Empa
Überlandstrasse 129
CH-8600 Dübendorf
T+41 58 765 11 11
F+41 58 765 11 22
www.empa.ch

Empa
Materials Science and Technology

Bundesamt für Umwelt BAFU
Abt. Laerm und NIS
Sektion Eisenbahnlärm
z.H. Herr F. Kuster
3003 Bern

Towards noise and weight reduction by application of FRP wheelset for freight wagons – Acoustic Modelling

Report reference: Empa-Nr. 5211.01393.100.02-2
Issue date: 13 August 2018
Number of pages: 24

Table of contents

Dübendorf, 13 August 2018
The Author:
Gwenael Hannema

Department of Acoustics / Noise Control
Head of department:
K. Eggenschwiler

Note: Report and records are archived for 10 years.

Zusammenfassung

In vorliegendem Bericht wird die komplette entwickelte Modellierungskette, ausgehend von der Geometrie der Radsätze bis hin zur Berechnung des abgestrahlten Schallfeldes, erklärt.

Der Vernetzungs-Strategie wird zu Beginn der Simulationskette besonderes Augenmerk gewidmet, da hier ein grosses Potential zur Effizienzsteigerung und Minimierung numerischer Ungenauigkeiten ausgeschöpft werden soll. Deshalb wurden sämtliche räumlichen Disktretisierungen am Laboratory for Acoustics/Noise Control durchgeführt und für die Prüfung der strukturellen Integrität zur Verfügung gestellt.

Parallel zur Prüfung der strukturellen Integrität (statisch) wurde aus dem Arbeitspaket T.1-3 des Structural Engineering Laboratories die strukturdynamische Analyse vom Laboratory for Acoustics/Noise Control übernommen. Der Ansatz zur Berechnung der erforderlichen Oberflächen-Schwinggeschwindigkeiten, welche zur Berechnung des abgestrahlten Luftschallfeldes benötigt werden, umfasst drei Analyseschritte. In einem ersten Schritt wird eine statische Strukturanalyse für den Lastfall mit gerader Strecke durchgeführt, um die Vorspannung auf die Radsätze miteinbeziehen zu können. In einem nachfolgenden Schritt wird eine Modalanalyse durchgeführt, um die Resonanzfrequenzen zu identifizieren. Schliesslich wird als letzter Schritt in der dynamischen Analysekette eine harmonische Analyse des Radsatzes ausgeführt. Um die Oberflächen-Schwinggeschwindigkeiten über den gesamten Frequenzbereich (200-5000 Hz) effizient zu berechnen, werden zusätzlich zu den aus der Modalanalyse erhaltenen Eigenfrequenzen fünf Stützpunkte pro Terzband verwendet. Basierend auf dem SonRAIL-Projekt wurde eine verbesserte frequenzabhängige Kontaktkraft (Rad/Schiene) abgeleitet. Die resultierende spektrale Leistungsdichte (PSD) der Verschiebung am Kontaktpunkt basiert auf den Rauhigkeitsspektren und der Fahrzeuggeschwindigkeit und wird als frequenzabhängige Verschiebung am Rad/Schiene-Kontaktpunkt verwendet. Schliesslich werden die Oberflächen-Schwinggeschwindigkeiten extrahiert und weiter als Eingangsdaten für die Schallstrahlungsberechnung verwendet (Arbeitspaket T.1-4).

Das abgestrahlte Luftschallfeld wird in der Workbench von ANSYS als frequenzabhängige harmonische Systemantwort berechnet. Das finite Elemente Modell verwendet die vorgängig berechneten Oberflächen-Schwinggeschwindigkeiten als Eingangsgrössen in jedem Knotenpunkt. Somit kann der Schalldruckpegel im Abstand von 3.7 m als Schmalband-, Terzbandspektrum und schliesslich als Einzahlwert ermittelt werden. Was schon aus der strukturdynamischen Analyse hervorgegangen ist hat sich in der Berechnung der Schalldruckpegel bestätigt – die Terzbandpegel werden durch die für die Luftschallabstrahlung relevanten Eigenmoden dominiert. Der FRP Radsatz D2 führt zu einer beachtlichen Reduktion des abgestrahlten Luftschalls von ca. 23 dB(A) im Vergleich zum konventionellen Stahl-Radsatz. Allerdings, berücksichtigt man die Beitrage von Schiene und Schwelle zum gesamten Immissionspegel während einer Vorbeifahrt, reduziert sich der Effekt des FRP D2 Radsatzes auf eine Minderung von ca. 3 dB(A).

Da die Unsicherheit des numerischen Modells nicht quantifiziert werden kann – es fehlen Validierungsdaten – wurden beim Erstellen der Modellierungskette durchwegs konservative Annahmen getroffen. Beispielsweise wurde bei der Generierung des Verschiebungsspektrums am Rad/Schiene Kontaktpunkt die Reduktion der ungefederten Masse nicht kompensiert. Auch wurden die Materialdämpfungseigenschaften unverändert von Stahl auf den Faserverbund-Werkstoff übertragen. Insgesamt darf also davon ausgegangen werden, dass die prognostizierte Reduktion des Vorbeifahrtspegels von ca. 3 dB(A) als eher konservativ zu betrachten ist.

1 Introduction

The aim of the current project is to study, manufacture and test the application of FRP composite material to produce freight wagon wheelsets. Although an application has not yet been implemented, an initial feasibility study is carried out in Phase 1 of the project as detailed in **Figure 1**.

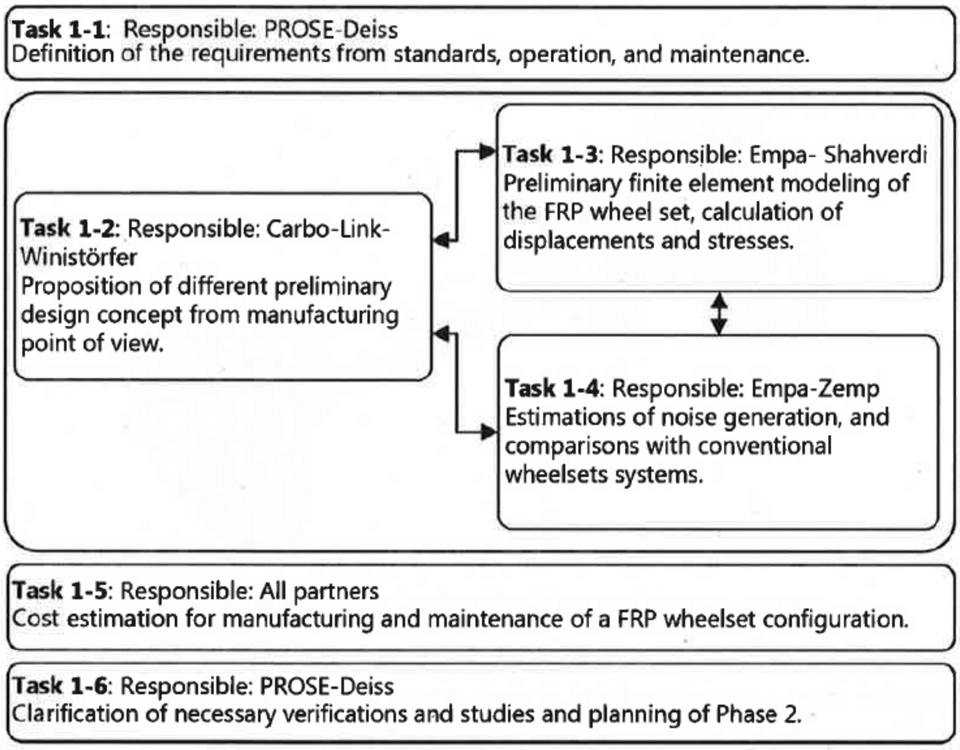


Figure 1: Project overview - Phase 1

The Empa Laboratory for Acoustics / Noise Control is responsible for the calculation of the radiated sound field caused by the structure borne sound field and the estimation in noise reduction compared to a conventional wheelset. The required inputs are the structural vibrational velocities calculated in Task 1-3. The full modelling workflow is represented in **Figure 2**.

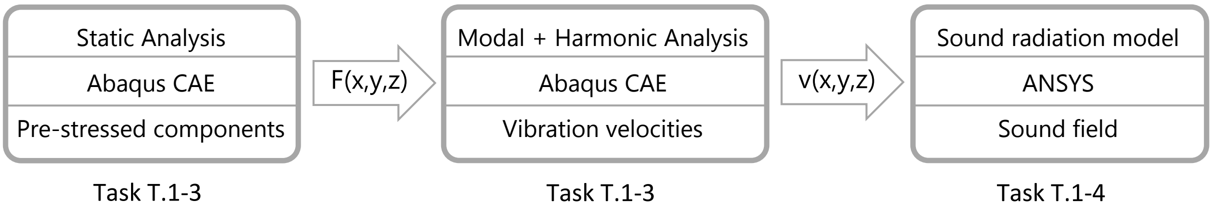


Figure 2: FEM modelling chain for structure borne and airborne sound calculation of a wheelset

To successfully complete the last component of the simulation tool chain and accurately predict the sound field, inputs from tasks T.1-3 are required. Concerns were raised during an intermediate project meeting at Empa on the 29/11/2017 regarding the structural FEM model derivation, mainly due to the long simulation time and large output data. To address the main issues and improve the FEM models accuracy of Task 1-3, the Empa Laboratory for Acoustics / Noise Control took over part of Task 1-3. First, an improved and accurate geometry representation of the standard steel wheelset is generated. Second, geometry discretization is carried out to create high quality quadratic hexahedral meshes of both standard steel and FRP wheelsets (design D1 and design D2). Third, FEM structural dynamics analysis (modal and harmonic) are performed to obtain the structural vibrational velocities required as inputs for the acoustic calculation of Task 1-4. Finally, the radiated sound field is calculated up to 5kHz using calculation points at the structural eigenfrequencies in addition to the third octave bands distribution. An energetic summation is used for the relative comparison between the conventional steel and FRP wheelsets.

2 Component geometries

The 3D geometry (CAD) is an essential input to properly setup the numerical model and to avoid additional discretization errors. The importance of an accurate geometrical input is crucial to derive an accurate FEM model.

2.1 Standard wheel geometry

The initial geometry of a standard steel wheel was obtained from the Empa-Structural laboratory for further improvements. An accurate 3D CAD model is derived using the technical drawing provided by PROSE for the standard wheel profile EN 13715-S1002/h28/e30.5/6.7% illustrated in **Figure 3**.

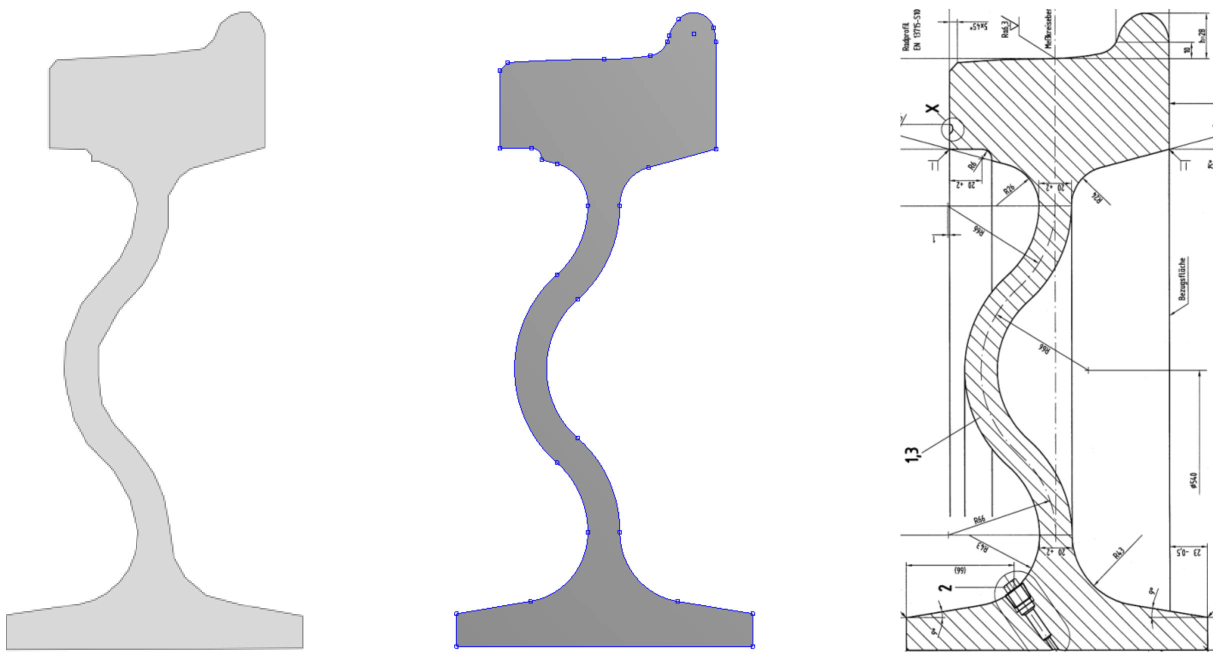


Figure 3: Steel wheel profile geometries (left: initial CAD; middle: updated CAD ; right: ref. 2d drawing)

2.2 Standard axle geometry

The initial geometry of a standard steel axle was obtained from the Empa-Structural laboratory for further improvements. An accurate 3D CAD model is derived using the technical drawing provided by PROSE for the standard axle profile. The initial and updated axle profiles are presented in **Figure 4**.

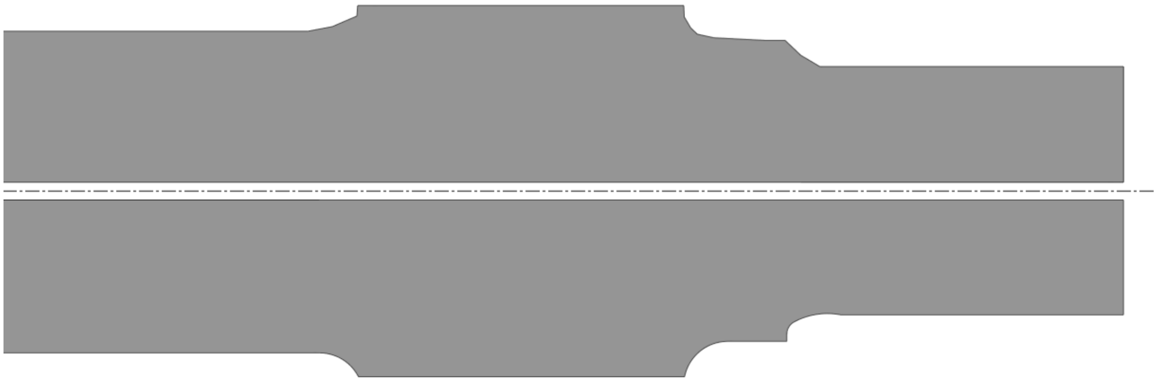


Figure 4: Steel axle profile geometries (upper: initial CAD; lower: updated CAD)

2.3 Wheelset – acoustic enclosure

The acoustic volume is represented by a geometrical enclosure around the wheelset. For obvious reasons, an infinite domain is not explicitly modelled (i.e. geometry // mesh), instead, FEM models require a truncated domain. Wave absorption conditions allow the user to model a smaller portion of the domain and assume that outgoing waves keep propagating outwards without reflecting backwards. Two options are available, either a radiation boundary or Perfectly Matched Layers (i.e. PML) conditions. Both model infinite propagation domain conditions and are applied to the outermost faces of the enclosure.

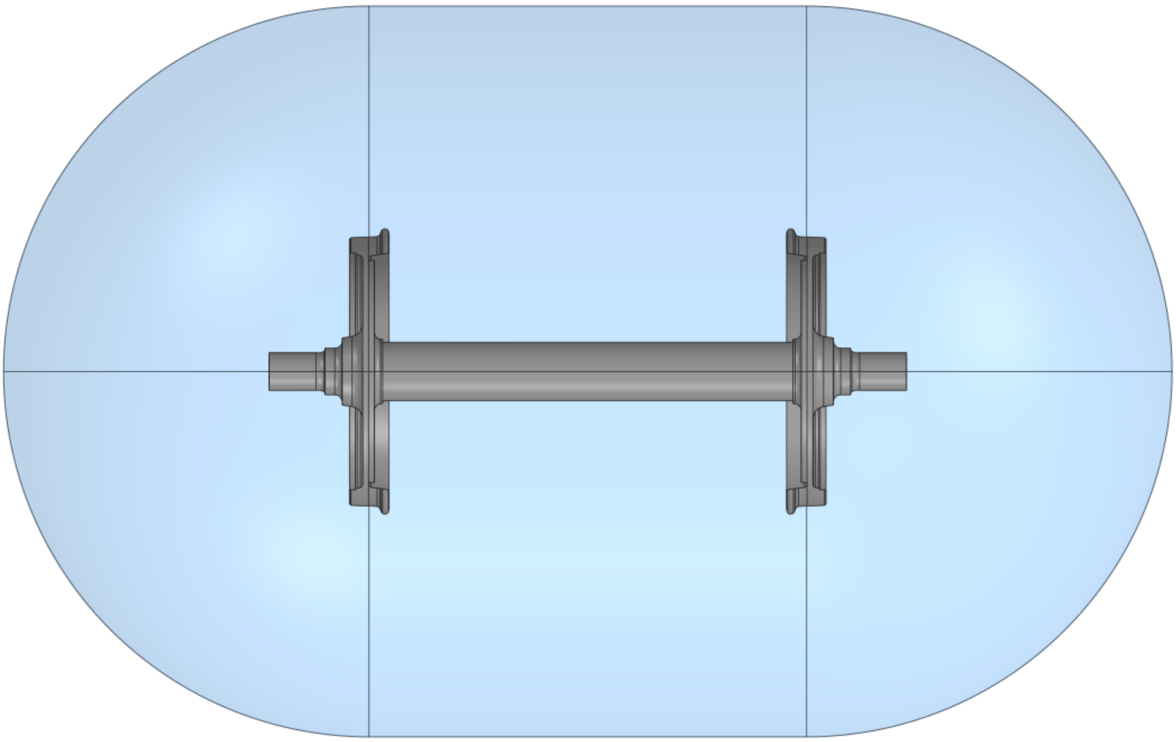


Figure 5: Acoustic enclosure around the wheelset (Carbolink FRP D1 illustration)

3 Component meshing

3.1 Meshing overview

The discretization of the geometrical inputs is achieved by using ANSYS ICEM CFD meshing software. The discretization procedure uses a top down approach to generate a structured grid with high quality 2nd order (quadratic) hexahedral mesh elements.

3.2 Standard wheelset (wheel / axle)

The initial mesh was created using the integrated meshing tools from Abaqus CAE as showed in **Figure 6**. To reduce the large number of initial elements and non-conforming radial distributions between the wheel and axis, a new mesh is created using ANSYS ICEM CFD as meshing software and the updated geometries for both the wheel and axle (**Figure 3** – **Figure 4**).

