D20.1
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1. Executive Summary

The aim of this report is to give insight into the topics and tasks of work package 20. The content and time schedule of the two tasks is defined and information about the distribution of work between the partners as well as the methods which will be used are given.
The WP is divided into two tasks, whose motivation and aims are explained. First results and the relevant methodologies are clarified.
Within the task 20.1, the work intends to expand the current state of the art and work towards new regulation requirements that could enable virtual certification in the foreseeable future. The aerodynamic topics, on which the studies will be based on, were defined and a generic train model was designed, which allows the study of the different methods and the validation of numerical results with experimental tests. However, no full-scale data of the generic train will be available. A comparison between numerical results gained with the developed method and full-scale data of a regional train will be delivered by a partner of the WP for validation purposes in the later progress of the WP.
The task 20.2 is dedicated to the optimisation of the train's roof equipment with regards to noise and mainly drag and therefore fuel consumption and CO_2-emission. The same generic train geometry will be utilised for the study of optimal train roof equipment placement. A generic pantograph was generated to give insight into the flow around different parts of the pantograph as well as the forces on the pantograph. The power transfer efficiency is to be optimised by adapting the pantograph aerodynamics.
All tasks are according to the plan, no delays have to be reported.

2. Abbreviations and acronyms

Abbreviation / Acronym	Description
Beneficiaries	signatories of the GRANT AGREEMENT Project 101101917 — FP4 - Rail4EARTH
CFD	Computational Fluid Dynamics
Cmx,lee	Roll moment coefficient over leeside
ERJU	Europe's Rail Joint Undertaking
FP	ERJU Flagship Project
SP	Sub-Project
SWG	Seitenwindkanal Göttingen (Crosswind Simulation Facility Göttingen)
WP	Work Package

3. List of Figures

4. Background

The EU-Rail project is considered the natural successor to Shift2Rail, a program framed within activities funded by the EU to promote innovative solutions in the railway sector. The activities planned for railway aerodynamics are covered by Work Package 20 (WP20), where two distinct activities have been identified:

- **Task 20.1:** The objective of this activity is to explore and work on methodologies aimed at achieving a good theoretical-experimental correlation, allowing us to describe the performance of railway vehicles through numerical models.
- **Task 20.2:** The objective of this activity is focused on optimizing drag in conventional vehicles (subtask 20.2.1), referring to those with speeds ranging from 140-200 km/h, and activities related to pantograph optimization (subtask 20.2.2).

    - **Subtask 20.2.1:** It is particularly relevant in the area of conventional vehicle roof, where equipment distribution plays a significant role in drag.
    - **Subtask 20.2.2:** Pantograph optimization activities are mainly aimed at high-speed vehicles (v > 250 km/h), where pantograph behavior is crucial.

According to the described tasks, it is evident that there is a clear commitment to delve into two activities considered key in the sector's development. One of the initiatives to explore is the possibility of using simulation tools wherever possible to reduce the number of on-track tests, potentially impacting the product lifecycle and resource utilization. Optimizing and consolidating this process would form the basis for a future virtual homologation procedure. Consolidated methodologies are therefore required to allow the use of simulation tools in the event that approval processes open the door to their use as alternatives to full-scale testing.

The vehicle homologation process requires the assessment of the following aspects related to the vehicle's exterior aerodynamics in the TSI LOC&PAS (see [1]):

- 4.2.6.2.1 Slipstream effect
- 4.2.6.2.2 Head pressure pulse
- 4.2.6.2.3 Maximum pressure variation in tunnel
- 4.2.6.2.4 Crosswind
- 4.2.6.2.5 Ballast pick-up

Additionally, even though the TSI LOC&PAS does not explicitly mandate on-track tests for obtaining running resistance, it is considered a key aspect of the vehicle performance too. Addressing all of the above activities is not realistic within the framework of the project activities, therefore, it has been considered appropriate to focus efforts on two of them. The chosen activities are:

- Crosswind
- Running resistance

The first one affects operational safety and is vital for the proper functioning of the railway system.

The second one is closely related to energy consumption, making it pivotal in the context of climate agenda activities for the upcoming years.

It's essential to consider that certification activities are currently regulated by European standards. Crosswind certification is performed according to EN14067-6 (see [2]), and running resistance tests are conducted according to EN14067-4 (see [3]). Both serve as the current European reference for crosswind stability and running resistance certification, in accordance with the homologation requirements outlined in TSI LOC&PAS and have been drafted by CEN TC256 WG06 by explicit mandate from ERA. Therefore, all the information provided here must be agreed upon with European group experts.

In this context, reading the Technical Report (TR 17833 [4]) elaborated by CEN as a guide for best practices is also interesting for working groups interested in considering calculation tools as alternatives to tests. Although a generic document, it defines the steps that should be followed when exploring such alternatives, including:

- Known references to establish the validity of the used models
- Accuracy and uncertainty of the methods used
- Validity range and limitations of their applicability
- Boundary conditions and level of knowledge of simulated scenarios
- Convergence criteria
- Risk analysis, such as the applicability of the methods used and whether the evaluation affects safety-related aspects

All these aspects are crucial and will be considered during the project activities.

It's worth noting that simulation alternatives to tests are already included in EN14067 standards where the state of the art is considered to be mature enough. However, the present working group's activities aim to go a step further and explore the possibility of using simulation tools where only physical testing is currently allowed. The goal is to develop new methodologies and criteria to achieve a good numerical-experimental correlation so that numerical simulations are considered a reliable alternative to tests.

However, the path is not straightforward. Evaluating crosswind stability requires wind tunnel tests, which are difficult to opt out. Although the correlation obtained is reasonably good for aerodynamic vehicles, the same cannot be said for conventional vehicles, which have messier geometries. Therefore, there is a need to develop a new methodology adequately adapted for these types of vehicles. A similar challenge exists for running resistance tests. Due to their nature, these tests have a considerable level of uncertainty, limiting the amount of available information to be compared with simulation results. To address these shortcomings, an intermediate stage is proposed through wind tunnel tests, allowing evaluation in more controlled situations and serving as a reference for future numerical simulations. Other challenges include extending this to correlation with tests in free field and defining a quality criterion for correlation exercises.

Furthermore, driven by the current context, one of the key activities should focus on reducing energy consumption. Hence, additional activities are proposed to reduce aerodynamic drag since it significantly affects running resistance and, consequently, energy consumption. Most passenger transport in Europe occurs through conventional vehicles, which are not always aerodynamically optimized. This is even more evident in urban and interurban vehicles. It is known that a significant percentage of aerodynamic drag comes from the contribution of rooftop equipment. Their design and distribution are conditioned by compliance with project requirements and constraints, where aerodynamic or energy consumption criteria do not always take precedence. Therefore, the aim is to delve deeper into this topic, studying various alternatives to establish guidelines for minimizing aerodynamic drag as much as possible. A similar approach can be extended to the study of the pantograph. In addition to its contribution to aerodynamic drag, its design will be studied to optimize the wear of the sliding elements and reduce contact intermittency.

All of the above aspects are considered necessary to consolidate the rail system as the main means of transport for transporting people and goods nationally and transnationally, with the exception of transoceanic transport. Current limitations in battery production and the planet's lithium reserves suggest that the electric car is not an alternative that can be generalized on a global scale and that there is a need for a means of transport that is capable of moving large numbers of people efficiently. Moreover, more and more studies suggest that rail can be an alternative to air transport over distances ranging from 600 km to 1000 km (depending on the case, the orography, the penetration of the extension of the lines, etc.). Therefore, in a context such as the one described above, a project is required in which the activities proposed can be analysed in depth.

5. Objective/Aim

The activities of the working group will be developed along two lines of action corresponding to 20.1 and 20.2. These lines of action are defined as follows:

- **Task 20.1:** Virtual Certification
- **Task 20.2:** Aerodynamic Demonstrator for Drag and Noise-Reduced Spoiler and Pantograph
    - **Subtask 20.2.1:** Aerodynamics of Roof Equipment
    - **Subtask 20.2.2:** Aerodynamics of Pantograph

Task 20.1 will focus on the study of crosswind stability and running resistance. The crosswind part will concentrate on a methodology allowing a good numerical-experimental correlation for conventional vehicles. This will combine wind tunnel tests and numerical simulations. Wind tunnel tests are necessary to provide a quality reference for comparison. Numerical simulations will study from meshing alternatives to turbulence models with the aim of reducing the error with respect to the tunnel tests. The main indicator for this will be the study of Cmx,lee, which is the rolling moment over the leeside.

The state of the art for running resistance is less developed than its crosswind counterpart. Therefore, establishing quality criteria for future correlations is considered one of the defined objectives. Running resistance evaluation is conducted through on-track tests according to EN14067-4. However, the utility of reduced scale tests for comparative studies and generating quality references for numerical simulations will be explored. Numerical simulations are another very important part of this exercise, the aim of which is to provide methodologies that allow a good theoretical-experimental correlation to be obtained. The final step will be to evaluate how to apply the conclusions obtained from reduced scale tunnel models to full-scale vehicles and open field conditions.

