

Numerical Comparison of Rolling Road Systems

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ABSTRACT

The entire automotive industry is moving towards lower CO₂ emissions and higher energy efficiency. Especially for higher driving speeds this can be achieved by minimizing aerodynamic drag. Additionally, aerodynamic downforce is essential to maintain or even improve the handling performance of a vehicle. In order to optimize the vehicle's aerodynamic efficiency in wind tunnel tests, the boundary conditions of a vehicle driving on a road must be simulated properly. Particularly for optimizing the underbody region of a vehicle, ground simulation is an important issue in every wind tunnel. Today rolling road systems featuring one or more moving belts on the wind tunnel floor are a standard tool to simulate the complex boundary condition of a vehicle driving on the road. But generally the technical effort to measure aerodynamic forces accurately increases with improvement of the aerodynamic ground simulation.

This paper presents an attempt to evaluate the influence of different rolling road systems. The use of CFD makes it possible to investigate their influence on different types of vehicles excluding wind tunnel interference effects and independent of force measurement techniques. A numerical study with a standard passenger car and generic racing cars is presented. This study includes rolling road systems like a 5-belt, a T-belt and a single belt system as well as a new 3-belt rolling road layout.

An investigation of surface pressures, force development graphs and integral values is shown to analyze the influences of different rolling road systems. It can be concluded that, particularly concerning aerodynamic developments for the vehicle underbody, single belt systems or at least multiple partial belt systems of similar dimensions are essential to

guarantee an optimal and reliable ground simulation in automotive wind tunnels.

INTRODUCTION

In automotive wind tunnels the use of endless moving belts has become standard practice to represent the ground boundary condition of a vehicle driving on the road. Such a system can consist of just one wide moving belt - the so-called single belt system - like it is mainly done in racing car development. Or it can be made up of multiple partial belts like it is realized in most of the wind tunnels used for aerodynamic development of passenger cars where mechanical handling of the system is more important. All these systems can be summarized as Rolling Road Systems (RRS).

Nowadays it is well accepted that a stationary ground simulation is not adequate for racing car development, because a lot of aerodynamic downforce is produced in the underbody region of these cars. Large errors in drag and lift have been observed using a stationary ground simulation in wind tunnels [1, 2]. But even for passenger cars, which have much greater ride heights and rough underbodies compared to racing cars, it has become more important to simulate the relative motion between the floor and the vehicle underbody more reliably. Particularly the improvement of the cooling system efficiency, which is largely affected by the ground simulation technique [3] as well as smoother underbodies have forced a better ground simulation in wind tunnel testing to enable lower drag values and enhance the aerodynamic efficiency.

Aerodynamic efficiency is a governing factor to realize lower CO₂ emissions and higher energy efficiency of passenger cars, especially with higher driving speeds. To improve the aerodynamic efficiency of a vehicle it is essential to have a

reliable ground simulation in the wind tunnel. Otherwise aerodynamic improvements could be misinterpreted and lead to undesirable aerodynamic developments.

This paper shows results of a comparative numerical study of different RRS, in order to gain a better understanding of their influences on vehicles in wind tunnel testing. The use of Computational Fluid Dynamics (CFD) to study rolling road effects has already been described in previous studies [e.g. 4, 5, 6]. The investigation of different RRS using CFD is significantly cheaper and easier than an experimental study and it offers the possibility to simulate also extraordinary concepts in an easy manner. All simulations were performed with Exa PowerFLOW. The inherently transient nature of the underlying Lattice-Boltzmann Algorithm makes it capable to capture most turbulent effects created at the transition from moving to non-moving boundary conditions.

ROLLING ROAD SYSTEMS

The variety of different rolling road systems implemented in automotive wind tunnels is limited, because of the high technical effort linked to these systems. This chapter introduces the common rolling road concepts and summarizes the benefits and problems associated with these systems.

For racing car development mainly single belt systems (see Fig. 1) are used. Such a belt is several times wider and longer than the vehicle providing an ideal underbody flow simulation. For these systems usually compromises have to be made concerning absolute accuracy of force measurements. But racing teams generally set a high value on data repeatability whereas absolute accuracy of the measured values is of less importance because aerodynamic development is done by evaluating incremental force changes [7].