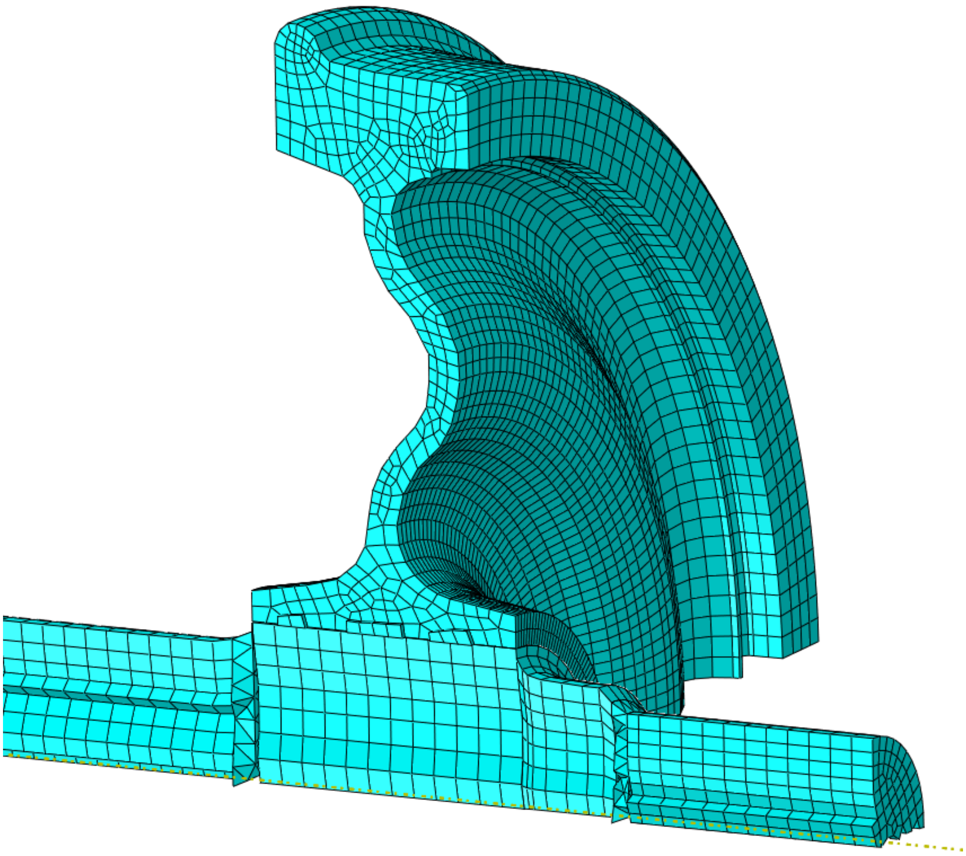


Figure 6: Initial mesh discretization of the steel wheelset

The dedicated meshing software permits the derivation of a blocking strategy that allows the user to fully control the mesh distribution. Only high quality hexahedral mesh elements are generated with an improved orthogonal quality compared to the previously generated hybrid tet/hexa mesh. The resulting mesh of the top down structured blocking strategy is presented in **Figure 7**.

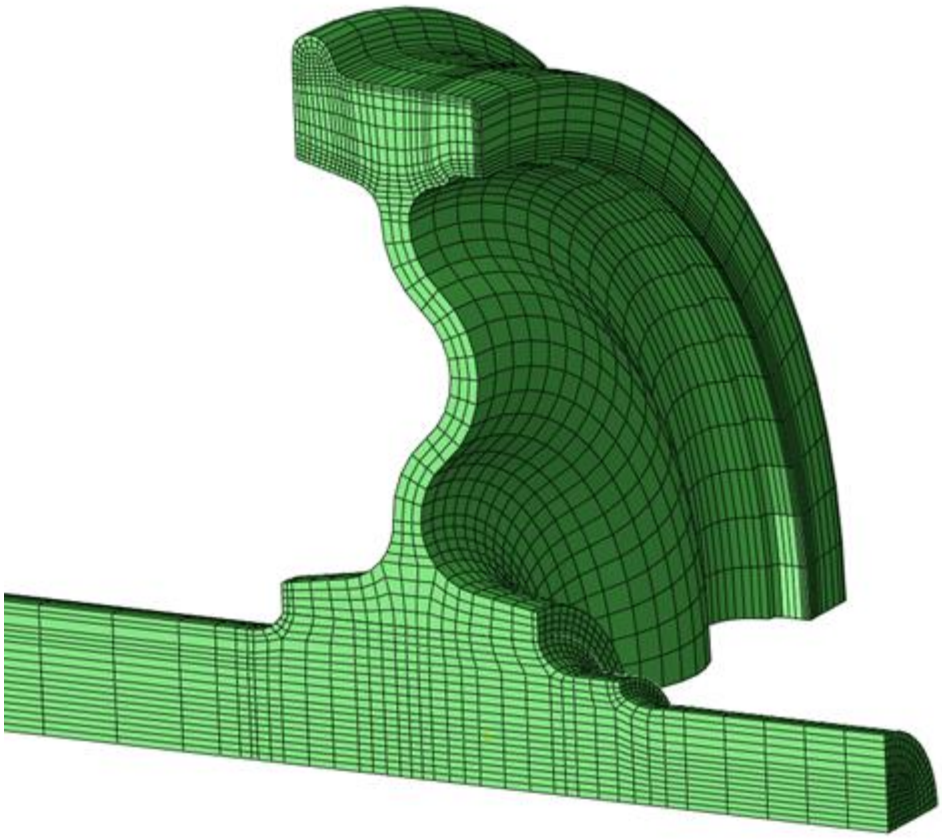


Figure 7: Improved mesh discretization of the steel wheelset

This blocking procedure can be duplicated to identical components (i.e. left and right wheel) to ensure identical meshes across parts. The consistent mesh element distribution is achieved along the wheel central "spine" section and the wheel / axle connection surfaces. Those surfaces are used later on in the FEM model to specify coupling constraints. A conformal mesh offers a better interface treatment for the coupling conditions as the matched pairs of nodes are coincident (i.e. nodes on the wheel side // nodes of the axle side).

3.3 FRP Carbo-link design D1 (FRP wheel / FRP axle / steel rim)

The initial mesh was created using the integrated meshing tools from Abaqus CAE as showed in **Figure 8** . Additional care needs to be taken when deriving the FRP wheelset meshes as non-uniform material properties are applied to represent the fibre directions in the FEM model. As for the steel wheelset, ANSYS ICEM CFD is used as meshing software and the initial CAD file provided by Carbo-link (ref. FRP-Radsatz_Design1_11058527) is updated with the accurate steel outer rim. A different blocking strategy is adopted to account for the additional interfaces between the parts. For instance, the initial gap between the FRP wheel and steel rim can be accurately discretized using a C-grid blocking topology as showed in **Figure 9**. The resulting mesh offers coincident node pairs at the contact interfaces, which improves the contact coupling conditions for the FEM model.

The generated meshes are further converted to Abaqus CAE input files by a developed interface and made available for the structural assessment analysis.

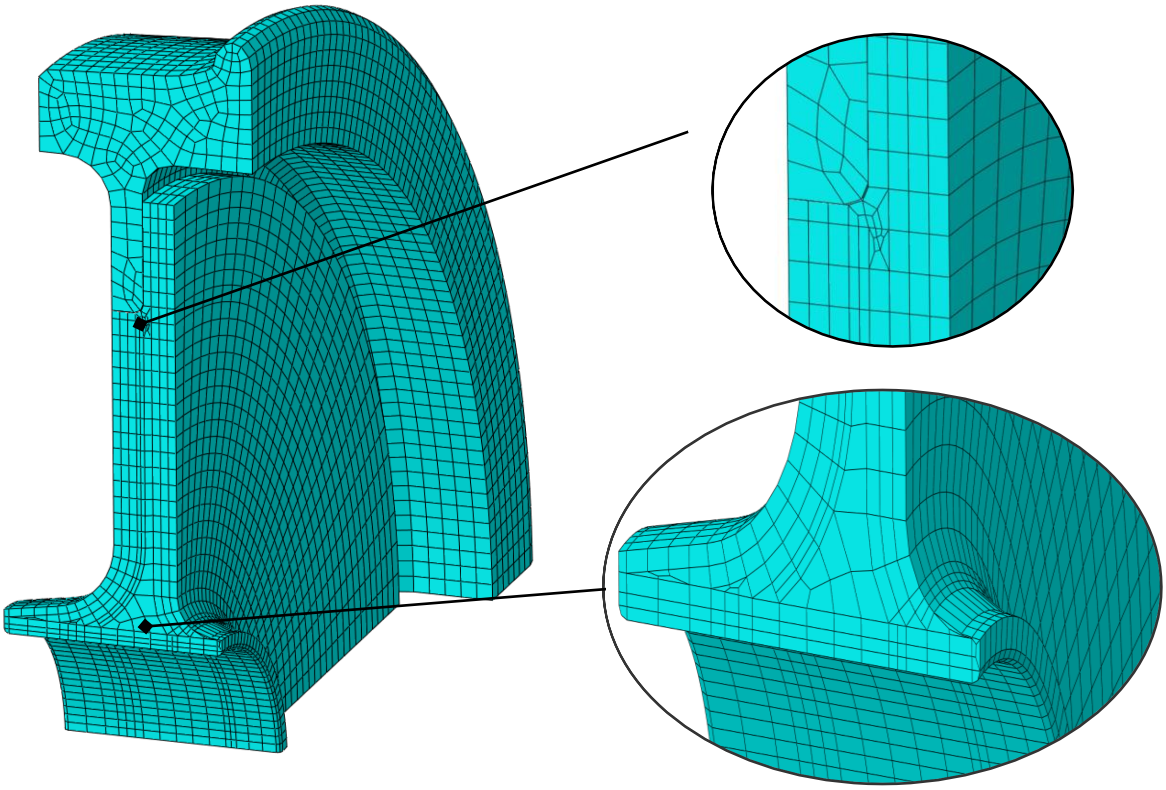


Figure 8: Initial mesh discretization of the FRP D1 wheelset

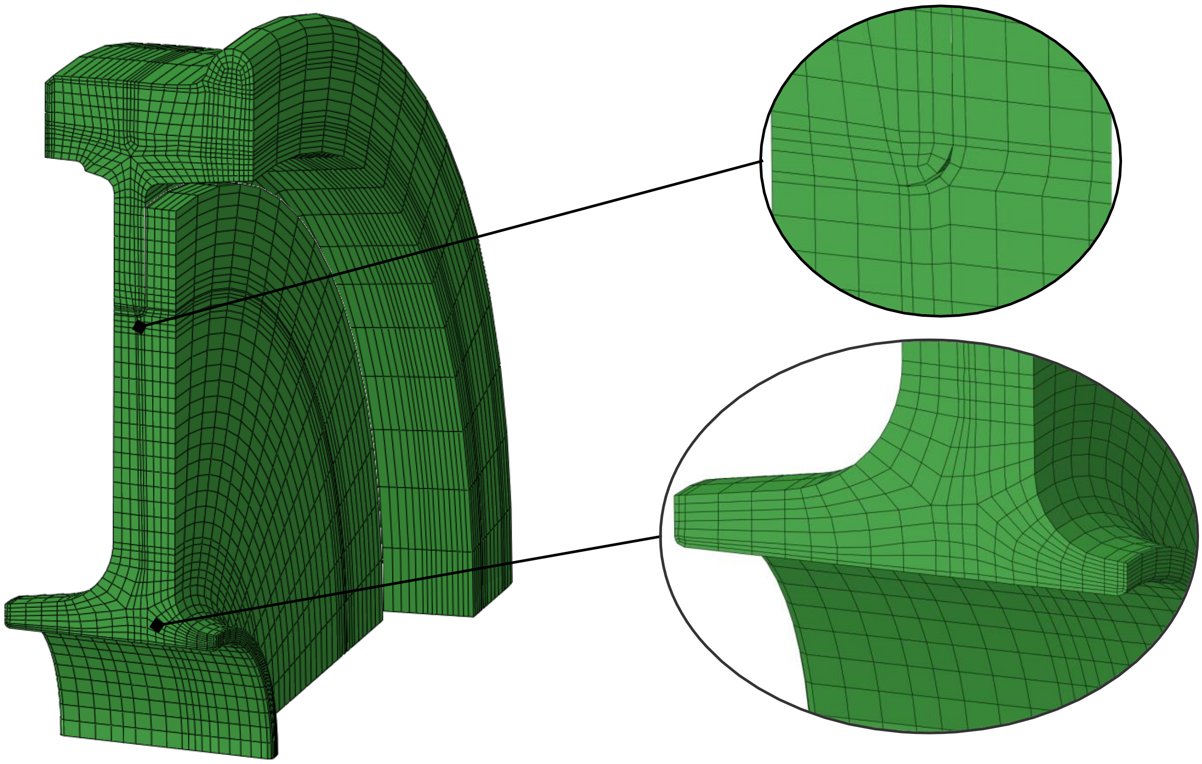


Figure 9: Improved mesh discretization of the FRP D1 wheelset

3.4 FRP Carbo-link design D2 (FRP wheel / FRP axle / steel rim)

Based on the outcome of the first design loop, Carbolink adapted the design D1 and proposed an improved design referenced as design D2. The blocking strategy used for design D1 was adapted and updated to the new geometry to create the new mesh. Compared to the previous design, additional features are included such as the break coupling elements and the disk break as showed in **Figure 10**.

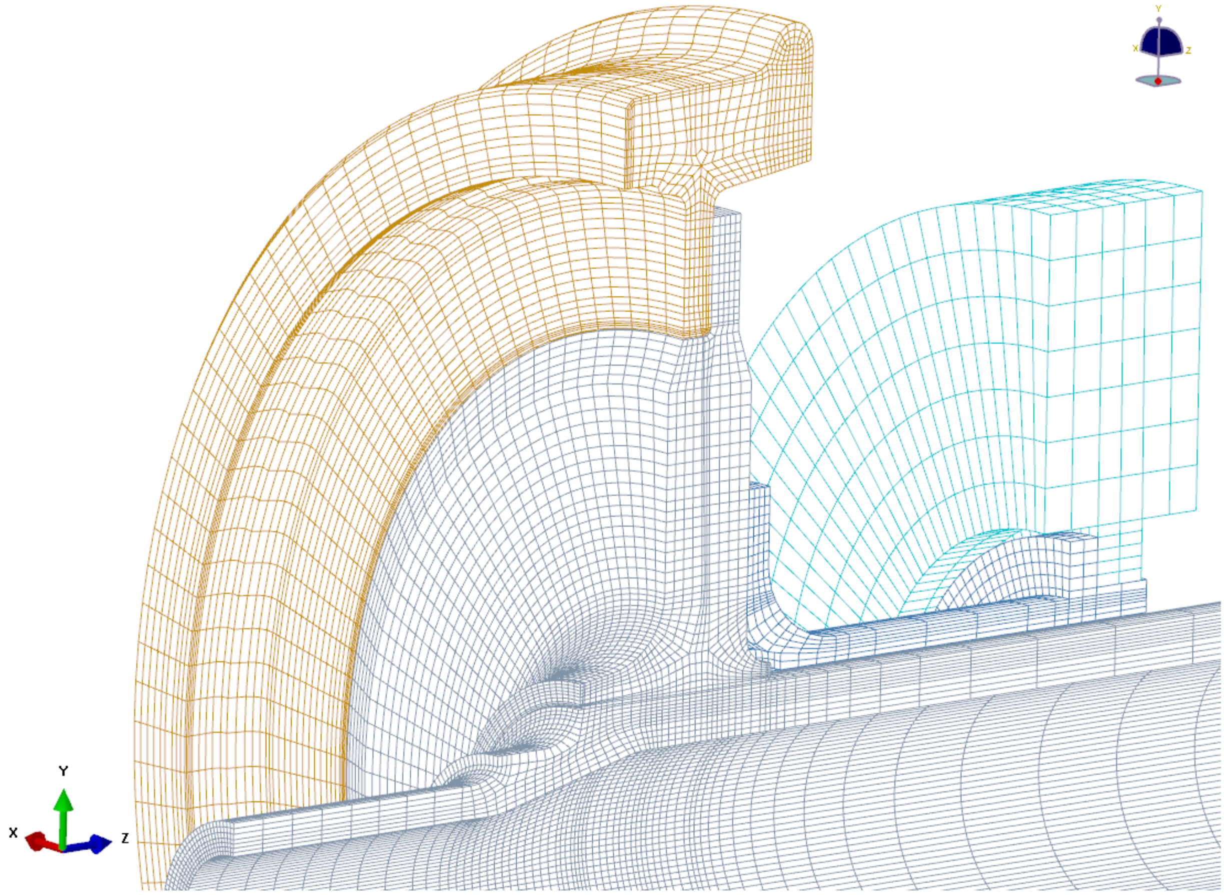


Figure 10: Carbolink design D2 wheelset geometry discretization including break coupling (dark blue) and disk break (light blue) elements.

The resulting mesh was handed over to the Empa-Structural laboratory to assess the structural integrity of the FRP D2 wheelset under the different standard loading conditions. The initial FEM model of the FRP D2 wheelset didn't explicitly include the bolt inserts due to the complex meshing generation procedure involved. A common modelling approach to represent a bolt connection is to model it with FEM contact technology such as Multi-Point Constrain (i.e. MPC). This allows to easily couple different parts together and is often sufficient for early design iteration to assess the overall structural integrity of the wheelset.

Nonetheless, to further improve the FEM model and calculate the local stress concentrations due to the geometrical discontinuities of the bolt coupling at the different interfaces (FRP wheel // steel outer rim, FRP wheel // break coupling, break coupling // disk break) a new fully hexahedral mesh is generated as showed in **Figure 11** - **Figure 12**.

