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KMF-Regio, a Generic Modular Designed Regional Train Model

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Abstract

A generic train model is presented, which is modular in design and intended to become a validation case for experimental setups and numerical methods. The geometry is based on the shape of a conventional regional train and can be extended to any desired length. Here, a three-part model is presented, which was 3D printed at scales of 1:20 and 1:25 and tested in two different wind tunnels. A key feature of the model is its modular design, allowing selected parts of the train body, like heads, bogies or inter-car gaps to be inserted, omitted, or exchanged to investigate their influence on aerodynamic coefficients. In particular, a wide variety of generic or realistic roof structures can be implemented to determine, for example, their aerodynamic drag, while the geometry of the actual train remains otherwise generic and is freely available.

Keywords: generic train model, regional train, drag measurements, crosswind testing, validation case, numerical simulation

1 Introduction

Within the European community, the three so-called reference models ICE 3, TGV Duplex, and ETR 500 (power car/leading vehicle + downstream body) are denoted as possible model shapes for demonstrating, for example, the reliability of the hardware setup during crosswind homologation tests and for documenting the suitability of a newly to be used wind tunnel for this purpose. This is done by comparing the values measured with a replicated model of at least one of the reference designs with given benchmark values as specified in the EN standard [1]. Furthermore, especially the ICE 3 design is widely chosen when a publicly accessible geometry is needed for numerical investigations of high-speed train flow phenomena (see, for example [2,3]).

For a regional train, so far no freely available geometry exists, neither for wind tunnel testing nor for numerical simulations. The aim to reduce aerodynamic drag in train traffic is becoming increasingly important, and the geometry of a regional train (especially due to the mostly protruding roof structures) differs significantly from the streamlined design of a modern high-speed train. It would be desirable to have a comparable model to the three reference models of the EN available that addresses the topic of the regional train. The wind tunnel results, for example, could be more sensitive to boundary conditions if the roof of the train model is equipped with blunt bodies, and the numerical methods may require different types of turbulence modelling and/or finer meshing to account for this case.

Therefore, the authors decided to create a generic train model that resembles a real regional train, but whose geometry does not correspond to any existing train model from a specific manufacturer. This geometry can thus be freely used to compare results from different wind tunnels, measured, for example, with different ground simulations or at different Reynolds numbers and to allow for the validation of numerical methods. Furthermore, a database will be created that is freely accessible to everyone and provides experimental and CFD results for a wide variety of configurations. In this sense, the KMF-Regio model presented here is comparable to the DrivAer model, which has been used in the automotive industry for many years [4,5] and which is the successor of the Ahmed body. For the future, the expansion of the geometry to a double-decker regional train is planned, as well as, for the sake of completeness, the development of a generic, modern high-speed train based on the existing geometry.

Two models of the KMF-Regio (KMF = "Kastentragendes Modulares Fahrzeug" = box-carrying modular vehicle) were manufactured using 3D printing and tested in two different wind tunnels for numerous configurations. The primary focus was on determining the drag for many different generic roof structures with the purest possible, isolated roof drag being measured by making the rest of the train model as smooth as possible. In addition, the influence of the shape of the train's head (smooth or realistic), the bogies (with or w/o), and the inter-car gaps (open/closed) were investigated. Wind tunnel test were performed in the DLR-Göttingen crosswind facility (SWG) [6], using a scale 1:20 model on a moving belt with boundary layer suction, and in the 3m-LSWT wind tunnel of VZLU in Prague [7], using a splitter plate and "Single-Track Ballast and Rail" (STBR) ground simulation. Reynolds numbers in the range $0.15 \leq$ Re $\leq 0.6 \cdot 10^6$ were tested to estimate the Reynolds number dependency of the results.

Numerical simulations using the KMF-Regio geometry are work in progress in the framework of the European Europ's Rail ERJU-FP4-Rail4Earth Project [8][9] in WP20. The simulations are work in progress. The focus is on different, generic roof configurations and the boundary conditions are adjusted to simulate the situation in the SWG wind tunnel with moving belt. Different partners (KTH from Sweden, Hitachi/CAF from Spain and Politecnico di Milano from Italy) use different approaches to establish suited boundary conditions and using different CFD tools, to compare the results to the SWG wind tunnel. Furthermore, DLR in addition also performs KMF-Regio simulations in house using OpenFOAM. Only a few selected experimental results of the wind tunnel tests will be shown here, since the introduction and explanation of the modular model is the main focus of this work.

2 The Modular Generic Train KMF-Regio

In this section we describe the philosophy of model construction as well as the concrete manufacturing of two wind tunnel models using the 3D printing process. In full scale, the dimensions of the design would be: 22.5 m length of end cars, 19.34 m length of middle cars, 2.8 m width and 4.07 m height, with respect to top-of-rail.

