the study focused on the bogie frame as this is the component with the greatest mass (17% of the bogie mass in the target bogie) apart from the wheelsets and traction motors.

To support the study, computer aided design tools were set up to analyse the potential of the new designs and the effects that the changes would have on the locomotive performance. A vehicle dynamics model was set up in VAMPIRE and a finite element analysis developed in ANSYS Workbench. VAMPIRE is a railway specific multibody simulation package. ANSYS is a well-known finite element package with wide application across a range of industries. Some simple analysis was also carried out to establish rolling resistance, energy consumption and track damage.

A simplified finite element model has been developed to examine the effects of changing stiffness on deflection, natural frequency, buckling and force/moment distribution. From a materials perspective, finite element modelling was necessary to establish the areas of highest stresses and the potential consequences of using thinner plates. The simplified finite element model preserved the basic geometric outline and constraints described above. However, the side frames and connecting beams were replaced by beam elements. Thus allowing, a parametric study to be undertaken, varying the stiffness of the beams to find an acceptable range of beam properties for the frame. Additionally, a linear buckling check has been produced from each of the load cases; however only the minimum buckling factors are reported. Sample results for the original design are shown in Figure 1.

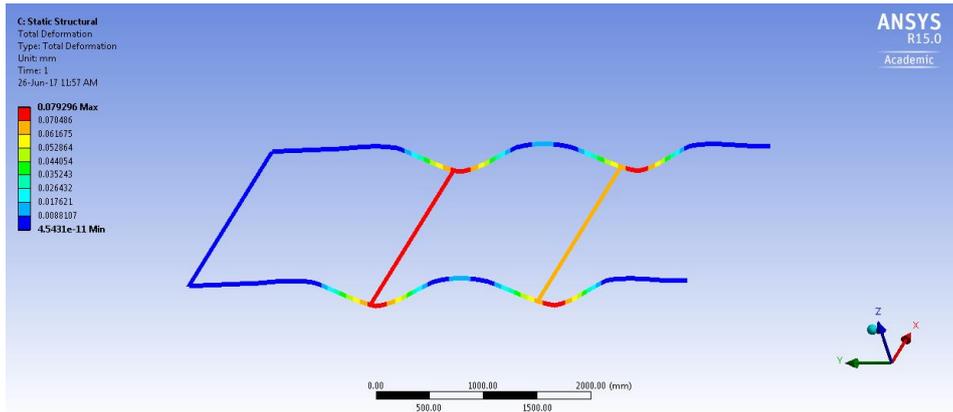


Figure 1. Sample finite element result – static structural for baseline design

A parametric study has been undertaken using the methodology described in above. This parametric study varied the width, height and wall thickness of assumed rectangular hollow section to ascertain the effect on deflection, natural frequency and stress.

Examination of this shows that a 43% reduction (highlighted) in mass is achievable. Deflection criteria would appear to be the limiting factor, particularly for lozenge load cases, see figure 2.

