THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

IN

MACHINE AND VEHICLE SYSTEMS

Investigation of Aerodynamic Resistance of Rotating Wheels on Passenger Cars

by

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Gothenburg, Sweden, 2013

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A L E X E Y   V D O V I N

THESIS FOR LICENTIATE OF ENGINEERING no 2013:13
ISSN 1652-8565

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Printed by Chalmers Reproservice
Göteborg, Sweden 2013

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Abstract

With the current conditions of rising fuel prices and the toughening of environmental legislation for CO_2 and other emission gases, vehicle manufacturers around the world are looking into the ways to make their vehicles more energy efficient and therefore more environmentally friendly. One of the ways to achieve this goal is to improve aerodynamic design of vehicles in order to decrease aerodynamic resistance forces. These forces are especially important for any vehicles capable of 50km/hour and higher, and that is basically any passenger or commercial vehicle.

In this thesis the focus is on passenger vehicle aerodynamics and more specifically on the area of the wheels and wheelhouses. There have been a number of studies of the aerodynamic performance of this area, which have shown that wheels and wheel-housing flows generate a significant part of the aerodynamic drag on a passenger car and can relate to as much as 25% of it. The studies also show the relative importance of tyre and rim design in having better aerodynamic characteristics.

Usually when speaking about aerodynamic resistance of vehicles one thinks about the aerodynamic drag force. Certainly it is the largest contribution to the overall resistance that the vehicle has to overcome when moving; but it is not the only contribution. The resistance moment acting on the wheels rotating in the air, commonly referred as ventilation resistance, plays an important role as well. This moment is not as easy to measure in a standard aerodynamic wind-tunnel as aerodynamic drag force, and therefore it is usually left unaccounted for.

In this thesis a closer look at ventilation resistance is taken, and different effects contributing to this resistance moment are discussed. In order to be able to measure ventilation resistance various modifications to a normal wind-tunnel set-up are presented.

The results and analysis of one of the studies investigating ventilation resistance, and its dependency on rim design, are also given in this thesis. It is shown that ventilation resistance has a significant effect on total aerodynamic performance and it should be taken into account when designing a vehicle.

Keywords: Wheel forces, wheel aerodynamics, ventilation resistance, aerodynamic moment, rim design

Acknowledgements

This work would not have been possible without the support from a large group of people.

First of all I would like to thank my supervisor and examiner Professor Lennart Löfdahl for his contributions and for giving me a great opportunity to work at Chalmers University of Technology with such an interesting topic as Road Vehicle Aerodynamics. Thank you to my co-supervisor Dr. Simone Sebben from Volvo Car Corporation for guidance, discussions and feedback during the project.

I would also like to express my gratitude to Tim Walker, and other engineers at external aerodynamics department at Volvo Car Corporation for a wonderful atmosphere and productive discussions. Special thanks go to my friend and former colleague Dr. Christoffer Landström whose expertise in the area of rotating wheels made a significant contribution to the project.

I would like to acknowledge some former and current Ph.D. students in the vehicle aerodynamics group: Dr. David Söderblom, Dr. Peter Gullberg, Dr. Lasse Christoffersen, Jesper Marklund, Lisa Larsson, Helena Martini and Lennert Sterken for supporting me and for all numerous discussions we had. Thanks to Teddy Hobeika, Johan Zaya and my other colleagues at Applied Mechanics department of Chalmers University of Technology.

I would especially like to thank Andrew Dawkes for sharing his great expertise in the area of vehicle design and proof-reading the manuscript of this thesis.

Furthermore, I am really grateful to the Swedish Energy Agency for funding this project.

Lastly, but by no means least, I would like to thank my dear family and friends for their constant support and encouraging during my studies at Chalmers.

Göteborg, 2013
Alexey Vdovin

List of papers

This thesis contains the following papers:

- Vdovin A., Löfdahl L., Landström, C., "Aerodynamic Wheel Force Measurements on a Detailed Scale-Model Car – Possibilities and Challenges", 8th International Symposium on Strain-Gauge Balances, 7-10 May, Lucerne, Switzerland, 2012;

- Vdovin, A., Bonitz, S., Landstrom, C. and Lofdahl, L., "Investigation of Wheel Ventilation-Drag using a Modular Wheel Design Concept", SAE Int. J. Passeng. Cars - Mech. Syst. 6(1):2013, doi: 10.4271/2013-01-0953.