2.1 Model design

In Figure 1 three possible, different variants of the KMF-Regio design are presented: a realistic outer shape with a head equipped with coupler and snowplow and the window surface as a recess with edges (top train assembly). Realistic (but simplified) bogies are applied and the inter-car gaps are open. Both end cars have raised fairings on the front roof and no fairings at the rear roof part (the steps at the roof edges are filled by filler parts). The middle car is completely equipped with raised fairings and a generic setup of roof boxes is used on both end cars. The middle train assembly in the figure shows a configuration to be used for wind tunnel tests addressed to the drag of roof equipment: the rest of the model is smooth to separate the drag established by the roof structure from other components as much as possible. No coupler or snowplows are attached to the heads, the recess for the window is closed and bogie cut-outs as well as the inter-car gaps are closed. The lower train assembly in Figure 1 finally represents the completely smooth configuration of KMF-Regio, so to say as the reference configuration offering the smallest drag value possible. Here, compared to the middle configuration, the roof is closed by suited filler parts in addition.

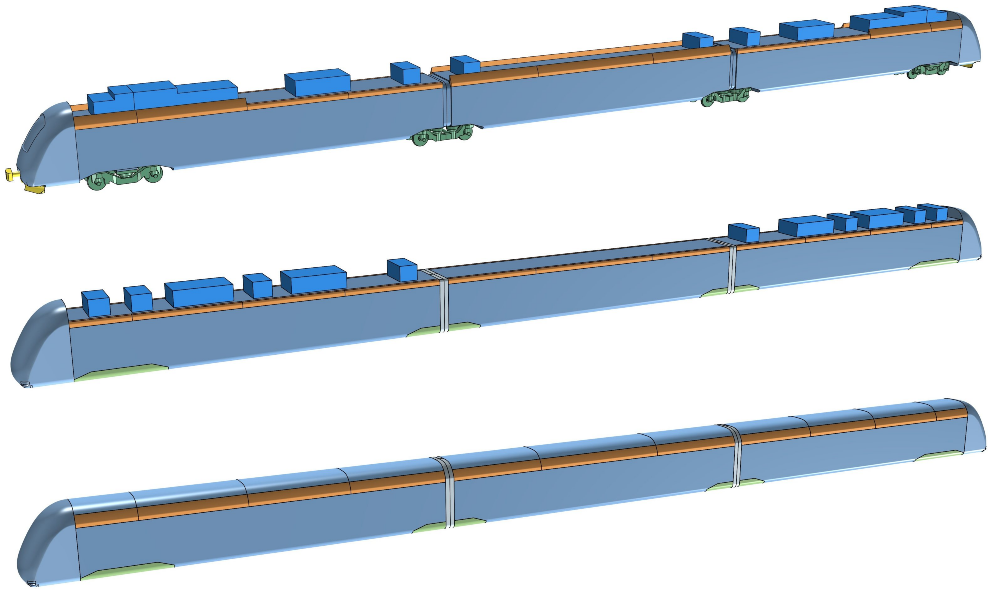

Figure 1: Three variants of the KMF-Regio design: generic roof setup on a realistic train (top), smooth train for investigations on pure roof drag (middle) and smooth model as reference with the lowest possible drag value (bottom)

In addition to the three assemblies shown in Figure 1, a variety of other configurations can be easily created from the modular concept of the model, which allows, for example, the investigation of designated components, such as the bogies, with regard to their contribution to the overall drag. Here, a three-car configuration is shown as was used for the wind tunnel tests. However, a train of any length can be created by simply copying the basic body of the middle car as many times as needed and inserting it in the center. The roof-mounted structures can then be chosen as desired.

Figure 2 shows this "LEGO box" concept as an explosive view. All single parts are provided as seen in the figure. Besides a set of bogies and the inter-car gaps being open, also filler parts are available to close bogie cut-outs and inter-car gaps.