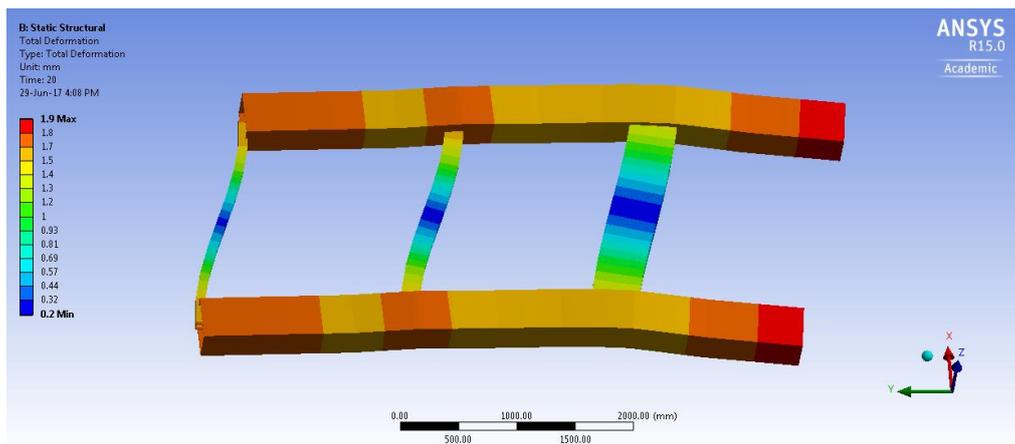


Figure 2. Maximum Deflection 43% mass reduction

One option considered in DYNAREIGHT replaces the welded beam sections in the current design with commercial available sections, substantially reducing welding requirements. Hollow sections are available as rectangular, circular and elliptical shapes and are preferred due to their good torsional stiffness and resistance to local buckling effects. Sections are available as either cold formed or hot formed sections in a large range of sizes. Rectangular or elliptical shape allow more flexibility as stiffness and strength can be directional ‘tuned’.

Joining hollow sections to create a ladder shape is challenging. Direct joining via welded T-joints locates welds within regions of relative high stress, due to stress concentrations. Alternatively, cast joints or ‘nodes’ allow welds (or an alternative joining technique) to be moved away from the highest stressed regions, see application for offshore structures as described by Billingham (2003) and bridges as described in Haldimann-Sturm (2008). A conceptual sketch of one option achieving a 32% weight reduction is shown in figure 3. This shows that the welds are located away from regions of highest stress; therefore, allowing improved fatigue performance.

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

a 12.5% reduction in track damage a 5% reduction in energy consumption and a 1% reduction in track access charges.

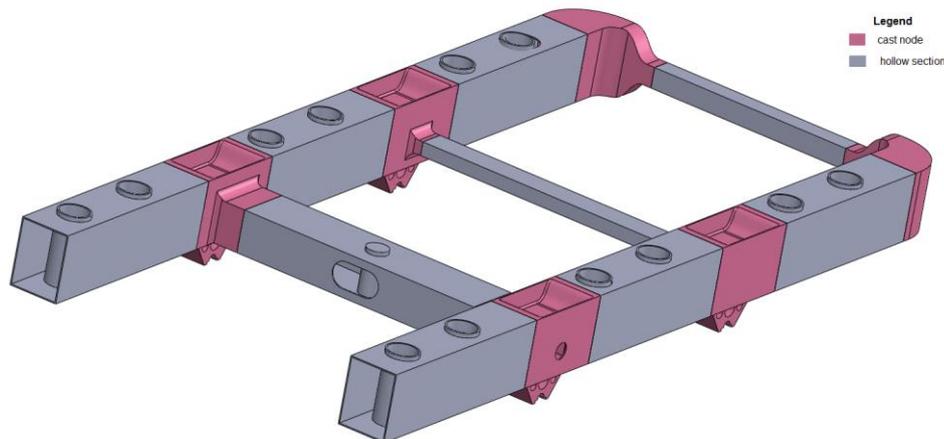


Figure 3. Sketch of one of the DYNAREIGHT bogie options with a 32% weight reduction

More radical construction methods and the use of novel materials such as glass or carbon fibre composites have been briefly reviewed and pointers taken from other industries. Although these more radical solutions offer significant potential mass savings they also face significant barriers to implementation and acceptance. They have not been considered further at this stage.

3. Passive and mechatronic systems for radial steering of bogies

This task of the project aims at defining new concepts for steering bogies for Co-Co freight locomotives which will allow improved running performances compared to conventional bogies. The main benefits expected are: significant reduction of wheel wear and damage, improved traction in curves and reduced resistance to motion in sharp curves.