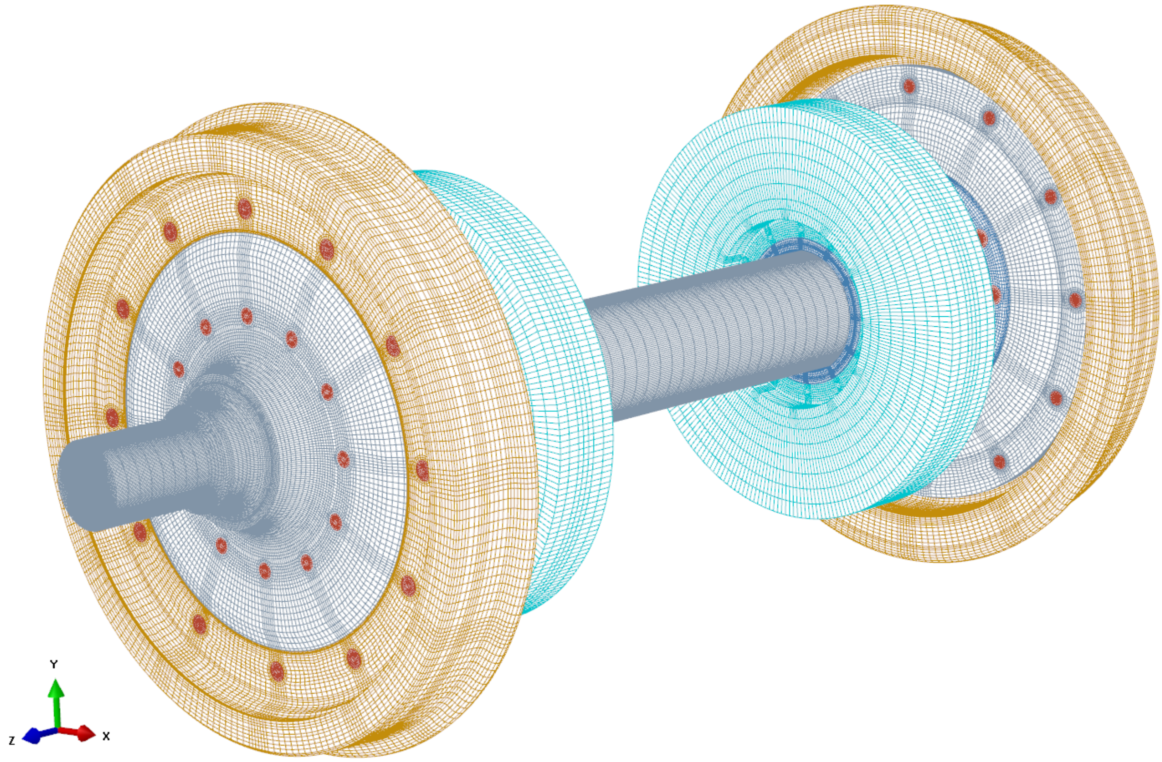


Figure 11: Carbolink design D2 wheelset geometry discretization including bolt inserts (in red) at the different interfaces (conformal mesh at interfaces with only quadratic hexahedral elements)

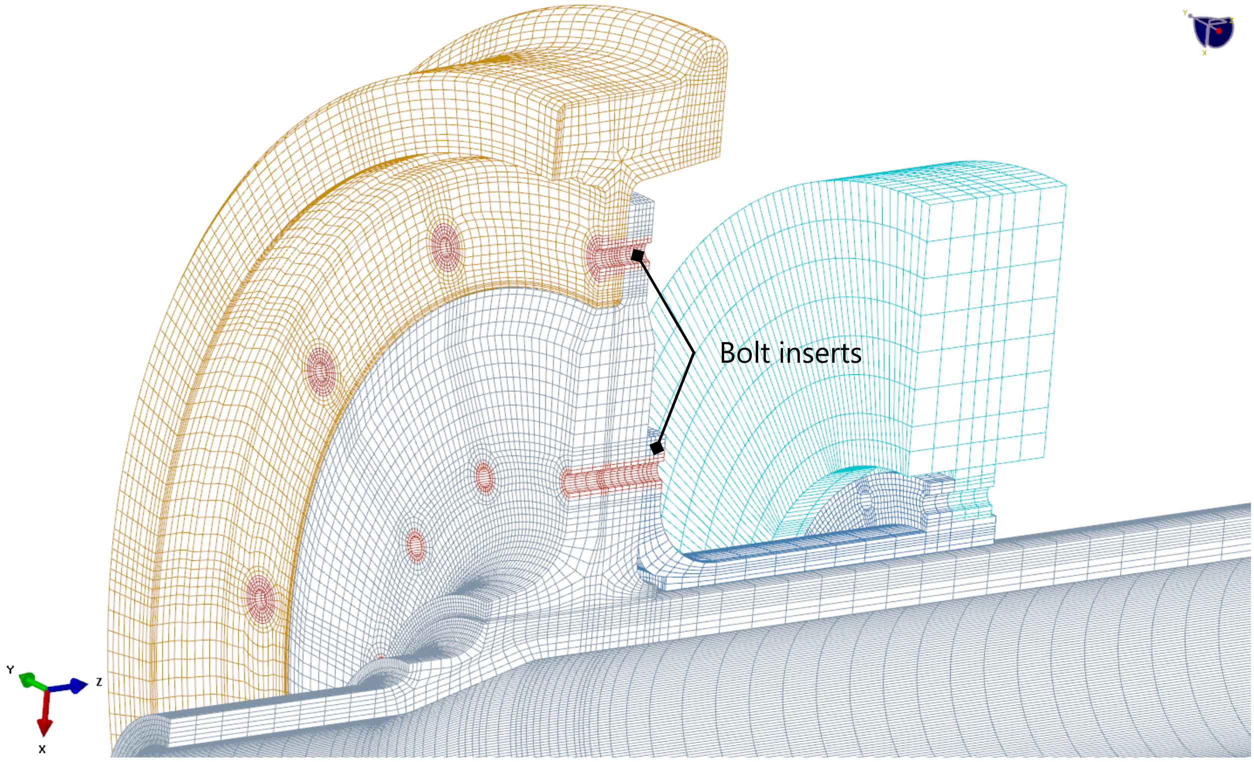


Figure 12: Section view of the Carbolink design D2 wheelset geometry discretization including bolt inserts (in red) at the different interfaces (conformal mesh with only quadratic hexahedral elements)

3.5 Acoustic meshing

In FEM acoustics, the driving parameter for the mesh derivation is the element size. The acoustic mesh should be fine enough to capture the pressure mode shapes. For linear element formulation, at least 12 elements per wavelength (i.e. $\lambda = c/f$) are needed while six elements per wavelength are needed for quadratic element formulation. High quality hexahedral quadratic elements (i.e. hexa 20) are used and derived with ANSYS ICEM CFD meshing software. The size criteria of the acoustic mesh element depends on the wave propagation speed of the material (i.e. c_{speed}) and the highest frequency of interest (i.e. f_{max}).

On the other hand, the acoustic enclosure of the FEM model requires to include at least one quarter wave length distance to the closest source point. This implies that the truncation of the far field domain (i.e. distance of the acoustic enclosure) is driven by the lowest frequency of interest (i.e. f_{min}).

Hence, to efficiently calculate the full frequency range from 200Hz to 5000Hz the acoustic enclosure needs to be adjusted as shown in **Figure 13**. The structural vibration velocities are imported and mapped to the acoustic mesh at the FSI interface of the wheelset.

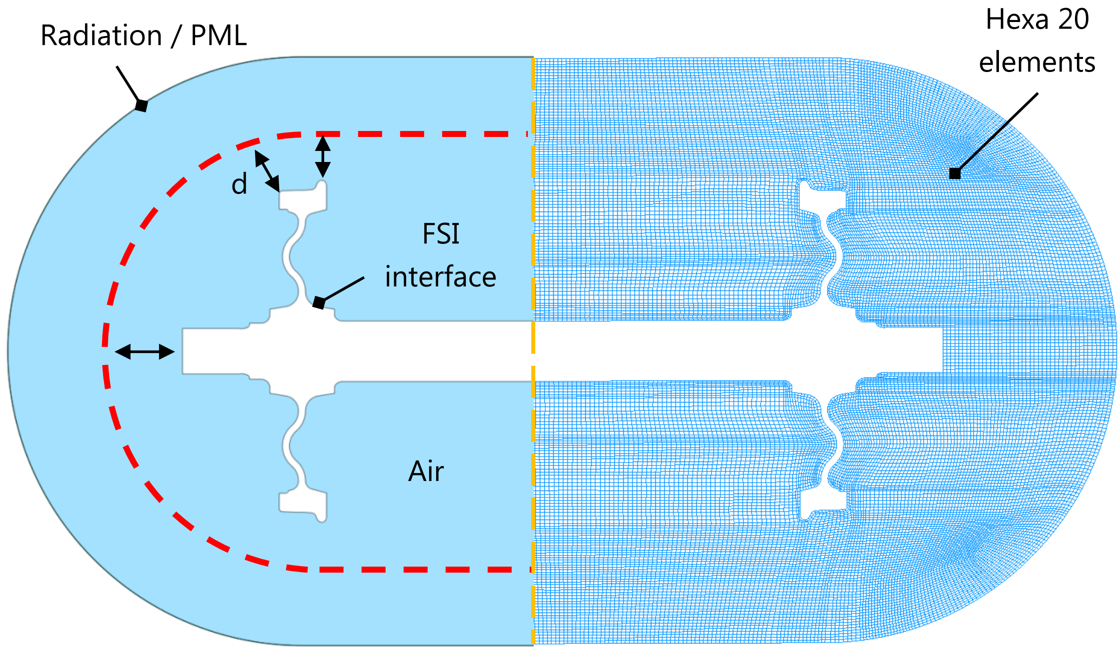


Figure 13: Section view of the acoustic domain of the conventional steel wheelset (left) and corresponding hexahedral mesh (right). The acoustic enclosure size d is adjusted to the studied frequencies

4 Structural dynamics analysis

To obtain the structural vibration velocities (T.1-3) required as input data for the downstream acoustic calculation (T.1-4) a structural dynamic analysis is required and was taken over by the Empa Laboratory for Acoustics/Noise control. This dynamic analysis involves several sub-steps as presented in **Figure 14**.

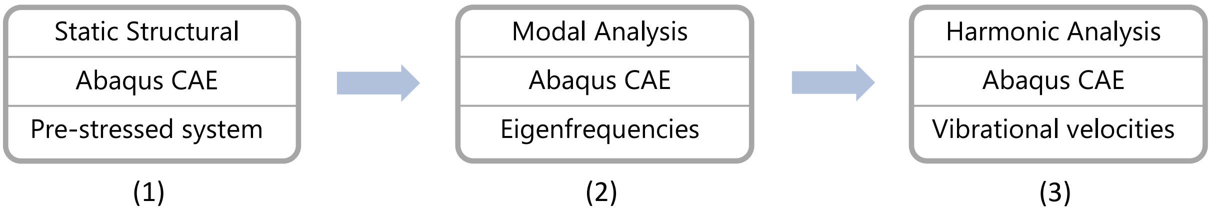


Figure 14: Structural dynamic analysis chain to calculate the resulting surface vibrational velocities (T.1-3) for the downstream acoustic calculation (T.1-4)

4.1 Static structural analysis

Different load cases (i.e. LC) are required to assess the structural integrity of the wheelset which are carried out by the Empa Structural laboratory according to the Structural assessment acc. EN 13979 (UIC-510-5) as:

- LC1 Gerade Strecke / Straight track (Fz3 = 1.25P, Fy1 = 0P)
- LC2 Gleisbogen / Curve (Fy2 = 0.6P)
- LC3 Weichen und Kreuzungen / Negotiation of points and crossings (Fy3 = 0.36P)

A straight track load case (LC1) is used for the acoustic calculation and the noise estimation to compare the FRP to the conventional steel wheelset. An even load distribution is assumed to calculate the static deflection of the wheelset and used in the downstream modal analysis.

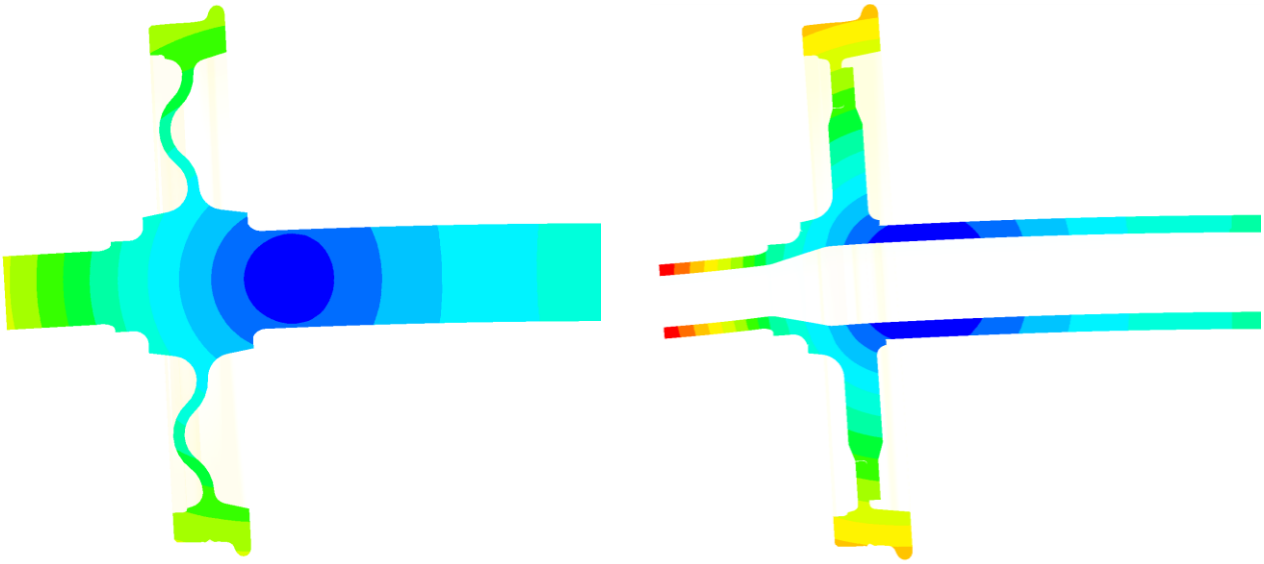


Figure 15: Section view of the prestressed wheelsets used for the downstream modal analysis (left: Steel, right: FRP D2 – identical displacement contour scale)

4.2 Modal analysis

The structural response of the system is performed after completion of the initial static loading to account for the pre-stress effects of the system. To efficiently calculate the harmonic response of the wheelset over the full frequency range, a modal analysis is used to identify the resonance frequencies of the wheelset. The obtained eigen-frequencies are used to properly select the frequencies for the harmonic analysis and reduce the simulation time (**Figure 16**).

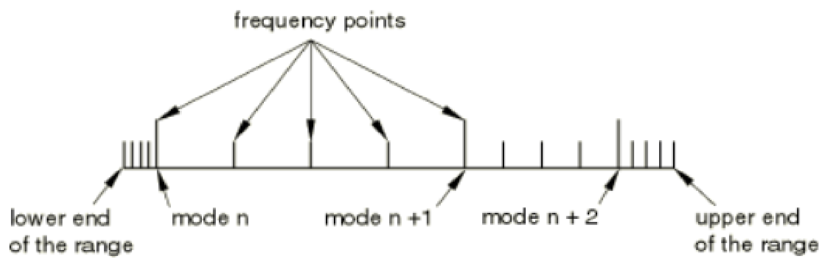


Figure 16: Example of the division of range for the eigen-frequency type of interval with 5 calculation points (Abaqus User Manual - Steady state dynamics)

Besides, eigen-modes can be categorised as dominant if they contribute significantly to the acoustic radiation. Dominant modes can be identified using the modal participation factor table which lists participation factors, mode coefficients, and mass distribution percentages for each mode extracted. Similarly as for experimental modal testing where the effective modal mass provides a method for judging the "significance" of a vibration mode. Examples of resulting dominant modes for both steel and FRP wheelsets are presented in **Figure 17 – Figure 18**.

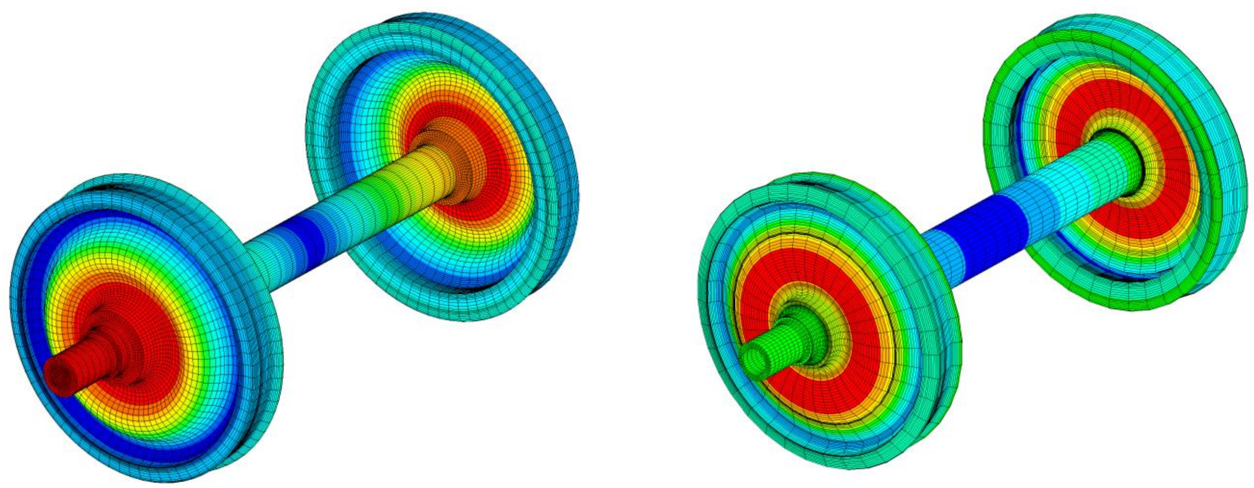


Figure 17: Modal analysis – structural response (left: Steel @1020.4Hz ; right : FRP D2 @ 1237.7Hz)

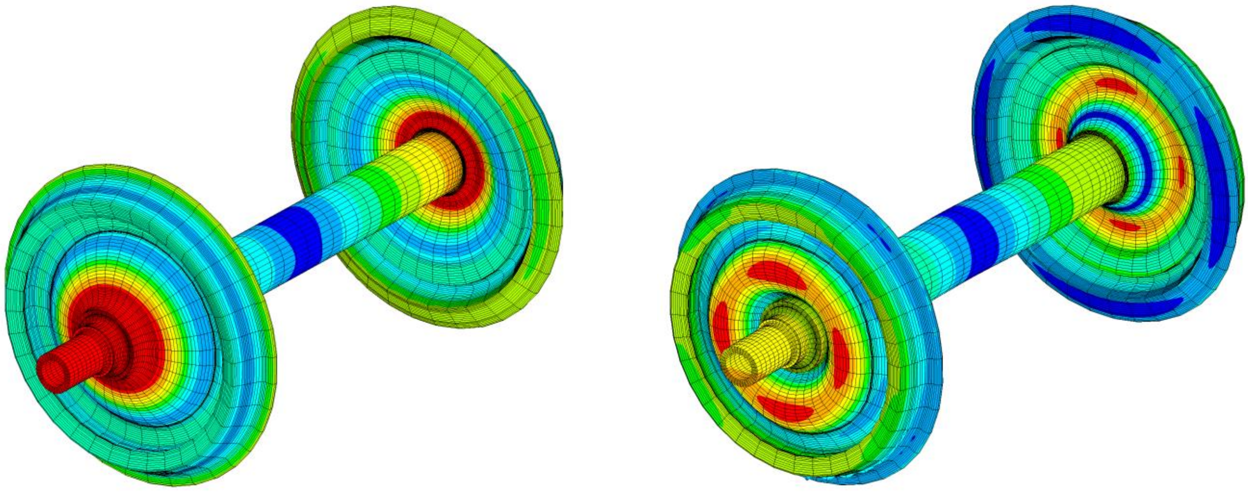


Figure 18: Modal analysis – structural response (left: FRP D2 @1771.8Hz ; right : FRP D2 @ 2818.0Hz)

4.3 Harmonic analysis

The third and final component of the structural dynamic analysis chain is a harmonic analysis. This steady-state dynamic analysis provides the steady-state amplitude and phase of the response of a system due to harmonic excitation at a given frequency. To efficiently calculate the harmonic response of the wheelsets over the full frequency range (200-5000Hz) , 5 calculation points are used per third octave bands (**Table 1**) in addition to the eigen-frequencies obtained from the modal analysis.

