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Future Freight Locomotive for Europe

D3.1 Evaluation report of three most promising designs

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Executive Summary

Within this report, the results of the evaluation of the three most promising wheelset guidance concepts for four axle freight locomotives are presented.

Within the evaluation several commercial and technical aspects were analysed to determine the overall best concept. The wheel wear was analysed regarding the influence of the concept on friction work in curves. The commercial benefit was analysed using the new Swiss track access charge (TAC) system. Further on the influence on the quasi static lateral forces in curves was investigated. Besides several further aspects (e.g. impact on vehicle LCC, traction behaviour) were regarded.

The three selected concepts for the detailed analysis were a hydraulic passive radial steering (RS-D), an active radial steering (ARS) and the concept of active yaw dampers (ADD).

The RS-D is characterised by using hydraulic cylinders instead of conventional rigid axle guides to enable radial steering of wheelsets in curves and providing sufficient running stability on straight tracks.

The ARS uses actuator to force a radial steering in curves by applying an outer force on the wheelset leading to a turning motion of the wheelset.

The ADD uses hydraulic actuators in the secondary suspension instead of hydraulic yaw dampers. These actuators produce a turning moment on the bogie in curves, leading to a better alignment of the bogie in curves.

In total the RS-D has shown to be the best solution under the considered criteria. It offers significant improvements regarding quasi-static lateral wheel rail forces in curves and significant cost savings on track access charges. Further on in comparison to an active solution it requires less integration efforts. It is therefore also possible to implement this concept in existing locomotives.

The RS-D is therefore further considered as the preferred concept and will be further analysed.

Report Contributors

Contributors		
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ABBREVIATIONS AND ACRONYMS

Abbreviations and Acronyms	
Abbreviation	Definition
ADD	Active yaw damper (Aktiver Drehdämpfer)
ARS	Active radial steering and stability
BT	Bombardier Transportation
BTG	Bombardier Transportation Deutschland GmbH
EN	European standard
EU	European Union
GTK	Gross tonne-kilometre hauled
MBS	Multi Body Simulation
NNTR	Notified national technical requirement
PB4	"Prüfbereich 4" Testing area 4 with curve radii between 250 and 400 m according to DIN EN 14363 2016
PB5	"Prüfbereich 5" Testing area 5 with curve radii below 250 m according to SBB-I-50127
RS-D	(passive) radial steering with internal damping
RCF	Rolling Contact fatigue
SBB	Schweizer Bundesbahn / Swiss Federal railway
TAC	Track Access charges
TSI	Technical specification for interoperability
UIC	Union internationale des chemins de fer
ÖBB	Österreichische Bundesbahn / Austrian federal railway
DB	Deutsche Bahn
$\mathbf{Y_{qst}}$	Quasi-static lateral wheel-rail force
$\mathbf{a_q}$	Unbalanced lateral acceleration at wheelset level in curves

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1 Introduction

1.1 Motivation

Within the last decades' overall freight traffic volumes in Europe have significantly increased due to the cut of boarder's. In 2014, the total inland freight transport inside the EU-28 reached a volume of 2.314 Mtkm.

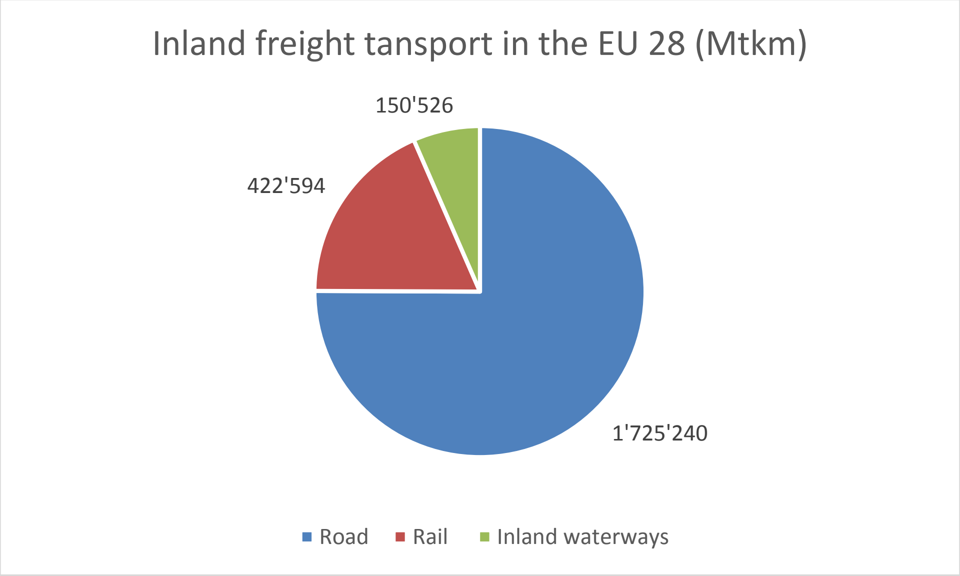


Figure 1 Inland haul capacity in the EU-28 in 2014 [1]

As shown in Figure 1 only 422.594 Mtkm (equals 18%) of freight advent inside the EU is transported by rail, while 75 % is transported on roads. To increases the share towards more sustainable, more environmental friendly rail traffic it is necessary to increase the cost efficiency of transport by rail. Within this work package the track friendliness, characterised by low wear and low wheel-rail-forces, of various freight locomotive bogie designs and their consequences on operating costs of freight locomotives will be analysed. As the track friendliness mainly depends on the wheelset guidance within a bogie the focus will be to analyse various wheelset guidance concepts for locomotives.

The benefit of the various wheelset guidance concepts on wear and operating costs will be evaluated using the new Swiss Track Access Charge (TAC) system, introduced in 2017. Further on the track friendliness of the various wheelset guidance concepts is evaluated by analysing wheel-rail-forces in curves.

The document is divided into four chapters. The targets of the analysis as well as the evaluation procedure are described within chapter one. In chapter two the evaluation criteria are presented. Within chapter three the three most promising concepts are presented. This report closes with the results of the evaluation and a conclusion.

1.2 Target of evaluation

The target of this work package is to identify and evaluate several potential, innovative means to reduce lateral forces and wear in curves. At the end of part 1 (see chapter 1.3) the most promising concept shall be identified, which shall then be examined more closely within part 2.

1.3 Evaluation process

The evaluation process was characterised by the following eight steps, clustered into two parts:

Step 1	Examination of state-of-the-art bogie designs regarding lateral wheel-rail-forces in curves	Part 1
Step 2	Collection of data on innovative bogie concepts	
Step 3	Definition of evaluation criteria besides wheel wear and quasi-static lateral wheel rail forces in curves	
Step 4	Clustering of collected data and determination of the three most promising and innovative freight locomotive bogie designs	
Step 5	Evaluation of the three bogie designs and determination of best concept	
Step 6	Further detailing of best concept	Part 2
Step 7	Analysis of best concept under laboratory conditions	
Step 8	Analysis of best concept on rail vehicle	

Table 1 Evaluation steps

Within this report the steps 1, 3 and 5 are described. The findings of part 2 will be described within the deliverable D3.3 “Test report”.

The specific characteristics for the TRAXX MS3 locomotive with FLEXX Power 140 EU3 bogies are considered during the evaluation. But the results can be transferred on other locomotives with similar running gear.

2 Evaluation criteria

In this chapter the various criteria for the evaluation of the solution concepts as well as the evaluation system itself are described.