3.1 Background

The design of railway bogies needs to take into account the conflict between curving ability on one hand and running stability (i.e. ensuring a sufficiently high critical speed) on the other hand. Despite the improved understanding of the bogies' running behaviour achieved in the last decades, bogies with a conventional design are presently very close to achieving their maximum running behaviour performance, so that only minor improvements can be expected in the future. However, the use of non-conventional bogie designs, particularly of passive steering bogies and of mechatronic technologies, represents a paradigm shift potentially removing the design conflict mentioned above. In this way, excellent running stability can be ensured at the same time reducing substantially lateral forces, wear and RCF damage resulting from curve negotiation.

Passive steering systems have been already proposed as a means to achieve the radial alignment of the wheelsets in a curve, but specific solutions for 3-axle powered bogies are not available and should be investigated. The use of mechatronic solutions represents an even more radical innovation, further raising the benefits as it enables the bogie to adapt to the particular service profile and always provide an optimal running behaviour. The use of mechatronic technologies is nowadays stimulated by the availability of reliable, affordable and relatively inexpensive sensors and actuators. Furthermore, the additional cost implied by the mechatronic components can be compensated by a simplified mechanical design of the bogie, also providing a reduced weight of the system.

3.2 Concepts for steering bogies

In the initial phase of the research, a review of existing concepts for steering bogies was performed, analyzing the existing State-of-the-Art and outlining the advantages and disadvantages of the different concepts considering the specific case a bogie for a freight locomotive with 3-axle bogies. As a result of this investigation, a selection of concepts to be further investigated in the project was identified. Figure 4 shows a matrix characterizing the various systems with regard of the suspension level considered (primary vs. secondary) and with regard of the characteristics (passive vs. active).

	Primary suspension level	Secondary suspension level	Primary and secondary suspension level
Passive	PSH	---	PSM
Active	ASH	SYC	SYC&WA

Figure 4 – Classification of concepts for steering bogie based on active/passive and on the suspension level considered (refer to the text below for an explanation of the acronyms used).

3.2.1 Passive steering using mechanical links (PSM)

In this concept, described e.g. by Ahmadian and Huang (2010), the external wheelsets of the bogie are interconnected by mechanical links which exploit the conicity of the wheels to steer the wheelsets so that they are aligned in radial direction. This is a relatively simple concept but, compared to other ones described below provides a less accurate radial alignment of the wheelsets as the steering is influenced by parameters such as wheel profiles, curve radius and also by wear and plays that may occur in the articulations.

3.2.2 Passive steering using hydraulic actuation (PSH)

In this concept, presented by Löwe (2014) for a 2-axle non powered bogie, the standard primary suspension connecting the bogie frame to the axle-boxes is replaced on the external wheelsets of the bogie by hydraulic cylinders. The cylinders are cross-connected so that the connection of the bogie frame to the wheelsets is stiff with respect to all movements (including traction, braking, shear deformation) but enables an almost free steering of the wheelsets. The advantage compared to the other concept for passive steering is that the pipes realizing the interconnection of the cylinders can be more easily accommodated on a locomotive bogie than mechanical linkages. However, in the same way as in the PSM concept, the steering effect is left to the capability of the wheelsets to self-align in radial direction, which depends on the conicity of the wheel-rail coupling.

3.2.3 Active steering using secondary yaw control (SYC)

In this concept, see Braghin et al. (2006), actuators are placed on the two sides of a conventional bogie, replacing the yaw dampers. In tangent track, the actuators are operated to mimic the behavior of passive yaw dampers, whereas during curve negotiation they are used to apply a steering torque on the bogie frame. The main advantage of this concept consists in the simple bogie configuration, requiring only minor re-design of a conventional bogie. The main disadvantage is that radial steering cannot be achieved because the wheelsets are linked to a rigid bogie frame via relatively stiff primary suspensions. Therefore, SYC can only be used to reduce the lateral forces on some wheels (particularly the outer wheel of the leading wheelset in each bogie) mitigating wear effects on that wheel, but with reduced effect (or even increased, in some cases) on the other wheels.