Although a single belt system represents an almost optimal aerodynamic ground simulation, significant practical problems are linked to that approach. Either major modification to the vehicle is required to cope with the force closure between the wheels and the moving belt, or a sophisticated vertical force measurement technique through the moving belt has to be applied. Former can be realized by detaching the wheels from the chassis and run on separate outriggers. This option removes the lift on the wheels from the balance measurements. The model itself has to be mounted on an overhead or rear sting that can produce significant interference errors [1]. The latter option is to measure the vertical forces from tire contact patches through the moving belt. Absolute accuracy of these measurements has not been validated in detail so far. Longitudinal and lateral aerodynamic forces can either be measured via instrumented restraints or the whole rolling road can be mounted on a force measurement platform so that aerodynamic forces are measured without being influenced

by the tire rolling resistance. Details to that approach can be found in [7], [8] and [9].

The development of passenger cars entails different requirements for wind tunnel testing. Generally a wide variety of vehicles are tested with frequent vehicle changes, which necessitates a higher absolute accuracy of force measurements. Furthermore, vehicle owners are often reluctant to modify vehicle structure for wind tunnel testing.

Passenger car developers generally use external balances located under the wind tunnel floor and vertical struts connected to the vehicle. These struts limit the width of the moving belt resulting in a narrow centerbelt that runs beneath the vehicle, just between the wheels. The wheel rotation is provided either by separate small moving belts (wheel drive units) or by rollers. In both cases the wheel drive units (WDUs) or rollers as well as the restraint struts are part of the balance. The main advantages of such a so-called 5-belt system (see Fig. 1) are the good accuracy and repeatability of force measurements, the possibility of changing the attitude of the vehicle very easily by acting on the support struts and - as stated above - a minimum of required changes to the vehicle. But this approach is posing problems concerning maintenance, as the RRS must be lifted above the test section floor to allow maintenance procedures [9, 10]. Furthermore, the 5-belt system only acts under the central zone of the vehicle, which leads to a reduced quality of aerodynamic ground simulation. And, additionally, the technical effort rises significantly with more (partial) moving belts complicating the RRS.

Another system already in use in full scale automotive wind tunnel testing is the so-called T-belt system (see Fig. 1) by Pininfarina [11], which can be regarded as a further development of the commonly used 5-belt system. The T-belt concept features two additional belts in front of the upstream wheel drive units which contribute to a better aerodynamic ground simulation at the vehicle front. A disadvantage of this RRS is the even more complicated partial belt system featuring seven moving belts.

Further rolling road concepts are conceivable, e.g. a 9-belt or 11-belt system extending the traditional 5-belt system even more. The suitability of those systems is doubtful, as technical requirements and also costs for acquisition and maintenance increase rapidly with more partial moving belts.

The prospective IVK/FKFS approach to meet the abovementioned requirements of an adequate aerodynamic ground simulation is an interchangeable 3-/5-belt system. A conventional and established 5-belt system is supplemented by a new RRS layout with three moving belts (see Fig. 1). This system consists of a narrow centerbelt, which is not part of the external force balance, and two side belts which are coupled to the balance to measure longitudinal and lateral