2.1 Track access charge system Switzerland – Wear factor

The term "track access charges" (TAC) characterises the costs a train operator has to pay to the owner of the infrastructure for operating a train on his infrastructure as well as for the demanded services, including for example holding sides or external power supply. The first part of the TAC consists in general on a large variety of different influencing factors, including operating factors (e.g. time of traffic, type of train path, etc.) as well as vehicle factors (e.g. type of load, type of vehicle (Noise bonus), etc.). Most TAC-systems have in common that they include a load depended factor within the vehicle factors to consider infrastructure wear of the train caused by the train mass. The calculation of this, following called wear factor, differs significantly between several countries:

- In Germany the wear factor is, for a train with up to 3000 t, included within the basic path price while for trains with more than 3000 t a top-up fee of 1.02 € per train kilometre is charged [2].
- In Austria the wear factor is calculated by multiplying the gross train mass with the path length, resulting in the gross tonne-kilometre hauled (GTK) value, and afterwards multiplying the GTK with a fix factor, which is 0.001293 €/GTK in 2017, to determine the gross tonne-kilometre hauled charges [3].

Both system have in common that they are very easy to handle as they require a minimum amount of input parameters. But they have two mayor disadvantages: Both only consider the mass of a train, respectively of a rail vehicle, as the only vehicle sided input parameter for the wear factor and the track length as the only track sided input parameter. Further vehicle sided influencing parameters, including for example unsuspended mass of a vehicle or longitudinal stiffness of wheelset guidance within a bogie, as well as track sided influencing factors, including top speed or density and radius of curves, are not considered.

To consider additional vehicle parameters the so called "Triebfahrzeugfaktor" was inaugurated in Austria. This factor depends on the on-track test results for Q_{dyn}, Y_{qst} and $\sum Y$ of a powered rail vehicle within three curve classes with radii above 250m. The advantage is that these forces are determined within the homologation according to EN 14363 [4] and therefore can easily be reused for the "Triebfahrzeugfaktor". Within the year 2017 the factor is defined as following: If the "Triebfahrzeugfaktor" is below 1 the rail vehicle gets a bonus of reduced GTK charges of -0.0280 € /train kilometre. If the "Treibfahrzeugfaktor" is above 1.03 additional charges of 0.0251 € / train kilometre are charged. This "Triebfahrzeugfaktor" enables train suppliers the possibility to calculate the commercial benefit of more track friendly vehicles which may have higher initial costs than a less track friendly vehicle.

But still route properties were not considered. This was done for the first time with the inauguration of the new Swiss TAC system on the 1st January 2017. This system replaced the previous, gross tonne-kilometre hauled (GTK) system calculated wear factor, which was identical with the Austrian wear factor except of the €/GTK-value and without a "Triebfahrzeugfaktor".

The target of the swiss TAC system is to distribute the maintenance costs for repair of track damages fairer on the initiators of the damage. Especially the consideration of the friction work in curve, as one influencing factor of wheel and rail wear, enables the calculation of the commercial benefits of bogies with advanced wheelset guidance concepts.

This system was also preferred for the evaluation during the design phase as it does only require results from Multi Body Simulations and analytic calculations as input and therefore has less uncertainties as the Austrian system in the determination of the wear factor and enables a more detailed calculation of the benefit on operation costs.

The calculation of the wear factor (C_X) according to the new Swiss TAC model shall following be shown on an example for a single DB Class 185.2 (TRAXX AC2) locomotive running between town A and B.

The wear factor is calculated by multiplying the row vector (C_V) of damage coefficients with the column vector (R_V) of route section length.

The damage coefficient for each rail vehicle within the train, in this case only for one vehicle, the locomotive, is determined for all following ten track classes. These track classes consist of six velocity classes and four radius classes with their characteristics shown in Table 2.

Name	v_0	v_{80}	v_{100}	v_{120}	v_{140}	v_{160}	r_0	r_{300}	r_{400}	r_{600}
Top speed [km/h]	< 80	81-100	101-120	121-140	141-160	> 160	-	-	-	-
Curve radius [m]	> 1200	> 1200	> 1200	> 1200	> 1200	> 1200	< 300	301-400	401-600	601-1200

Table 2 Track classes for wear factor according to Swiss TAC system

The damage coefficient for each track class is determined with the following formula:

$$C_{vi}=k_1*F_{RQ}*Q^m+k_2*Q^n+k_3*T_{PV}+k_4*F_{WRb}*W_b+k_5*\sqrt{f_{51}*Q_{185}^2+f_{52}*Y_{185}^2} \quad (1)$$

Each summand within this formula is representative for one type of track damage, e.g. the first one for the creation of track displacements or the fourth one for rolling contact fatigue (RCF) in curves. The different wheel-rail forces are determined with analytical formulas (e.g. Q-Force according to [5]) or via Multi body simulations (e.g. W_b). The other factors (e.g. cost calibration coefficients k_1 to k_5 as well as weighting factors F) are given by SBB-Infrastructure. The result of this formula is a damage coefficient C_{vi} in CHF/km for each track class. The damage coefficient for one train is determined by summing up all damage coefficients of each vehicle within a track class. The damage coefficient only has to be determined once for each vehicle type.

In a second step the path of the train from it starting point to its destination is analysed regarding the share of the different track classes, resulting into the route section length vector.

Afterwards the damage coefficient vector is multiplied with the Route section vector resulting into the total wear factor for one train, for one run, on this particular route. The result for the example of a route between A and B with a total length of 20 km is shown in the second row in Table 3. Track classes with a share of zero are not shown.

Name	v_{80}	v_{120}	r_0	r_{300}	r_{600}
Route section length [km]	5	10	2	1.5	1.5
Damage coefficient 185.2 [CHF/km]	0.3679658	0.5217627	2.5126985	0.8587885	0.5186123
				∑ (Total wear factor)	14.15 CHF

Table 3 Example calculation of wear factor according to TAC SBB

For the comparison of the different concepts and the determination of the maximum commercial benefit of reduced wheel wear the following assumptions were made:

As the TAC Switzerland requires a predefined track class share the following procedure has been defined for the purpose of determination of the potential cost savings:

1. Calculation of wear factor for one run on each of these four routes under the same boundary conditions (same top speed (140 km/h), same braking category (A100))
   a. **Route A:** Basel – Gotthard – Chiasso
   b. **Route B:** Basel – GBT **-** CBT **-** Chiasso
   c. **Route C:** Basel– Lötschberg **-** Domodossola 2
   d. **Route D:** Basel –LBT – Domodossola 2

   GBT: Gotthard Base Tunnel CBT: Ceneri Base Tunnel LBT: Lötschberg Base Tunnel
2. The wear factor is calculated for each concept, for a standard TRAXX 3 locomotive and for an optimum vehicle with a friction work of zero in all curve classes and low Y_{qst} forces in switches.
3. A total wear factor is calculated using the following formula:

$$C_{x,Total} = \sum k_y * C_{x,y} \quad (2)$$

   k_y is the weighting factor for route y and $C_{x,y}$ is the wear factor for concept x on route y.