3.2.4 Active steering using secondary yaw control with wheelset articulation (SYC&WA)

This concept was proposed by Simson and Cole (2008). It basically consists of joining SYC with mechanical links that produce the steering of the outer wheelsets in the bogie. The concept enables the precise radial alignment of the wheelsets and has the potential to provide large benefits in terms of reduction of wear on all wheels in the

bogie. However, this is the most complex design found in the review, so implementation costs are expected to be high. Additionally, fitting the linkages and actuators in the bogie frame could be challenging, and a specific RAMS analysis shall be performed to consider the effect of using active devices on the bogie.

3.2.5 Active steering using hydraulic actuation (ASH)

In this concept, in the same way as for PSH, the primary suspension is replaced on the external wheelsets of the bogie by hydraulic cylinders. In this case, however, a high pressure circuit and servo-valves are used to actuate the steering of wheelsets. The hydraulic actuation system is designed to provide the same stiffness as a conventional primary suspension when steering is not active, namely when the bogie runs on a straight track or in case of failure of the actuation system. This concept is being originally elaborated in the DYNAREIGHT project and provides at the same time excellent curving performances for the bogie and a relatively simple design which can be accommodated in a freight locomotive bogie. The main disadvantages are the need to incorporate a hydraulic circuit in the bogie and the need to carefully design the steering system as a fault tolerant one.

3.3 Modelling and simulation of passive and active steering systems

Following the identification of the concepts which are relevant to this study, multi-body system (MBS) models were defined with the aim of assessing the benefits that can be provided by passive and/or mechatronic steering systems. First of all, a baseline vehicle was defined, representing a realistic example of a freight locomotive with Co-Co bogies. This baseline vehicle is being used across different tasks of the project, including investigations on advanced materials and manufacturing processes (see Section 2).

The baseline model was demonstrated to comply with running safety requirements prescribed by EN14363. Then, other MBS models were defined to investigate the steering concepts described above. This work is still on-going, but a complete analysis is already available for the SYC concept and preliminary results are available for the SYC and ASH concepts. As an example, Fig. 5 compares the wear number for the baseline vehicle, SYC and ASH while the locomotive negotiates in steady state condition a curve with radius 300m at a non-compensated lateral acceleration of 0.6m/s^2 .

The wear number WN is defined as follows, see Braghin et al. (2006):

$$\text{WN} = T_1\gamma_1 + T_2\gamma_2 \quad \text{with } T_1, T_2 \text{ the longitudinal and lateral creep forces and } \gamma_1, \gamma_2 \text{ the longitudinal and lateral creepages for the considered wheel (a single wheel/rail contact point is assumed).}$$

The values shown in the figure are the average of the wear number obtained from the simulation on the inner and outer wheel for the six wheelsets of the locomotive.

These results show that the SYC concept brings limited benefits compared to the baseline case. Using this concept, the wear number on the leading wheelsets of the two bogies (wheelsets 1 and 4) is reduced by 12% in the front bogie and by 5% in the rear bogie. However, the wear number on the trailing wheelset of the two bogies (wheelsets 3 and 6) is almost unaffected and for the rear bogie is actually slightly increased. The reduction of the wear number on the central wheelsets of the two bogies (wheelsets 2 and 4) is significant, in the range of 20%, but these are the wheels on which the smallest wear numbers occur, so in absolute terms the expected wear reduction is still limited. On the contrary, the ASH concept enables the substantial reduction (90% and more compared to the baseline vehicle) of the wear index on all wheelsets for the case considered here. The benefits of this concept are of course emphasized by the sharp radius of the curve considered and also by the relatively high value of non-compensated lateral acceleration. However, further simulation results, not shown here for the sake of brevity, show that important benefits can be expected from this concept in a wide range of curve radii and cant deficiency values.