Task 20.2 is divided into two subtasks. Subtask 20.2.1 aims to evaluate different roof equipment configurations. The distribution of roof equipment is often influenced by design decisions unrelated to external aerodynamics. Various equipment configurations will be analyzed to establish guidelines for reducing running resistance. This will involve reduced scale tests and CFD simulations.

Subtask 20.2.2 will focus mainly on the pantograph. The objective is to study those design parameters that can result in a pantograph design that optimizes the contact time with the catenary (fewer cuts and less wear) and reduces its drag as far as possible. To this end, two courses of action will be combined. On the one hand, numerical simulations will make it possible to determine the flow conditions acting on the pantograph as a function of its relative position on the vehicle. These conditions will be reproduced in a wind tunnel on a 1:1 scale pantograph. This will allow a better understanding of the interaction between pantograph and flow and a more detailed study of the variables to be evaluated in order to meet the target criteria.

6. Link to KPI matrix

The different tasks are related to several KPIs baselines.

In task 20.1, a methodology to certificate a train virtually is planned to be developed. The methodology is the demonstrator of WP20.

The current certification of trains requires a high number of full-scale tests, which are immensely expensive. By certifying a train using virtual methods, time and money would be saved leading to reduced Life cycle costs.

Especially in subtask 20.2.1 (aerodynamics of roof equipment) methodologies to reduce the energy demand of the system train are developed and studied by reducing the drag and the running resistance of the train. Therefore, the aim of this subtask is to reduce the physical energy consumption, which is listed in the KPI-matrix.

In the subtask 20.2.2, a pantograph is optimized regarding energy transmission efficiency to reduce maintenance costs and regarding the noise emission of the pantograph. Aim of both subtasks is to reduce the life cycle costs of the train.

7. Task 20.1: Virtual Certification

7.1. Scope of Work

The scope of task 20.1 is to improve the aerodynamics of the trains, especially conventional as well as high speed, by proposing innovative solutions and improving evaluation methods. This is an important way to contribute to the environmental sustainability of railway systems. The focus of the work is mainly the study of crosswind stability and running resistance.

For both cases the aim is to have reliable numerical tools that can provide information for crosswind and running resistance. The numerical tools will be based and tuned according to experimental tests.

The importance of crosswind stability estimation is related to the safety of rail transportation. The running resistance, on the other hand, is deeply affected by the aerodynamic drag. Aiming to reduce energy consumption, the aerodynamic drag is of main importance, especially in the design phase.

Conventional trains (i.e. trains in the 140-200 km/h speed range which are the backbone of the European rail system) are usually not streamlined and therefore it is possible to lower drag by optimizing the external shape. The train shape optimization and a better control of the current tools (CFD, for example enhanced Reynolds Averaged Navier Stokes (RANS) or Large Eddy Simulation (LES) methods, wind tunnel, etc.) and their limits will enable to reduce the aerodynamic drag and cross-wind forces on the train and thus to reduce the energy consumption of the trains or increase their autonomy and safety. In this sense, better numerical tools could open the door to assess simulations as a substitute for testing in those scenarios where there is sufficiently established knowledge. This could speed up the homologation process in different cases.

The number of full-scale tests and therefore costs will be reduced by introducing enhanced experimental and numerical methods. At the moment many certification processes regarding TSI and EN standards need full scale tests and are therefore expensive and protracted (see references). With objective to simplify certification processes, there is a commitment on the railway sector to impulse virtual certification methods where possible, which will be tested and adapted to ensure safe railway operation. The EN14067 already allows numeric simulations for vehicle assessment in those scenarios where there is a robust body of science. This work intends to expand the current state of the art and work towards new regulation requirements that could enable virtual certification in the foreseeable future. This will require the definition of new criteria that will have to be tailored to the specific needs of each case.

Eventually, there is a commitment to share the obtained results with the European experts of the CEN technical committee that shape the European standards, to update (if possible) the use of numerical tools that are already present in the EN14067 in the aerodynamic assessment of railway vehicles. Therefore, considering numerical simulations as a trustworthy alternative to full-scale test wherever it is possible.

7.2. Methodology

Both numerical as well as experimental simulations are planned. Numerical simulations will be based on computational fluid dynamics codes (CFD) while the experimental tests will be conducted mainly in wind tunnel. The idea is to simulate the wind tunnel condition and the scaled train model so to have a good match with the experimental test. The wind tunnel environment is the first one to be tuned in the numerical simulation. The characteristics of the experimental flow are required to be as close as possible to the simulated one. Special focus will be on the boundary layer developing over the running belt. Once the environment is properly modelled, the following phase is the simulation of the benchmark train model that will be compared with the experimental data of the wind tunnel. Repeating the process for different configurations, in the flow, boundary conditions and train models provides robustness to the CFD model. Full-scale experimental tests could provide information on the scaling effects and tune the CFD model predictions accordingly. A comparison of existing full-scale data with numerical data generated using the newly developed method will give insight into the capability of the method to reproduce full-scale conditions. Depending on the outcome of this exercise it will be assessed the ability of CFD simulations to reduce costly and time-intensive track tests.

The aerodynamic performance of regional/conventional trains is crucial for the operation also at moderate speeds beyond 200km/h. The aerodynamic drag counts for a large part of the rolling resistance. Cross-wind stability and dynamic effects from gusts, tunnel passage and passing trains are crucial for safe and comfortable operation. Aerodynamics of conventional trains is less studied than for high-speed trains and poses more challenges due to more complex / less streamlined geometries.

Estimating the aerodynamic performance of trains with the available means is far from trivial. Experimental wind-tunnel tests cannot represent the real physics of a full-scale train due to size (Reynolds number) limitations and wind-tunnel installation effects. Numerical CFD models suffer from insufficient accuracy and reliability. Full-scale tests have the problems with precise definition of the test conditions and measurements of the aerodynamic forces.

The methodology will be focused on the relation between experimental measurements and CFD simulations with the full-scale tests to be used mostly as final verification. We have defined three key elements:

1. Validation of the CFD simulations with experimental data on the wind-tunnel configuration and settings.

2. Extrapolation of the experimental data to full-scale and real operational conditions by means of CFD simulations.

3. Focus on repeatability for best possible accuracy in deriving “delta effects” by applying local modifications as far as possible. This applies for both experimental and CFD methods.

Both the experimental and CFD methods should consider these elements as far as possible.

7.2.1. Experimental Methodology and Reference Model

In the DLR-Göttingen wind tunnel of the Institute of Aerodynamics and Flow Technology, experiments are being carried out on a scale model of a generic train geometry, which represents a typical shape of a regional train (DLR KMF-Regio) according to the following premises:

- Although it is not a real train, its shape is similar to any of the conventional trains running across Europe within a speed range of 140 km/h to 200 km/h.
- It has been built in a modular way that allows different roof configurations to be installed. Thus, the vehicle geometry is not constrained to a single roof configuration but can be adapted to represent the roof configuration of a wide variety of conventional vehicles

The cross-wind wind tunnel Göttingen (SWG) is a low-speed wind tunnel of Göttingen design, operated horizontally, with a relatively long test section of 9 m in length and a cross-section area of 2.40 m × 1.60 m (width x height), as seen in Fig.1. The maximum wind speed is about 65 m/s and the wind tunnel is operated at ambient conditions.

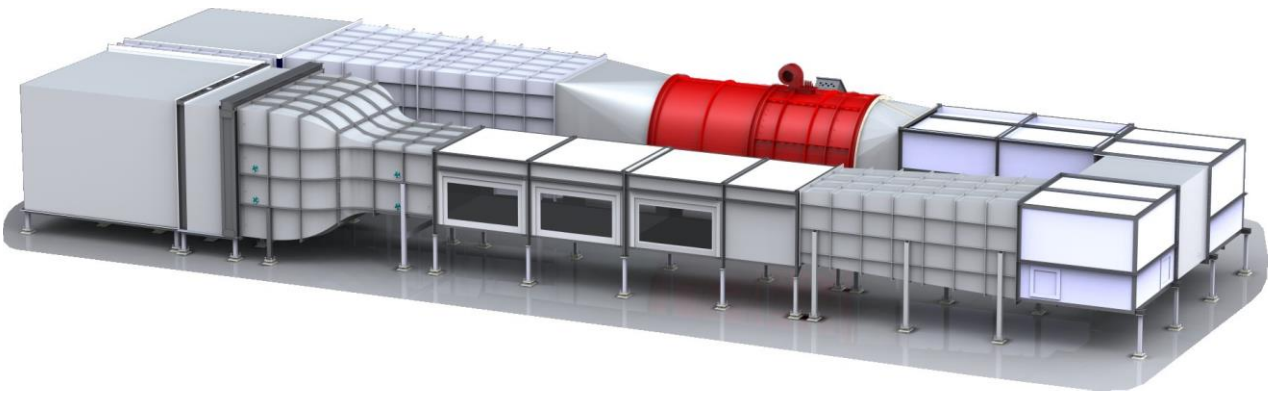

Fig. 1: Cross-wind wind tunnel (SWG) of DLR-Göttingen

For the validation experiments with respect to drag, a moving belt of 4 m x 1 m (length x width) can be operated (along with two boundary-layer suction devices) to simulate driving over solid ground. This is very important if you want to determine the aerodynamic drag, as the pressure conditions between the train's underbody and the track bed are different than if the wind tunnel model were standing on a solid plate. Currently a maximum speed of 30 m/s can be set for the moving belt, but work is underway to increase this to 40 m/s for the planned validation tests. With a scale 1:20 KMF-Regio model the Reynolds number then becomes Re = 0.4 x 10^6 for the wind tunnel tests. Fig.2 shows the setup when using the moving belt along with suction to minimize the boundary layer thickness on top of the belt. This is necessary to come as close as possible to a linear boundary layer profile near the surface of the belt. With the shown setup, the remaining velocity deficit (i.e. the deviation from a linear profile) is of the order of 4% at about 10 mm distance from the surface of the moving belt. The underfloor of the KMF-Regio model, on the other hand, is located 38 mm distance from the surface, thus outside the remaining velocity deficit.