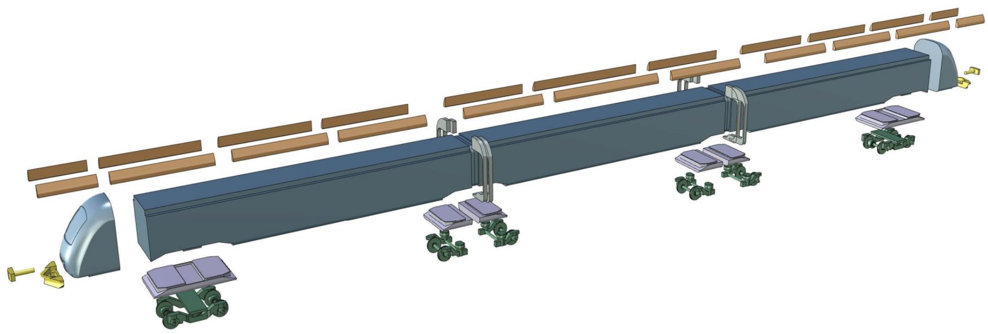

Figure 2: "LEGO box" concept for the modular design of KMF-Regio

As the first and last bogies, a single-car bogie is given while the inter-car bogies are represented by Jacobs bogies. The parts follow a systematic naming convention which is described in detail in a "Quick-Start Guide" provided with the STEP and STL files for download. If someone still wishes to design their own bogies or train heads (in more or less detail), this is quite simple: one only needs to use the connection surfaces from the existing parts as an interface for the design (see figure 3) and can then construct any generic or real heads and bogies and examine their specific contribution to, for example, the overall drag. For comparison purposes, it is advantageous if the rest of the train geometry has the same shape in all cases.

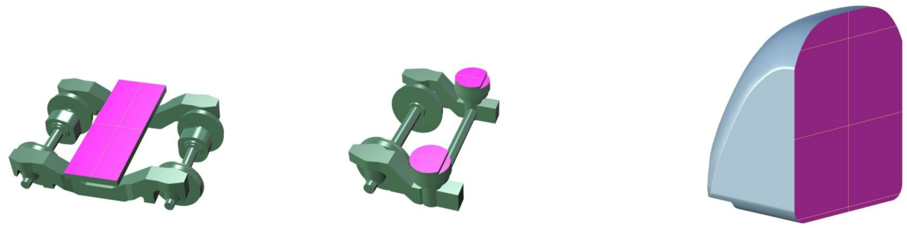

Figure 3: Interface surfaces to be used for own designs of bogies and train heads (purple areas): single-car bogies (left), Jacobs bogies (middle) and heads (right)

All parts of KMF-Regio can be downloaded from Zenodo [10]. Zenodo is a general-purpose open repository developed under the European OpenAIRE program and operated by CERN. It allows researchers to deposit research papers, data sets, research software, reports, and any other research related digital artefacts [11]. For each submission, a persistent digital object identifier (DOI) is minted, which makes the stored items easily citeable. It is planned for the future, that experimental and numerical results using the KMF-Regio train geometry can also be made publicly available for the community using Zenodo as the host.

The components are provided in the widely used STEP format, and a variety of configurations can be assembled from them. Some basic configurations are also provided in STL format for numerical calculations. Besides the completely smooth configuration, there is a smooth configuration with an open roof (for easy upgrading with any STL roof boxes), as well as the configuration with real heads and bogies, once with a smooth roof, once with an open roof. These files can be used, for example, by students using OpenFOAM who do not have access to commercial meshing software: the STL files have sufficient resolution and can be directly used, for example, by SnappyHexMesh.

Constructing a wind tunnel model from the existing geometry requires more effort, as a defined internal structure is necessary for 3D printing. Furthermore, the very long model must be divided into printable parts, and a method must be found to precisely assemble these parts into the complete model. Especially for force- and moments measurements, it is important to consider how an internal force balance can be implemented inside the model or how an external balance can be connected.

2.2 Construction of two wind tunnel models

Figure 4 shows the construction of the KMF-Regio wind tunnel model, built to a 1:20 scale for use in the SWG wind tunnel at DLR Göttingen, which is equipped with a moving belt and boundary layer suction. An internal six-component force balance was implemented using four appropriately mounted force transducers. The three cars are guided on a rigid aluminum beam, which transmits the forces and moments to the model's support. The model is suspended free-floating above the moving belt by means of a sword attached to a structure behind the top wall of the test section. Carbon fiber rods help align the individual, 3d-printed segments of each car during assembly.

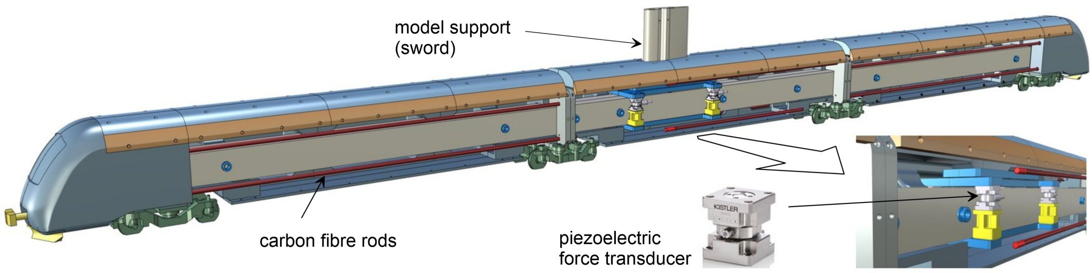

Figure 4: Scale 1:20 model of KMF-Region built for force and moments measurement in the SWG wind tunnel with moving belt and boundary layer suction