In conclusion, it can be stated the SYC is a concept for active steering that can be easily implemented, with reduced impact on the design of the bogie, but only brings limited benefits in terms of reduction of wheel wear (and rail profiles wear), whereas the ASH concept is a more challenging concept from the point of view of bogie design, but could potentially lead to a substantial reduction of wear, especially in sharp curves. Other concepts are being studied in the project and results will be reported in future publications and communications.

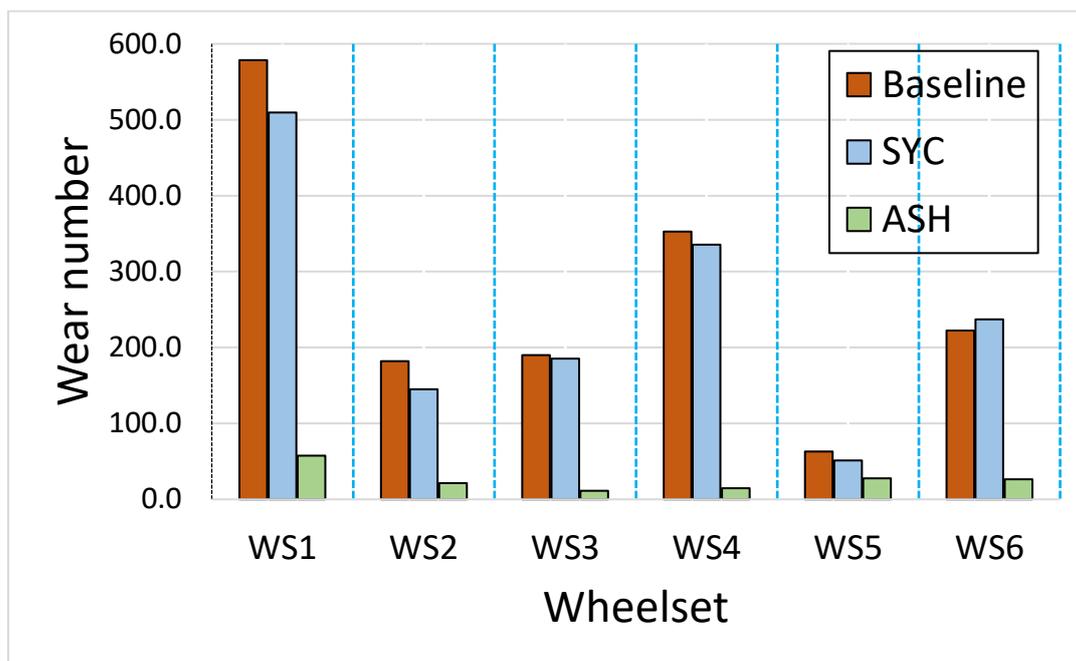


Figure 5. Comparison of the T_y wear number in steady state condition for the baseline vehicle, SYC and ASH while the locomotive negotiates in steady state condition a curve with radius 300m at a non-compensated lateral acceleration of 0.6m/s^2 . The values shown are the average of the wear number the inner and outer wheel for the six wheelsets of the locomotive

4. Noise reduction

4.1 The problem

Noise is the biggest environmental problem for railways. In all other environmental topics railways have huge advantages compared to other transport modes, for instance greenhouse gas emissions and particles. But regarding noise the behavior of rail is worse than other traffic modes. Today in Germany for example more than 6 million people are affected by unacceptable noise with values of sound levels L_{den} above 55 dB(A). As an example, figure 6 shows the noise map for the city of Boppard in the Rhine valley. All coloured areas have above acceptable noise levels indicating that no single house gives appropriate living quality. The good news is that there are low cost and effective solutions to overcome the problem but more research is required to establish methods to achieve this quickly.

As populations and politicians are not willing to wait longer, more and more “full protection” is demanded. That is to transfer the railways to tunnels. Tunnels are expensive to build and to maintain and sometimes cause significant disruption. For instance the main European corridor Rotterdam-Cologne-Basel-Genoa was blocked for two months during August and September 2017 because of a collapse of a full protection noise tunnel under the existing tracks. A better option than full protection tunnel or noise barriers are therefore the reduction of noise on vehicles and tracks.