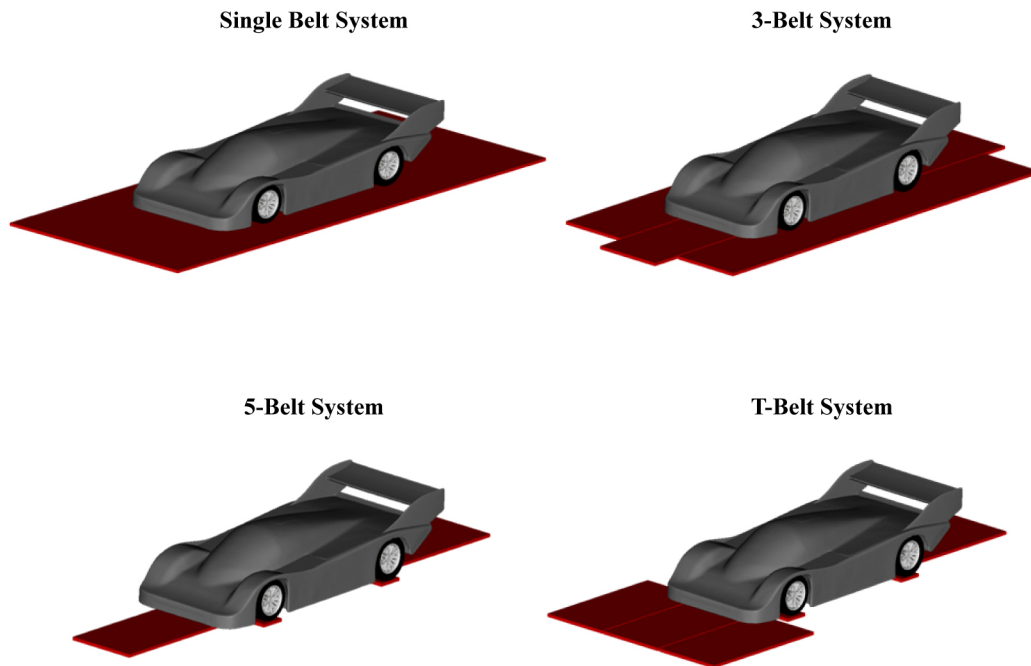


Figure 1. Investigated Rolling Road Systems (pictured with the LMP racing car)

aerodynamic forces without being influenced by the tire rolling resistance. Vertical force measurements are provided from tire contact patches through the moving belt. The centerbelt is also included in the common 5-belt layout. Compared to a single belt system the 3-belt RRS has substantial advantages concerning practical handling and maintenance.

Lots of different rolling road layouts have been investigated in this numerical study, but for reasons of clarity only the commonly used RRS will be presented in this paper. This includes the single belt system as well as the 3-, 5- and T-belt system.

COMPUTATIONAL PROCEDURE

All CFD simulations were performed using Exa PowerFLOW based on the Lattice-Boltzmann method [12]. PowerFLOW is widely applied in the automotive industry and a variety of validation reports is available [e.g. 13, 14]. It features an automatic discretization of the simulated fluid volume, which leads to a reduced overall setup time. For high Reynolds numbers, a wall-model is used to simulate the boundary layer. Due to the transient nature of PowerFLOW, a Very Large Eddy Turbulence Model is used to calculate the effects of the generated turbulence [15]. The lattice in PowerFLOW is composed of three-dimensional cubic cells (voxels) as well as surface elements that occur where the surface of a body intersects the fluid (surfels).

Each RRS was simulated using the same CFD setup and the same digital vehicle models. A typical CFD setup was

chosen, setting the boundary conditions far enough away from the model position to have little influence on the flow around the model. This approach is referred to as the PowerFLOW Digital Wind Tunnel (DWT) [16]. A comparison between interference corrected experimental values (using the Mercker / Wiedemann correction method described in [17]) and DWT simulation results, which are also free of wind tunnel interference effects, has been published by Fischer et al. [16, 18].

The floor boundary condition was set to provide a development of the boundary layer to match an idealized boundary layer conditioning in front of the rolling road. This means, that the boundary layer thickness at the beginning of the RRS is zero. Friction was applied to the floor of the simulation volume in an area of 10 m length and 8 m width (see Fig. 2). The vehicle was centered on the rolling road systems, which all have a length of 8 m and are not exceeding 3.2 m width for the single belt and the 3-belt system. The centerbelt of the respective partial belt system is 1.1 m wide. For all moving belt surfaces a surface roughness of 0.05 mm (equivalent sand roughness) was applied.

PowerFLOW discretizes the entire volume using different levels of variable resolutions (VR). In the results shown here, the smallest voxels have an edge length of 2.5 mm. The VR schemes are the same for all cases and correspond to the common best practice applied in industrial CFD computations. The computational mesh, featuring approximately 70 million voxels and 10 million surfels for all simulations, is refined for boundary layer regions to resolve the flow close to the ground accurately. The wind velocity

was set to 140 kph. Wheel rotation was simulated using rotating wall boundary conditions and local rotating reference frames. This approach is correct for truly axisymmetric geometry like the full covered wheels of the Formula 3 model presented in this paper. For the other cases representing detailed wheel shapes, the transient effects from the motion of the wheel spokes are neglected. However, the utility of this approach is established through validation studies [4].