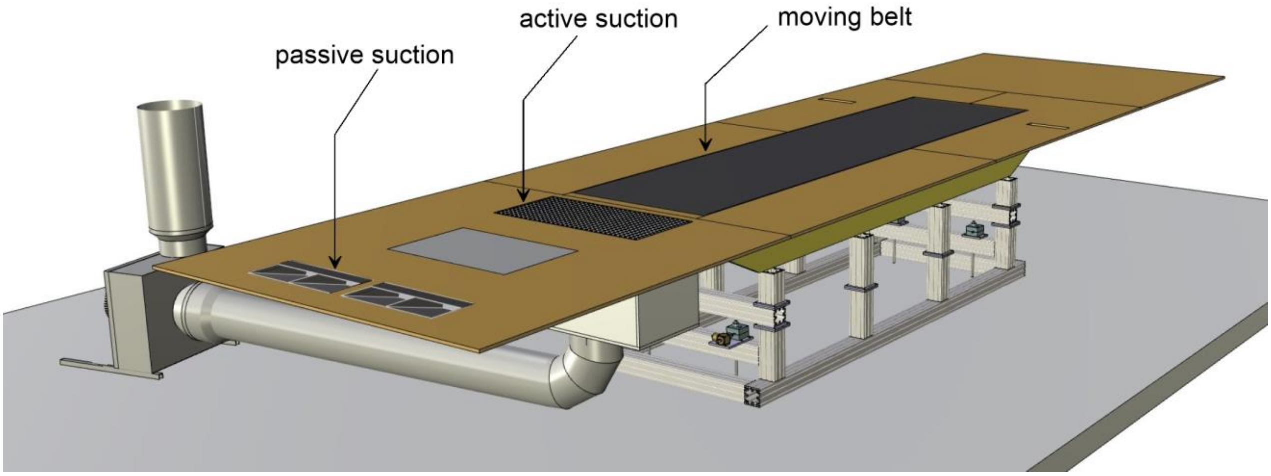

Fig. 2: Setup for moving belt: a passive- and an active suction upstream of the belt minimize the boundary layer before it enters the belt area (side walls and top wall of the wind tunnel's test section are removed in the figure for better visibility of the setup)

Boundary-layer profile measurements have been performed in the empty wind tunnel, with fixed bottom as well as with a moving belt and suction. Furthermore the (static) pressure gradient along the side wall was determined at a height, where the model will be mounted in the tests. The turbulence level of the oncoming flow is known as well as the turbulent fluctuations in the boundary layer near the moving belt. Together with the CAD of the wind tunnel geometry, all data necessary for simulating the empty wind tunnel using numerical methods has been distributed to the partners and can be used to adjust meshing, numerical boundary conditions and turbulence models. In the actual wind tunnel tests, dynamic pressures at different locations in the test section, static pressures along the side walls, inflow velocity profiles and boundary-layer velocity profiles atop the moving belt will be obtained in parallel to the force- and moment measurements (using an internal balance) for selected configurations.

With the background of the establishment of a sophisticated, experimental database for validation of numerical methods, DLR has designed and built a generic regional train model, the KMF-Regio. The model is constructed in a modular way to enable for easy configuration changes, in the experiments as well as in the numerical simulations. Fig. 3 shows an exploded view of the KMF-Regio "Lego-Box", consisting of several single parts which can be added or removed from the car bodies. In particular, it is possible to close all gaps given on a real train (for example bogie cut-outs, coupler cut-out, inter-car gaps), to establish a closed surface. So to say as-smooth-as-possible, which can be considered as a representation for the minimum possible drag.

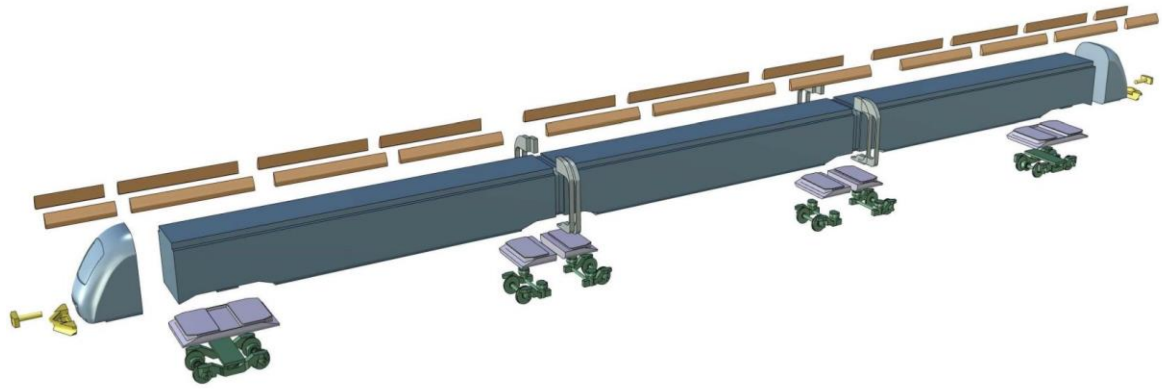

Fig. 3: DLR generic regional train model KMF-Regio, designed as a “Lego-Box” for easy configuration changes (seen here w/o roof boxes)

A certain configuration built from the “Lego-Box” parts has to be implemented in a certain representation of the wind tunnel for numerical simulations. Here, we decided to provide four different versions of the wind tunnel domain for CFD, with increasing level of detail (and with different levels of complexity with respect to available computer power and skills of the different parties).

The most simple setup A is the representation of only the test section for the computational domain as seen in Fig. 4. The bottom wall can be fixed or defined as a moving boundary in the simulations. A version B of the computational wind tunnel domain includes the contraction part given by the upstream nozzle, as seen in Fig. 5 (fixed bottom or moving wall possible). The version C to be used for the computational domain is the same as version B, but with the moving belt represented in real size inside the bottom wall (see Fig. 6 and, finally, a version D of the numerical setup was defined which includes the moving belt as well as the upstream suction devices and the surrounding tunnel hall (see Fig. 7). Moreover, some kind of combination of the four proposed representations may be used as the computational domain.

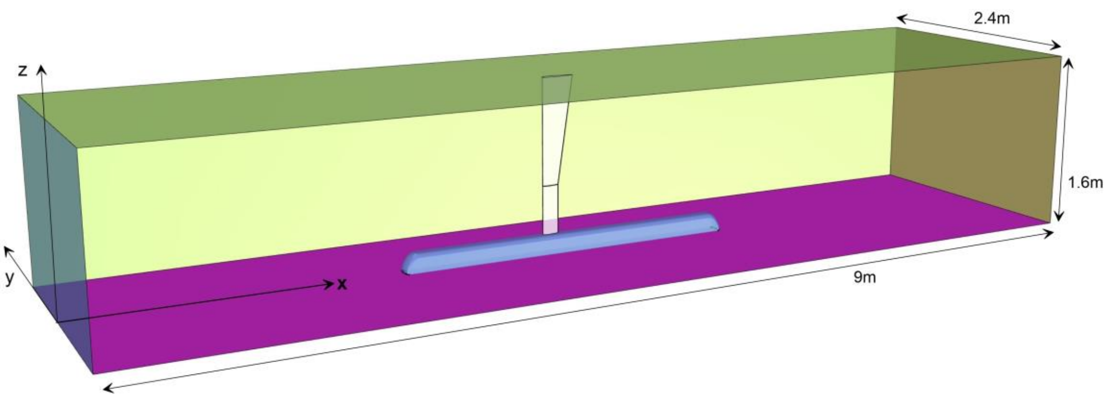

Fig. 4: Simplest representation of the numerical domain, representing the test section of the wind tunnel only (here with the smooth configuration of KMF-Regio mounted in the middle)