Nomenclature

Symbols

A	Projected front area	[m^2]
C_D	Drag coefficient	[-]
$C_{D(vent)}$	Ventilation drag coefficient	[-]
C_L	Lift coefficient	[-]
C_p	Pressure coefficient	[-]
C_{vent}	Ventilation resistance coefficient	[m^3/s]
f_r	Rolling resistance coefficient	[-]
g	Gravitational acceleration	[m/s^2]
F_a	Acceleration force	[N]
F_{drag}	Aerodynamic drag force	[N]
F_D	Aerodynamic drag force	[N]
F_G	Driving force due to gravity	[N]
$f_{inertia}$	Distributed inertial forces due to rotation of the masses	[N/m^3]
F_{lift}	Aerodynamic lift force	[N]
F_R	Rolling resistance force	[N]
F_{trac}	Traction force	[N]
F'_{trac}	Part of the traction force, responsible for ventilation resistance	[N]
F_{vent}	Equivalent ventilation resistance force	[N]
F_x	Tractive force	[N]
F_{x_mech}	x-component of the equivalent mechanical force	[N]
F_{z_mech}	z-component of the equivalent mechanical force	[N]
m	Mass of vehicle	[kg]
$M_{inertia}$	Resistance moment due to inertia of the rotating parts	[Nm]
M_{y_mech}	Equivalent mechanical moment around y-axis	[Nm]
M_{rr}	Moment of rolling resistance	[Nm]
M_{vent}	Ventilation moment	[Nm]
N	Normal force in a contact patch	[N]
P_{vent}	Power required to overcome ventilation resistance	[W]
V	Absolute vehicle velocity	[m/s]
V_{rel}	Vehicle velocity relative to air	[m/s]
α	Road inclination	[deg]
γ	Coefficient including the inertia of rotating parts	[-]
ρ	Air density	[kg/m^3]
ω	Rotational velocity	[rad/s]

Abbreviations

CFD	Computational Fluid Dynamics
CoG	Centre of Gravity
FVM	Finite Volume Method

WDU	Wheel Drive Unit
SLS	Selective Laser Sintering

Table of Contents

1. Introduction

Nowadays it is hard to imagine our lives without convenient ways of transportation that include both public and personal vehicles. As the human population grows the number of passenger vehicles increases as well. In Figure 1 one can see the global production of passenger vehicles increasing from year to year. There was an obvious drop in production in 2008-2009 due to economic crisis, but since 2010 production continued to grow every year.

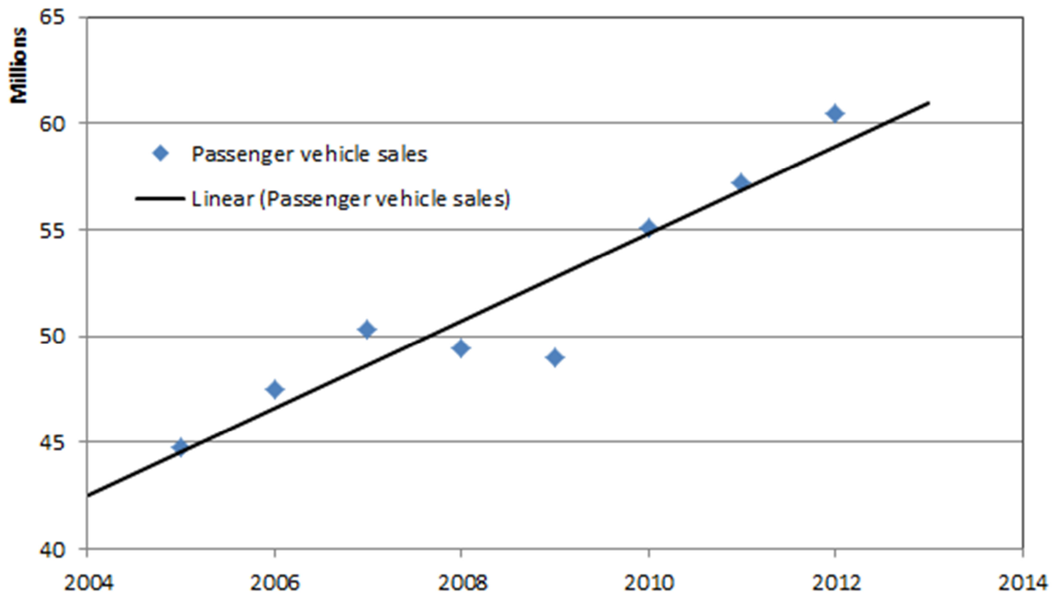

Figure 1. World passenger vehicle production in millions [1]

Having so many new vehicles produced it is hard to ignore environmental issues associated with road-vehicle transportation. As a result of the combustion process traditional passenger vehicles produce emissions and most importantly carbon dioxide (CO_2), which is an important greenhouse gas. It is considered to be responsible for anthropogenic climate change in terms of causing global warming. Even though road transportation is only accountable for 15.9% of man-made CO_2 emissions [2], there is a huge pressure on vehicle manufacturers to produce more environmentally-friendly cars.

European Union legislation from 2009 sets targets for fleet average CO_2 emissions per kilometre for every manufacturer. Thus, by 2015 only 130 grams of CO_2 per kilometre should be produced by an average vehicle [3]. The target value for 2020 is 95g/km. These are fleet average values meaning that heavier cars are allowed to have higher emissions than lighter cars, but an overall average should not exceed the limit being set. The manufacture, who is failing to meet the goals, will have to pay a fee for each car registered. The European Union is not unique in its campaign for lower emissions: USA, China, India, Japan and other countries worldwide are also promoting similar regulations.

Since it is obvious that vehicle emissions have to be reduced, automotive manufacturers are looking for ways to achieve this goal. One of them is decreasing fuel consumption; this is especially interesting if one also takes growing fuel prices into consideration.