Lower Band Limit (Hz)	Centre Frequency (Hz)	Upper Band Limit (Hz)
178	**200**	224
224	**250**	282
282	**315**	355
355	**400**	447
447	**500**	562
562	**630**	708
708	**800**	891
891	**1000**	1122
1122	**1250**	1413
1413	**1600**	1778
1778	**2000**	2239
2239	**2500**	2818
2818	**3150**	3548
3548	**4000**	4467
4467	**5000**	5623

Table 1: Studied frequencies for the structural and acoustic FEM analysis. Five calculation points are used per one-third octave band in addition to the eigen-frequencies of the wheelsets (modal analysis)

In the intermediate report (Empa-Nr. 5211.01393.100.02-1), the dynamic load factor was applied through an interaction contact force (wheel / rail) using standard values found in literature [Thompson, Railway noise and vibration, 2009]. This constant interaction force was used for the initial design assessment of the FRP D1 which resulted in satisfying results. Nonetheless, to further improve the model and take into account the frequency dependent nature of the interaction force for the FRP D2 wheelset an excitation signal based on sonRAIL measurements is used. The excitation signal is generated using a rail roughness spectrum of high quality rails typically found in Switzerland and a wheel roughness spectrum of composite brake block braked wheels. The combined roughness signal of a 1000m length system is transformed into the time domain to account for the vehicle speed. The resulting displacement Power Spectral Density (i.e. PSD) is used as a frequency dependent imposed displacement at the wheel/rail contact point in the harmonic analysis (**Figure 19**).

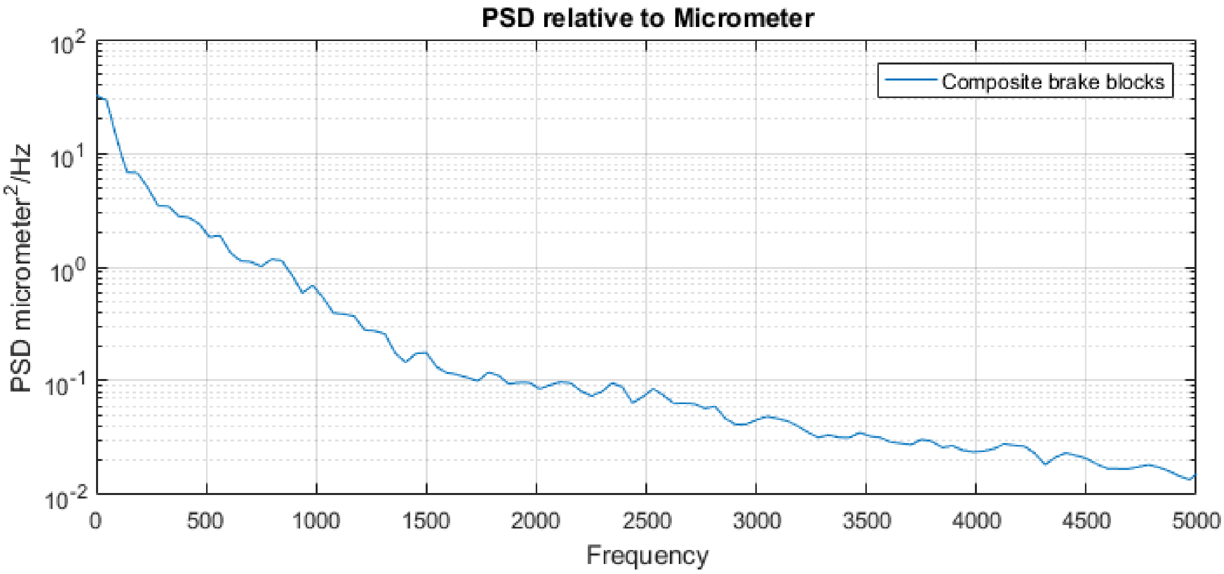


Figure 19: Displacement PSD based on combined roughness spectrum (wheel/rail) used as frequency dependant imposed displacement at the wheel/rail contact point

The imposed displacement obtained from the PSD is used for both the conventional steel and the FRP D2 wheelsets harmonic analysis. To look at the sensitivity of the geometry and material properties, an additional analysis is performed using the FRP D2 geometry with steel material properties. Surface vibrational velocities of the fluid-structure interface are exported from Abaqus and used as inputs for the acoustic calculation in ANSYS. The directional vibration velocities in the Z axis (i.e. axis along the wheelset axle) of the 3 studied wheelsets are presented in **Figure 20**.

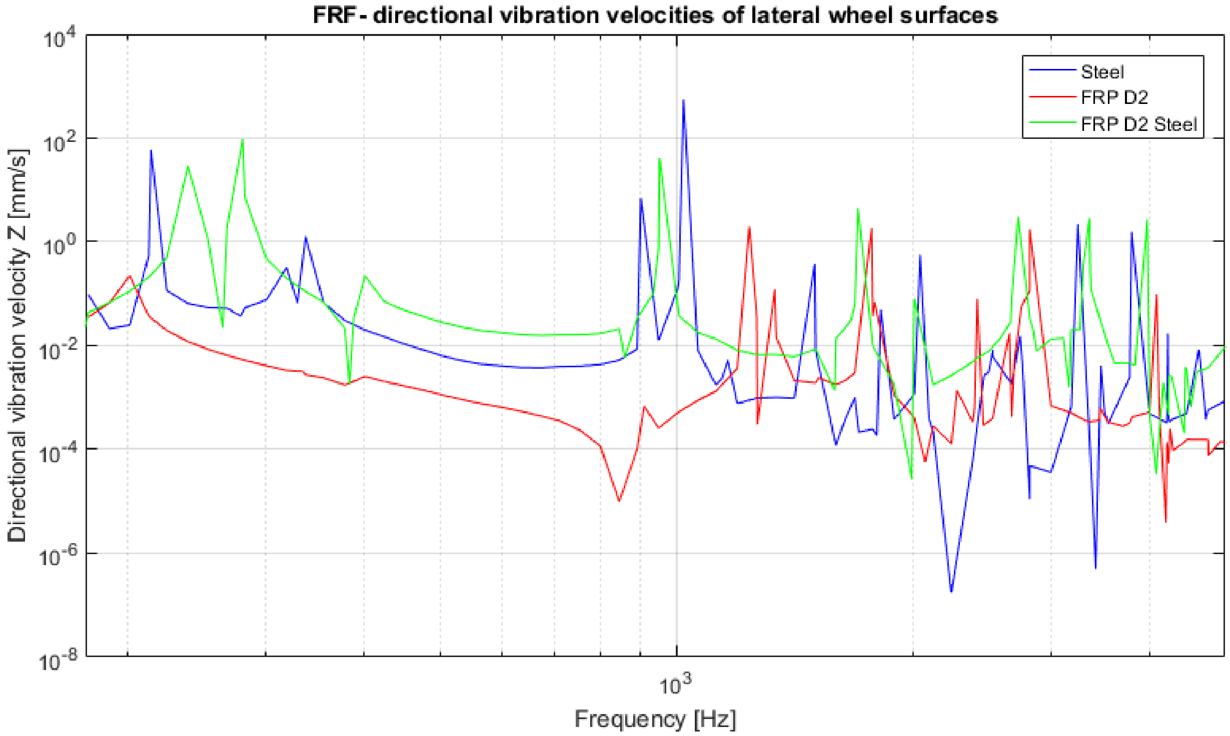


Figure 20: The directional vibration velocities in the z axis (i.e. axis along the wheelset axle) of the lateral wheel surface of the 3 studied wheelsets (steel, FRP D2, FRP D2 with steel material properties)

Below 1.2kHz, the vibration levels of the FRP D2 wheelset are lower compared to conventional steel geometry and the FRP D2 geometry, both with steel material properties (i.e. Steel and FRP D2 steel in **Figure 20**). The modal nature of the studied systems is clearly visible, with high peak vibration amplitudes at 213.9 / 1020.4Hz for the conventional steel wheelset and 1237.7 / 1771.8 / 2818 Hz for the FRP D2 wheelset. Those frequencies correspond to dominant eigen-modes illustrated in **Figure 17 – Figure 18**. In addition the levels obtained for the FRP D2 geometry with steel material properties show a main dependency on material properties rather than the geometry (FRP D2 vs FRP D2 steel - in **Figure 20**). In the current case, the dominant factors are the mass to stiffness ratio and stiffness directional dependency (anisotropic for FRP vs isotropic for steel).

5 Harmonic acoustic analysis

5.1 Acoustic FEM setup

The sound radiation calculation is performed by means of a harmonic response system analysis in the ANSYS Workbench environment. The required inputs are the structural vibrational velocities and the acoustic high quality mesh created in ANSYS ICEM CFD. **Figure 21** depict the required Ansys Workbench project schematic layout.

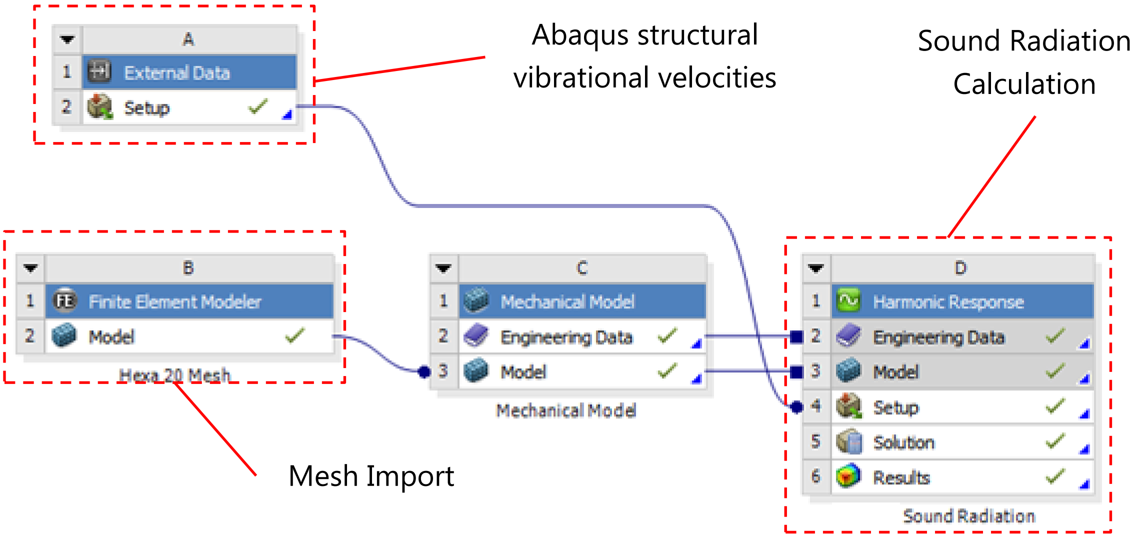


Figure 21: Ansys Workbench project schematic for sound radiation calculation

By linking the external data component to the harmonic response, the imported velocities are transferred and mapped to the geometrical entities as shown in **Figure 22** . The FEM model uses the resulting velocities for the sound radiation calculation by utilizing them as local vibrating sources (i.e. at each mesh node).

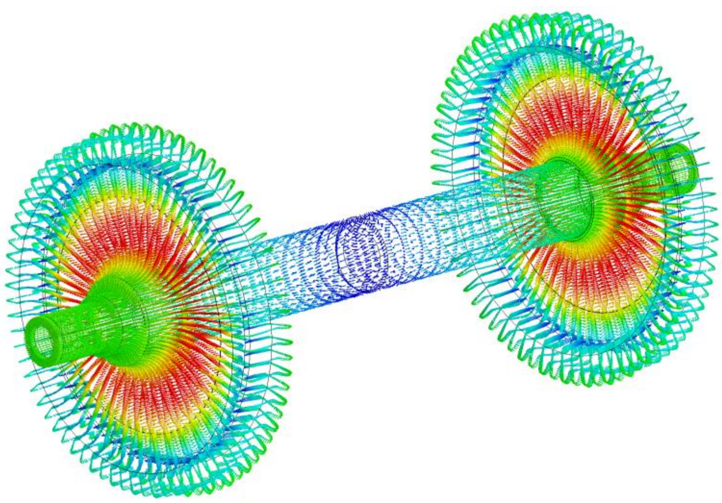


Figure 22: Structural vibrational velocities imported in the Ansys acoustic model (FRP D2 @ 1237.7Hz)

Standard acoustic properties of air are used and are available in the ANSYS material database and listed in **Table 2**. The reference pressure is used to derive the sound pressure levels from the nodal acoustic pressures of the radiated sound field.

Parameter	Value
Mass Density	1.2041 [kg.m^{-3}]
Sound Speed	343.24 [m.s^{-1}]
Ref. Temperature	20 [°C]
Ref. Pressure	2e-5 [Pa]
Ref. Static Pressure	101325 [Pa]
Fluid Behaviour	Compressible

Table 2: Air acoustic properties

5.2 Acoustic radiation calculation

The acoustic radiation calculations are performed up to 5kHz using 5 calculation points per third octave band (**Table 1**) in addition to the wheelsets eigen-frequencies. This corresponds to roughly 100 calculation points per wheelsets. Post-processing of the acoustic calculation is done using a divergent colour map to better represent the positive (i.e. red) and negative (i.e. blue) pressure fluctuation around the reference pressure. The acoustic pressure fluctuations are illustrated in **Figure 23 - Figure 24**.

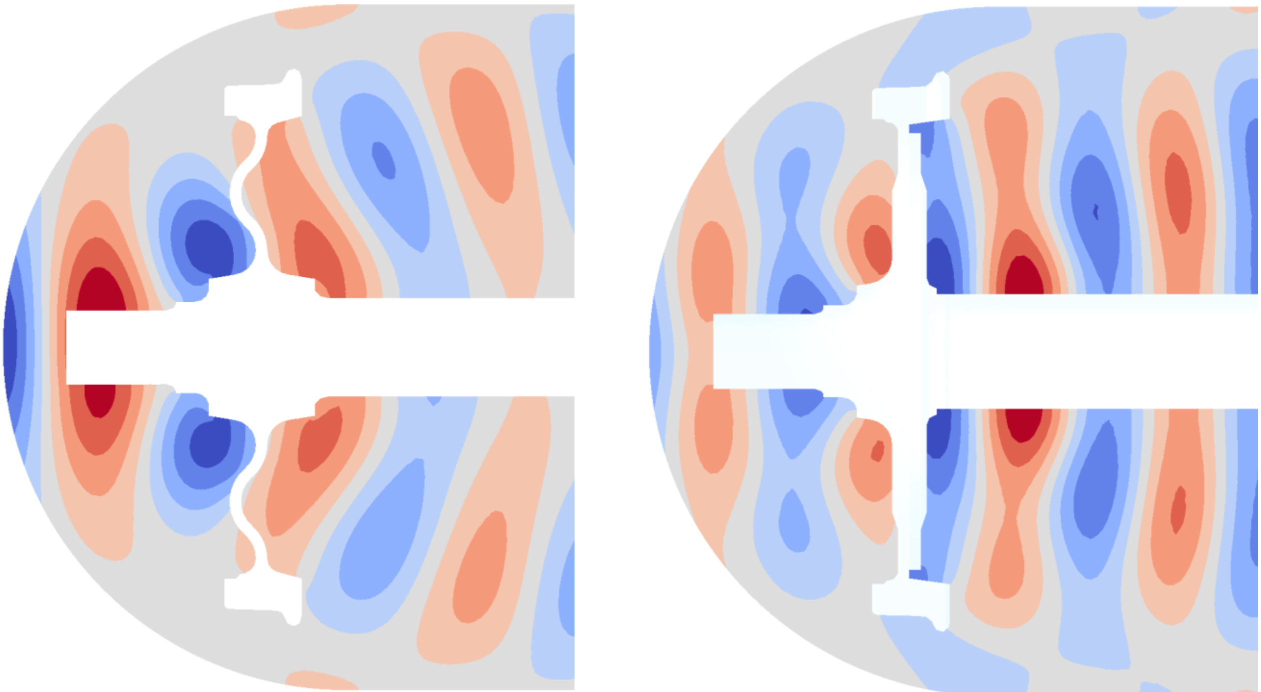


Figure 23: Section view of the acoustic pressure fluctuation field of dominant modes (red = positive, blue = negative compared to the ref. pressure – left: steel @ 1020.4Hz, right: FRP D2 @1237.7Hz)

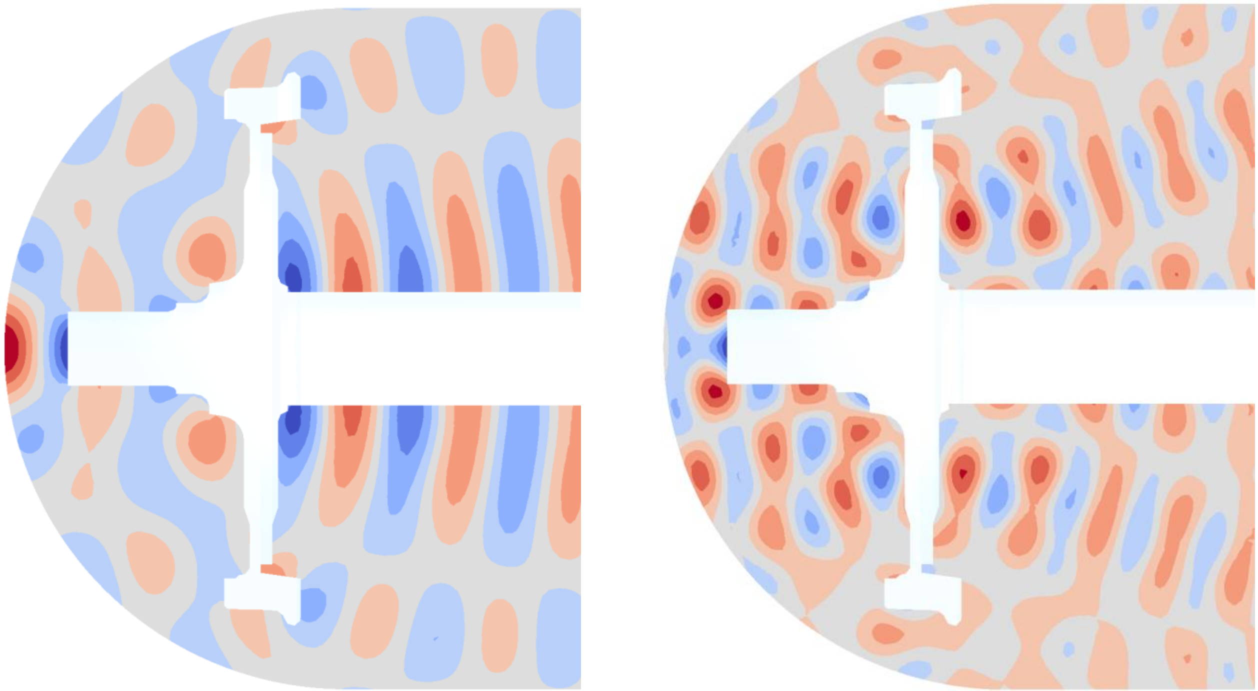


Figure 24: Section view of the acoustic pressure fluctuation field of dominant modes (red = positive, blue = negative compared to the ref. pressure – left: FRP D2 @1771.8Hz, right : FRP D2 @ 2818.0Hz

The strong directional pattern of the pressure waves along the central axis can be observed. The lateral structural motion of the wheel at the dominant eigen-modes act similarly as a loudspeaker vibrating membrane. The dominant modes contribute significantly to the overall wheelset sound pressure levels calculated in the energetic summation.