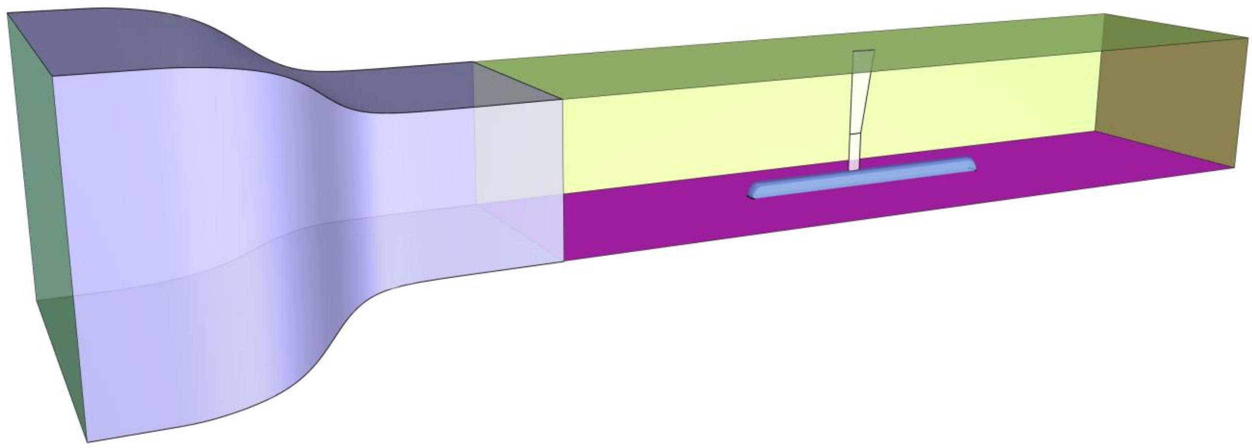

Fig. 5: Representation of the wind tunnel domain including the contraction nozzle

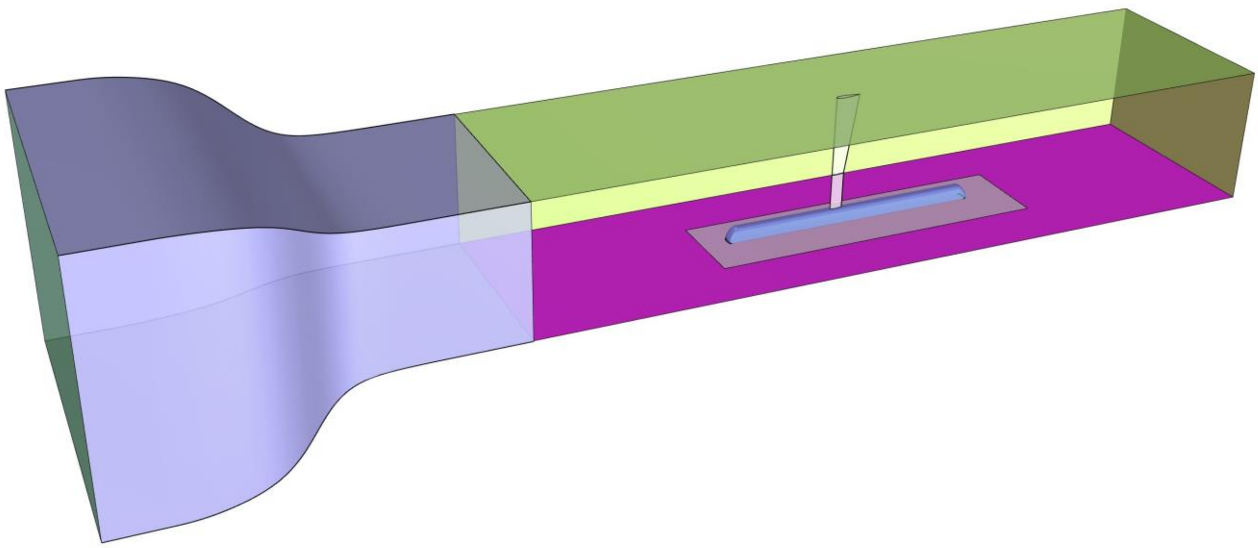

Fig. 6: Wind tunnel domain as given for version B, but with moving belt included

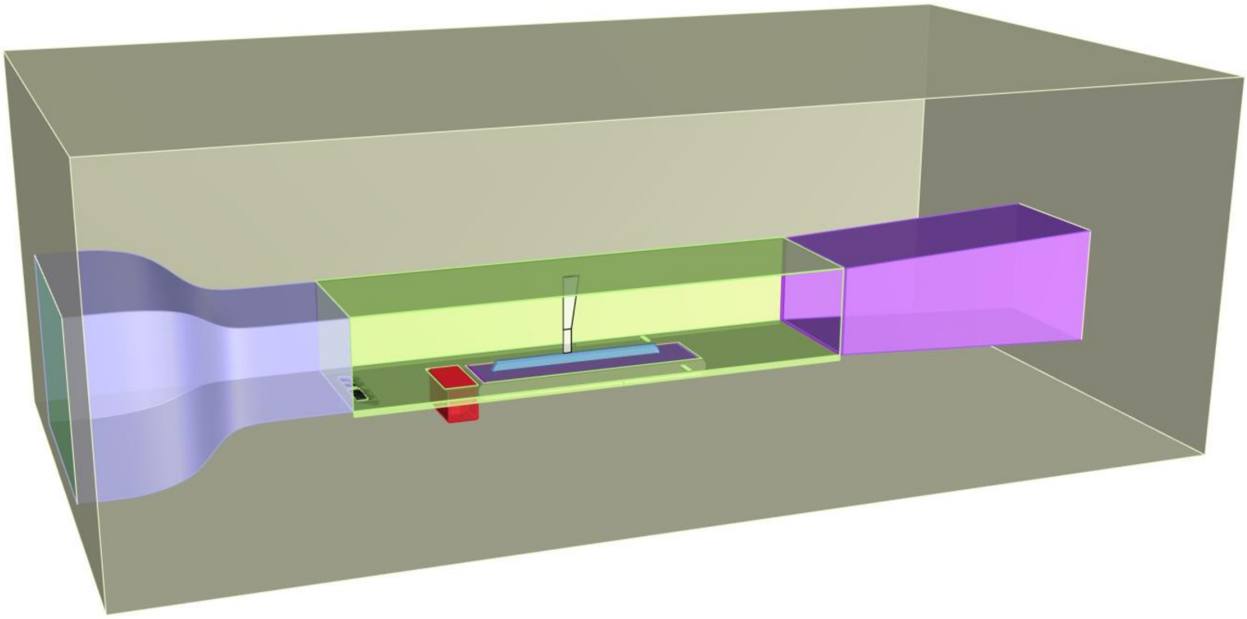

Fig. 7: Most sophisticated computational domain with the moving belt, the active- and passive suction, the diffuser downstream of the test section and the surrounding tunnel hall included. Also, a 360° gap between test section and diffusor, as well as some open gaps in the bottom wall of the test section are present

The domain to be chosen from the different versions, besides available computational power and skills, depends on the questions to be addressed. If only interested in total drag *differences* given by different setups of roof boxes, the simplest domain (version A) may be sufficient. If interested in absolute values of drag and side forces or pressure differences, the domain closest to the real wind tunnel setup should be used, i.e. version D. All experiments for the determination of the total aerodynamic drag will be performed with the moving belt and both suction devices in operation.

The KMF-Regio wind tunnel model is made from 3D printed parts, showing a certain roughness on the surface related to nozzle size and layer thickness of the 3D printer (FDM = Fused Deposition Modeling). First, a smooth version of the KMF-Region model (closed gaps) will be investigated in the experiments with no surface post-treatment applied to the 3D printed parts. This represents a rather rough model surface. After completing these test runs, the model surface will be polished and painted and the drag measurements will be repeated. This should give an idea of the influence of roughness on the experimental results which also has to be taken into account for the numerical simulations, if absolute values are of interest.

In a next step, a more common configuration of the KMF-Regio will be used for the drag measurements, equipped with bogies, couplers, snow plugs, open inter-car gaps and maybe roof fairings (shielding an open roof). Here, the influence of these parts on the total drag can be assessed.
Finally, the roofs of the cars will be equipped with different, representative roof structures – so to say generic roof setups – and the influence of size, order, shielding, edge shapes of the boxes will

be experimentally investigated with respect to total aerodynamic drag (and cross-wind stability later on). The planning of such generic roof structures is the subject of Subtask 20.2.1.
The setup described above also allows the study of the influence of a certain crosswind on the loads on the train. However, this holds only for small angles of attack (up to 5°). For the study of the crosswind loads, a second wind-tunnel model will be built, which will later be tested with the official cross-wind setup according to the EN14067-norm in a larger wind tunnel. This setup as well as the test results will be part of the two following deliverables.
The results of the wind tunnel experiments are to be compared to the result of the numerical simulations using different computational domains (versions A to D), different CFD tools, different boundary conditions and different turbulence models. Thus, an extensive validation database can be established with the aim to finally give best-practice advice for the use of numerical tools. As a missing step it than remains to adjust the numerical procedures, optimized by evaluation based on comparison to wind tunnel results, to deliver reliable results for full-scale simulations.