Today the NOI TSI gives limits of the vehicle noise under certain track conditions. But the NOI TSI values are not sufficient. For one reason they are not oriented to the emission values and also not on technical constraints nor are all relevant operation conditions included. For instance curve running values and values for activate process do not exist at all. Additionally very many noise problems are affected to curves or activate trains at night in the depots near houses. Methods of overcoming the noise problem have been available for some time, for example as presented in the EU Project STAIRRS 2003. Actually the EU Noise Expert Group (9th convention at 30 Nov. 2017) waits for technical solutions according to the DSTINATE results to improve the situation.

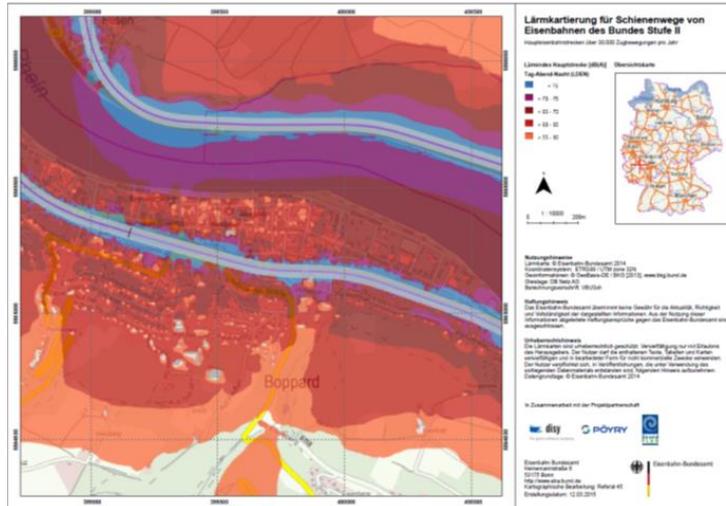


Figure 6. Noise map (2nd iteration) of the Rhine valley, 4 lane freight track of corridor A, near the City of Boppard in Germany where no single house has acceptable living quality, published by EBA (EisenbahnBundesAmt)

1.1 Potential solutions

One good example for successful noise reduction is the modification of a large old Diesel locomotive to actual TSI Noise values, Figure 7. This needed noise abatement measures up to -8 dB(A). Silencers for different cooling systems. Gearboxes with low structure borne excitation and small wheels are essential for further success. Mainly low frequency attenuation gives significant benefit.



Figure 7. Refurbished Diesel locomotive of operator HVLE, Germany, power 2500 kW, traction force 517 kN, Vmax 120 km/h, mass 126 t, Length 23410 mm, 7 locos rebuilt since 2008

Improvement in braking systems can also have a significant effect on noise levels although that is not the main focus of this study.

In the DYNAREIGHT project one task is to investigate the most effective way to reduce noise levels for a modern locomotive with 3 axle bogies. A number of mitigation methods are being evaluated but an initial aspect is the localization and characterization of the main noise sources of a freight Co'Co' locomotive under different running conditions. Noise levels and locations have been measured at a test track as shown in figure 8. The higher noise emitted at the end axles compared with the intermediate axles can be seen. The project focuses the mitigation potential of measures such as wheel optimization and lateral skirts. These will be reported on at a later stage.



Figure. 8. Sound source localization for a Co'Co' locomotive under electric mode at 120 km/h and 2500 Hz

5. Condition monitoring

Condition monitoring of the dynamic interaction between locomotive and track has a large potential to reduce the system LCC, but is today essentially confined to sensors put in the track at a limited number of sites. The present work is focussing on introducing sensors in the bogies to continuously monitor system performance and key bogie components like wheelsets, bogie frames and suspension components. Also monitoring brake and lubrication equipment is included in the work. In each application described below the increase in initial bogie cost is compared with expected benefits like reduced bogie inspection and maintenance cost. Advanced monitoring from the bogies can also result in less track damage and reduced track access charges imposed by the infrastructure manager. Cf. the so-called Universal Cost Model proposed in the Shift2Rail pre-project Roll2Rail.