Figure 5 shows the internal structure and the corresponding 3D-printed model part, using the train's head as an example. The individual segments produced in this way were glued together using carbon fiber guide rods, creating the individual cars as cohesive units. Their surfaces were then polished and painted to achieve a smooth finish. The three-car train is formed by placing the individual cars over the aluminum beam, with the middle car having been previously equipped with the force transducers and attached to the sword. This specific design means that forces and moments can only be measured for all three cars as a whole.

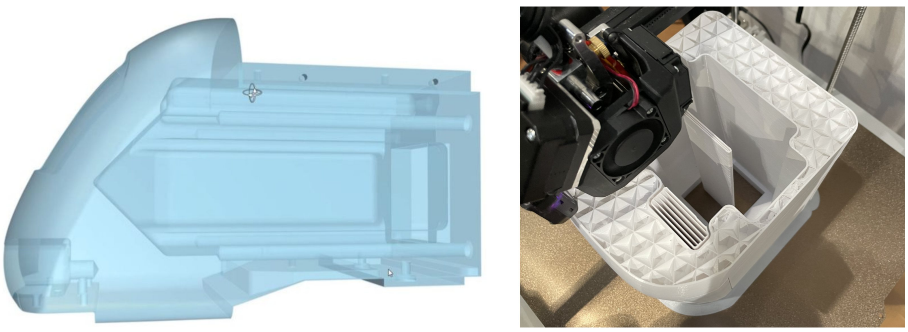

Figure 5: The trains head as prepared for 3D printing: left) transparent view of the part in CAD, right) head being printed on a conventional filament printer

Finally, Figure 6 shows the completed model in the DLR Göttingen's crosswind wind tunnel (SWG) as a smooth configuration with a specific, generic roof structure. In this way, various roof structure arrangements were investigated with regard to their drag coefficients during an extensive measurement campaign in 2025.

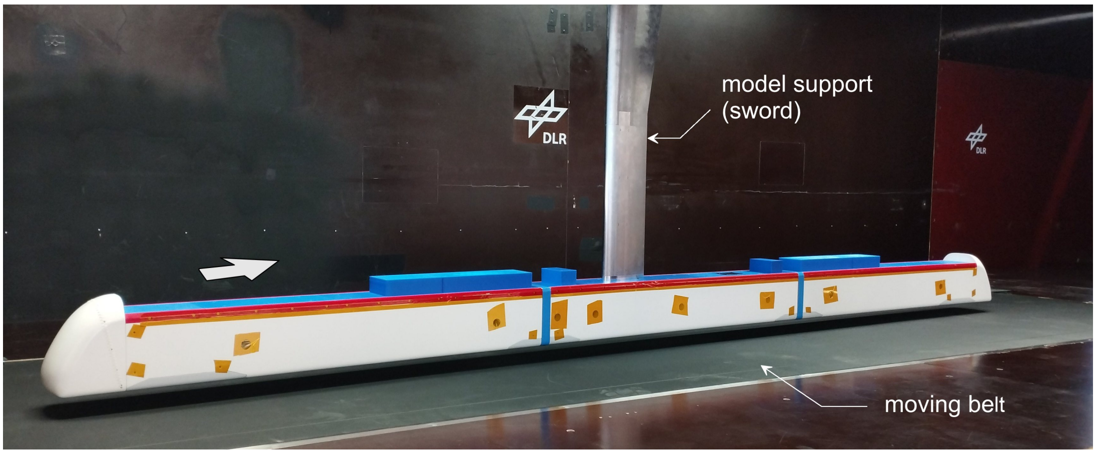

Figure 6: KMF-Regio scale 1:20 model as mounted in the SWG wind tunnel

As a second wind tunnel model, the geometry of the KMF-Regio was designed at a scale of 1:25, also using 3D printing, to accommodate two internal block-type strain gauge balances from RUAG Aerodynamics. One of the two 6-component balances is located in the leading end car (CarA) and the other in the middle car (CarC) as can be seen in Figure 7, where CarA and B are opened in the CAD to visualize the balances. Rotating this setup by 180°transposes the leading end car to the trailing end car, allowing the forces and moments of each car of the 3-car setup to be determined individually (provided that the roof setup for both end cars is the same). In Figure 8, this setup is shown as realized in the 3m-LSWT wind tunnel of VZLU in Prague [7]. The 3m-LSWT (3-meter Low-Speed Wind Tunnel) at VZLU (Czech Aerospace Research Centre) in Prague-Letňany is a specialized research infrastructure used for aerodynamic testing and industrial development. It is a closed circuit, open test section wind tunnel with a circular test section of 3 m in diameter and 3.5 m in length, operating at atmospheric conditions. The maximum flow speed is 80 m/s when using the active cooling system, 90 m/s without cooling.