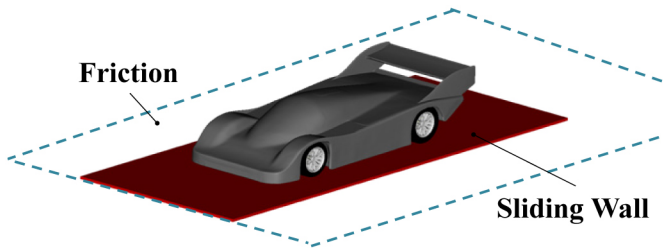


Figure 2. Friction area around the RRS

VEHICLE MODELS

Three different types of vehicles were used in the numerical study presented in this paper. A detailed model of a passenger car was simulated including a detailed underbody design but no underhood flow. Pictures of the passenger car model cannot be published in this paper. Generic models of a Formula 3 and a Le-Mans-Prototype (LMP) racing car were used to investigate the influence of different RRS on ground effect vehicles (Fig. 3).

All vehicle models were simulated without cooling air flow. The two generic racing car models are based on three-dimensional scan data of quarter-scale models. The geometry was simplified before discretization.

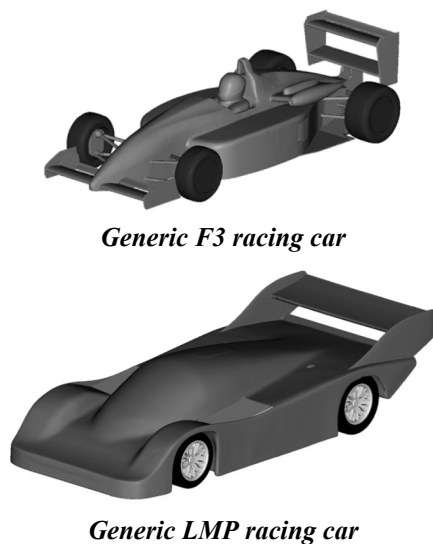


Figure 3. Digital vehicle models

COMPARISON

For reasons of clarity the results presented in this paper will focus on integral force coefficients, force development graphs and surface static pressure distributions on the vehicle underbody. For all simulations the respective full road simulation is used as a reference. In this case the complete floor of the simulation volume has a sliding wall boundary condition representing a moving ground which is approximately twenty times longer and wider than the vehicle. In addition to the presented RRS also simulations with only wheel drive units (WDUs) were carried out. For these cases a smooth stationary test section floor was simulated, but still wheels are rotating and the boundary layer is removed in front of the test section. Compared to the 5-belt system these simulations show the influence of the coated moving centerbelt.

PASSENGER CAR

In this section, results from different RRS simulations in the DWT are compared and discussed for the passenger car model. Figure 4 below shows a comparison of delta drag and delta lift values for the several RRS including the “only WDUs” case. Every case is referenced to the full road simulation ($\Delta C_x = C_{x,RRS} - C_{x,Full\ Road}$).

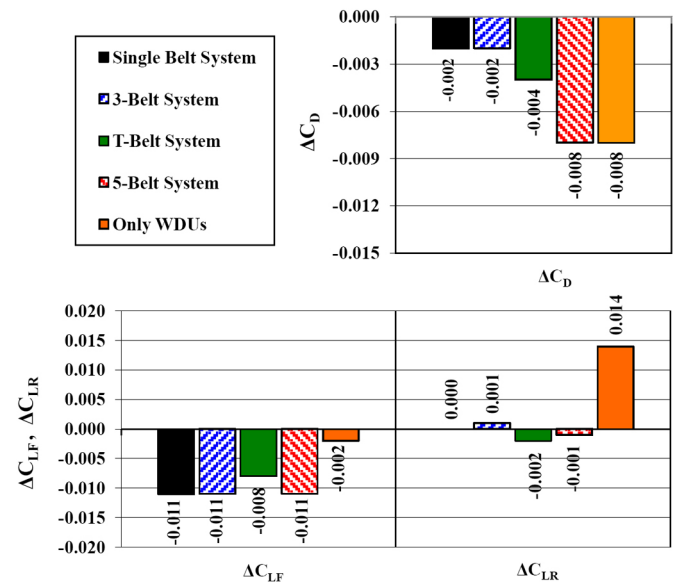


Figure 4. Delta drag and lift values of the passenger car model (referenced to the full road simulation)

As shown in Fig. 4, the difference in drag for all rolling road systems is in a range up to 8 drag counts (2.8 %). The single belt and the 3-belt system have similar force values and only deviate two drag counts from the full road simulation. The 5-belt and the T-belt system show larger deltas in drag compared to the full road case (8 and 4 drag counts, respectively). The simulation with only WDUs shows no