7.2.2. Numerical Methodology, CFD

The final reporting at the end of the project will contain a “best practice” guide with recommendations of the different details in setting up the CFD analysis. The starting point presently is here given as very indicative.

The mesh will be assembled as “building blocks” for the different parts. These blocks are replaceable for different levels of geometry details and modelling fidelities. E.g. the bogies can be included in detail or just represented by a smooth insert by replacing the “bogie” block keeping the rest of the mesh identical. The building block approach will be applied at different levels, see Fig. 8.

The assembly process will be the following:

- The different parts are assembled into one car.

- The cars are assembled into a train set. Different numbers of cars and different combinations can be assembled. The train set super block is limited in size but including the details and the boundary layers and will contain the majority of the grid nodes.

- Added to the train set is an external domain, which will represent different conditions such as the wind tunnel or an open domain. Different cross-wind conditions in the wind tunnel will be represented by different external meshes, keeping the train set mesh identical. Moreover, tunnel passage and passing trains, can be represented by altering the external field with e.g. the complete train set mesh moving inside the external domain (by overset meshes or sliding interfaces). The train set external domain is relatively trivial to generate and not expected to be very important for the accuracy of the results.

This is in contrary of the common approach of regenerating the whole mesh with every change of geometry. Hence, we can afford to spend some more manual work to generate a good and efficient mesh within each block with “structured” surface meshes and basically “hexa” extruded through the boundary layer. Different approaches are available for the block interfaces.

Conformal matching will enable merging of all blocks as part of the preprocessing, while non-conformal interfaces must be processed by the CFD solver with some interference. We will study and report possible impacts on the solution from the blocking interfaces.

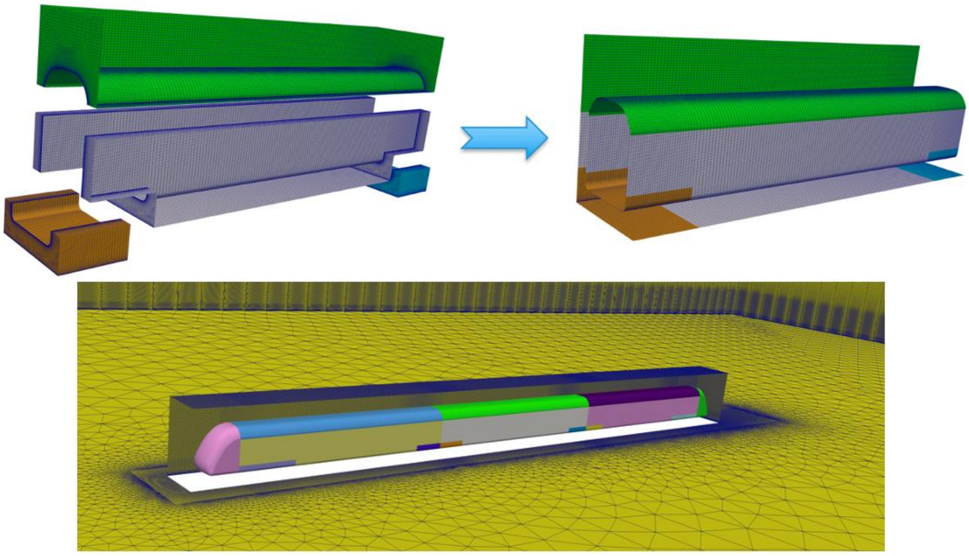

Fig. 8: Illustration of assembling the meshing blocks for one car (top) and assembling the cars to a train set with the external domain attached (example by KTH). E.g. the covered bogie blocks can be replaced by blocks with the bogie geometries resolved

The CFD solver is generic, which means that any generic flow solver can be used, commercial/proprietary as well as open source. Even though the free-stream velocity is fairly low (in the incompressible regime) the local velocity can reach above Mach=0.3 in some situations and a CFD solver for compressible flows is recommended. This is particularly true e.g. for tunnel passage and passing trains. The solver should have up-to-date RANS models implemented for the bulk computations also with wall-function boundary conditions available. Moreover, hybrid RANS-LES methods might be necessary in certain situations, which will be part of the validation study to identify.

The starting point for the procedure with the three key elements discussed above will be outlined.

The foundation of the CFD analyses for different situations and conditions is a thorough validation with wind-tunnel data. For a consistent validation, the wind-tunnel conditions must be reproduced in all essential details. For this study, it will be adopted the DLR generic regional train KMF regio (see below), which is well defined also concerning the wind-tunnel setup. The wind tunnel is, though, non-trivial with suction panels and partly running floor and the first step is to reproduce the empty wind tunnel by CFD, see Fig. 9. After that, the train model can be introduced in the CFD analysis, keeping the wind-tunnel model. A large part of the CFD study during 2024 will be dedicated to the CFD analysis of the model in wind tunnel with different configurations. Mesh refinement and sensitivity of turbulence modelling will be assessed. A few well-chosen hybrid RANS/LES simulations will be made to assess the validity and limitations of RANS approaches and to give some information about in what situations hybrid methods might be necessary. Comparisons of results obtained will be made by the partners doing CFD analysis and differences between CFD and wind-tunnel data will be identified and explained.

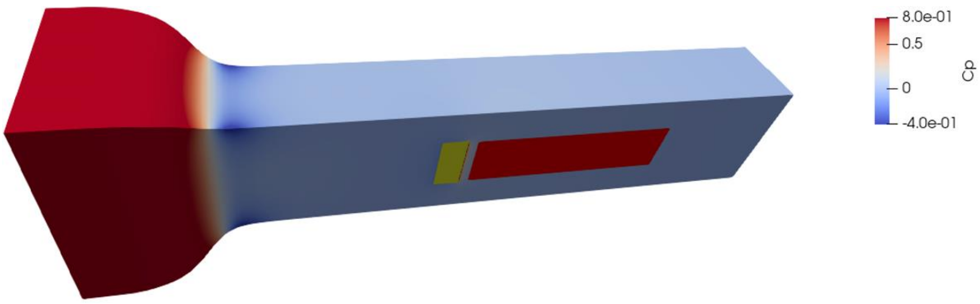

Fig. 9: CFD analysis of the empty wind tunnel incl. suction panel (yellow) and running belt (red)

The CFD model can then be used for deriving different wind-tunnel installation effects.
These are:

- The wind-tunnel wall blockage giving some additional acceleration of the flow around the train with somewhat overestimated aerodynamic resistance.
- The effect of the sting extending from the roof of the model to the wind-tunnel wall. The purpose of the sting is to hold the model in a precise position in relation to the running floor and to measure the aerodynamic forces on the train.
- The effect of the floor installation with suction panels and running belt in comparison with a train travelling on open ground.
- The effect of the model size and operating velocity (the Reynold number effect).

The ground floor of the wind tunnel is put in motion at the same speed of the incoming air flux to provide the relative wind profile of the full scale real operating conditions of a train. The same applies for the numerical simulations.
However, this is not needed for the surrounding walls of the wind tunnel (physical or numerically simulated). Indeed, the walls are sufficiently far from the train model and their influence could be considered as negligible. The figure 10 below shows that the boundary layer of the wind tunnel walls (simulated through CFD) has a thickness in the order of 0,1 m, with close to non-disturbed wind flow at the central section of the wind tunnel (slice positioned at midspan in lateral direction as depicted in the following figure).

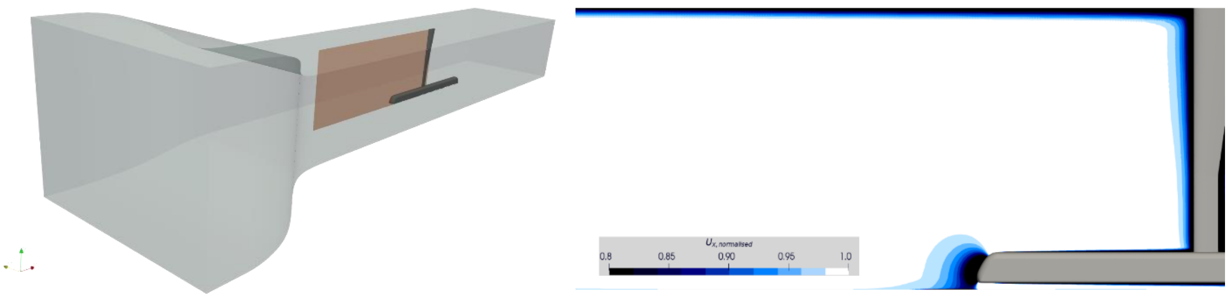

Fig. 10: CFD analysis of the KMF train in wind tunnel to evaluate the boundary layer effect

The wind tunnel test section is characterized by a rectangular cross section area of 2.4 x 1.6 m. The lateral distance between the model and the walls can be considered similarly to cause negligible boundary effects.
Moreover, the blockage effect given by the boundary layer development and the train model presence is considered through the correction of the wind speed for the estimate of non-dimensional aerodynamic coefficients.