In Figure 2 oil price development for the last 20 years is shown. As it can be observed prices are growing, there was a significant drop in 2008-2009 due to previously mentioned economic crisis but now the world is recovering and oil is becoming more expensive every year. This means that by making a vehicle with lower fuel consumption one can not only reduce emissions but also make it more attractive for the final customer in terms of money spent on fuel.

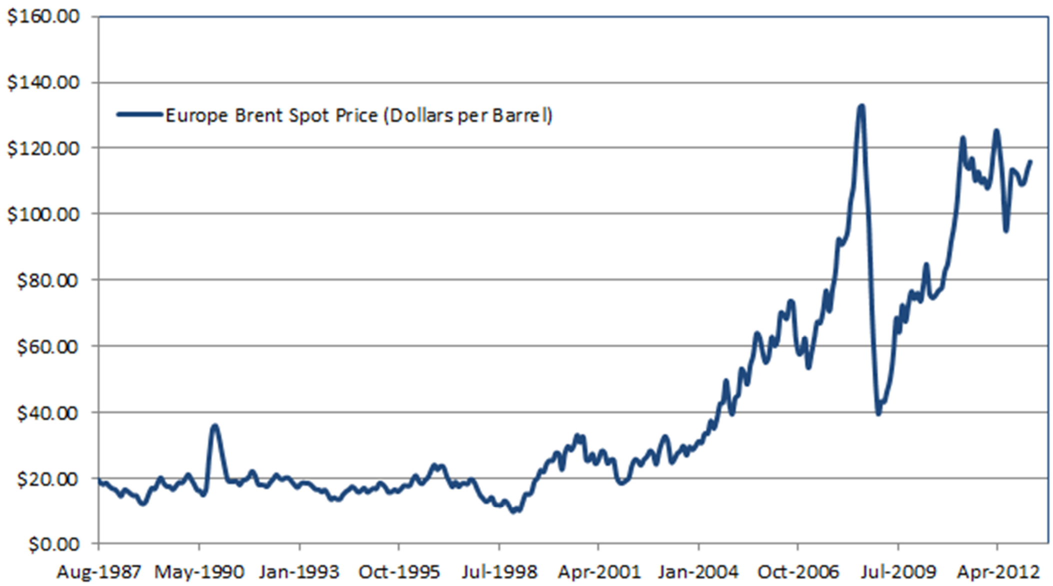

Figure 2. Oil prices in development in US dollars per barrel [4]

1.1. Project background

Since environmental legislation is getting stricter and fuel prices are growing there is a demand from both governmental institutions and customers to reduce the fuel consumption of passenger vehicles. There are numerous ways to achieve this goal: introduction of better tyres with lower rolling resistance; improving drivetrain by minimizing losses in different systems; introducing supplementary electrical motors with batteries, allowing part of the journey to be driven using electrical power stored; etc. But one of the most effective ways to reduce the fuel consumption is by improving aerodynamic properties of the vehicle. It is especially important in the case of highway driving since aerodynamic resistance is a quadratic function of vehicle speed. A vehicle with better aerodynamic properties will not only consume less fuel, it will also have better acceleration capabilities, higher maximum speed and increased driving range, which is especially important for hybrid and completely electrical vehicles.

Designers and aerodynamicists are working hard finding compromises to achieve both good looking and aerodynamically efficient shapes. A lot of work has already been done to the upper body of the vehicles, but there are other areas that can be interesting to be investigated. In Figure 3 one can see the approximate percentage of aerodynamic losses associated with parts of the car [5].

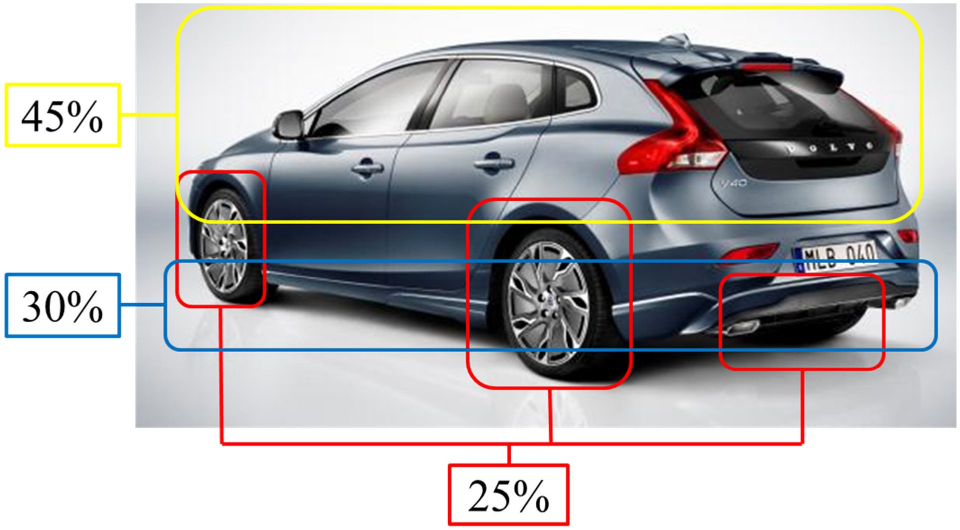

Figure 3. Contributions to the aerodynamic drag from different parts of a passenger car