5.3 Acoustic energetic summation

From the post-processing of the acoustic pressures, one can easily extract the sound pressure levels (i.e. SPL) defined as:

$$L_p = 20\,log\left(\frac{p_{rms}}{p_{ref}}\right)$$

where p_{rms} is the root-mean-square of the pressure, and p_{ref} the reference pressure in air which is typically taken as $20\mu Pa$. Sound pressure levels are extracted at a distance of 3.7m from the wheelset on the Z axis central line (coincident with the wheelset axle). Moreover, in an effort to account for the relative loudness perceived by the human ear, as the ear is less sensitive to low audio frequencies, A-weighted SPL levels are used for the energetic summation. This summation is reported per one-third octave band chart for each wheelset in **Figure 25**.

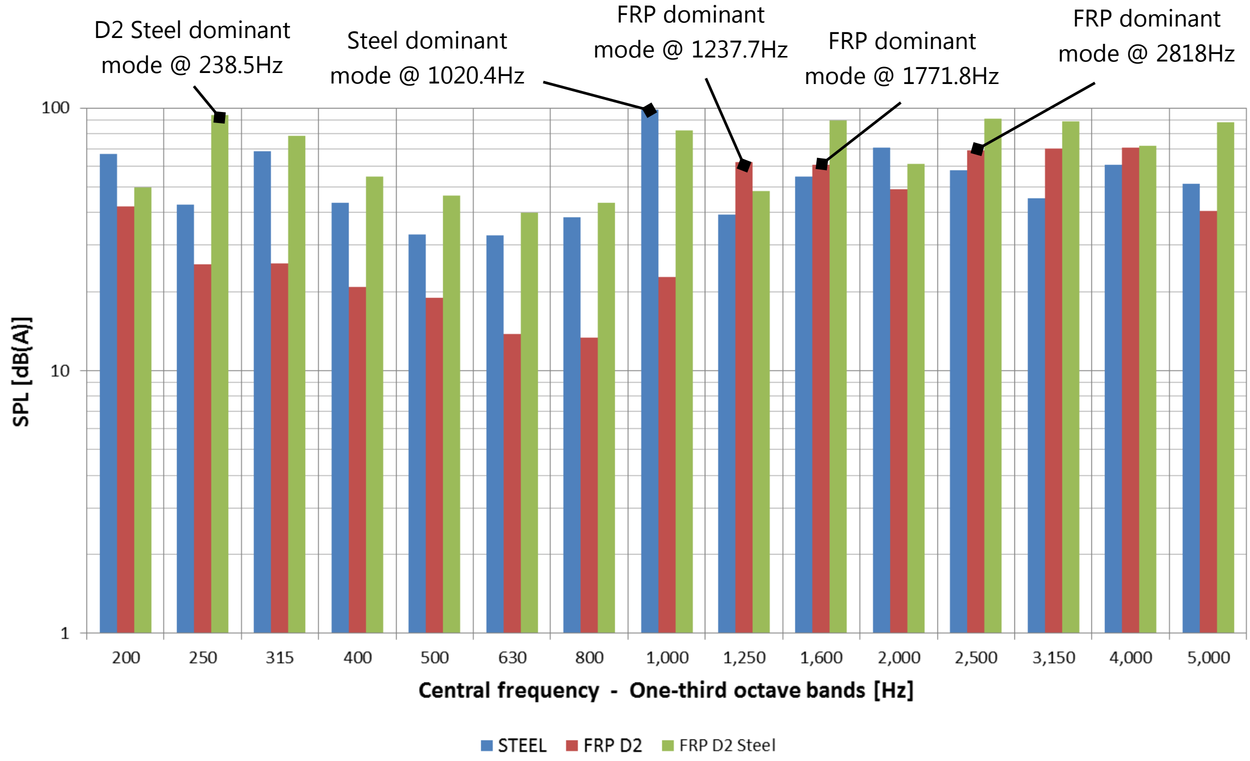


Figure 25: SPL energetic summation chart of the studied wheelsets (conventional steel, FRP D2 and FRP D2 geometry with steel material properties). Dominant eigen-modes identified in the structural dynamic analysis clearly contribute to the third octave band SPL values.

As expected from the vibration levels of the structural dynamic analysis, dominant eigen-modes contribute significantly to the overall SPL levels per third octave band as referenced in **Figure 25**. The reported levels of the conventional steel wheelset exhibit higher values compared to the FRP D2 up to the 1250Hz central frequency band where the first dominant eigen-mode of the FRP D2 kicks in (i.e. 1237.7Hz). To get a better overview of the potential dB reduction of the FRP D2 wheelset a second energetic summation is carried out to obtain a single SPL number summarised in **Table 3**.

	Wheel [dB(A)]	**Delta [dB(A)]**
Steel (reference)	**98.29**	-
D2 steel	**98.08**	-0.21
FRP D2	**75.12**	-23.17

Table 3: Energetic summation of the A-weighted sound pressure levels extracted at a distance of 3.7m from the wheelset Z axis . Values represent the contribution of the wheel in a straight track load case.

The value obtained for 98.29 dB(A) for the conventional steel wheelset is close to 94.4 dB(A) prediction obtained with TWINS model for a similar test case found in literature [Thompson, Railway noise and vibration, 2009]. The spectrum of the steel wheelset is mainly driven by the dominant mode at 1020.4Hz whereas the FRP D2 geometry with steel material properties presents a higher dominant modal density contributing at different frequency bands but with slightly lower dB(A) values. Hence the effect of the steel material properties on the FRP D2 geometry show only a slight reduction of 0.21 dB(A). In addition, the FRP D2 wheelset exhibits dominant contributing modes above the 1250Hz band with overall lower peak values. As shown in **Table 3** the FRP D2 design presents a relative reduction of about 23.17 dB(A) which is significant. Nonetheless this value represents the potential relative reduction for the contributions of the wheel only. Special care needs to be taken when extrapolating this value to a real "by-pass" situation as detailed in the next section.

5.4 Comparison of railway rolling noise prediction with TWINS

Railway rolling noise is caused by small-scale roughness variation on the running surfaces of the wheels and rails. The surface irregularities of the wheel and rail cause a variation in the contact interaction force which influences the system's response. As implemented in the current FEM model of the wheelsets with the frequency dependent contact force, TWINS uses a similar approach to calculate the overall railway rolling noise, including the contributions of the wheel, rail and sleepers as illustrated in **Figure 26**.

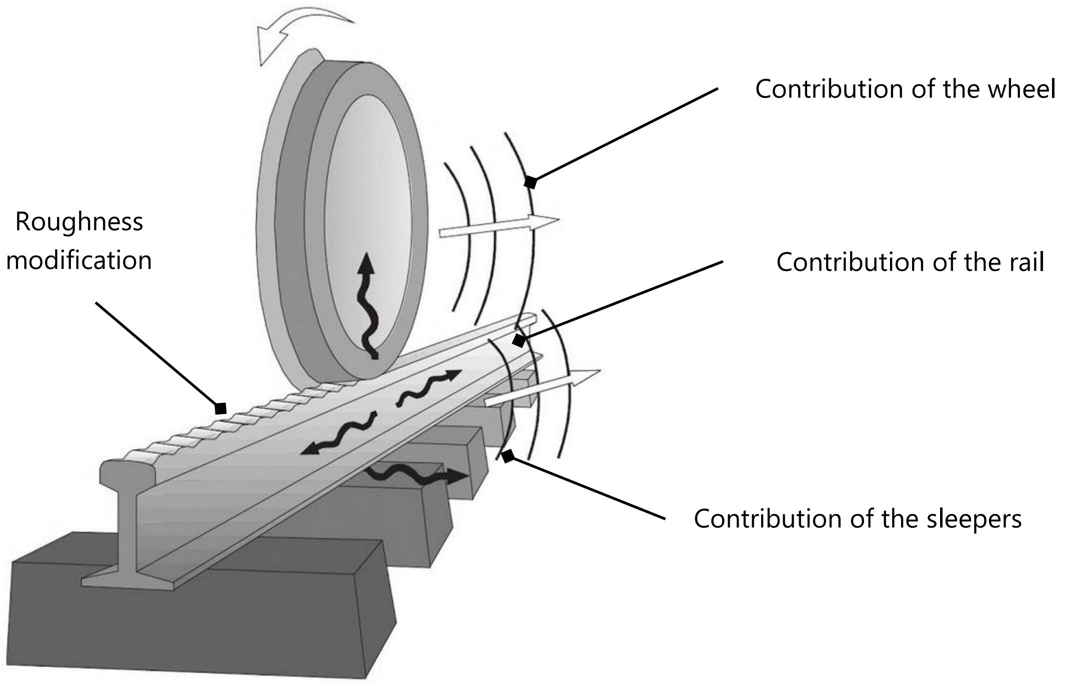


Figure 26: Illustration of the mechanism of generation of rolling noise [Thompson, Railway noise and vibration, 2009]

An example of total noise prediction of a typical freight wagon under similar conditions calculated with TWINS is depicted in **Figure 27**. The individual contributions of the rail, wheel, and sleepers to the total sound pressure level spectrum at 3.7m can be identified. The energetic summation of the wheel obtained with TWINS is about 94.4 dB(A) which is lower than the 98.29 dB(A) obtained with ANSYS for the conventional steel wheelset. This rather small difference can be explained by the fact that the system modelled is slightly different (wheelset only compared to full system in TWINS) or a difference in the frequency dependent contact force excitation signal which is directly linked to the roughness spectrum of the wheel and the rail as well as the type of railpad used.

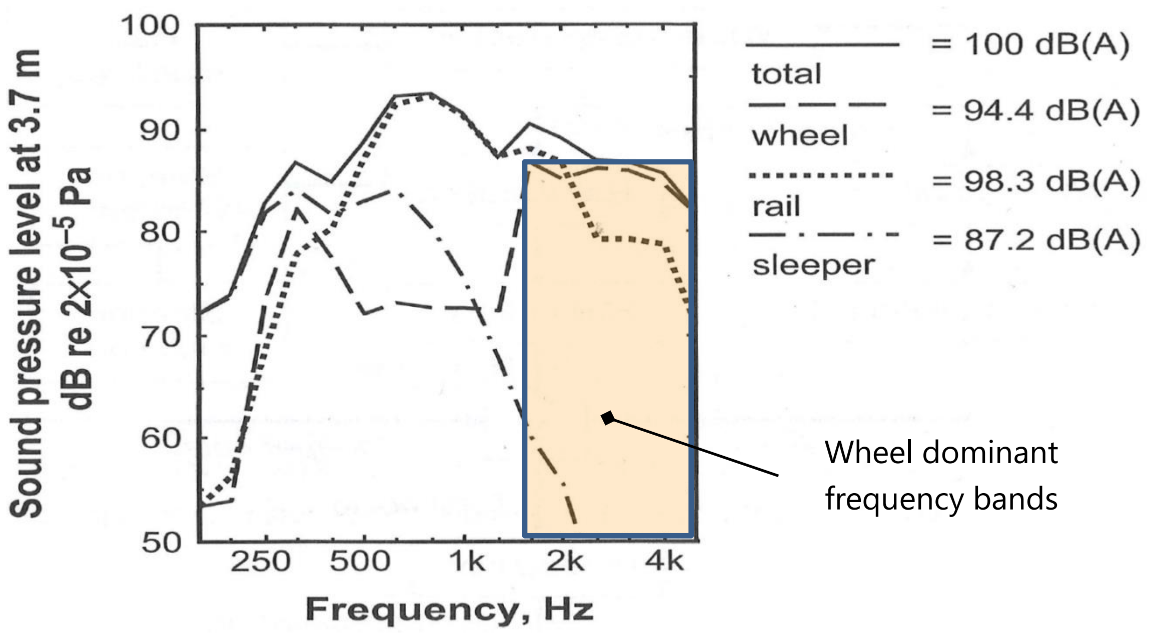


Figure 27: Results from typical prediction using TWINS model for freight wagon showing contributions of the wheel, rail and sleepers in the total noise level [Thompson, Railway noise and vibration, 2009]

Nonetheless, as the goal of this feasibility study is to assess the potential relative reduction between conventional and the FRP D2 wheelsets, the contributions of the rail and sleepers are used to calculate the overall energetic summation (**Table 4**).

	Wheel [dB(A)]	Overall [dB(A)]	Delta [dB(A)]
Steel (reference)	**98.29**	101.47	-
D2 steel	**98.08**	101.37	-0.1
FRP D2	**75.12**	98.64	-2.83

Table 4: Energetic summation of the A-weighted sound pressure levels for the studied wheelsets including the contributions of the rail and sleepers at a distance of 3.7m from the wheelset Z axis.

The overall energetic summation shows a relative potential reduction of about 2.8 dB(A) for the FRP D2 compared to the conventional steel wheelset. As the uncertainties of the predictions couldn't clearly be quantified without experimental measurements, conservative assumptions were made to build the whole modelling chain and include the potential contributions of the rail and sleepers in the overall noise level estimation. The displacement spectrum imposed at the wheel / rail contact point which doesn't include to potential weight reduction of the FRP wheelset and could also affect the vibration levels of the rail and sleepers. Moreover, identical material damping for both wheelsets was chosen which is a conservative approach as loss factors of the FRP could be increased compared to steel depending on the matrix resin. Nonetheless, the obtained resulting delta dB(A) reduction should be taken into consideration when evaluating if the increased initial costs can be justified based on the potential acoustic benefit of the FRP D2 wheelset.

6 Conclusion

In this report, the derivation of the full modelling chain from the geometrical inputs to the equivalent acoustic radiated sound field has been presented. The conventional wheelset geometry is derived based on technical drawings and the acoustic volume is represented by a geometrical enclosure around the wheelset. A meshing methodology has been proposed in order to optimize the components with respect to simulation time and solution accuracy including the adjustment of the acoustic enclosure based on the solved frequencies. The updated meshes were used as inputs for the structural assessment analysis conducted by the Empa Structural Laboratory.

In parallel to the structural assessment of the wheelsets, the task T.1-3 involving the structural dynamic analysis was taken over by the Empa Laboratory for Acoustics/Noise control. A methodology to obtain the required surface vibration velocities involved 3 sub-analyses. First, a static structural analysis is performed for the straight track load case to account for pre-stressed effects on the wheelsets. Second, a modal analysis is used to identify the resonance frequencies. Third, the final component of the structural dynamic analysis chain is a harmonic analysis. In order to efficiently calculate the surface vibration velocities over the full frequency range (200-5000Hz) , 5 calculation points are used per third octave bands in addition to the eigen-frequencies obtained from the modal analysis. An improved frequency dependent contact force (wheel / rail) was derived based on sonRAIL measurement. The resulting displacement Power Spectral Density (i.e. PSD) is based on the roughness spectrums and vehicle speed and is used as a frequency dependent imposed displacement at the wheel/rail contact point. Finally, the surface vibration velocities are extracted and further used as inputs for the acoustic radiation calculation (Task T.1-4).

The sound radiation calculation is performed by means of a harmonic response system analysis in the ANSYS Workbench environment. The FEM model uses the resulting velocities for the sound radiation calculation by utilizing them as local vibrating sources (i.e. at each mesh node). Sound pressure levels (i.e. SPL) are extracted at a 3.7m distance from the wheelsets and two energetic summation were obtained. As expected from the vibration levels of the structural dynamic analysis, dominant eigen-modes contribute significantly to the overall SPL levels per third octave band. The FRP D2 wheelset presents a relative reduction of about 23.17 dB(A) when compared to the conventional steel wheelset (total 98.29 dB(A)) which is significant. Nonetheless this value represents the potential relative reduction for the contributions of the wheel only and special care needs to be taken when extrapolating this value to a real "by-pass" situation. To this end, a comparison with TWINS predictions for a typical freight wagon under similar conditions was performed. By including the contributions of the rail and sleepers, the overall energetic summation shows a relative potential reduction of about 2.8 dB(A) for the FRP D2 compared to the conventional steel wheelset. This result should be taken into consideration when evaluating if the increased initial costs can be justified based on potential acoustic benefit of the FRP D2 wheelset.

Empa
Überlandstrasse 129
CH-8600 Dübendorf
T +41 58 765 11 11
F +41 58 765 11 22
www.empa.ch

Bundesamt für Umwelt BAFU
Abteilung Lärm und NIS
Worblentalstrasse 68, 3063 Ittigen
Postadresse: 3003 Bern

Assignment	**Final report Task 1-5 and 1-6**
Client:	BAFU, Switzerland
Client's ref:	Mr. Franz Kuster
Number of pages:	25

Empa, Swiss Federal Laboratories for Materials Science and Technology

Input from all partners: PROSE, Carbo-link, Empa acoustic (Empa 509) and Empa structural (Empa 303)

Dübendorf, 24.08.2018

Contents

1 Summary (in English and in German)

Cost estimation for the manufacturing and maintenance of the proposed FRP wheelset configurations is presented in this report. The total life cycle costs for a FRP wheelset were estimated based on manufacturing costs, maintenance costs, and some reductions (bonus) due to high-added values, i.e. less noise and lower weight. According to the detailed estimations, the ratio for total costs of a new FRP wheelset to total costs of a conventional steel wheelset both with brake disks and designed for 1’500’000 km is ***4.17*** (i.e. 18’420/4’420)

According to the addressed clarification of necessary verifications (see report of task 1-1), introduction of a new material and interface elements requires a significant number of tests and on-track measurements. It has to be noticed that on-track testing is only possible in collaboration with a company (like SBB Cargo for example) which have access to the necessary rolling stock and would apply for such tests at BAV and the infrastructure body in charge.

Based on the outcome of the feasibility studies, all criteria for starting Phase 2 of the project (as defined in the project application) are fairly satisfied. However, the cost ratio seems to be relatively high and judgment will be done by BAFU.

Our proposal for Phase 2 of the project includes two plans, **Plan A** (original plan as continuation of the FRP wheelset application) and **Plan B** (a new idea on feasibility studies for application of self-steering FRP bogies). Very brief descriptions on tasks in Plan A and Plan B are presented in this report, however, when we receive feedbacks from BAFU, a detailed description in format of a project proposal for pursuing any of the proposed Plan A and/or Plan B can be worked out.

Summary in German

Im vorliegenden Bericht wird die Abschätzung der Kosten für die Herstellung und den Unterhalts des vorgeschlagenen CFK-Radsatzes beschrieben. Die Kosten über die ganze Lebensdauer für 1’500’000 km wurden aus den Herstellungs- und Unterhaltskosten und allfälligen Kostenreduktionen wegen des reduzierten Lärms und tieferem Gewicht abgeschätzt. Der Faktor der totalen Kosten des neuartigen CFK-Radsatzes im Verhältnis zum konventionellen Stahl Radsatzes (beide mit Bremsscheiben) beträgt ***4.17*** (i.e. 18’420/4’420).

Für die Einführung von neuen Materialien und Verbindungselementen müssen viele Bauteilversuche und auch Fahrversuche durchgeführt werden, siehe dazu die detaillierten Angaben im Teilbericht 1-1. Es muss beachtet werden, dass Fahrversuche nur in Zusammenarbeit mit einer Firma, wie z.B. SBB Cargo, möglich sind, da nur diese Zugang zu den nötigen Schienenfahrzeuge haben und zudem auch solche Versuche beim BAV und den zuständigen Behörden beantragen können.