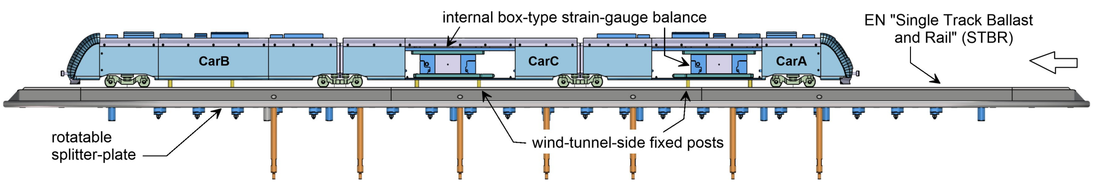

Figure 7: Scale 1:25 model equipped with two strain-gauge balances

The setup as realized in the real wind tunnel is presented in Figure 8 as a realistic configuration with a smooth roof, and a comparison of the scale 1:25 to the scale 1:20 model, as presented after polishing and painting of the outer surfaces, is shown in Figure 9. While the primary purpose of the scale 1:20 model, made for the SWG wind tunnel with moving belt, was the measurement of the drag coefficient for various representations of car details and different roof structures, the scale 1:25 model was built with cross-wind measurements in mind. While the SWG model is equipped with high-sensitive, piezoelectric force transducers and is restricted to testing at 0°yaw angle (or only small yaw angles, caused by the use of the moving belt), the 3m-LSWT model is equipped with less sensitive strain-gauge balances being able to handle the large side forces which occur, for example, at 90°yaw angle.

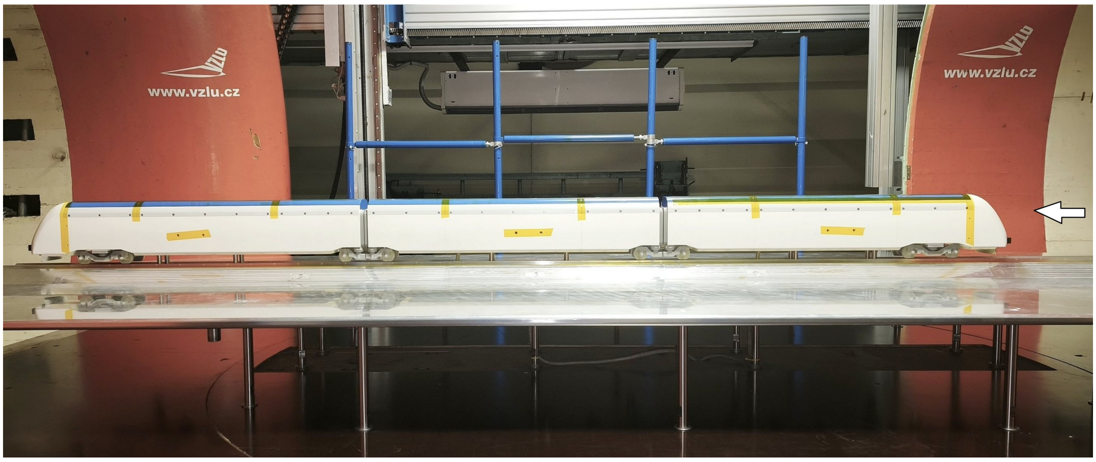

Figure 8: Scale 1:25 KMF model on rotatable splitter-plate and STBR in the VZLU 3m-LSWT (realistic heads, open inter-car gaps, bogies and smooth roof)

Figure 9: Comparison of scale 1:25 to 1:20 model (left) and comparison of smooth head to realistic head (right: realistic head w/o coupler and snow plow)

The appropriate Reynolds number for the scale 1:20 model in SWG is Re=300,000, restricted by the maximum speed for continuous use of the moving belt of 32 m/s. The maximum Reynolds number for the scale 1:25 model in the VZLU 3m-LSWT is Re=600,000. Despite its main purpose, being built for cross-wind testing, the scale 1:25 model of KMF-Regio was also used for measurements of the drag coefficient at $\beta = 0°$yaw angle for comparisons to the SWG data.