As one can see less than 50% of aerodynamic drag force is generated by the upper body [5]. Wheels and wheel-houses can generate up to one quarter of the total drag [6], [7]. Since the underbody and wheel-houses together are responsible for the largest part of the aerodynamic drag force these areas are considered to great potential for improvement. Aerodynamic engineers work hard to understand the phenomena associated with the areas in question and vehicles in general. For example a lot of automotive wind-tunnels have been updated with different kinds of ground simulation techniques in order to properly represent real road conditions [8], [9]; and growing computer power has allowed computational fluid dynamics (CFD) engineers to create much more complicated and detailed models to test in a simulated environment.

The increasing complexity of models allows engineers to more thoroughly investigate different aspects associated with airflow around the vehicle, for example, engine-bay air flow and its interaction with underbody flow or flow control by vortex generators.

1.2. Project goals

The main goal of the project is to find a way to reduce fuel consumption of passenger vehicles by reducing the aerodynamic contribution to resistance forces. The main area of interest is wheel and wheel-house aerodynamics and its interaction with underbody and cooling flow.

Traditionally the resistance effects, counteracting vehicle propulsion force, due to air environment are only viewed from the perspective of aerodynamic drag force. For a typical medium-sized European passenger vehicle, with highway speeds above 60-70 km/hour, and assuming level roads, this force dominates all other forces [5], see Figure 4.

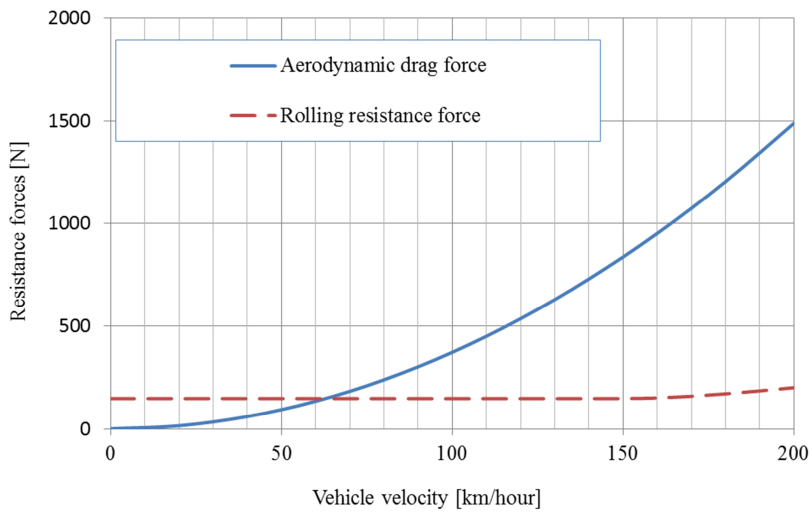

Figure 4. Aerodynamic drag force and rolling resistance force versus vehicle velocity for a typical passenger vehicle

As will be shown later, there are also other effects, originating from the interaction of vehicle parts with the air, which should be taken into account if one wants to achieve a deeper understanding of passenger-vehicle aerodynamics and improve simulation models that are currently being used. One of the effects, investigated in this project, is the ventilation resistance moment acting on rotating wheels.

To begin with, ventilation resistance is defined and discussed. Since it is not easy to measure this resistance, different problems associated with this process are highlighted. Later, a study at Volvo Car Corporation wind-tunnel is presented and the results are analysed and discussed.

2. Passenger vehicle aerodynamics

As already discussed, aerodynamic forces have an important role for passenger cars, and even though their effects on vehicle performance (maximum speed and acceleration) and emissions are probably most vital, it is important to remember other aspects related to air flow around the vehicle.

Firstly, mention should be made of cooling and thermal management; since there are numerous components that require temperature management within strict criteria, for example engine, transmission, brakes, condenser and, in the case of hybrid and electrical vehicles, battery packs. This is usually achieved by directing some of the air through the areas specified, where the excessive heat is removed by thermal conduction and convection.

Another important area to consider is cabin/occupant comfort. This includes: ventilation of the passenger compartment, which may also require air conditioning; and wind noise, especially from rear view mirrors, that may be quite disturbing for the driver and passengers.

Aerodynamics has a significant effect on the vehicle stability on the road: lift- or downforce can considerably change the available traction or grip forces, thereby affecting handling of the car. Moreover side-winds and especially sudden gusts may introduce additional forces that the driver should compensate for.

Mention should also be made regarding visibility and contamination aspects. On roads the air is never clean; it contains dust and mud particles that tend to stick to different surfaces of the vehicle. In wet conditions it is also important to consider splash and spray that need be controlled.