Based on the validation and the wind-tunnel installation effects, considering both experimental and CFD data, the aerodynamic performance of a real train can be estimated with good confidence and accuracy. Additional full-scale tests will be used for further verification.

The resulting CFD model of the full-scale train will have the accuracy and confidence reinforced by the wind-tunnel experimental data and analyzed wind-tunnel installation effects. One must, however, be aware of that the CFD model, similar to the wind-tunnel model, is a substantial simplification of a real train with details, imperfections and running conditions that cannot be completely captured.

This model, together with the modular mesh concept, can be used for many different extended analyses. E.g. cross wind, wind gusts, tunnel passage, passing trains, platform safety with passing train, trains in different terrains (e.g. mountains and bridges). Fig. 11 shows preliminary CFD analysis of the DLR generic regional train KMF regio.

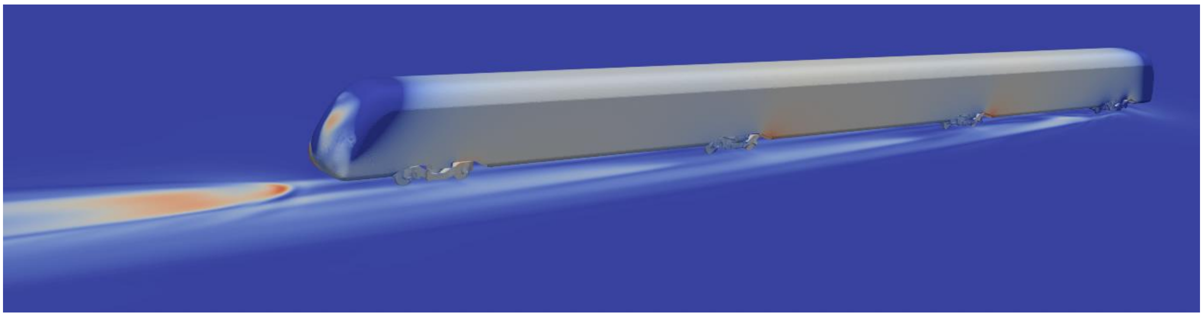

Fig. 11: Preliminary analysis of the DLR generic regional train KMF regio with bogies at 3° cross wind running in the right direction. Colour shows skin friction at the ground

Moreover, and maybe more importantly, the CFD model will be used for analyzing the effect of modifying or replacing different components by replacing only the local CFD block, keeping all the remaining part of the CFD model unchanged. These "delta effects" can be compared to those obtained by wind-tunnel measurements and can be used for estimating the overall impacts on the train aerodynamics as well as being a basis for virtual certification of these component modifications. The methodology will be further exercised and evaluated on the studies of roof equipment and pantograph in task 20.2.

8. Task 20.2: Aerodynamic Demonstrator for Drag and Noise Reduced Pantograph

8.1. Subtask 20.2.1: Aerodynamics of Roof Equipment

Conventional rail trains (i.e., trains in the 140 – 200 km/h speed range) are usually not streamlined and often have equipment in the roof area which, because of their shape and arrangement on the train, reduces the train's overall drag.

The objective of this subtask is to study the impact on drag of the positioning and shape of roof equipment on conventional trains in order to be able to provide recommendations or best practice for limiting the impact of this equipment on drag and therefore energy consumption.

To achieve these objectives, the studies will be based on drag measurements performed on the KMF train during wind tunnel tests at DLR, for different roof configurations. CFD simulations will also be carried out for a selection of configurations. CFD will provide more accurate information concerning the flow (pressure field on the train, turbulence areas, ...) and will help to identify the areas that contribute most to drag.

The train that will be used for these studies is the generic train model KMF Regio designed by DLR. Two roof configurations already exist for this train and will be tested in the wind tunnel - a flat roof without any equipment and a complete rounded roof – The third study configuration, which has not been defined yet, is a configuration with equipment installed on the flat roof. This configuration will be a reference configuration for the future parametric studies (distance between equipment, shape/size of equipment, positioning of equipment on first vehicles….).

To define the most realistic reference configuration, the dimensions of the main roof-mounted equipment were collected from the manufacturers in this working group (overview over configurations: Fig. 12).
The next step, based on this information, will be to finalize the reference configuration, i.e. to specify the size/shape of the equipment selected and their location on the train vehicles.

N° configuration	Main Group of configuration	Roof modification description	Equipment distribution on vehicles		
			Vehicle 1	Vehicle 2	Vehicle 3
0	No roof equipment	Train without roof equipment			
1	Reference vehicle	REF- Narrow roof equipment / narrow bellow/ without fairings	SB+BB+BB+SB	BB+SB+SB	SB+BB+BB+SB
2	Distance between equipment	Realocation of equipment to extreme cars	SB+BB+BB+SB+SB	BB	SB+SB+BB+BB+SB
3		Realocation of all equipment to extreme cars	SB+BB+BB+BB+SB+SB		SB+SB+BB+BB+SB
4	Equipment distribution	No space between equipment	SB+BB+BB+BB+SB+SB		SB+SB+BB+BB+SB
5		No space between equipment [Rear side]	SB+BB+BB+BB+SB+SB		SB+SB+BB+BB+SB
6	Equipment size - Height	Higher first BB block	SB+BB+BB+SB	BB+SB+SB	SB+BB+BB+SB
7		Higher first BB block	SB+BB+BB+BB+SB+SB		SB+SB+BB+BB+SB
8		Higher last BB block	SB+BB+BB+BB+SB+SB		SB+SB+BB+BB+SB
9	Equipment size - Width	Wide roof equipment	SB+BB+BB+SB	BB+SB+SB	SB+BB+BB+SB
10		First BB wide	SB+BB+BB+SB	BB+SB+SB	SB+BB+BB+SB
11		Last BB wide	SB+BB+BB+SB	BB+SB+SB	SB+BB+BB+SB
12	Equipment shape	Inside section boundaries	SB+BB+BB+SB	BB+SB+SB	SB+BB+BB+SB
13		Inside section boundaries + upper round edges	SB+BB+BB+SB	BB+SB+SB	SB+BB+BB+SB
14	Fairings	Longitudinal (X) intermediate fairings	SB+BB+BB+SB	BB+SB+SB	SB+BB+BB+SB
15		Longitudinal (X) extreme fairings	SB+BB+BB+SB	BB+SB+SB	SB+BB+BB+SB
16	Intercar gap	Wide bellow	SB+BB+BB+SB	BB+SB+SB	SB+BB+BB+SB
17		Wide gangway gap	SB+BB+BB+SB	BB+SB+SB	SB+BB+BB+SB
18	Roof cover	Half roof covered - Extreme cars	SB+BB+BB+SB	BB+SB+SB	SB+BB+BB+SB
19		Full roof covered - Extreme cars	Covered	BB+SB+SB	Covered
20		Full roof covered - Complete unit	Covered	Covered	Covered
21	Equipment size - Width - Not centred	Wide roof equipment	SB+BB+BB+SB	BB+SB+SB	SB+BB+BB+SB
22		First BB wide	SB+BB+BB+SB	BB+SB+SB	SB+BB+BB+SB

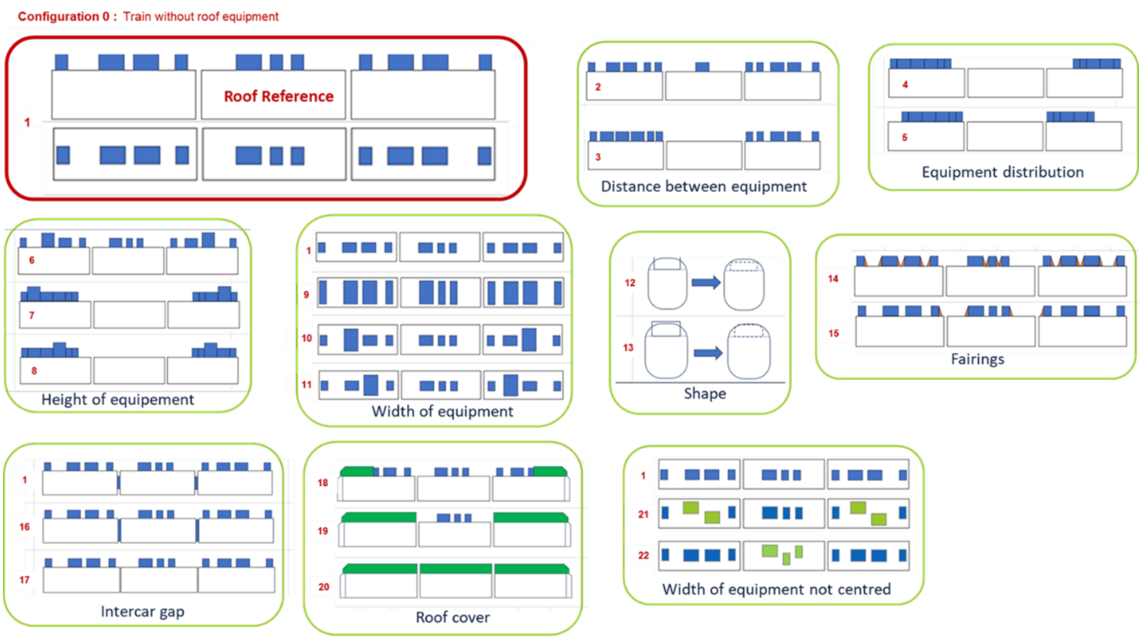

Fig. 12: Roof configurations under consideration for parametric studies

8.2. Subtask 20.2.2: Aerodynamics of the Pantograph

The objective for the first step on the subject of “aerodynamics of the pantograph” was to design a wind tunnel model of a pantograph, which will initially be used in the cross-wind wind tunnel of DLR-Göttingen (SWG) to study the aerodynamic behavior. The design of this model should be a generic geometry, i.e. the model should not represent the design of a specific manufacturer, but does not yet exist on a real scale. This guarantees that the results obtained from the investigations to be carried out can be freely published. Nevertheless, the geometry of the pantograph model should be chosen so that, firstly, it is very close to the design of a real pantograph and secondly, it is representative of a type of pantograph used on high-speed trains (see Fig. 13).