A first application is to monitor the highly stressed and maintenance-demanding component of wheelsets. This monitoring is also challenging due to the rotating nature of the wheelset. Different sensor types have been considered to monitor the health of the wheelset axles. The goal is to extend the interval for wheelset examinations in workshop and to increase the reliability, availability and safety. The load spectra recorded, showing bending and torsional stresses, also have a spin-off in the design of wheelsets. The other main steel component of bogies, the bogie frames, should also be monitored from a strength and load perspective.

Accelerometers should play a key role in bogie monitoring. In the present work axle box accelerometers are in focus where the vertical acceleration component highlights bearing and wheel imperfections but also large track irregularities and damaged rails. The lateral component as well as lateral bogie frame accelerations are to alert for bogie ride instability and high equivalent conicity of the system. Also accelerometers should be used to find defects in the rubber elements and hydraulic dampers of the bogie suspension systems. It is important to find a robust monitoring design and a clear methodology to pin-point various system malfunctions.

Methods monitoring the status of brake discs and brake pads are also suggested in the work. Here high temperatures is an issue in the choice of sensors, which primary are intended to measure thickness and wear of the two components. In improving the performance of on-board equipment for wheel flange lubrication, improved monitoring functions are also proposed.

The ultimate goal of the present condition monitoring activities is to reduce the LCC costs of locomotive bogies. This is also likely to reduce the LCC for the track. Moreover, a spin-off towards passenger rail vehicles is expected.

6. Summary and conclusions

This paper reports on the work being carried out in the Shift2Rail ‘DYNAREIGHT’ project to develop a novel freight locomotive bogie which will reduce wheel and track wear and run with lower noise than current locomotive bogie designs.

A high performance freight locomotive with 3 axle ‘Co-Co’ bogies was chosen as the target for the study and several areas were considered including the use of advanced materials and manufacturing processes; the adoption of passive and mechatronic systems for radial steering of bogies; the use of noise optimized wheelsets and noise absorbing structure and condition monitoring of key components. The aim was to allow improved running performance compared to conventional bogies including significant reduction of wheel and rail wear and damage and reduced noise levels as well as improved reliability and availability and reduced costs. To support the study, computer aided design tools were set up to analyse the potential of the new designs and the effects that the changes would have on the locomotive performance.

One option considered in DYNAREIGHT replaces the welded beam sections in the current design with commercial available sections, substantially reducing welding requirements. For more conventional construction methods the work has shown that optimisation of the specifications of the existing design including variations in material thickness and the use of higher strength steel can potentially result in a reduction by 43% of the bogie frame mass. The vehicle dynamics studies show that this would translate into a 12.5% reduction in track damage a 5% reduction in energy consumption and a 1% reduction in track access charges.

Several steering concepts are being considered for Co-Co freight locomotives which will allow improved running performances compared to conventional bogies. The main benefits are significant reduction of wheel wear and damage, improved traction in curves and reduced resistance to motion in sharp curves. One concept that can be relatively easily implemented is ‘Secondary Yaw Control’ active steering although this only brings limited benefits in terms of reduction of wheel and rail wear. Active steering using hydraulic actuation is a more challenging concept from the point of view of bogie design, but could potentially lead to a substantial reduction of wear, especially in sharp curves.

Ongoing work in DYNAREIGHT includes investigation into the most effective way to reduce noise levels for a modern locomotive including the mitigation potential of measures such as wheel optimization and lateral skirts and the use of condition monitoring to improve reliability and availability. These will be reported on at a later stage.

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