   The k factors, representing the operating share between these routes, are defined as following:

	k_A	k_B	k_C	k_D
Value [-]	0,05	0,45	0,15	0,35

Table 4 Weighting factors for total wear factor

4. The final value for the rating is determined by the following formula:

$$N_x = \frac{C_{TRAXX3,Total} - C_{X,Total}}{C_{TRAXX3,Total} - C_{Optimum,Total}} \quad (3)$$

   With $C_{TRAXX3,Total}$ is the total wear factor for the standard TRAXX 3 and $C_{Optimum,Total}$ is the total wear factor for an optimum vehicle with the maximum achievable wear factor reduction, achievable with modified wheelset guidance. This calculation is required to show the maximum, commercially representable reduction achievable with a changed wheelset guidance as a wheelset guidance only influences the last two summands in equation (1). The scaling allows a better presentation of the achieved reduction. Such, Nx = 0 represents same performance as standard TRAXX 3, and Nx = 1 represents the theoretical optimum.

The value N_X is afterwards classified according to Table 5 resulting in a grade:

Grade	
-2	$N_x \leq 0$ (equals higher TAC than standard TRAXX 3)
-1	$0 < N_x < 0.2$
0	$0.2 \leq N_x < 0.5$
1	$0.5 \leq N_x < 0.85$
2	$0.85 \leq N_x$

Table 5 Grades for the rating of the wear factor

2.2 Wheel-rail-forces in curves

Rail and wheel wear in curves significantly depends on the quasi-static lateral forces in curves. With increasing lateral forces, resulting for example from increased axle loads, rail wear increases. To limit the rail wear limits for Y_{qst} in curves are defined, depending on the curve radius. According to UIC 518 [6] Y_{qst} is limited to:

$$Y_{qst} = 30 + \frac{10500}{R_m} \text{ [kN]} \qquad \text{with } R_m \text{ mean curve radius in m} \tag{4}$$

According to EN 14363 [4] Y_{qst} is limited to 60 kN in curves with radius down to 350 m. For curves between 280 m and 350 m the measurement results are reduced by an curve radius depended factor and compared to the limit of 60 kN. For curves between 350 m and 280 m the limits of [4] and [6] are identical. Curves with a radius of 250 to 400 m are following called “very narrow curves” in accordance with [4].

Y_{qst} forces for curves below 250 m are not limited according to general European guidelines. Only in Switzerland a special NNTR exists, limiting Y_{qst} in curves below 250 m preliminary to 60 kN. Curves with a radius below 250 m are following called “extra narrow curves” in accordance with SBB-I 50127 [7].

The NNTR was inaugurated to consider the special geographic conditions within Switzerland with local routes with a high density of very and extra narrow curves.

These requirements can hardly be fulfilled with 90 t locomotives with conventional bogie designs and, under consideration of upcoming, stricter limits currently in discussion, an analysis of potential, advance concepts for wheelset guidance within locomotive bogies becomes mandatory.

This Y_{qst} forces, calculated by MBS as described within chapter 4, are rated as following:

Grade	Requirement EN 14363/UIC 518 Degree of limit utilisation Y_{qst}	Requirement SBB I-50127 Degree of limit utilisation Y_{qst}
-10*	Requirement EN14363/UIC 518 Degree of utilization $Y_{qst} > 1$ Requirement SBB I-50127 Degree of limit utilization $Y_{qst} > 1$	
-1	Requirement EN14363/UIC 518 Degree of utilization $Y_{qst} < 1$ Requirement SBB I-50127 Degree of limit utilization $Y_{qst} > 1$	
0	Requirement EN14363/UIC 518 Degree of utilization $Y_{qst} < 0.9$ Requirement SBB I-50127 Degree of limit utilization $Y_{qst} < 1$	
1	Requirement EN14363/UIC 518 Degree of utilization $Y_{qst} < 0.75$ Requirement SBB I-50127 Degree of limit utilization $Y_{qst} < 1$	
2	Requirement EN14363/UIC 518 Degree of utilization $Y_{qst} < 0.5$ Requirement SBB I-50127 Degree of limit utilization $Y_{qst} < 1$	
	* -10 because it is a mandatory homologation requirement according to TSI Loc&Pas [8] (k.o. criteria)	

Table 6 Rating for Wheel-rail-forces in curves

2.3 Further technical criteria

Further criteria are considered for the determination of the most promising wheelset guidance concept:

- Necessary implementation efforts in new TRAXX vehicles

  As mentioned in chapter 2.2 these systems may not be required for all locomotives (e.g. vehicles not running in Switzerland). To minimize the vehicle costs and vehicle LCC it is preferred that the new concept can be used as an option only for the affected TRAXX 3 locomotive platform.

Grade	
-2	Mayor changes on or exchange of mayor existing part for implementation required (e.g. Modification of bogie frame)
-1	Medium changes on or exchange of medium existing part for implementation required (e.g. new axle-box)
0	Small changes on or exchange of small existing part for implementation required (e.g. Changed machining of a component)
1	Minor changes on or exchange of minor existing part for implementation required (e.g. Modification of design of non-structural parts)
2	Only replacement of components (e.g. new spring with identical interfaces)

Table 7 Rating table for implementation efforts (new vehicle)

- Necessary implementation efforts in existing TRAXX vehicles

  A concept which can be fitted as an option into existing TRAXX 3 and TRAXX 2 locomotives is preferred. It offers the possibility to decrease operating costs of these existing locomotives, especially for ones with high running distances in Austria and Switzerland.

Grade	
-2	Mayor changes on or exchange of mayor existing part for implementation required (e.g. Replacement of bogie frame)
-1	Medium changes on or exchange of medium existing part for implementation required (e.g. axle-box)
0	Small changes on or exchange of small existing part for implementation required (e.g. Replacement of a component not directly required for new concept (e.g. Rail guard))
1	Minor changes on or exchange of minor existing part for implementation required (e.g. Modification of design of non-structural parts)
2	Only replacement of components during overhaul (e.g. new spring with identical interfaces)

Table 8 Rating table for implementation efforts (existing vehicle)

- Influence on mass of vehicle

  Locomotives are always designed to have masses which are very close to the limits to maximise the traction effort. For light locomotives, additional ballast is used to reach the appreciated mass. Additional mass due to new system can then be compensated by removing ballast. Modern multi system locomotives require additional electrical equipment to be capable of running under different voltages which compensates the whole ballast. If additional components are required, the additional mass of these components require a reduction of mass elsewhere to stay within the mass limits. It is therefore necessary to minimize the additional mass to minimize the required changes. At the current development stage, the mass can only be estimated.

  The changes in mass are rated as following:

Grade	
-2	Mayor increase in mass (≥ 400 kg per vehicle)
-1	Significant increase in mass (200 kg to 400 kg per vehicle)
0	Increase in mass (< 200 kg per vehicle)
1	Similar mass in comparison to current design
2	Decrease of mass in comparison to current design

Table 9 Rating table for influence on mass of vehicle

- Adaptability of concept

  A concept with high degree of flexibility and adaptability for the transfer of the concept on other locomotives within the FLEXX Power bogie family (e.g. bogie with fully suspended drive) is preferred.

Grade	
-2	Concept not suitable for other locomotive types
-1	Mayor redesign for other locomotive types require
0	Replacement of parts within the concept required
1	Replacement of minor parts within the concept required
2	System can 1:1 be reused for other locomotive types

Table 10 Rating table for adaptability of concept

- Influence on traction behaviour

The mayor task of locomotives is to pull freight or passenger waggons. With increasing amount of waggons the efficiency of a locomotive increases, leading to increased margins. The amount of waggons a locomotive can pull on a given route section depends on the traction behaviour under the specific environmental conditions. An improved traction behaviour leads to an increased amount of hauled load. It is therefore highly appreciated that the new concept shall have a positive influence on the traction behaviour. At the current stage the influence on the traction behaviour can only be estimated.