2.1. *Driving resistance*

Driving resistance is the total resistance force acting on the vehicle when it is moving; usually this force is expressed using equation 1 [10]:

$$F_x = F_a + F_R + F_G + F_D = \gamma ma + f_R mg \cos\alpha + mg \sin\alpha + \frac{1}{2} C_D A \rho V_{rel}^2 \qquad (1)$$

The first term here, γma is vehicle mass multiplied by vehicle acceleration; it represents driver behaviour in terms of acceleration or deceleration. Coefficient γ is used to take into account the inertia of rotating parts, e.g. flywheel, shafts, gears etc. The second term is for the rolling resistance, as can be seen it is proportional to the normal force between the tyres and the road (α is an inclination angle of the road). $f_R$is a coefficient of rolling resistance which depends on wheel and road properties, and some other factors. Quite often it is assumed to be constant for simplicity reasons. The third term here characterizes the part of gravitational force that acts on a vehicle when going uphill or downhill. The last term in the equation is usually denoted as aerodynamic drag force or simply aerodynamic drag.

As can be seen from equation 1, aerodynamic drag force is proportional to air density ρ and the square of velocity V_{rel}, it is a relative velocity between the vehicle and the air. Another component of the equation is reference area A, which is the projected frontal area of the vehicle. The last term here C_D is an aerodynamic drag coefficient of the vehicle. It is a dimensionless factor that mainly depends on the general shape of the vehicle and can vary from 0.5 – 1 for older vehicles down to values around 0.18 – 0.24 for modern concept vehicles [11], [12]. Often when comparing two vehicles a product of frontal area and drag coefficient ($C_D A$) is used. It is sometimes referred to as drag factor and it allows comparison of aerodynamic characteristics of vehicles of different sizes and shapes.

2.2. Aerodynamic drag of passenger cars

When talking about the aerodynamic drag of vehicles it is important to mention two components of this force: pressure and viscous drag.

Pressure drag originates from the fact that the static pressure around the vehicle varies to a considerable extent, see Figure 5 for a pressure-coefficient plot, at the symmetry plane, of a simplified passenger vehicle obtained via CFD simulation.

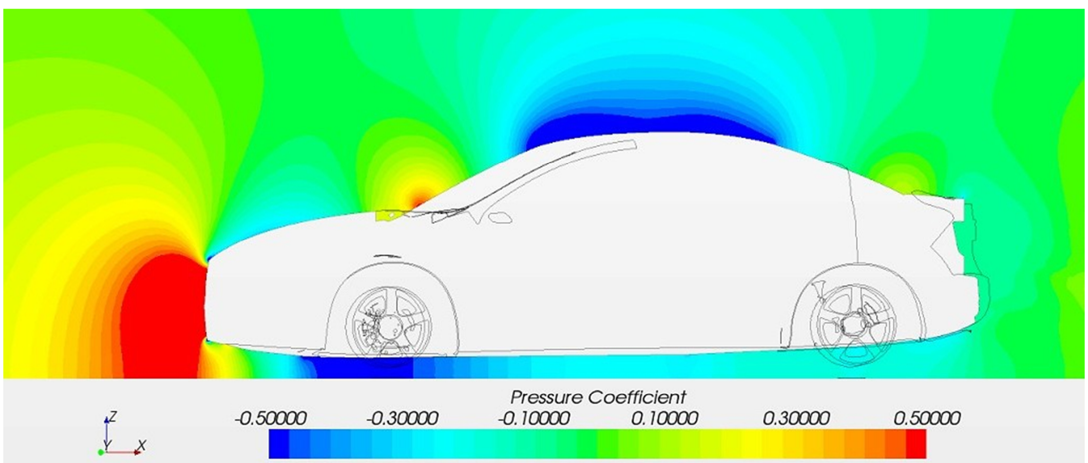

Figure 5. Pressure coefficient at the symmetry plane of the vehicle

One can see that in front of the vehicle there is an area of high pressure, usually referred to as the stagnation region. On the other hand at the rear the pressure is not as high. This difference gives net force acting against the movement of the car, this force is called pressure drag.

The second source of aerodynamic drag is generated by viscous surface friction between the air and the vehicle. This friction results in shear forces acting parallel to vehicle surfaces. The drag associated with these forces is usually called viscous or friction drag.

For a typical passenger vehicle pressure drag dominates over viscous drag, but as vehicles become more and more streamlined the relative importance of viscous drag is increasing [5], [10].

2.3. Wheel and wheelhouse aerodynamics

Wheels are essential parts of any passenger vehicle, but due to limitations in simulation techniques the importance of the wheels has not been studied for quite a long time. There have been a number of early studies investigating wheel wake and the effects of rotation on drag and lift coefficient [13], [14]. Even though these studies were very important for understanding the airflow around the wheel, the results were hard to apply to real life cases, since the wheels were studied in isolation and all the tests were conducted using scale models. With the advances in wind-tunnel equipment more thorough investigations have become possible [6], [15], [16].

The realisation of the importance of proper road simulation and rotation of the wheels has led to general improvements for automotive wind-tunnels, and to the fact that nowadays more and more wind tunnels are equipped with different moving-ground systems with proper boundary-layer treatment. It has been shown that introducing of such systems increased the complexity of the airflow, especially in the area of wheelhouses, and has led to the reduction of overall drag force compared to a stationary case [17]. It has also lead to increased complexity of measurement procedures since there are forces generated between the tyre and moving belt which must be subtracted in order to obtain correct values for drag and lift forces.