Die Machbarkeitsstudie ergab, dass die Kriterien zum Starten der Phase 2 (wie im Projektantrag definiert) erfüllt sind. Davon ausgenommen ist der Kostenfaktor der relativ hoch ist und vom BAFU beurteilt werden muss.

Für Phase 2 des Projektes schlagen wir zwei mögliche Szenarios vor; **Plan A** (wie im ursprünglichen Projektantrag vorgesehen) und **Plan B** (eine neue Idee einer Machbarkeitsstudie eines selbstlenkenden Drehgestells aus faserverstärktem Kunststoff). Im vorliegenden Bericht wird nur eine kurze Beschreibung der beiden Szenarios gegeben. Aufgrund der Rückmeldung des BAFU kann eine detaillierte Beschreibung in Form eines Projektantrages zur möglichen Weiterführung des Projektes mit Plan A und/oder Plan B ausgearbeitet werden.

2 Task 1- 5: Cost estimation for manufacturing and maintenance of a FRP wheelset configuration

Cost estimation for the manufacturing and maintenance of the proposed FRP wheelset configurations is presented in this section. Although FRP composites have high strength and stiffens compared to metals and they are known for being less susceptible for deterioration, the initial cost of products made of FRP composite can be very high. In addition to the initial cost of manufacturing, cost of maintenance along the operation life of wheelsets is very important for the end user. The total life cycle costs for a FRP wheelset can be estimated as follow:

- Manufacturing costs
  - Raw materials
  - Labor costs
  - Cost saving for series production
- Maintenance costs
  - Requirements for maintenance based on existing standards (possible modifications on the intervals)
  - Additional requirements for the new FRP wheelset (ex. interlaminar cracks…)
- Total costs
  - Pure sum of the costs
  - Some reductions (bonus) due to high-added values, i.e. less noise and lower weight.

2.1 Manufacturing costs (estimated by Carbo-link)

The estimation of the manufacturing costs for a FRP wheelset is carried out for two different settings:

1. Prototype (one or two wheelsets)
2. Series production (about 1’000 wheelsets)

2.1.1 Prototype

The cost estimation for the prototype is based on the following assumptions:

- Laminated parts manufactured in Switzerland (e.g., by Carbo-Link AG)
  - Wheelset axle made from E-752-LT (Park Advanced Composites Materials), winding process on mandrel and subsequent machining to final dimension
  - Wheel disc made from AS4 fibres, RTM process with mould

- Metallic parts manufactured in Switzerland (e.g., by Carbo-Link AG):
    - All parts made from corrosion-resistant material
    - Torsion tube and wheel rim hammer forged and machined to final dimension (basis: price indication from possible supplier)
- Non-recurring costs for CFRP parts for production engineering, tools (moulds, mandrel) etc.
- Materials procurement in small batches

Table 1. Manufacturing cost estimation for FRP wheelset prototype

	Value [CHF]
Raw material	32'880
CFRP	*7'930*
metallic components (small)	*950*
torsion tubes (incl. machining)	*9'000*
wheel rims (incl. machining)	*15'000*
Labour	21'560
CFRP	*7'280*
metallic parts	*14'280*
Non-recurring costs CFRP	17'400
Total	**71'840**

2.1.2 Series production

The cost estimation for the series production is based on the following assumptions:

- 1'000 wheelsets
- Laminated parts manufactured with efficient process in region with lower salaries → labour costs -30% compared to prototype
- Metallic parts:
    - Small parts in large-scale production (no preparation of machines) → machining time -10% compared to prototype
    - Small parts manufactured in region with lower salaries → labour expense -30% compared to prototype
    - Torsion tube and wheel rim hammer forged and machined to final dimension (basis: price indication from possible supplier)
- Non-recurring costs for CFRP parts for production engineering, tools (moulds, mandrel) etc. divided by 1'000 pieces
- Materials procurement in large batches → material costs -10% compared to prototype (CFRP and metals)

Table 2. Manufacturing cost estimation for FRP wheelset series production

	Value [CHF]
Raw material	28'350
CFRP	*7'140*
metallic components (small)	*810*
torsion tubes (incl. machining)	*7'650*
wheel rims (incl. machining)	*12'750*
Labour	14'100
CFRP	*5'100*
metallic parts	*9'000*
Non-recurring costs CFRP	20
Total	**42'462**

2.1.3 Additional possibilities for cost reductions

- Manufacturing of wheel rim by supplier of railway wheel discs (e.g., Bochumer Verein Verkehrstechnik GmbH):
  Costs per wheel about CHF 1'200 (source: presentation "Kostensituation bei einem Faserverbundradsatz im Vergleich zu einem Standardradsatz", PROSE AG)
  → estimated cost per wheel rim: CHF 1'000 leads to possible cost savings of ***CHF 10'750*** per wheelset

Cost assumption by PROSE regarding the share of metallic parts for serial production:

- Labour cost's concerning metal parts considered only for mounting of the wheelsets, purchase costs from suppliers include the machining and therefore no additional labour costs for metallic single part must be considered
- For the mounting of the metallic parts to a complete wheelset: 30 hours x 65 EUR (manufacturing outside CH) = approx. 2'000 EUR or 2'200CHF.
- Plus for logistics, balancing etc. additional 500 CHF
- These assumptions lead to the further potential reduction of labour costs from 9000CHF to approx. 3000CHF compared to Table 2 above.
- Further a comparable price for the rim in the range of the price for a wheel is expected (same production method); and also forged torsion tube part and the same range as a wheel price.
- Therefore approx. 10'000 CHF-12'000 CHF instead of approx. 20'000CHF for the big metal parts seem to be feasible/reasonable for large batches under serial production methods.

The mentioned assumptions related to the metallic parts of the wheelset are based on "cross-comparison" and not yet verified by discussions with potential suppliers. Nevertheless, we consider a potential target price of about **24'000**.- for a serial FRP wheelset (>1000 pieces) manufactured in large batches, by the use of serial manufacturing and assembly tools/methods and comparable steel prices as feasible.

2.2 Maintenance costs (estimated by PROSE)

Information regarding the maintenance cost are listed in the PROSE-presentation "Cost situation for a fiber composite wheel set compared to a standard wheel set" presented on the Project meeting 02.07.2018. The main topic of this presentation is ECM = Entity in Charge of Maintenance. Maintenance is defined in EN 15313 (Railway applications - In-service wheelset operation requirements - In-service and off-vehicle wheelset maintenance). Based on this regulation the operator set-up maintenance guidelines of which one example is the VPI[1] 04 - Instandhaltung von Güterwagen – Radsätze. The following Table 3 shows in general the relevant inspection and service steps. In these tables positions are indicated which are of importance for a comparative maintenance cost estimation. Of special importance is the non-destructive testing (ZfP) and the change of components since these positions are different for the CFRP-wheelset (cp. Table 4).

Table 3. Maintenance guidelines acc. VPI 04 Appendix 4

Instandhaltungsrichtlinien gemäss VPI 04 Anhang 4
/ Maintenance guidelines acc. VPI 04 Appendix 4

lfd. Nr.	Arbeitsinhalte Arbeits- und Prüfschritte	Instandhaltungsstufe IL	IS1	IS2	IS3
1	Kennzeichnung bei Zuführung prüfen (Einstufung in IL, IS1, IS2 oder IS3)	X	X	X	X
1.1	Radsatzmarken prüfen	X	X	X	X
1.2	Einstufung außerplanmäßig zugeführter Radsätze durchführen			X	X
2	reinigen (mechanische Trockenreinigung)		X		
2.1	bleibt frei				
3	prüfen vor Instandsetzung	X	X	X	X
3.1	beurteilen der Wellen nach Anhang 7			X	X
3.2	ZfP durchführen (vor Instandsetzung)		X	X	X
3.3	Lager äußerlich prüfen, ggf. Umstufung in IS2		X		
3.4	ggf. Umstufung in IS2/3, reinigen nach lfd. Nr. 2		X		
3.5	ggf. Umstufung in IS3 und Kennzeichnen			X	
3.6	Kennzeichnen für IS3				X
3.7	ggf. Schäden melden (Formular ausfüllen)	X	X	X	X
4	messen vor Instandsetzung	X	X	X	X
4.1	ggf. Umstufung in IS1	X			
4.2	ggf. Umstufung in IS2/3, reinigen nach lfd. Nr. 2		X		
4.3	ggf. Umstufung in IS3 und Kennzeichnen			X	
4.4	kennzeichnen für IS3				X
4.5	Durchmesserdifferenz (A-B-Seite) errechnen		X	X	X

Legende:
- IL Radsatzlageruntersuchung / bearing inspection
- IS1 Profilbearbeitung im ausgebauten Zustand mit ZfP / profile processing in the removed state with NDT
- IS2 IS1 mit Radsatzlageruntersuchung und erweiterter ZfP / IS1 with bearing inspection and extended NDT
- IS3 Bewellen, Bescheiben mit IS2 ggf. ohne Reprofilierung / New axle, wheel with IS2 without reprofiling possible

Quelle / Reference:
VPI 04 - Instandhaltung von Güterwagen – Radsätze
Anhang 4 Instandhaltungsstufen der Radsätze
/ Appendix 4 Maintenance Levels of Wheelsets

Instandhaltungsrichtlinien gemäss VPI 04 Anhang 4
/ Maintenance guidelines acc. VPI 04 Appendix 4

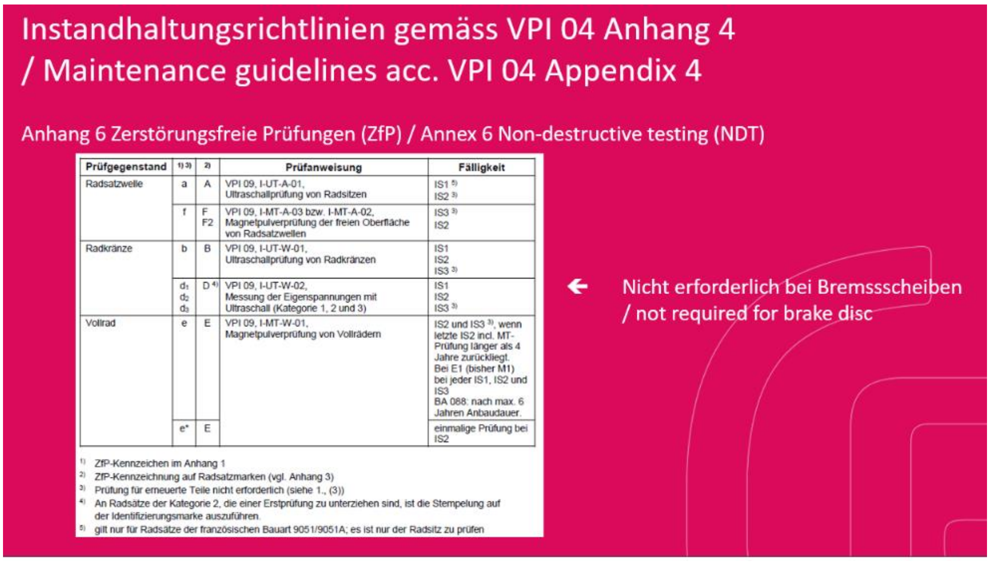
Anhang 4 Instandhaltungsstufen der Radsätze / Appendix 4 Maintenance levels of wheelsets

5	Radsatzlagerdeckel abbauen (bei IS1 Sichtprüfung Fett und darauf achten, dass kein Schmutz in das Lagerinnere gelangt)	X	X	X	X
5.1	Schutzdeckel anbauen, die nur den Durchtritt der Körnerspitzen gestatten		X		
6	bleibt frei				
7	ggf. Behandlung thermisch überbeanspruchter Vollräder durchführen	X	X	X	X
8	Profilbearbeitung durchführen		X	X	X
8.1	bleibt frei				
8.2	bleibt frei				
8.3	Schutzdeckel abbauen, Radsatzlagerdeckel reinigen, mit neuen Dichtungen versehen und anbauen		X		
9	Radsatzlager untersuchen	X		X	X
9.1	Radsatzlager abbauen, zerlegen und reinigen	X		X	X
9.2	Radsatzlager prüfen und messen	X		X	X
9.3	Radsatzlager instand setzen, befetten, zusammen- und anbauen	X		X	X
10	Radsatzwelle instand setzen oder erneuern (je nach Erfordernis)				X
10.1	prüfen und messen bei Arbeiten nach lfd. Nr. 11				X
11	ab- und aufpressen der Vollräder (je nach Erfordernis)				X

lfd. Nr.	Arbeitsinhalte Arbeits- und Prüfschritte	Instandhaltungsstufe IL	IS1	IS2	IS3
11.1	prüfen und messen bei Arbeiten nach lfd. Nr. 12				X
12	auswuchten				X
13	prüfen nach Instandsetzung		X	X	X
13.1	ZfP durchführen (nach Instandsetzung)		X	X	X
13.2	Prüfergebnisse dokumentieren		X	X	X
14	messen nach Instandsetzung		X	X	X
14.1	Messergebnisse dokumentieren		X	X	X
15	Anstrich, Anschriften und Korrosionsschutz ausbessern bzw. neu anbringen	X	X	X	X
16	bleibt frei				
17.1	Kennzeichnungen auf Radsatzmarken ergänzen. Wird ein Radsatz bei der IS3 aus einer neuen Welle und neuen Rädern gefügt, so ist dieser wie bei der Herstellung zu kennzeichnen.	X	X	X	X
17.2	Dokumentation (04 03 Radsatzinstandsetzungsblatt)	X	X	X	X

[1] Verband der Güterwagenhalter in Deutschland e.V. (Vereinigung der Privatgüterwagen-Interessenten

Table 4. Maintenance guidelines acc. VPI 04 Appendix 4 comment regarding ZfP/NDT


Instandhaltungsrichtlinien gemäss VPI 04 Anhang 4 / Maintenance guidelines acc. VPI 04 Appendix 4

Anhang 6 Zerstörungsfreie Prüfungen (ZfP) / Annex 6 Non-destructive testing (NDT)

Prüfgegenstand	1) 3)	2)	Prüfanweisung	Fälligkeit
Radsatzwelle	a	A	VPI 09, I-UT-A-01, Ultraschallprüfung von Radsitzen	IS1 5) IS2 3)
	f	F F2	VPI 09, I-MT-A-03 bzw. I-MT-A-02, Magnetpulverprüfung der freien Oberfläche von Radsatzwellen	IS3 3) IS2
Radkränze	b	B	VPI 09, I-UT-W-01, Ultraschallprüfung von Radkränzen	IS1 IS2 IS3 3)
	d_1 d_2 d_3	D 4)	VPI 09, I-UT-W-02, Messung der Eigenspannungen mit Ultraschall (Kategorie 1, 2 und 3)	IS1 IS2 IS3 3)
Vollrad	e	E	VPI 09, I-MT-W-01, Magnetpulverprüfung von Vollrädern	IS2 und IS3 3), wenn letzte IS2 incl. MT-Prüfung länger als 4 Jahre zurückliegt. Bei E1 (bisher M1) bei jeder IS1, IS2 und IS3 BA 088: nach max. 6 Jahren Anbaudauer.
	e*	E		einmalige Prüfung bei IS2

1) ZfP-Kennzeichen im Anhang 1
2) ZfP-Kennzeichnung auf Radsatzmarken (vgl. Anhang 3)
3) Prüfung für erneuerte Teile nicht erforderlich (siehe 1., (3))
4) An Radsätze der Kategorie 2, die einer Erstprüfung zu unterziehen sind, ist die Stempelung auf der Identifizierungsmarke auszuführen.
5) gilt nur für Radsätze der französischen Bauart 9051/9051A; es ist nur der Radsitz zu prüfen

Prior to a comparative maintenance cost comparison some issues are to be known or have to be investigated in further steps, respectively. These issues are listed in Table 5. Additional assumptions for this comparative maintenance cost comparison are listed in Table 6.

Table 5. Comments to maintenance guidelines

Topic	Comment
VPI 04 Appendix 6 Non-destructive testing (NDT)	To be defined for the fibre composite wheel set
Assessment of the wheelset shaft with installed ballast protection	End cap with inspection hole for UT mandrel is to be provided (design change)
Brake arrangement	No thermal overstressing of the wheel discs due to the disc brakes → no residual stress measurement of the wheel disc but still UT crack detection of the wheel rim
VPI 04 Appendix 7 Surface conditions of wheelset shafts - error classes	To be defined for the fiber composite wheelset. Assessment of a visual inspection of the wheelset shaft with installed ballast protection is to be evaluated. a) How can the integrity of the wheelset shaft be concluded without dismantling the ballast protection? b) Up to which state of the ballast protection can be concluded without its disassembly on the integrity of the wheelset shaft?

Table 6. Assumptions for a comparative wheelset maintenance cost estimation

Assumption
The metallic reference wheel set is equipped with pad brake or shaft brake discs
In the case of disc brakes there is less wear on the running surface compared to block-braked wheels (no thermal damage).
The metallic reference wheel set is designed for a mileage of 600'000 - 1'500'000 km
Profile machining interval (maintenance) after 100'000 – 200'000 km (influence of track profile & brake)
Diameter change per reprofiling: 10 mm (Ø: 920mm – 840mm → last profiling: 850mm → theoretical 7 reprofiling, probably 6. → no advantage for a composite wheel set

The input in Table 3 to Table 6 leads with the corresponding cost per position to the maintenance cost comparison listed in Table 7. Further background information for maintenance cost is listed in Table 8.

Based on the values listed in Table 7 it is evident that the composite wheelset axle is to be designed for the service lifetime of the WS to be replaced, since a replacement of the composite wheelset results in significant cost.

Table 7. Maintenance cost comparison

Difference in maintenance costs [CHF] for 1.5 Mio km	steel & brake pads	steel & brake disk	CFK-High-performance WS for 1 Mio km	CFK-High-performance WS for 1.5 Mio
Wheelset axle designed for 600'000km	4740	2260	420	420
Wheelset axle designed for 1'000'000km	3820	1340	420	420
Wheelset axle designed for 1'500'000km	2900	420	18820=18420+420	420

Table 8. Background information for maintenance cost comparison

Topic	Influence on maintenance cost
No thermal induced stresses due to brake disk	Reduction per WS: CHF 40.-
At end of reprofiling	Scraping of metal wheels per WS CHF 2400.-, only costs of the wheel tires with less material
No press on/off of wheel but change of rim	The wheel change is possible without press. Simpler with less heavy machine. The wheelset has to be balanced resulting in the investment of a balancing machine.
At end of wheelset axle lifetime	Scrapping of metal wheelset CHF 920.-

2.3 Total costs including reductions (bonuses)

Costs saving due to lower wheelset weight: as the FRP wheelset is lighter than the conventional steel wheelset, it is possible to take into account some added values in terms of CHF per each kilogram. Such estimation has been carried out based on a paper by Hörste et. al.[2], text below.