Grade	
-2	Significant decreased traction behaviour
-1	Slight decreased traction behaviour
0	Similar traction behaviour
1	Slight improvement in traction behaviour
2	Significant improvement in traction behaviour

Table 11 Rating table for traction behaviour

2.4 Further commercial criteria

Next to the reduced TAC the following commercial criteria are considered:

- Estimated concept costs: recurring costs (RC) for the concept including material and labour costs, evaluated on vehicle level

Grade	
-2	Large increase in RC than for current product
-1	Medium increase in RC than for current product
0	Small increase in RC than for current product
1	Similar RC than for current product
2	Decreased RC than for current product

Table 12 Rating table for recurring costs

- Estimated impact on life cycle costs (LCC): in this report this includes only costs (material and labour) for planned maintenance and overhaul, evaluated on vehicle level.

Grade	
-2	Large increase in LCC than for current product
-1	Medium increase in LCC than for current product
0	Small increase in LCC than for current product
1	Similar LCC than for current product
2	Decreased LCC than for current product

Table 13 Rating table for LCC

2.5 Evaluation system

A weighted benefit-analysis is used to determine the final grades for each concept.

In a first step, the weighting for every criteria is determined using a differentiated dual comparison between the criteria. The criteria are compared to each other and depending which criteria is regarded as more important one of the following grades is given:

- 5 a lot more important
- 3 more important
- 1 equally important
- 1/3 less important
- 1/5 a lot less important

The weighting for each criteria is added together and afterwards normalised by dividing this sum with the sum of all weightings of all criteria.

Every concept is rated by the various criteria. The criteria are divided into technical criteria (e.g. Compliance with force limits or mass) and commercial criteria (e.g. Life cycle costs). For each criteria grades between -2 (worse) and +2 (very good) are given.

The final grade is determined by multiplying the weighting with the grade for each criteria (as explained in chapter 2.1 to 2.4) and afterwards all multiplied values for each concept are added together resulting in the final grade for each concept. A Grade of +2 would be the best one while -2 is the worst one.

3 Innovative bogie concepts

3.1 State of the Art benchmark vehicle

As mentioned in chapter 1 the reference vehicle for the evaluation is a TRAXX MS 3 locomotive with *FLEXX* Power 140 EU3 bogies. This vehicle is described within this chapter.

Figure 2 TRAXX MS3 locomotive (Source: BT)

The TRAXX MS3 is the successor to the successful TRAXX MS2E locomotive. The locomotive will be able to serve transnational traffic. In the first step, the Maxikorridor D-A-PL-NL-CZ-SK-HU-SLO-I-B-CH-HR-RO (combining East-West and North-South corridors) is planned, which will be enlarged with further countries later on. The locomotive is therefore suitable for all usual European networks 15 kV 16.7 Hz, 25 kV 50 Hz AC and 1 x 5 or 3 kV DC. With a power of max. 6.4 MW, the locomotive is designed for top speeds of 140-160 km/h with nose suspended drive (*FLEXX* Power 140 EU3) and for 160-200 km/h with the hollow-shaft drive (*FLEXX* Power 200 EU3). It exhibits a traction force flat-top characteristic of 300-340kN at 21-22.5t axle load. Unique is the Last Mile drive with a diesel power of 230kW. This makes the TRAXX MS3 the only MS locomotive to be operated on non-electrified lines.

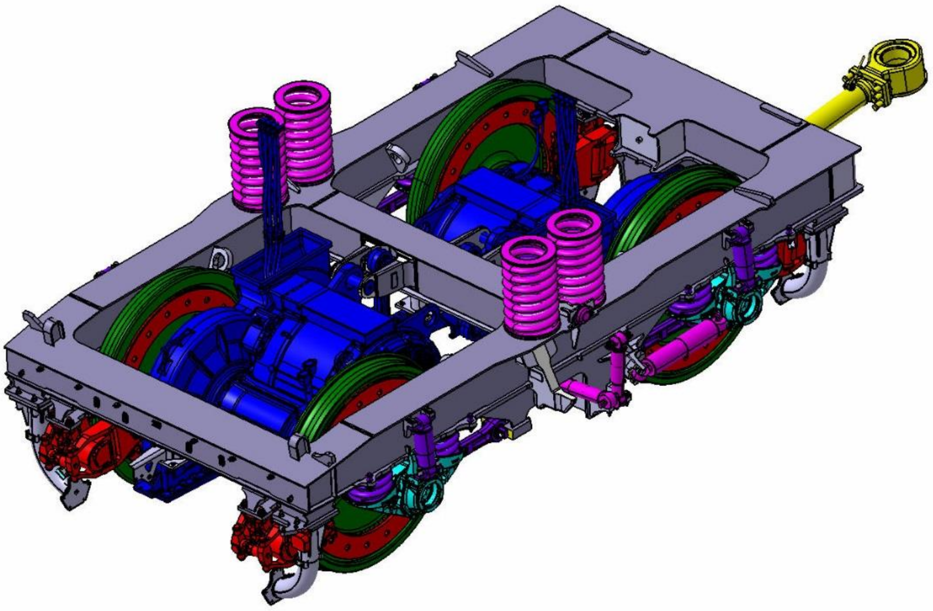


Figure 3 Flexx Power 140 EU 3 bogie

The *FLEXX* Power 140 EU3 bogie is the newest generation of two axle nose suspended bogies for TRAXX locomotives. *FLEXX* Power bogies are characterised by the following attributes:

- The wheel sets are designed according to European or local standards. The wheel set shafts can be designed as solid or hollow shafts. The wheel set bearing is usually carried out with cylindrical roller bearings which, mounted on the center wheel set of three axle bogie, can be designed as sliding roller bearing. As an alternative, taper roller bearings can be provided. The axle box housings are usually made of resistant nodular cast iron.
- The bogies have a maintenance-free primary suspension by means of coil springs and a one-sided, wear-free wheelset guidance. The stiffness and damping characteristics of the wheelset guidance can be optimized regarding running stability and low wheel-rail forces, depending on the application.
- The support of the carbody on the bogie is realised by wear free secondary coil springs, which can be deflected into vertical and horizontal directions according to the flexicoil principle when the bogie is moving below the carbody.
- The bogie frame is characterised by its simple, very robust steel fabricated design, in which casted or forged components can be integrated depending on the loads and the availability of the components at the manufacturing place.
- Different types of drives can be integrated e.g. the robust nose suspended drive or variants of fully suspended drives, which offer lower wheel rail forces und shall be preferred for locomotives with higher top speeds.

A disadvantage is, that the adjustability of the wheelset guidance regarding low wheel-rail-forces and running stability is limited. Therefore the following, innovative concepts are analysed regarding their benefits.

3.2 Concept 1: ARS

ARS stands for active radial steering and stabilization and is part of BT's mechatronic bogie platform [9]. The mechatronic bogie is a modular bogie, allowing the train operator to choose between several modules, which improve the running behaviour of the vehicle. Besides the ARS, the bogie can be equipped with a tilting mechanism module for higher curving speeds, an active lateral suspension module for increased running comfort, semi active dampers module or a bogie condition monitoring system.