It should also be mentioned that with the increased complexity of the equipment and better understanding of the flow field around the wheel, there has been a shift to more complex models for evaluating the aerodynamic performance of vehicles. One of the methods is to take aerodynamic resistance moment into consideration. This phenomenon is sometimes referred to in literature as pumping losses, aerodynamic resistance torque or ventilation resistance [6], [18], [19].

2.4. Different methods for assessing aerodynamics on passenger cars

In this thesis the main focus is on the experimental measurements of different forces, but before discussing wind tunnel set-ups, it is useful to briefly describe other methods available to aerodynamic engineers when investigating aerodynamic performance of different parts and passenger vehicles, in general.

2.4.1 Computational fluid dynamics

The first approach that is often used is CFD or Computational Fluid Dynamics. Here the governing equations for the flow in fluid dynamics: continuity, momentum and energy, are solved numerically using finite volume method (FVM); and the computational power offered by constantly evolving computers. In the beginning this method only allowed the solving of very simple cases; but with computer performance doubling every two years, according to Moore's law [20], the complexity of the models and cases grows all the time. Nowadays it is hard to imagine fluid dynamics without CFD tools.

2.4.2 Coast down tests

The second approach is probably the oldest since it does not require building any facilities or having computer clusters. This method involves driving the vehicle on a flat road, disengaging the clutch and simultaneously recording velocity and distance travelled, till the vehicle stops [21]. It is often called the coast-down test and has a number of limitations, e.g. compensating for the wind speed, separating rolling resistance from aerodynamic resistance, etc.

2.5. Wind tunnel tests

The third and the last method discussed here is wind-tunnel testing. Wind tunnels have been used by vehicle manufactures for many years. In the beginning aeronautical wind-tunnels with a ground plane to represent the road were used [22]. Later, the first dedicated automotive wind-tunnels were built [23]. These wind tunnels had a stationary ground, but as time passed the research reached the point when it was generally accepted that rotating wheels and advanced moving-ground simulation systems were absolutely necessary for proper simulation of the on-road conditions.

The idea of using a moving belt for simulating realistic boundary-conditions under the vehicle is not new [24], but it has evolved significantly with time. In this part different moving ground systems used in automotive wind-tunnels are discussed.

2.5.1 Single belt system

The first system to be discussed is a single belt, often referred to as a full-width system, see Figure 6. In this case there is one belt that moves under the vehicle. This belt is wider and longer than the model tested.

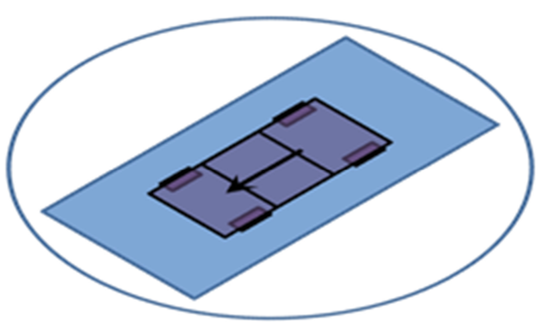

Figure 6. Single belt moving ground system

Together with a suction scoop and distributed suction zones, removing boundary-layer air before the belt, this system produces almost ideal underbody flow. This is one of the reasons this system is popular for racing car development. Another application of this set-up, due to its simplicity, is in scale-model wind tunnels [25].

One of the drawbacks of this system is that the vehicle has to be suspended by an overhead or rear sting, the force balance is usually located inside the model. The sting has to support the weight of the model, therefore depending on the model size it can be rather large, consequently producing some interference effects and affecting force measurements [26], [27]. Additionally it may be rather difficult to separate rolling resistance of the wheels from aerodynamic drag, since the wheels are in contact with the running belt. One of the ways to solve this problem is to use separate wheel struts, one to support each wheel, see Figure 7 for an example from Chalmers wind-tunnel.

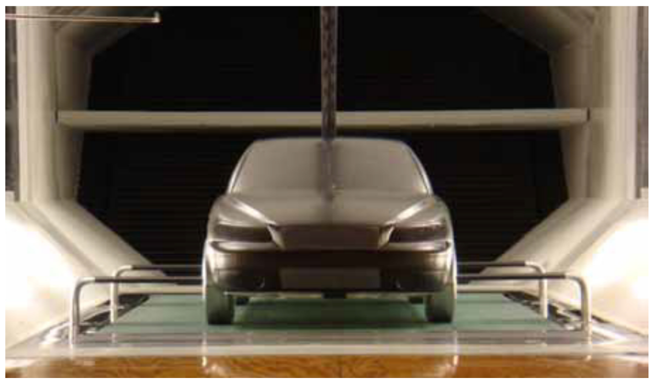

Figure 7. Single belt moving ground set-up in Chalmers wind tunnel

In this case the wheels are completely detached from the model, and aerodynamic force measurements for the vehicle body are no longer a problem. In order to measure forces acting on the rotating wheels, separate wheel balances may be used [28]. Interference effects of wheel struts must also be taken into account.