Fig. 13: Design for a generic Pantograph to be used for wind tunnel experiments and CFD

The model to be manufactured should be installed in the SWG wind tunnel on a 1:1 scale and equipped with various sensors. The objective of an initial measurement campaign is to experimentally investigate the aerodynamic behaviour of the pantograph and the scaling as a function of the Reynolds number, as well as the unsteady effects arising from the aerodynamics of the individual components. To do this, the entire pantograph should be placed on a 6-component balance (consisting of four piezoelectric 3-component force transducers) in order to determine the three components of the force and the three moments in the wind tunnel test with high temporal resolution. Another, independent force measurement should enable the contact force of the collector head to be determined on the contact wire. For this purpose, a second 1-component balance is to be installed underneath the top wall of the wind tunnel's test section, which is in appropriate contact with the contact strips of the pantograph (see Fig. 14).

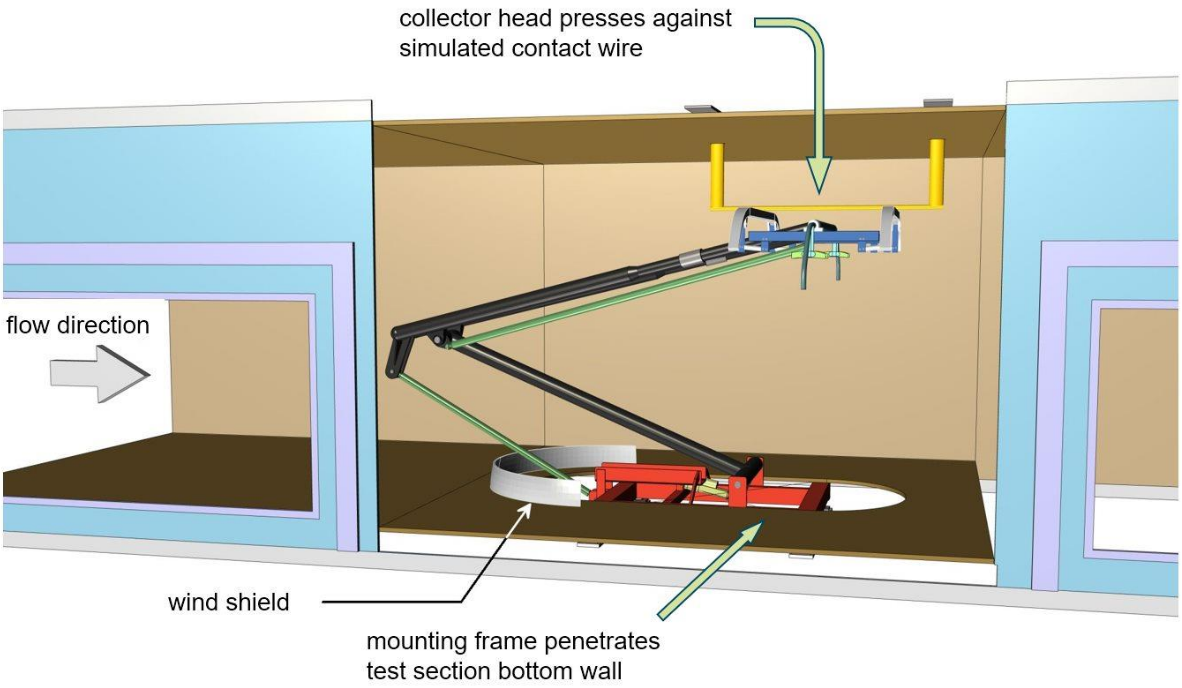

Fig. 14: Scale 1:1 pantograph model as planned to be mounted in the SWG wind tunnel

The illustration shows how the pantograph is intended to be installed in the test section of the SWG wind tunnel. In order not to expose the piezoelectric force transducers (not visible here) to the flow, the base frame of the model is installed below the floor of the test section. This also corresponds to the situation on most high-speed trains (in relation to the outer roof skin). The base frame is guided through a suitable opening in the base plate of the test section. More shielding against the flow in the lower area of the pantograph can be achieved using an additional wind shield (see figure).

The planned implementation for determining the contact force is shown in Fig. 15: The contact wire is represented by a piece of steel pipe, which is attached between two aerodynamically profiled struts. These in turn sit on piezoelectric force transducers which are attached to cross members on the opposite side, which are stretched between two aluminum profiles given as part of an existing outer frame near the test section. Only the z-component of the force is measured as the mean value of the two force transducers.

All views of the pantograph model shown here show the pantograph in what is known as “knee walk” (“knee” between the upper and forearm in the direction of travel). It is immediately obvious that the structure can be rotated by 180° without any major effort in order to simulate the “skewer walk” (collector with contact strips ahead in the direction of travel).

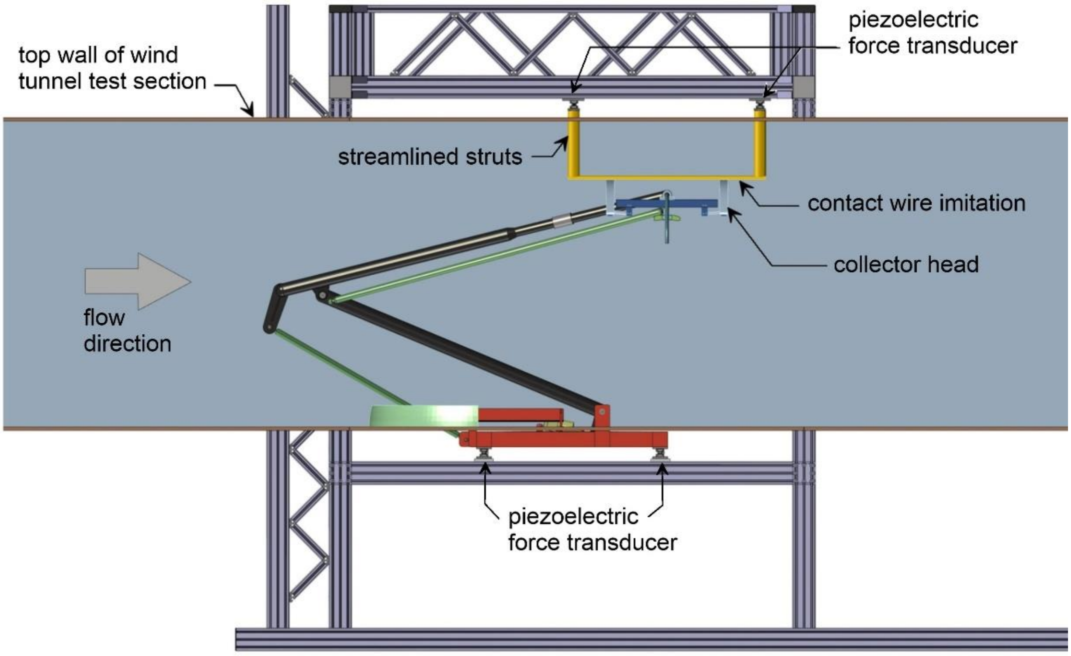

Fig. 15: Side view of the setup showing the piezo-resistive force transducers

The figures 16-18 in the following show the dimensions of the planned wind tunnel model of the generic pantograph in different views. In Fig. 18 one can see two so called wind deflector plates (small, green parts between the collector strips) widely used to adjust the contact force to meet the desired force range, based on train speed. These deflector plates are usually optimized by expensive full-scale tests on the real train. It is one aim of this project to proof, if this optimization can also be done to a certain level only by wind tunnel testing.