The ARS system consists of two, bogie frame mounted electro-mechanical or hydraulic actuators which are each connected to one wheelset, preferred mounted on opposite sides of the bogie on the longitudinal beams of the bogie frame. ARS further consists of sensors to detect lateral track disturbances and track curvature and a controller for avoiding running instabilities by counterbalancing any track disturbances and to optimise the wheel set's adjustment in curves according to the chosen optimisation scheme.

The development of ARS was initiated in 2002. The first tests were done on a roller rig in 2003, showing a stable run at speeds up to 400 km/h without yaw dampers. A series-ready system was certified regarding running stability in 2006 on a Regina train. The system was further developed in the years 2010-2012 for the TWINDEXX Swiss Express train. Instead of an electro-mechanical actuator a hydraulic actuator was used. This system was tested under an IC 2000 coach in 2011. The results show a reduction in the $\sum$ Y forces and a significant decrease of the lateral forces on the outer wheel of the leading axle [10].

A variant of the ARS is the so-called ARS-C. The C stands for "Curving". It contains only the control algorithm for low frequent movement. For higher frequencies the actuator stiffens to achieve the running stability. Further on the ARS-C needs yaw dampers like conventional bogies to enable running stability at higher speeds.

The ARS concept is modified to consider the special requirements (e.g. higher longitudinal forces between wheelset and bogie frame due to higher traction forces). To avoid the support of longitudinal forces via the actuator a mechanism in the bogie shall be integrated enabling radial adjustment in curves and supporting longitudinal forces, resulting from traction forces. Further on the mechanism shall be designed to move left and right wheel by using only one actuator per wheelset.

One possible concept is shown in Figure 4.

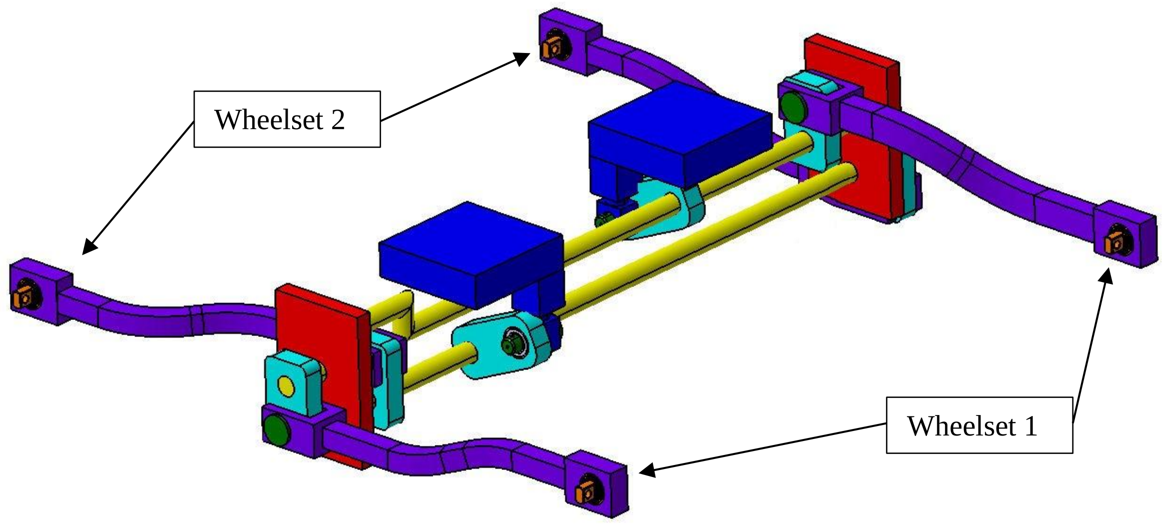


Figure 4 ARS-Concept design

3.3 Concept 2: RS-D

The abbreviation RS-D stands for (passive) "radial steering with internal damping". The main difference between active and passive radial steering is that the passive radial steering relies exclusively on the wheel-rail forces for the radial adjustment while in an active system additional external forces can be applied to change the steering angle of the wheelset.

Several passive radial steering's have been realised within the last years

- SBB Re 460: mechanical coupling of wheelsets within a bogie
- DB VT 612: mechanical coupling of wheelsets within a bogie
- Alstom H3: hydraulic coupling of wheelsets
- SBB ICN: mechanical coupling of carbody-bogie and wheelset-bogie yaw movements

The concept, further analysed for *FLEXX* Power bogies, is a passive hydraulic coupling of wheelsets within a bogie. The hydraulic coupling is preferred instead of a mechanical solution as it allows a higher flexibility within the design and therefore can more easily be fitted into existing bogie designs. Within this concept the conventional rigid axle guides are replaced by hydraulic cylinders, although other forms of hydraulic consumer elements (e.g. Hall-Elements) can be used.

The hydraulic chambers of the cylinders are connected via hoses and tubes to enable the transfer of motions between the wheels and wheelsets, depending of the variant of coupling between the cylinders.

To enable a self-steering radial adjustment of the wheelsets in curves a modified primary suspension with reduced longitudinal stiffness is required. During the development of the 3rd generation of *FLEXX* Power 140 bogies an interface on the bogie frame was foreseen right from the beginning to enable the integration of different primary springs without changes on the bogie frame.

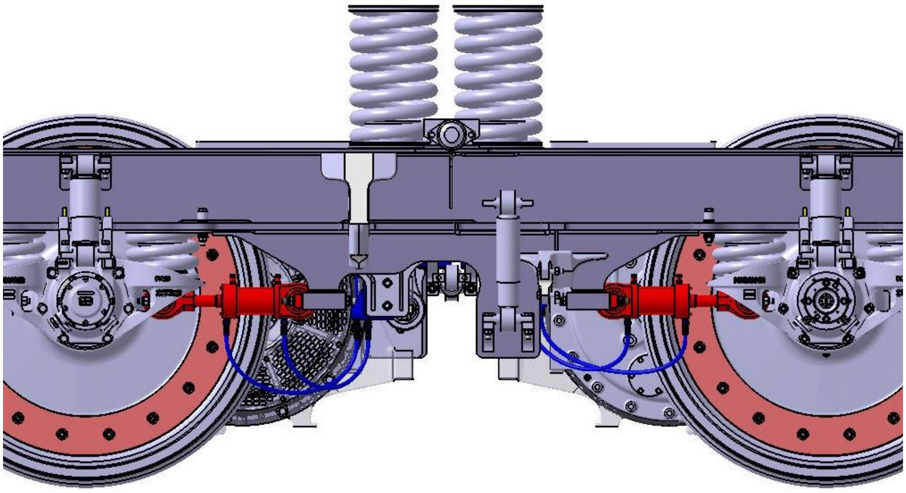


Figure 5 Hydraulic cylinders (red) mounted in a FLEXX Power 140 bogie, replacing conventional wheelset guides

3.4 Concept 3 ADD Active yaw damper

The active yaw damper (ADD) was developed in the year 2004 by Siemens Transportation Systems and Liebherr Aerospace. The target of this system is to reduce lateral forces in curves by achieving a better alignment of the bogie in curves. This shall lead to a more equal distribution of lateral forces in curves and so to a reduction of the maximum lateral quasi static forces at the leading wheelset.