3 First wind tunnel results

In the SWG wind tunnel, using the moving belt and BL suction, 32 different roof setups were tested with the rest of the model being smooth as shown in Figure 6. Beforehand, extensive test runs were performed for the completely smooth train (see Figure 1, bottom) since this should represent the smallest drag coefficient possible and shall be used for comparison. It was already evident from the results of these measurements, that at Re=300,000 the resulting drag coefficient is still Reynolds number dependent and Zick-Zack tape was used as a boundary layer tripping at different locations on the train's leading head, for the smooth configuration 01. The result for the drag coefficients C_{Fx} are presented in Figure 10, where the red curve in the right plot denotes the drag values w/o BL tripping, the blue curve represents BL tripping by Zick-Zack tape at the heads rear, which was doubled for the yellow curve. For the green curve, in addition a Zick-Zack tape was applied around the heads nose. The single Zick-Zack tape at the heads rear (blue curve) leads to the smallest drag values possible and therefore it remained so for the rest of the measurements in the SWG wind tunnel. The grey curve in the right-hand diagram in Figure 10 shows the case for the moving belt and boundary layer suction deactivated, so to speak with the model over a flat ground, which noticeably reduces the overall drag. All drag measurements with different roof setups in the SWG wind tunnel were carried out at a Reynolds number of Re = 300,000, with the moving belt and the BL suction operated.

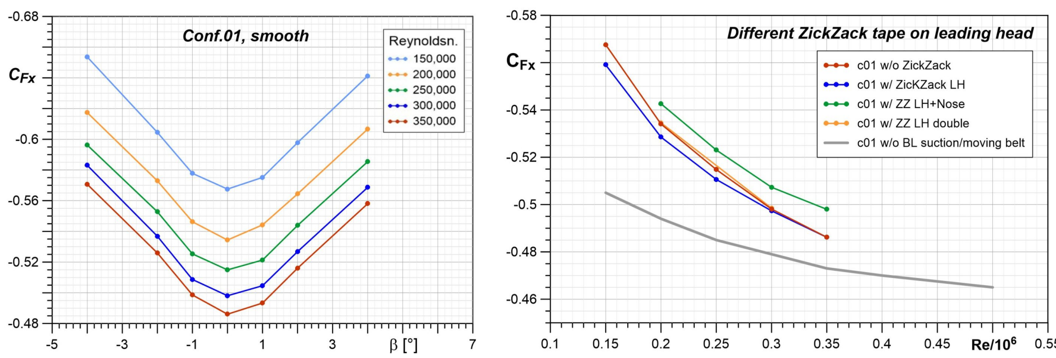

Figure 10: Yaw angle sweeps for different Reynolds number (left) and Re-dependency for different applications of Zick-Zack tape (right) for the smooth train

In the VZLU 3m-LSWT, a first study was performed using the scale 1:25 KMF-Regio model to check for Reynolds number dependency of the drag coefficient C_{Fx} up to Re=600,000 now, using again the completely smooth configuration (config.01). In addition, Re-dependency of the drag coefficient for a reference roof-box setup was investigated as well (config.10). The equipped model for this case is shown in Figure 11 and the results for Reynoldsnumber dependency of config. 01 and config. 10 are plotted in Figure 12. Note, that in SWG the total drag of the 3-car model was gathered as a whole, while in 3m-LSWT, using the scale 1:25 model, the drag of the single cars is obtained (trailing end car, CarB, is measured by rotating the setup by 180°). Thus, the drag coefficients for the single cars are plotted in the figure (red, blue and green curves in the lower part of the diagram) as well as the sum of all cars (dark blue curve above). For comparison, the results from SWG testing are included (red and pink curves). Note, that here the absolute values $|C_{\mathrm{Fx}}|$ are plotted against Re.

Three important results emerge from the curves shown in Figure 12: First, for Re $>$ 500,000, the Reynolds number dependency is already significantly smaller than at Re = 300,000. Second, the main component of the Reynolds number dependency appears to be due to the flow around the leading end car (CarA), while the drag of the middle car and the trailing end car is largely independent of the Reynolds number.