Abschließend wird aus diesen Ergebnissen abgeleitet, welche Kosten für die Einsparung von einem kg Fahrzeugmasse entstehen dürfen, damit sie während der Lebensdauer des Fahrzeugs durch die eingesparte Energie amortisiert werden können. Dabei werden folgende Annahmen für die Berechnung der Kosteneinsparung getroffen: Betriebsdauer des Fahrzeugs 30 Jahre, Energiepreis Strom ab Stromabnehmer 12,44 Ct/kWh, Energiepreis Diesel 1,15 Euro/l entsprechend 11,533 Ct/kWh. Verzinsung des eingesetzten Kapitals und Preissteigerung bei den Energiekosten werden nicht berücksichtigt. Die Tabelle 2 enthält die berechneten Werte in Abhängigkeit von Fahrzeug und Serviceprofil.

	in Euro/kg	UIC-Serviceprofil			
		Suburban	Regional	Intercity	High-speed
Fahrzeug	BR 611 - DMU	76	96	50	---
	BR 423 - EMU	15	19	13	---
	BR 403 - HST	---	---	12	15

Tab. 2: Kosteneinsparung verschiedener Fahrzeuge im UIC-Serviceprofil

The FRP wheelset is about 400 kg lighter than a conventional steel wheelset, a total amount of about 400x13=5200 Euros (~6000 CHF) can be considered as a cost saving.

Bonuses for lower wheelset noise: based on the document by BAFU on March 2017[3] when a train produces less noises compare to conventional running train, if noise reduction criterion in Section 4.1.1. is satisfied, such train can benefit from awarded bonuses by BAFU.

In case of FRP wheelset, presumably if it satisfies the noise reduction criterion, bonuses for lower noise generation will be allocated.

7 Finanzhilfen des Bundes

7.1 Gesetzliche Grundlage

Nach Massgabe von Art 10a des Bundesgesetzes über die Lärmsanierung der Eisenbahnen (SR 742.144) kann der Bund für den Erwerb und Betrieb von besonders lärmarmen Güterwagen Finanzhilfen gewähren.

Die Höhe der Finanzhilfen richtet sich nach der Lärmverminderung und dem Beitrag an die Innovation im Schienengüterverkehr, namentlich bezüglich Energie und Sicherheit. Die Finanzhilfe beträgt im Jahr 2016 maximal 70 Prozent der Differenz zu den Investitionskosten eines konventionellen Drehgestells. Sie wird in den folgenden zwei Jahren schrittweise auf maximal 50 Prozent der Kostendifferenz reduziert (Art. 9 Absatz 2 VLE).

Die Finanzhilfe für den Erwerb ist einmalig. Sie richtet sich nach Kap.8.5.

Der Betrieb von lärmarmen Güterwagen wird über einen abgestuften Trassenpreisbonus gefördert. Die Bonusberechtigung ist in der Netzzugangsverordnung (NZV), Art. 19b[3] geregelt und beträgt für scheibengebremste Güterwagen in der Regel 3 Rappen pro Achskilometer.

[2] Hörste et. al. Wissenschaftliche Ansätze für einen energieoptimierten Eisenbahnbetrieb
[3] Der besonders lärmarme Güterwagen PFLICHTENHEFT (MÄRZ 2017)

Table 9. Comparison of total costs for conventional steel wheelsets and the new FRP wheelset

	Conventional **steel** wheelset (brake pad, 600'00 km)	Conventional **steel** wheelset (brake disk and 1.5 mil)	New **FRP** wheelset (brake disk and 1.5 mil)	New **FRP** wheelset (brake disk and 1.5 mil), share of metallic parts for serial production estimated by PROSE
Manufacturing costs (CHF)	~4'000	~4'000	~42'462	~24'00
Maintenance costs	~4'740	~420	~420	~420
Reduction due to weight saving (CHF)	-		400 kgx13 Euros ***~6'000***	400 kgx13 Euros ***~6'000***
	~8'740	~4'420	~36'882	~18'420

Based on Table 9, the ratio for total costs of a new FRP wheelset to total costs of a conventional steel wheelset with brake disk both designed for 1'500'000 km is ***4.17*** (i.e. 18'420/4'420).

2.4 Discussions on Task 1-5 critical points

In the view of cost estimation for manufacturing and maintenance of the FRP wheelset, critical points are as following:

-whether the initial cost for manufacturing is justified?

Answer: the total costs for a FRP wheelset is by a factor of 6 higher than the conventional steel wheelset. Decision on whether such a factor is justified needs to be discussed. As the FRP wheelset will generate lower noise, it can receive some bonuses from BAFU. For new generation of steel wheelset this is also applicable, however, BAFU may add more value for the FRP since it has higher db reduction.

-whether additional training will be required for the maintenance incl. non-destructive testing?

Answer: Yes (but it is not a critical point for the project, a few days training course will be enough for technicians.)

-whether new tools and new procedure are needed for maintenance, inspections and repair?

Answer: Yes (repair normally by patches)

-whether inspection intervals and lifetime will be acceptable for operators?

Answer: Yes/No. This point can be further investigated in a possible follow up project.

3 Task 1-6: Clarification of necessary verifications and studies and planning of Phase 2.

3.1 Clarification of necessary verifications

A detailed listing of all proofs and information to be provided for an FRP wheelset is given in the document "Lieferspezifikation Verbundradsatz[4]". Next to the chapter 2 "Anforderungen an den Radsatz (requirement for the wheel set)" in the named document the chapter 3 "Technischer Nachweis (technical proof)", 3.7."Experimentelle Nachweise (experimental proof)", 4 "Erstmusterprüfungen (first article inspection)" and 5 "Typentests (type test)" do cover all issues regarding the design, proof calculation, testing and on-track measurements required for such a railway component, in general. The current status of the project at the end of the feasibility study corresponds approximately with the end of the design phase in a usual design and verification process for a railway component. Especially the introduction of a new material and interface elements requires a significant number of tests and on-track measurements. In Table 10 are some on-track tests listed which are either to be performed in reference to the component on the FRP-prototype (e.g. 1, 3) or to be performed with the FRP-wheelset during prototype phase or a later measurement campaign in case of a homologation. The cost for these tests with a pure testing time of 4-5 weeks are estimated to approximately 230'000 – 250'000 CHF. It has to be noticed that on-track testing is only possible in collaboration with a company (like SBB Cargo for example) which would be interested in providing the rolling stock and would apply for such tests at BAV and the infrastructure body in charge. Significant costs are generated in the provision of test rail, rolling stock and personnel (i.e. driver) during the tests as well as implementing the FRP wheelsets into the bogie. These costs are not included in the given number before. Not included in these tests are the material and component tests for either validation of the fatigue strength values or required for homologation. It is assumed that these laboratory tests are not required for on-track testing of prototypes. A detailed listing of the proof documents expected to be provided for prototype testing of an FRP wheelset is given in the document "Nachweisplanung zum Betrieb eines Prototypens des Verbundradsatzes[5]".

---

[4] Lieferspezifikation Verbundradsatz, 04-02-00517 Rev. 1.00, PROSE AG, R. Paradies, 14.08.2018
[5] Nachweisplanung zum Betrieb eines Prototypens des Verbundradsatzes, 04-02-00500, PROSE AG, R. Paradies, 15.08.2018

Table 10. Overview of on-track measurements to be advised during prototype test for a possible homologation

#	Wheelset component	Verification topic	On track measurement	Regulation
1	Wheel	Vertical & lateral loading	Measuring wheelset	EN 14363
2	Wheelset axle	bending & torsion stresses, torsional oscillation during braking	Bending-/torsional-stiffness	DIN pocket book 491/1
3	Wheelset near brake disk and interface to FRP-structure	Temperature	Brake test	UIC 544-1

3.2 Criteria to start Phase 2 of the project:

1-Production and maintenance costs: the total costs including the initial costs and the maintenance costs of a FRP wheelset on duration of about 12 years compared to the total costs in the case of a conventional wheelset is by a ratio factor of ***4.3***.

2-Noise reduction: application of the FRP wheelset will result in a noise reduction of about 2.5 db.

3-**Durability and service life of the FRP wheelset**: there is no major problem with the durability of the FRP wheelset in the life time. There is one main critical point on the high temperature on the axle due to braking. If this issue cannot be solved, application of steel axle with FRP wheel disk can be a solution.

4-**Risk management of FRP wheelsets:** with the "early damage detection procedure" it is possible to avoid any catastrophic failure in the FRP wheelsets.

5-Enviromentally friendly production and life time usage: as the FRP wheelset is lighter, less energy will be consumed on the running and also less wear will be expected. The product is therefore an environmental friendly production.

6-Implementation: complimentary comments have been raised by SBB-Cargo about the FRP wheelset. However, a successful implementation by end users will depend on the total costs of the production as well.

7-Quality of the product: assurance of high quality product is feasible.

8-Product certification (homologation): The feasibility of the FRP wheelset regarding the requirements of the applicable standards is not completely assured. Although the structural analysis of the wheelset includes only the composite wheel, wheelset axle and some investigated interfaces the results of the feasibility study indicate that the strength and stability requirements due to mechanical loading should be fulfilled. Based on the available material data these components show sufficient margin of safety. Of course, for a possible homologation, all wheelset components have to be investigated (incl. torsion tube and wheel rim) according to their specific regulations following the mandatory verification process for each component. In addition, the results of testing, type test are to be provided as planned in a next verification step. At the time, the fulfillment of the brake requirements according to TSI-WAG (chapter. 4.2.4.3.3 resp. 6.2.2.6.) is missing. It is evident that due to the high temperature at the wheel brake disk thermal insulation is necessary for this thermal load condition. A proof that sufficient thermal shielding of the composite component is provided is not available for this design. Thereby, an important issue for a possible homologation is still missing on the design certification level.

3.3 Planning of Phase 2

The outcome of the Phase 1 shows basically the feasibility of the application of FRP wheelset. The main (critical) issue could be the initial costs for the FRP wheelset manufacturing. In case that such high initial cost is justified, continuation of the project in Phase 2 as "Plan A" is recommended. However, if such a high cost is not justified, in the framework of a more future oriented product, "feasibility study on application of self-steering FRP bogies" as a "Plan B" in Phase 2 is recommended.

3.3.1 Short description of "Plan A" of Phase 2

In the following, a short description of "Plan A" of Phase 2 is presented. In Phase 2, recommended configuration(s) from Phase 1 will be studied deeper in detail to design, manufacture and test a FRP wheelset. The design procedure, the manufacturing methodology establishment, and the testing on coupon and sub-component specimens will be perform in parallel. Close collaboration among project partner in these three sub-phases, as shown in *Figure 1*, is needed to optimize the final product which is the manufacturing of two real scale FRP wheelset prototypes.

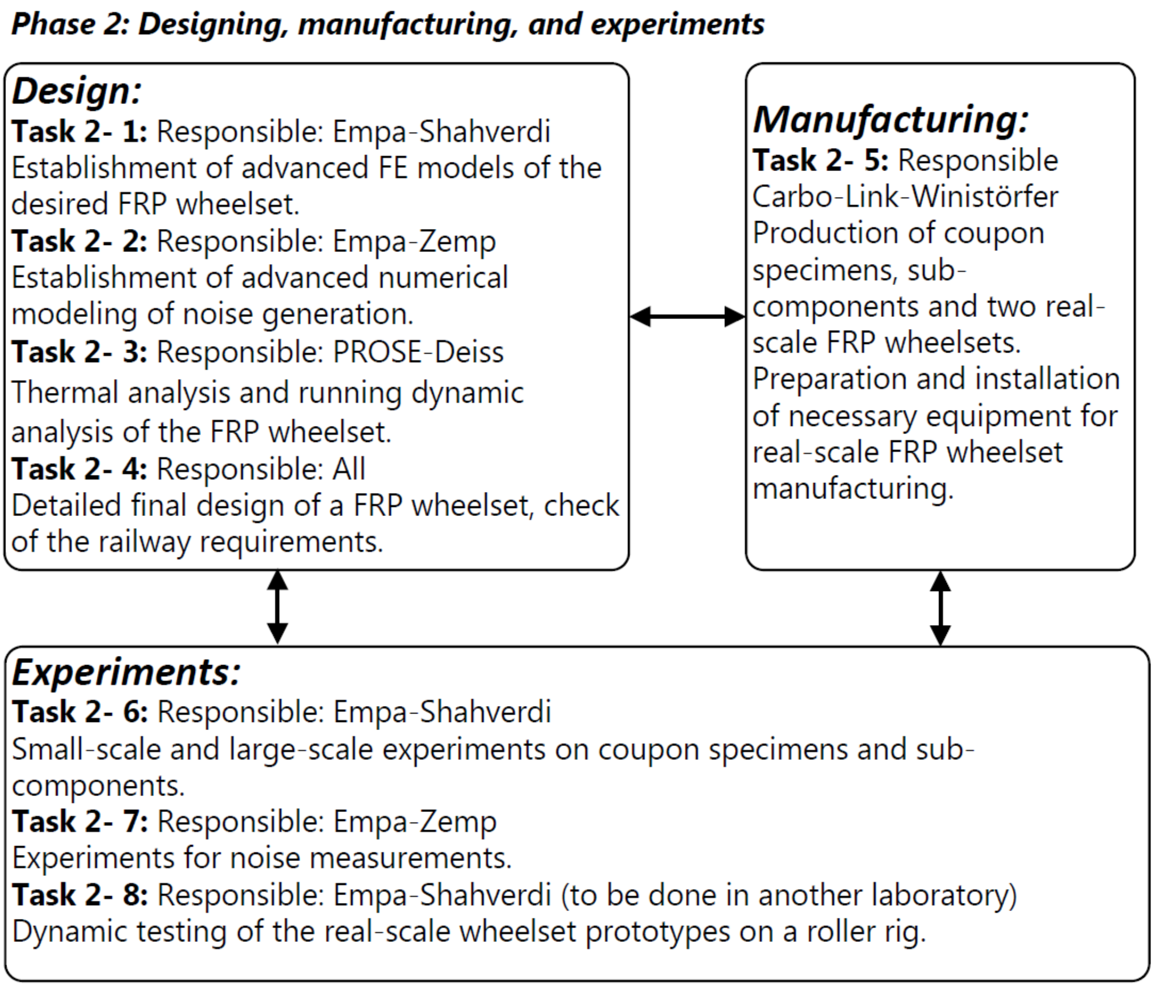


Figure 1: Overview of the project, Phase 2, Plan A. The phase 2 is to be followed by the possible proof of concept and homologation.

Design

Design of the wheelset will be based on the requirements approved by **BAV** and BAFU. The design will be an iterative procedure to fully satisfy the requirements, to be practically possible manufacture with a reasonable cost, and to achieve the objective of noise and weight reduction. Within this phase following tasks will be completed.

Task 2- 1: Establishment of advanced FE models of the desired FRP wheelset. Responsible: Empa (Moslem Shahverdi)

The selected configuration(s) from Phase 1 of the project will be modeled numerically. Advanced nonlinear 3D finite element models of the proposed configuration will be developed to determine the stresses and strains in the wheelset under different load scenarios. Material input will be gathered from the literature and verified/completed by the coupon testing specimens, see tasks in Section 3.3. The numerical models will be calibrated by the experiments, either performed within the scope of this project or by experimental results found in the literature.

Task 2- 2: Establishment of advanced numerical modeling of noise generation. Responsible: Empa (Armin Zemp)

The advanced numerical modeling of the noise generation in contrast to the simplified assessment in Task 1-4 assumes a realistic excitation of the rotating wheel at the contact point between wheel and rail including the subsequent unsteady contact force based on the combined roughness of wheel and rail. Simulations will be performed for varying track stiffness and combine roughness properties as well as for varying loads and speeds.

Task 2- 3: Thermal analysis and running dynamic analysis. Responsible: PROSE (Christoph Deiss)

Based on the current of the feasibility study and their findings thermal insulation is required, i.e. thermal analysis/investigation are required in other hand, the running behavior of the FRP-wheelset will be investigated by multi-body simulations. It will be considered as part of a standard freight bogie. Thereby a comparison is possible of this bogie with a standard freight bogie and wheelsets made of steel. Next to the typical running conditions to be assessed like running stability, safety against derailment and curve running behavior, the wheel wear will be assessed.

Task 2- 4: Detailed final design of a FRP wheelset, check of the railway requirements. Responsible: All

Within this task, the detailed design of the studied FRP wheelset including the design concept will be discussed and documented. Analysis and design of joints will be performed; load carrying capacity and the life time of the wheelset under cyclic loading, and strength of the wheelset under sustained loading will be estimated. Within this task, which is the last step of the design, all the requirements will be double checked by all partners involved in the project and the design will be approved based on the analysis and experiments performed within other tasks.

Risk management of FRP wheelset: Risk management of the FRP wheelset are to be considered during the life time usage of the wheelsets. Occurrence probability failure and detection probability problem before the failure and error sequence severity at the occurrence of the failure have to be determined.

By embedding the sensors inside the FRP wheelsets during the production, it may be useful to monitor the FRP wheelset continuously during operation (including location, running power, further data, and energy supply via moving wheel axles).

Milestone 2-1: Report on the detailed design of the FRP wheelset

Milestone 2-2: Detailed drawings ready for manufacturing

Milestone 2-3: Strategy for the risk management of the FRP wheelset

Manufacturing

Manufacturing of a designed wheelset made of FRP composites with a reasonable price, an optimized weight, and in high quality is very challenging. In this sub-phase of the project, such challenges will be tackled. The tasks of this sub-phase are:

Task 2- 5: Production of coupon specimens, sub-components and two real-scale FRP wheelsets. Responsible: Carbo-Link (Andreas Winistörfer)

Coupon test specimens designed to characterize composite material behavior and subcomponents to determine the global behavior of the wheelset will be manufactured by Carbo-Link and delivered to the structural engineering research Lab and laboratory acoustics/noise control at Empa for the experimental examinations. These specimens are used for allowable verification and for fulfillment of structural-integrity requirements specific to the materials and geometry of the component under the defined requirements.

Within this task, minimum two FRP wheelset prototypes will be manufactured in a real-scale that can be used for the experimental investigations under cyclic loadings, acoustic emission measurements, and roller rig.

Preparation and installation of necessary equipment for real-scale FRP wheelset manufacturing will be performed within the Task 2-5.

Milestone 2-4: Production of minimum two FRP wheelset prototypes in real-scale

Experiments

According to standard homologation process any new wheelset type has to be tested on the component level if certain boundary conditions are violated. In case of this wheelset fatigue tests are to be conducted for sure on the material level (e.g. laminate) as fatigue limit under rotating bending up to 1E7 cycles and as full scale test of the wheelset-axle acc. EN 13261. Similar (i.e. material and component) is expected for the wheel following EN 13979-1. This is mandatory standard procedure during homologation for a wheelset with new material and/or changed manufactures.

Testing of the small scale coupon specimens, prototype, and full scale FRP wheelsets are needed to verify the design concepts, to optimize the design and to proof the functionality of the manufactured wheelsets. Two main sets of experiments will be performed accordingly. First set of experiment on small scale coupon specimens and sub component will be performed in parallel to the design and manufacturing procedure to support and verify the concepts. The second set of experiments on real-scale wheelsets will be done on roller test bench in another laboratory where such facilities exist. Tasks which will be therefore carried out within this sub-phase are:

Task 2- 6: Small-scale and large-scale experiments on coupon specimens and sub-components. Responsible: Empa (Moslem Shahverdi)

Coupon testing specimens can be experimentally examined to determine the materials characteristics. Testing of subcomponents are necessary because the behavior of composites is not adequately characterized using two-dimensional coupon testing as in homogeneous or isotropic materials, especially in areas of structural joints and complex geometry.