The ADD can be mounted instead of a conventional yaw damper between bogie and carbody and, in curves with a radius above 350 m, works as a conventional yaw damper [11]. In curves of less than 350 m radius, the curve radius and curve direction is detected by path sensor (Pos. 1, Figure 7) inside the damper measuring the stroke of the damper and a constant push or pull force is created by the damper. The forces are created by pressurizing the left or the right surface of the piston (Pos.3) with hydraulic oil from a pump (Pos.2). These push or pull forces lead to a momentum between carbody and bogie which turns the bogie and leads to a better alignment of the bogie in very narrow curves.

Figure 6 Active yaw damper mounted on a ÖBB class 1016 locomotive [12]

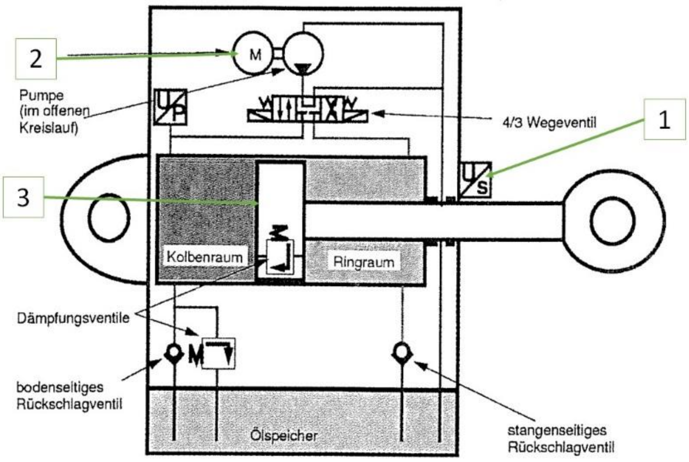


Figure 7 Hydraulic diagram of active yaw damper [11]

4 Analysis of running behaviour in curves

4.1 MBS Model

The locomotive is modeled by using SIMPACK software package including non-linear characteristics for damping and stops. The system locomotive / track is consisting of all relevant mechanical bodies like vehicle body, bogies, drives, pendulums, wheelsets, bearings, wheelset guiding links, push-pull rods and track elements. All necessary connection elements between the bodies are also included in the model.. Wheel profiles as well as rail profiles are modelled as non-linear functions in SIMPACK. Track errors are modeled by track functions.

A locomotive mass of 90 t is considered in the simulations as a conservative assumption. A typically friction coefficient of 0.4 between wheel and rail is considered in the simulations.

The following figure shows the simulation model of the locomotive. Hydraulic elements are visible by means of the elements shown in grey color.

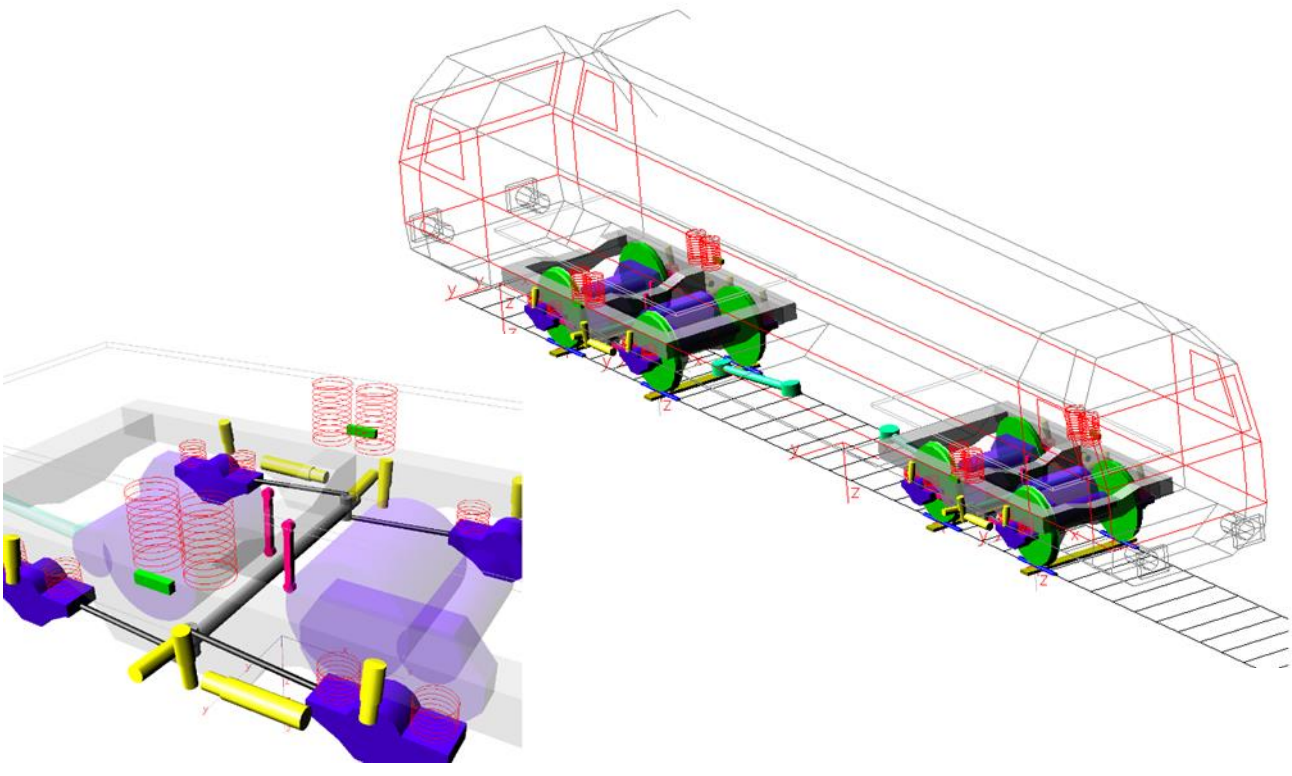


Figure 8 SIMPACK locomotive model including hydraulic elements

4.2 Results

Within Figure 9 the results for the limit utilization for the quasi-static lateral force of the leading wheelset on the outer rail in a 280 m curve (1:40; a_q=1m/s²) are shown.

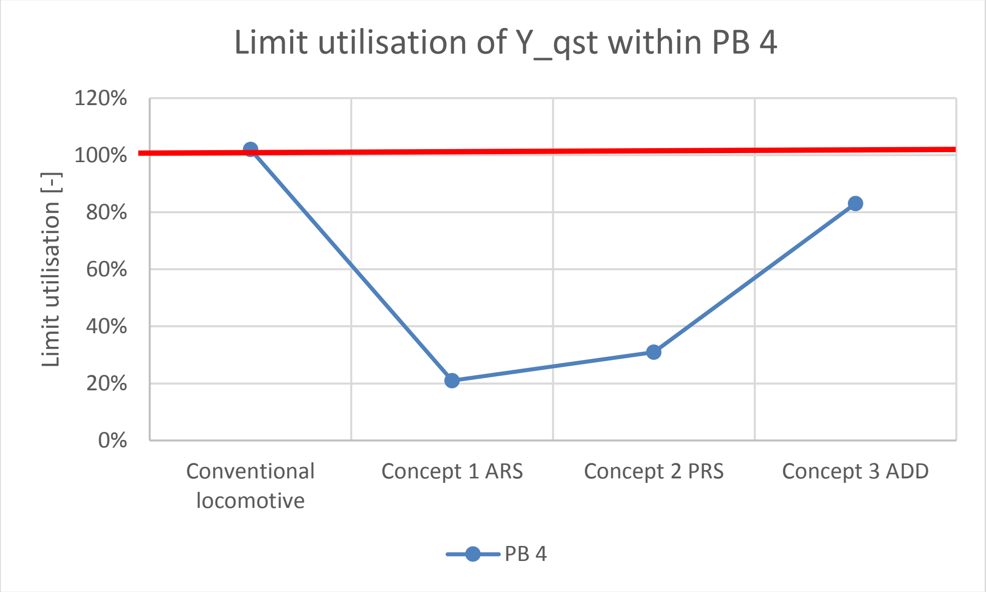


Figure 9 Limit utilisation of Y_{qst} in a 280 m curve for the three concepts

It is seen that for a locomotive with a total mass of 90 t the limit of Y_{qst} is exceeded with 103%, showing the necessity for improvements on the vehicles to fulfill current standards. All three concepts provide these improvements, while the ARS (21% utilization) and the RS-D (31%) provide significantly better improvements than the ADD (83%) within the 280 m curve.