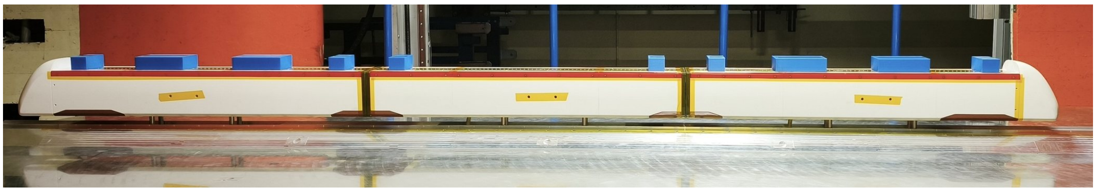

Figure 11: KMF-Regio model in scale 1:25, equipped with reference roof boxes (config. 10) as mounted in the test section of 3m-LSWT

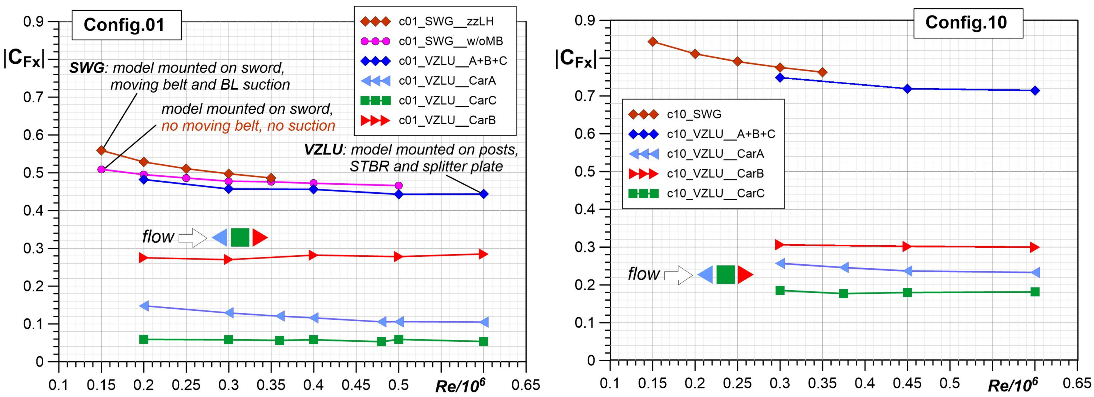

Figure 12: Reynoldsnumber dependency for config. 01 and 10. Absolute value of drag coefficient for single cars and for the sum of the three cars is plotted against Re in the range $0.15 \leq Re \leq 0.6 \cdot 10^6$

Thirdly, the values of the 3m-LSWT measurements smoothly follow the course of the SWG results, separated by an offset that is due to the different underbody-flow conditions (moving belt and BL suction in the SWG, splitter plate and STBR in the 3m-LSWT). If the focus is solely on the differences rather than the absolute values, e.g., between different roof configurations or comparing open to closed inter-car gaps, the Reynolds number dependence of the results and the influence of different ground situations are initially secondary, and the deltas obtained in the SWG should be comparable to the deltas gathered in the 3m-LSWT. Especially for validating numerical methods, only the differences between various configurations should be considered initially before attempting to reproduce absolute values.

However, this may change when the contribution of, for example, the bogies becomes the subject of investigation: here the influence of the ground flow should become more apparent and the ground moved along by the moving belt in connection with the BL suction in the SWG should represent the better ground simulation, albeit to the disadvantage of the smaller available Reynolds numbers.

An intensive investigation into the contribution of the various flow-influencing components to the overall drag of a train in both wind tunnels is currently work in progress, and the results will be published. The aim of these studies is to establish a comprehensive database that can be expanded by anyone with further experimental and numerical results. Maybe, some day the results can be projected to full-scale trains, at least with respect to differences caused by different details rather than for absolute drag values.

In addition to the potentially higher Reynolds number, the 3-m LSWT of the VZLU in Prague offers the possibility of carrying out crosswind tests with the KMF-Regio model in accordance with the EN certification standard [1]. Here, the drag coefficient is of minor interest but the moment acting on the lee-side wheels, $C_{\mathrm{Mx\_lee}}$, becomes the focus of interest, since this is the value which determines the overturning risk when a train drives in strong crosswinds. The generic KMF-Regio model is well suited to investigate the influence of different train parts on the forces and moments acting on the train when it is subject to crosswind. Based on the already mentioned EN standard, yaw angle sweeps with the model mounted on "Single Track Ballast and Rail" (STBR) on top of a splitter plate from $\beta = 0°$ to $\beta = \pm 90°$ have been performed for various configurations of KMF-Regio. The results of crosswind testing for the configurations 01 (completely smooth model) and 10 (reference roof setup, see Figure 11) are presented in Figure 13.

Since the leading end car is crucial for a potential train derailment, only the values for the front car, CarA, are shown here. The smooth configuration 01 exhibits a very steady curve in all coefficients compared to the model with roof boxes, while the curves for the configuration with roof structures show some jumps for $\beta > 60°$. This is likely due to the phenomenon of flow separation at the edges of the relatively simple geometry of the roof boxes. However, it does reflect the behaviour of realistic models during homologation measurements.