2.5.2 Five-belt system

Another popular moving-ground system is a five-belt one, see Figure 8 for a simplified view.

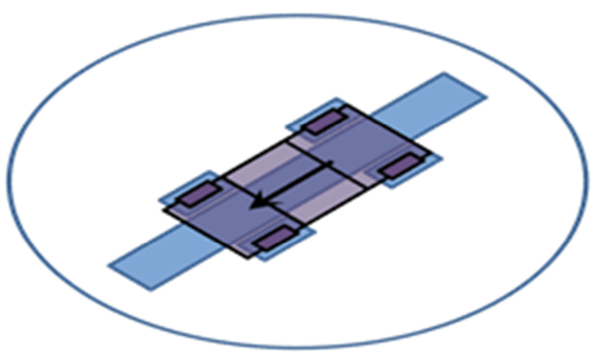

Figure 8. Five-belt moving ground set-up

This system and its variations, discussed later, are quite popular for full-size testing. Here the vehicle is supported by four struts located underneath, thus there is no need for an overhead sting. In order to enable wheel rotation, the wheels are positioned on small belts or rollers, usually referred to as wheel drive units or simply WDUs, an example from the Volvo wind-tunnel is shown in Figure 9. The WDUs and vehicle struts are all connected to the vehicle balance, located under the test section permitting direct measurement of aerodynamic-drag force without interference of rolling resistance.

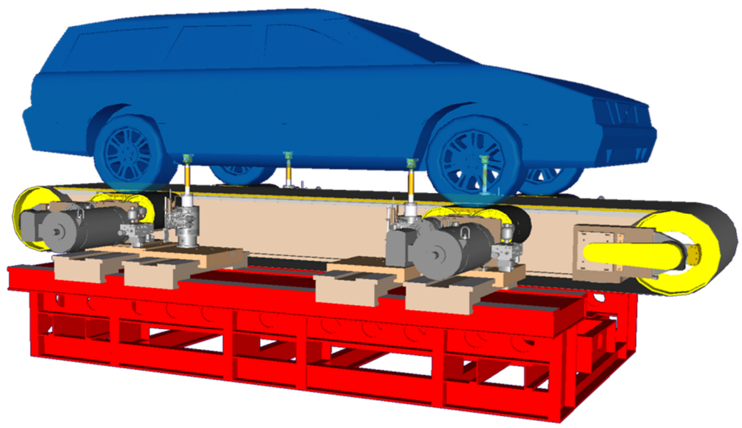

Figure 9. Five-belt moving ground system used in Volvo aerodynamic wind tunnel (courtesy of Volvo Car Corporation)

In order to simulate the moving ground there is a long centre-belt running under the vehicle. The drawback of this system is that due to the positioning of the vehicle struts the centre belt is limited in width and it does not cover the entire underbody; therefore altering the airflow in the region. In order to compensate for this, tangential blowing and distributed boundary-layer suction may be used [8]. It must also be remembered that the struts themselves can produce some interference effects on the force measurements.

2.5.3 Other moving ground systems

It is logical that covering a larger area with moving belts will increase the accuracy of the airflow representation under the vehicle; therefore a number of modifications to five-belt systems have been introduced during recent years. Two of them are presented here, Figure 10.

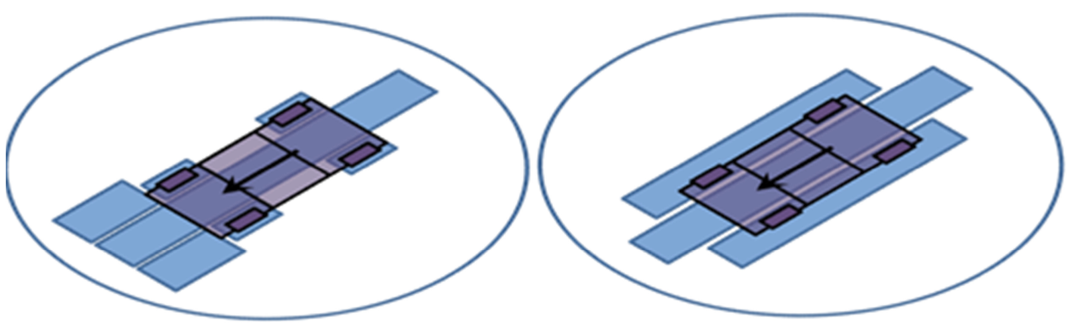

Figure 10. T-belt and three-belt moving ground systems

The left-hand example is called the T-belt system, having two additional belts in front of the vehicle [29]. There are also concepts using nine or even eleven belts [30].

The right-hand example in Figure 10 has a reduced number of belts in comparison with the five-belt system but has an increased area covered by the belts. In this case the vehicle is still supported by struts and WDUs are replaced by the additional long belts.

3. Forces acting on rotating wheels and ventilation resistance

A rotating wheel is a complex system and there are many forces and moments acting on it. In order to simplify matters, a 2-dimensional picture will be considered; moreover since forces have different application points and different directions most of the forces will be replaced by equivalent force and moments acting at the centre of gravity (CoG) of the wheel.