The quasi-static lateral force of the leading wheelset on the outer rail in a 190 m curve (1:40; aq=0,85 m/s²) are shown in Figure 10.

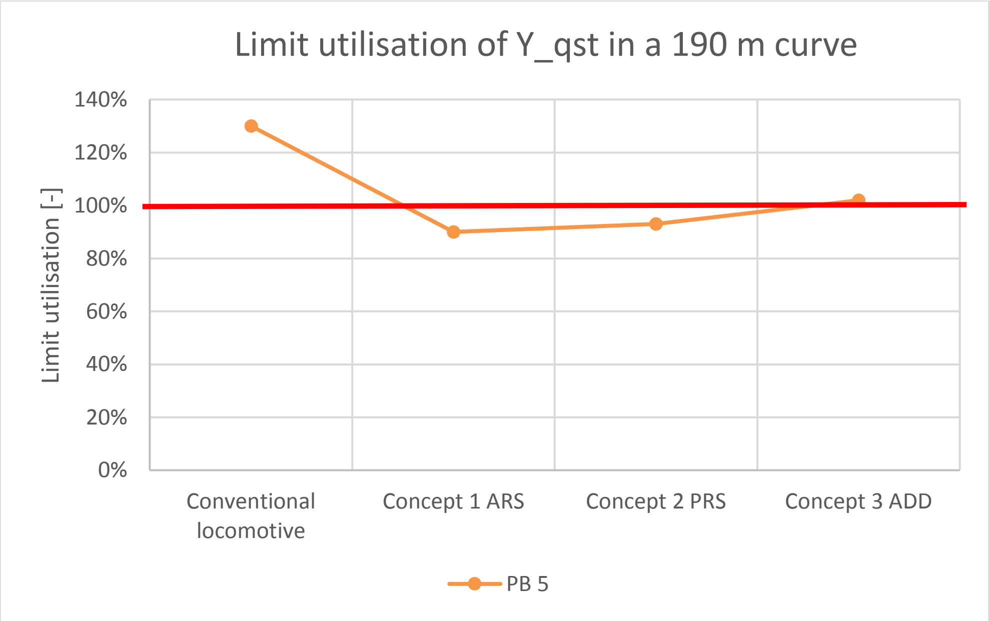


Figure 10 Limit utilisation of Y_{qst} in a 190 m curve for the three concepts

Figure 10 shows that significant improvements are required to fulfil the ambitious target of Y_{qst}= 60 kN within a 190m curve. Both, RS-D and ARS show similar, sufficient performance and reduce the utilisation to about 90 %. The ADD also provides a distinctively reduction, but it is not enough to meet the Limit value.

The simulations have shown that under similar conditions both, ARS and RS-D provide sophisticating reduction of the quasi-static lateral force to meet the regulations also with 90 t locomotives. Differences between ARS and RS-D are relatively small because the simulations were done with ideal track conditions. At real tracks with track damages as for example displacements and worn wheel and rail profiles the ARS may show better results than the RS-D.

5 Results of benchmark of concepts

The complete rating table for all criteria is shown in Chapter 8.

Results Track-Access Charges

Within Figure 11 the results of the TAC calculations are shown. The active yaw damper (ADD) achieves a reduction of the TAC by 18% of the maximum possible reduction, achievable with reduced friction work in curves. The RS-D is with 76% significantly better. The ARS has shown to offer the best reduction of TAC by achieving the maximum possible reduction of 100%. The benefit on wheel wear may be even better but it is not possible to quantify the commercial benefit using the Swiss TAC system.

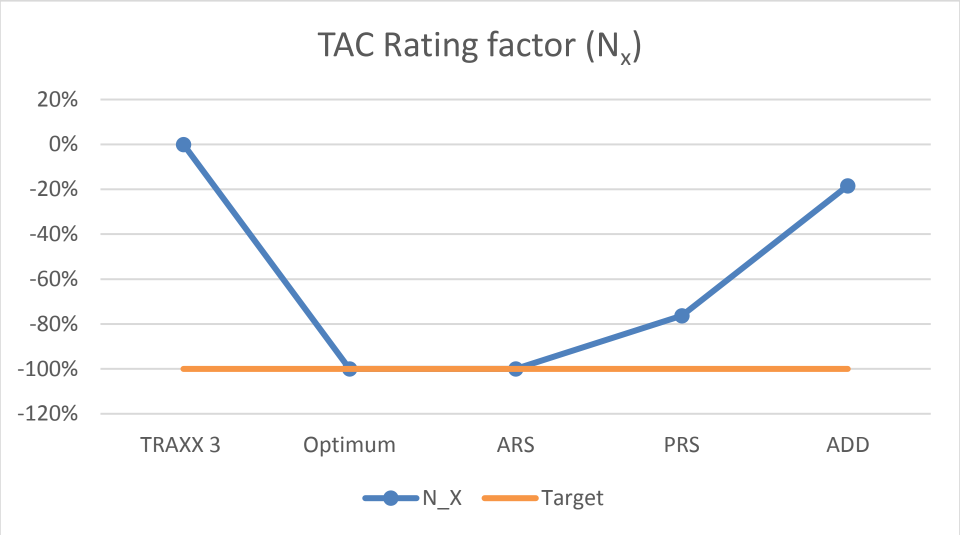


Figure 11 Results for TAC rating factor

Results Wheel-rail forces in curves

See chapter 4.2.

Results for the integration of the system

During the analysis it was seen that the RS-D requires the least integration efforts. The ADD requires the integration of an additional control unit within the machine room of the locomotive, the installation of additional cables and the definition of the software interface and therefore requires changes on bogie and carbody. The advantage of the RS-D, in comparison to the ADD, is that all changes are realised within the bogie, leaving carbody and vehicle software untouched. The RS-D requires further a modified primary suspension to fulfil the requirements regarding running stability and radial adjustment in curves, leading in sum to slightly reduced efforts according to the grade definition in chapter 2 in comparison to the ADD.

The ARS requires significant changes on bogie and requires the integration of a control unit inside the carbody and the integration of the ARS into the vehicle software. The integration of the supporting mechanism for the longitudinal forces and the use of only one actuator requires a complete redesign of the bogie frame. The redesign of the bogie frame produces high non-recurring costs because new laboratory fatigue and on-track tests acc. to EN 13749 would be required. The use of only one actuator on one side was also investigated but showed even higher integration efforts because a redesign of the complete drive unit, especially of the fully suspended drive unit, would be required to achieve the same steering angles of the wheelset within the bogie.

The other results and the explanation for the grades is given within the table in Annex 8.