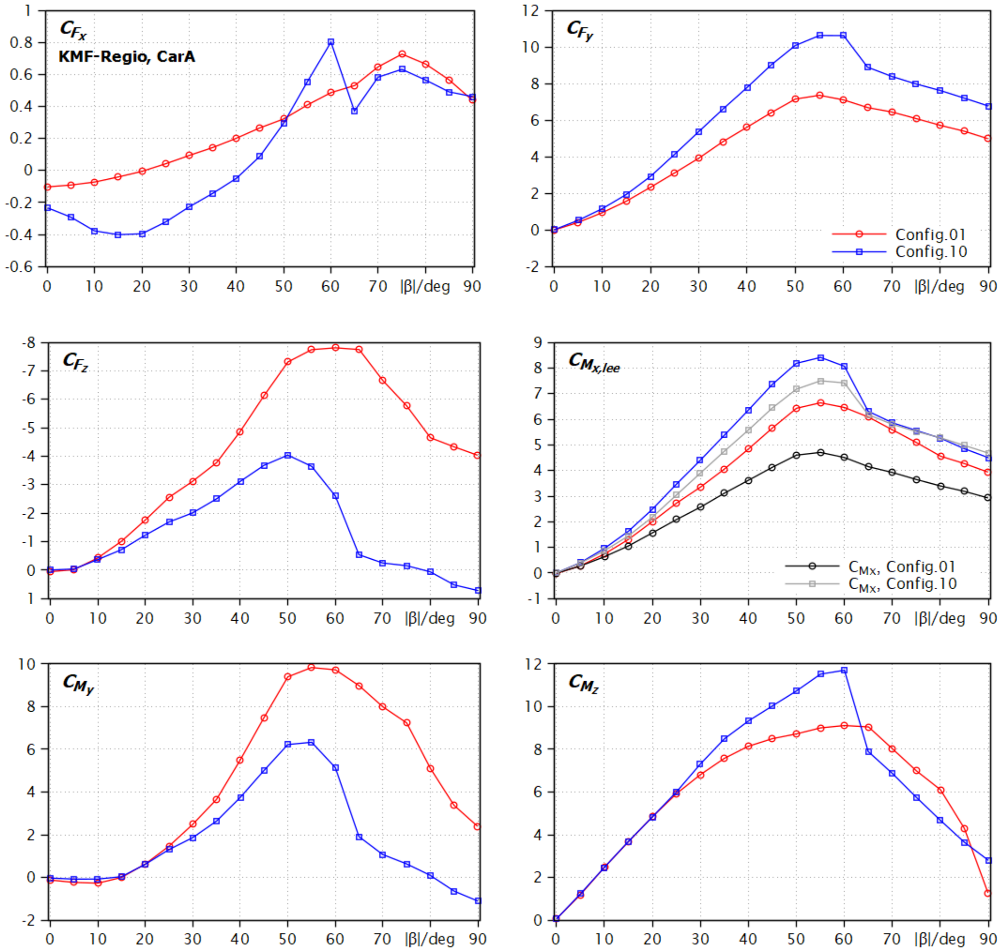

Figure 13: Coefficients of forces and moments for KMF-Regio at Re = 600,000. Smooth configuration (red curves) compared to the setup with reference roof boxes (blue curves). Grey curves in the $C_{\mathrm{Mx\_lee}}$ diagram denote the pure moments C_{Mx} and red/blue curves the $C_{\mathrm{Mx\_lee}}$ values

Very noticeable, though expected, is the large contribution of the lift coefficient, C_{Fz}, for the smooth configuration 01. This leads to the results, that the differences in $C_{\mathrm{Mx\_lee}}$ become smaller than the differences in C_{Mx} only. It would be interesting to see how the single components of the train structure (realistic heads with snow plow and coupler, open inter-car gaps, realistic bogies) will contribute to the different coefficients in crosswind-testing, in addition to their share of the aerodynamic drag. Furthermore, the influence of a certain packing of roof structures and the use of fairings on the roof's edges would be interesting to address. As already mentioned, this is work in progress and results will be presented in the near future.

4 Concluding remarks

The design of a generic train model as presented here has proven useful in initial wind tunnel tests to investigate the influence of different components on the aerodynamic drag and the forces and moments in crosswind measurements. Its modular design enables quick changes on the train's shape and grade of realism. Numerical simulations are work in progress and comparison to experimental results will be done in the future, as well as the provision of further experimental data. The given two, 3D printed wind tunnel models allow for comparison of different ground simulations and specifically the allocation of the contributions of the individual cars to the aerodynamic drag of the entire train assembly.

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