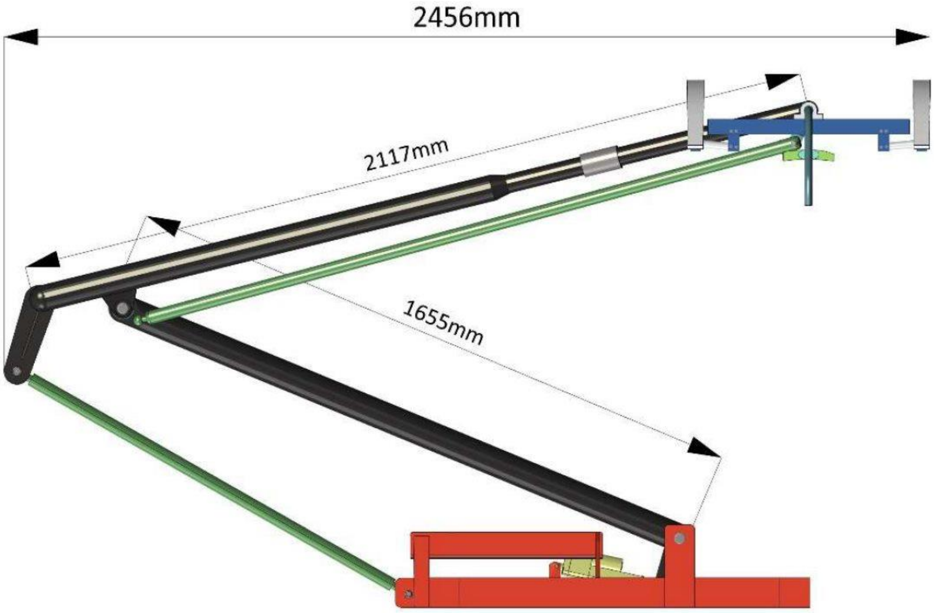

Fig. 16: Dimensions of the planned wind tunnel model in side view

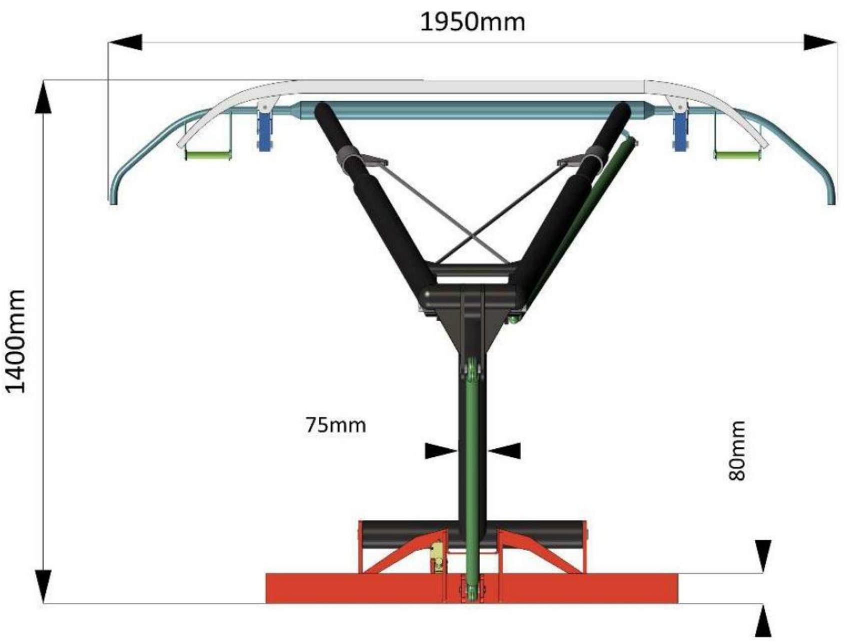

Fig. 17: Dimensions of the planned wind tunnel model in front view

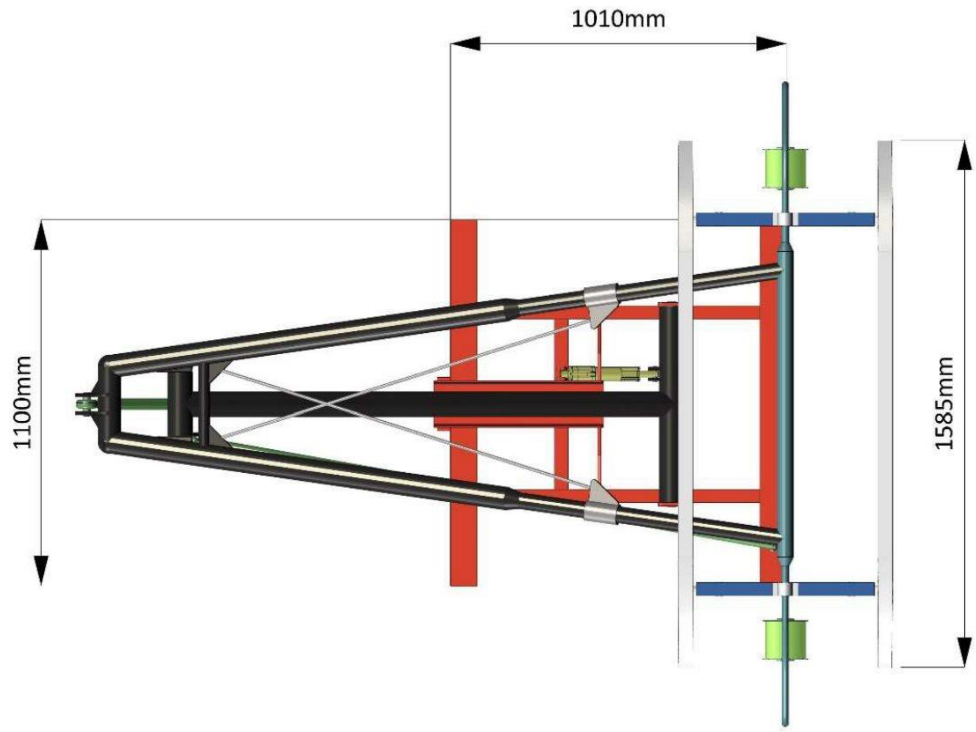

Fig. 18: Dimensions of the planned wind tunnel model in top view

The basic model of a pantograph described here is to be constructed on a 1:1 scale and prepared for aerodynamic measurements in the SWG wind tunnel. The use of piezoelectric force transducers allows the time-resolved recording of forces and moments with a high sampling rate. The pantograph can be measured in both knee- and skewer walk and should also be able to be examined at yaw angles in the range of at least ± 7°. Easy-to-manufacture (3D printing) deflector plates can be tested in various versions with regard to their suitability for stabilizing the contact force. Furthermore, aerodynamically favorable coverings for the individual components of the pantograph (also produced using 3D printing) can be adapted and examined with regard to their possible contribution to reducing drag. In principle, the planned model can also be used to carry out acoustic measurements in order to possibly reduce sound radiation. However, this is rather difficult to do in the SWG wind tunnel and requires the model to be used in a special acoustic wind tunnel. The model is modular and in particular can be easily modified in terms of the dimensions of the contact strips and the horn.

9. Conclusions and Outlook

The status of the WP is summarised and further steps are defined within this report.
In both tasks, the main topics to study were identified and the methods were determined. A reference train model was designed with which the studies will be performed in both tasks.
The first task will focus on crosswind loads as well as on wind resistance of trains using both numerical and experimental methods.
First numerical simulations of the train model as well as the wind tunnel used in this project were executed and the results of these simulations were analysed. Different numerical methods were tested to determine the best method to predict the loads on the train model.
The current TRL level of the tasks is TRL 3, with the help of the ongoing studies and iteration of the methodologies, the aimed TRL level 4 will be reached within year 2024.
The next steps of task 20.1 will be the experimental tests in the wind tunnel (and related to this model construction and building) as reference as well as the ongoing work regarding numerical simulations: Based on these works the results will be compared to identify the best numerical practice for simulating and predicting the loads.
For the task 20.2, different roof configurations were chosen and their influence on the wind resistance discussed. Next steps will be the preparation and instrumentation of the models as well followed by the experimental tests in the SWG wind tunnel. In parallel, numerical simulations based on the results of task 20.1 will be performed to validate the test results and to give a better insight into the generation of specific flow structures.
In subtask 20.2.2, a generic pantograph was developed which allows the study of the pantograph's aerodynamic behaviour. In the further progress of the project, numerical simulations will be prepared to analyse the influence of the position of the pantograph on the train roof, as the train's boundary layer varies with varying position.
The first experimental tests in the wind tunnel for the different tasks are planned to take place in summer 2024.

10. References

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[2]: EN 14067-6:2018+A1:2022 Railway applications - Aerodynamics - Part 6: Requirements and test procedures for cross wind assessment
[3]: EN 14067-4:2013 Railway applications - Aerodynamics - Part 4: Requirements and test procedures for aerodynamics on open track
[4]: CEN Technical Report PD CEN/TR 17833:2022-08-15: Railway applications. Guidance for the use of simulations. Guidance for the use of simulations to demonstrate compliance with technical and regulatory requirements and on the introduction and development of simulation requirements into standards