6 Conclusion

Within this report it was shown that all three analysed concepts are offering improvements for the running behaviour of locomotives in curves. All three concepts are suitable to reduce the Y_{qst} force to enable the fulfilment of the EN 14363 requirements for 90 t locomotives. The ARS and RS-D provide a satisfying reduction to also meet the even stricter requirements regarding SBB-I50127. All three concepts achieved at least 20% of the possible reduction of the TAC.
At the end the RS-D is the best concept for the TRAXX locomotives. It offers a satisfying reduction of the wheel-rail-forces and, in comparison to the ARS, is more suitable as an option for *FLEXX* Power bogies. The benefit of the ARS regarding wear cannot counterbalance the increased recurring costs for this system. The RS-D is therefore the preferred solution and will be further developed.

7 Bibliography

[1] n.n **Eurostat - Statistik des Güterverkehrs**, Call up 2017-08-10; http://ec.europa.eu/eurostat/statistics-explained/index.php/Freight_transport_statistics/de

[2] n.n **Trassenpreissystem (TPS) Liste der Entgelte der DB Netz AG 2017 für Zugtrassen, Zusatz- und Nebenleistungen**, DB Netz AG, 2015

[3] n.n **Produktkatalo Netzzugang - Zugtrasse, Zugfahrt und sonstige Leistungen 2017 der ÖBB-Infrastruktur AG**, ÖBB Infrastrutkur AG, 2017

[4] DIN EN 14363 **Bahnanwendungen - Versuche und Simulationen für die Zulassung der fahrtechnischen Eigenschaften von Eisenbahnfahrzeugen - Fahrverhalten und stationäre Versuche**, Deutsches Institut für Normung e.V., DIN Deutsches Institut für Normung, Oktober / October 2016

[5] GM/TT0088**Permissible Track forces for Railway vehicles**, British Railway Board Group Standard, October 1993

[6] UIC 518:2009 **Testing and approval of railway vehicles from the point of view of their dynamic behaviour - Safety - Track fatigue - Running behaviour**, 4th edition, International Union of Railways, UIC, September 2009

[7] I-50127 **Interimistischer Leitfaden: Strecken mit Radien R<250 m (Prüfbereich 5)**, 1-0, Regelwerk SBB, SBB CFF FFS, Oktober / October 31, 2014

[8] TSI rolling stock - locomotives and passenger CR (EU) 1302/2014 **Commission Regulation concerning a technical specification for interoperability relating to the ‘rolling stock - locomotives and passenger rolling stock’ subsystem of the rail system in the European Union, Official Journal of the European Union**, European Commission, Dezember / December 12, 2014

[9] n.n. **Active radial steering and stability control with the mechatroni bogie**, Himmelstein, Günther; Schneider, Richard, UIC, 2007

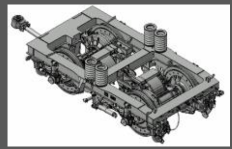
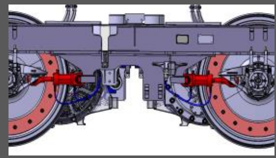
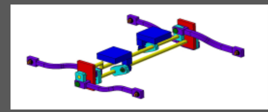
[10] n.n **Wear factor - From the vehicle's producer's point**, Schneider, R., Bern, 2016

[11] n.n. **Aktive Drehdämpfer für Lokomotiven**, ZEV Rail, p. 518-520 October 2004

[12] n.n **Bestimmung des Verschleißminderungspotential der ÖBB Lokomotiveflotte: Ergebnisse eines Konzernübergreifenden Projektes**, et.al., Schmid R., 43. Schienenfahrzeugtagung Graz, 2016

[13] n.n. **Logserv, aktive Drehdäampfer und Funkfernsteuerung im Kalkverkehr**, Eisenbahn Revue, p. 65-67 2008

8 Annex

System / measure	TRAXX with Conventional bogie	TRAXX with PRS (Hydraulic Passive Radial Steering)	TRAXX with ADD (Active yaw damper)	TRAXX with ARS-C (Active Radial Steering)
Implementation on bogie	FLEXX Power 140 EU3a	FLEXX Power 140 EU3a	FLEXX Power 140 EU3a	FLEXX Power 140 EU3
Main sub-suppliers involved	-		LIEBHERR (SIEMENS)	
Picture				
Remark / Change description	-	Hydraulic wheelset guides with hydraulic coupling in bogie	Conventional yaw dampers replaced by ADD (requires control unit in machine room + power supply + cabling)	1. Mechanical decoupling device of traction / brake forces from guiding actuators 2. Elektro-hydraulic actuators (one per wheelset) with control system

	Customer benefit	Evaluation paramter	Limit / Target	W	Characteristic	P	Characteristic	P	Characteristic	P	Characteristic	P
	Benefit description	Implementation efforts for new build TRAXX 3 locomotives		10%	-	2	- additional holder and brackets for tubes and hoses required - Change of primary suspension (lower longitudinal stiffness required)	0	- Integration of control unit (mechanically, electrically, SW interface) - Changes on mechanical yaw damper interfaces on bogie and carbody required	1	- New bogie design required (Interfaces to carbody unchanged; drive unit and wheelset can be reused)	-2
		Implementation efforts for existing TRAXX 2/3 locomotives (Retrofit)		2%	-	2	TRAXX 3: - additional holder and brackets for tubes and hoses required - Change of primary suspension (lower	0	- Integration of control unit (mechanically, electrically, SW interface); different versions of ADD for TRAXX 3 and TRAXX 2 locomotives required	1	- Change of bogie required (Interfaces to carbody unchanged;drive unit and wheelset can be reused)	-2
		Adaptibility for use in other bogies of the FLEXX Power bogie product family		5%	-	1	- Different cylinders required (different strokes and loads)	0	- Adaption of software and damper required (differen bogie distance, different damper loads)	0	- Redesign of every existing bogie required; Increased design efforts for new bogies	-1
		Additional mass per vehicle	as low as possible	6%	0 kg	1	approx. +140 kg	0	approx. +180 kg	0	approx. +400… 600 kg	-2
		Y_qst R = 190 m (PB5, Reihe R)	Utilisation_60 kN	21%	130%	-10	90%	2	102%	-1	93%	2
		Y_qst on R = 280 m (UIC, PB4, aq = 1 m/s2)	Utilisation_67,5kN		102%		21%		83%		31%	
		Influence on traction behaviour		14%		0	- Similar traction behaviour expected	0	- Slightly increased traction behaviour in curves will running; no influence on starting effort (Taurus locomotive ÖBB 2016)	1	- Similar traction behaviour expected	0
Technical evaluation												
		Estimated recurring costs (per bogie)	as low as possible	18%		1	- small increase calculated (including new primary springs)	0	- Hydraulic actuator and control unit lead to increased costs in comparison to PRS concept	-1	- Hydraulic actuator and control unit lead to increased costs in comparison to PRS concept - mechanical decoupling device	-2
Commercial evaluation												
		Delta on bogie LCC		12%		1	- medium increase in LCC due to new primary suspension and hydraulic cylinders	-1	- small increase due to increased maintenance efforts in comparison to conventional yaw damper	0	- medium increase in LCC due to hydraulic actuators and mechanical decoupling device	-1
		TAC Switzerland Reduction	-100%	13%		-1	-76%	1	-70%	1	-100%	2
In-service evaluation												
Total result						**-1,63**		**0,42**		**0,00**		**-0,15**