In order to proceed with the homologation, at least three wheels, three axles, and two complete wheelsets have to pass the fatigue test without any indication of failure. The two former tests will be carried out as illustrated in Figure 2, while the last one will be carried out in Task 2-8.

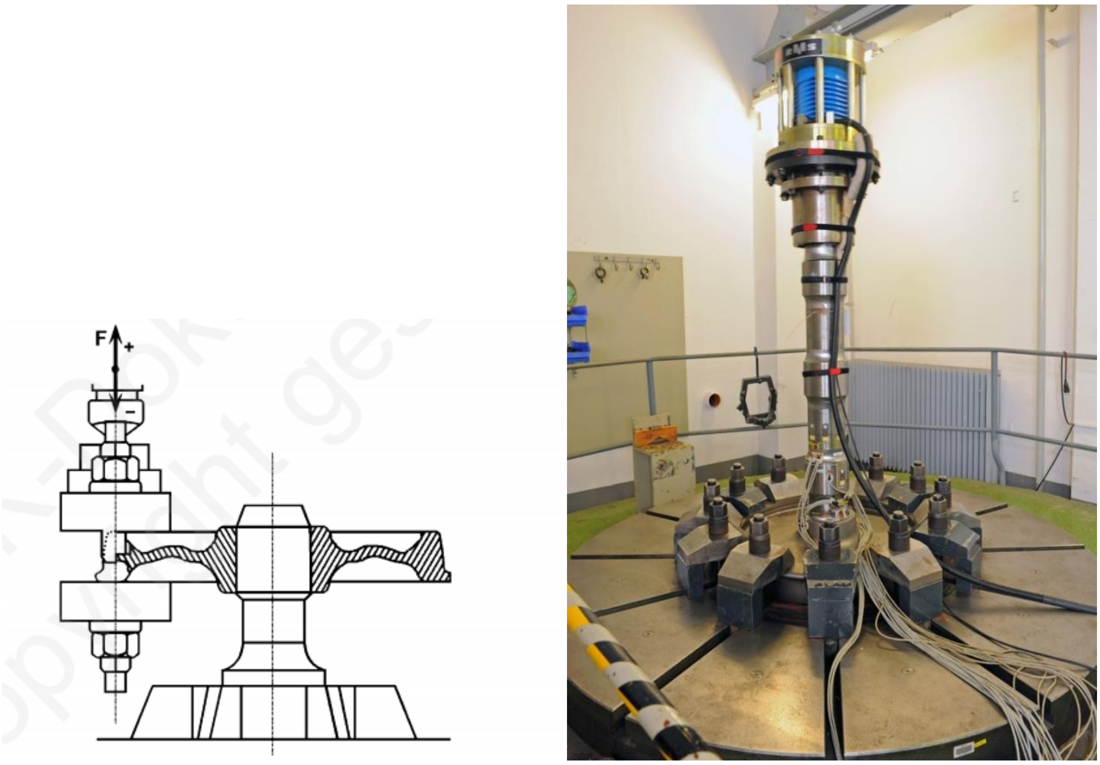


Figure 2: Left: Scheme of a standard fatigue bench test for wheels [from PROSE), Right: Photo of a standard testing facility for wheelset axles [from DB-Sytemtechnik webpage], similar experiments will be performed at Structural Engineering Research Laboratory at Empa.

The following experiments will be considered to be performed at Structural Engineering Research Laboratory at Empa:

- Long-term sustainability characterization of the FRP wheelset elements (effect of temperature, humidity, .)
- Studies on the possible interaction between steel and FRP (contact corrosion)
- Studies on the impact resistance of the FRP wheelset components
- Studies on fatigue behavior of the FRP wheelset components
- Studies on the high temperature resistance of the FRP wheelset

Milestone 2-5: Material characterization

Task 2- 7: Experiments for noise measurements. Responsible: Empa (Armin Zemp)

Noise Measurements could be performed during the dynamic testing of the real-scale wheelsets or then at the track during real pass by events.

Task 2- 8: Dynamic testing of the real-scale wheelsets on a roller rig. Responsible: Empa (Moslem Shahverdi)-to be done in another laboratory

Real-scale roller rigs are known as useful test methods to investigate wheel-rail contact/damage issues especially for newly developed wheelset and/or new proposed solutions to extend the life and improve the behavior of railway systems. In such experiments, usually the real tracks are replaced by a pair of rollers on the roller rig. Utilization of such experimental setup, Figure 3, will be a cost-effective solution compared to "running tests on real tracks" experiments to study the global behavior of the FRP wheelsets. Measurements on the mechanical behavior and acoustic emissions of the real-scale FRP wheelset will be carried out while doing such experiments.

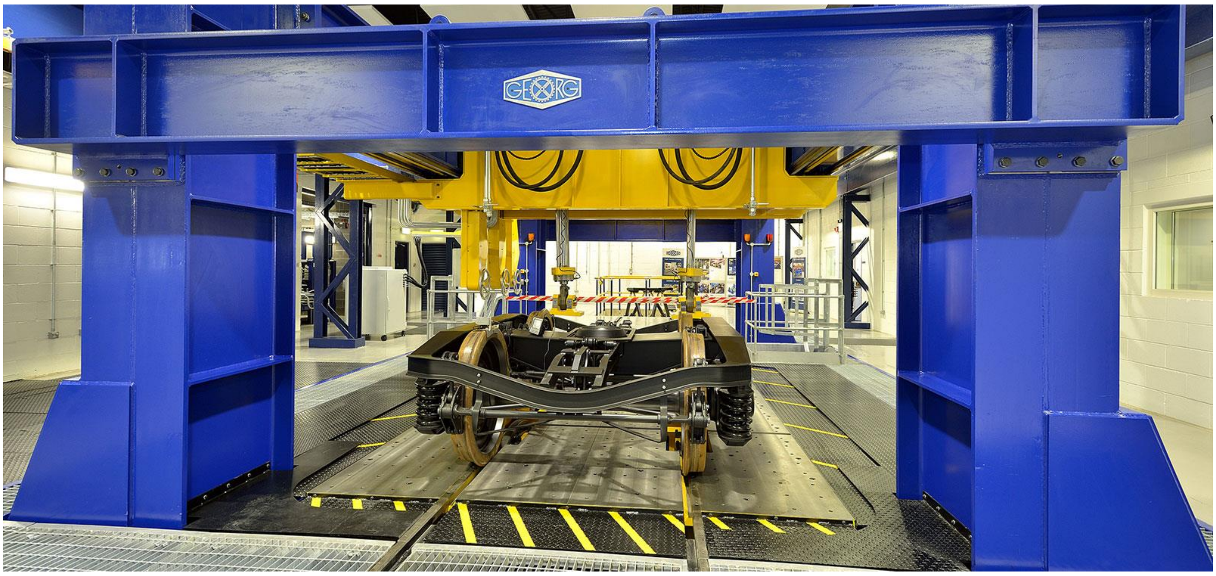


Figure 3: Photo of a roller rig testing at University of Huddersfield and GEORG UK, [from the University webpage]

Experiments within this task will be carried out at another laboratory with additional costs.

Milestone 2-6: Real-scale roller rigs

Milestone 2-7: Decision on running tests on real tracks. Prior to any running tests on real tracks BAV will be asked for permission and this requires at least a request for derogation.

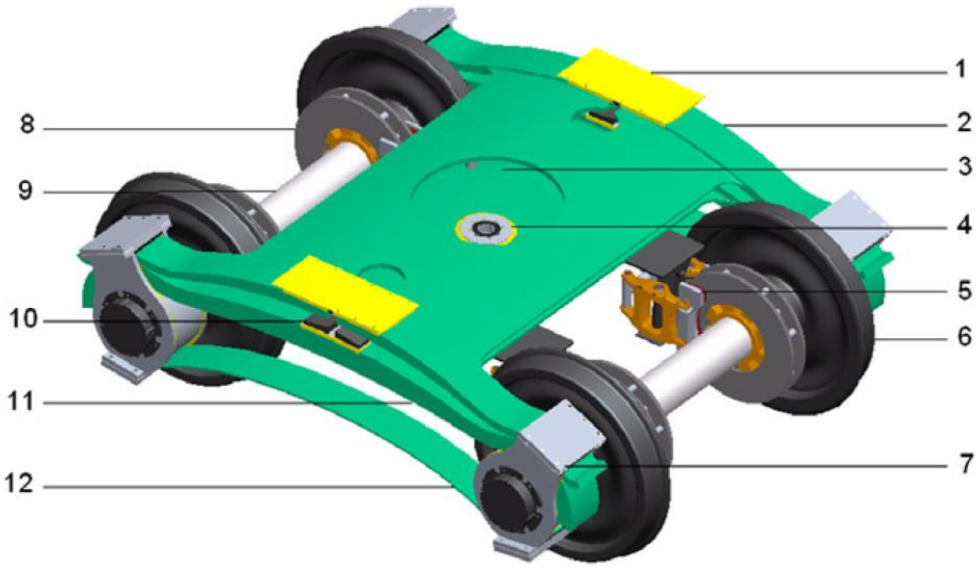
3.3.2 Short description of "Plan B" of Phase 2

In case that BAFU prefers to extend the application of FRPs in broader range by pursuing Plan B, feasibility application of self-steering FRP bogies will be studied.

Remarks on a full FRP bogie (CFRP and GFRP):

- ✓ More future oriented product
- ✓ Much more weight saving
  - ✓ Less wear, less energy consumption,...
  - ✓ Possibility to add more live load
- ✓ Better to justify the high manufacturing price
- ✓ Combination of GFRP and CFRP
- ✓ Possible additional noise reduction due to FRPs
- ✓ Possibility to integrate a self-steering system

In past there have been some attempts, **Figure 4**, to bring the FRP bogies on the real market, however, to our best knowledge they were not successful due to some technical problems. Self-steering metal bogies exist in the market already, **Figure 5**. Our proposal is to study the feasibility of a FRP bogie that has the feature of self-steering also. In following short descriptions of Plan B is presented.



Summary of the name and material of each part

Number	Name	Material
1	Side bearer	Polyurethane, nylon and rubber
2	Upper bogie frame	Glass fibre reinforced epoxy
3	Lower bogie transom	Glass fibre reinforced epoxy
4	Central pivot point	Steel, rubber and polyurethane
5	Calliper	Steel, rubber and brake pads
6	Wheel	Steel
7	Axlebox	Steel, rubber and polyurethane
8	Brake disc	Steel
9	Axle	Steel
10	Bogie frame bearer	Rubber, polyurethane
11	Lower bogie frame	Glass fibre reinforced epoxy
12	Axle tie	Glass fibre reinforced epoxy

Figure 4: example of a FRP bogie[6]

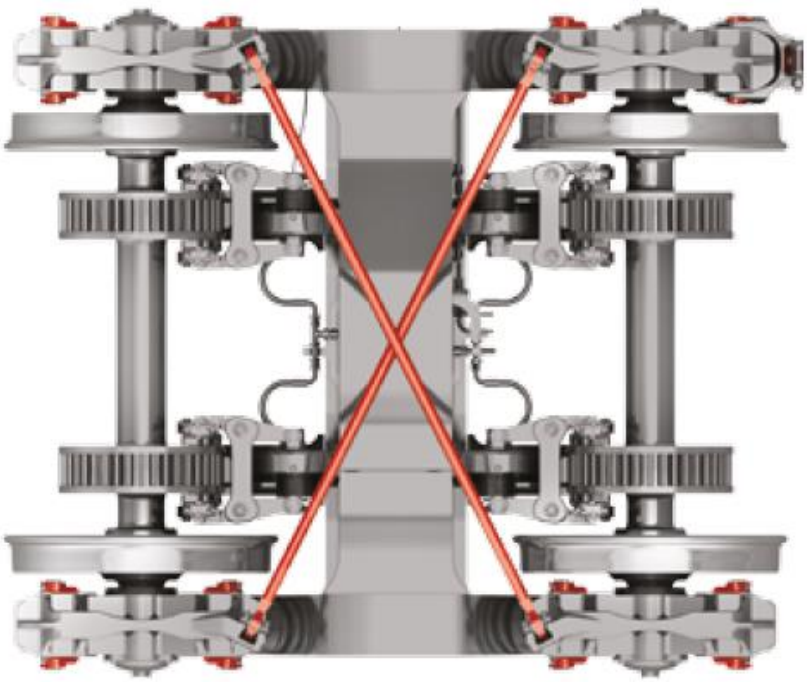


Figure 5: example of a self-steering bogie[7].

[6] Jinping Hou and George Jeronimidis, A novel bogie design made of glass fibre reinforced plastic. Technical Report, Materials & Design, Volume 37, May 2012, Pages 1-7
[7] http://tatravagonka.sk/bogie/?lang=en

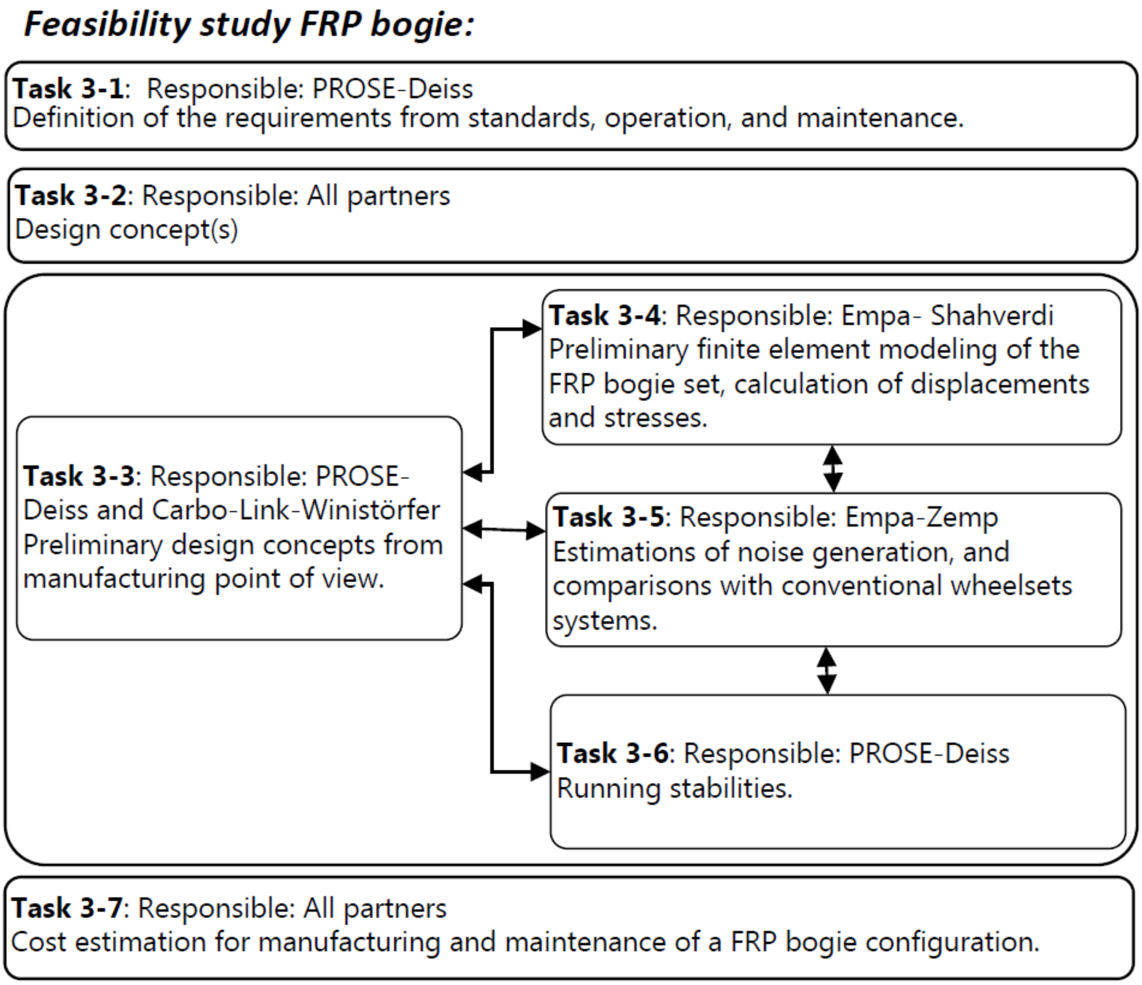


Figure 6: Overview of the project, Phase 2, Plan B.

Task 3-1: Responsible: PROSE-Deiss, Definition of the requirements from standards, operation, and maintenance: All the requirements which need to be satisfied that a FRP bogie can be used in real traffic will be gathered and documented by PROSE. A possible homologation approach for such a component and a patent research for providing the current status in this field of application are also included.

Task 3-2: Responsible: All partners, Design concept(s): a workshop with the complete consortium will be held in order to collect and discuss conceptual solutions towards a suitable self-steering FRP bogie configuration.

Task 3-3: Responsible: PROSE-Deiss and Carbo-Link-Winistörfer, Preliminary design concepts from manufacturing point of view: Carbo-Link will provide some conceptual designs of FRP self-steering bogies based on Task 3-2 outcomes. These preliminary configurations will then be modeled in Task 3-4 and 3-5 to study their functionality. In round exchanges, possible modifications of the proposed configurations will be performed for further improvement and optimization of the concepts.

Task 3-4: Responsible: Empa- Shahverdi, Preliminary finite element modeling of the FRP bogie set, calculation of displacements and stresses: Preliminary mechanical analysis on the proposed configurations of Task 3-2 and 3-3 will be performed to obtain their stress levels, deformations, and rigidity. 3D nonlinear finite element models will be developed to perform such a study. Wherever possible, the outcome of the finite element models will be compared by analytical solutions in general and the hand calculations.

Results obtained in this task will be delivered to Carbo-Link to improve and optimize the proposed configurations.

Task 3-5: Responsible: Empa-Zemp, Estimation of noise generation, and comparison with conventional bogie systems: Numerical modeling of the acoustic emission of the proposed configuration will be developed within Task 3-5 (level of complexity – cf to feasibility study CFR wheelset).The result will be a relative comparison of the preliminary design concepts with the traditional solution as the reference.

Task 3-6: Responsible: PROSE-Deiss, running stabilities: modeling of running stability for the self-steering FRP bogie will be perform within this task.

Task 3-7: Responsible: All partners, Cost estimation for manufacturing and maintenance of a FRP bogie configuration: Cost estimation for the manufacturing and maintenance of the proposed configurations is a crucial issue for the FRP bogie in reality. In addition to the initial cost of manufacturing, cost of maintenance along the operation life of wheelsets is very important for the end user. The total costs for manufacturing and maintenance of a self-steering FRP bogie will be compared with conventional bogies on the market. As the FRP bogie will be lighter compare to conventional bogies, some saving costs equivalent to the value of each kg in CHF can be considered. If we can assume that the FRP bogie will be 50% lighter (total weight reduction of about 2’500 kg) with a value of 13 Euros/kg[8], a total added value of about ***38’000 CHF*** is expected.

[8] Der besonders lärmarme Güterwagen PFLICHTENHEFT (MÄRZ 2017)