3.1. Forces classification

In dynamic situations when the wheel rotates, the forces can be divided into external and inertial components as shown in Figure 11.

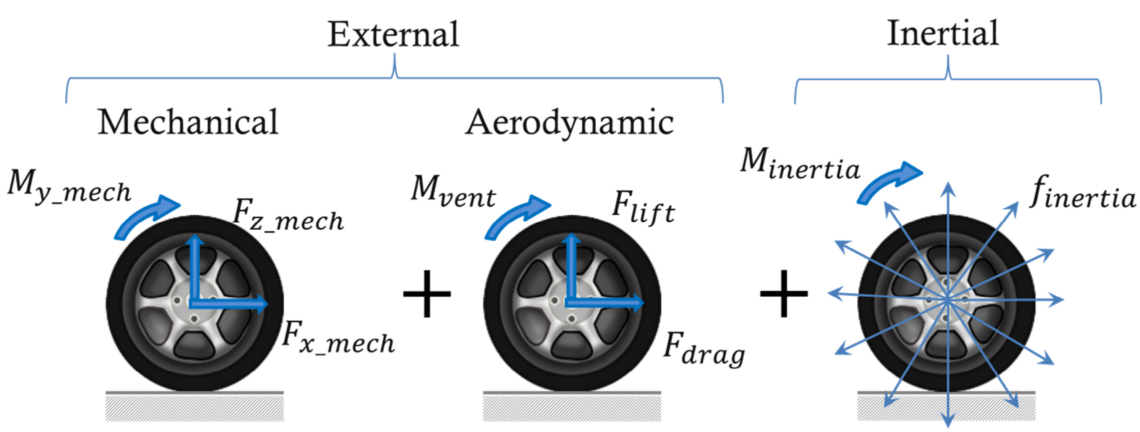

Figure 11. Forces acting on a rotating wheel

Inertial forces include: moment of inertia of the rotating wheel that only occurs when the rotational velocity is changing; and distributed inertial forces or centrifugal forces. The last tend to change the geometry of the tyre, as has previously been investigated [31]. In Figure 12 a simplified figure showing axial compression and radial expansion of the tyre is represented.

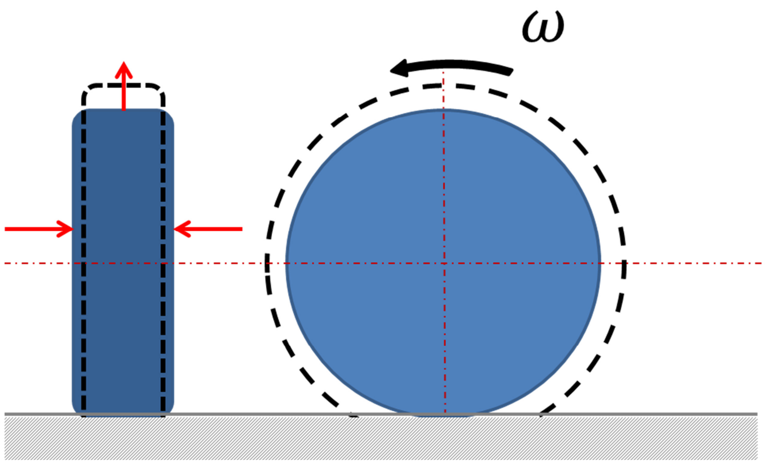

Figure 12. Deformations due to inertial forces

Depending on the load on the tyre, and tyre characteristics, axial compression may be as high as 6-8 mm from each side [32], leading to a significant change of the tyre geometry. Radial expansion can also be rather significant, up to same 6-8mm increase over the initially loaded wheel. This expansion will result in the axle of rotation of the wheel moving up inside the wheelhouse.

External forces can be divided into mechanical and aerodynamic components. Here, aerodynamic lift, drag and aerodynamic resistance moments originate from the fact that the wheel is rotating in moving air. The mechanical part includes all other elements.

One very important moment from the mechanical part, that must be mentioned separately, is rolling-resistance moment. It occurs due to an uneven pressure distribution in the contact patch when the wheel is rolling, see Figure 13. So, the equivalent normal force N is shifted slightly forward of the wheel centre; the moment $M_{rr} = N \cdot e$ is called rolling-resistance moment.

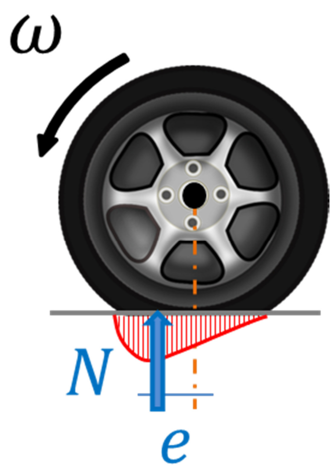

Figure 13. The origin of rolling resistance moment

3.2. Ventilation resistance

The aerodynamic component of a resistance moment M_{vent} , as already mentioned in chapter 2.3, is sometimes referred to as pumping losses, ventilation torque or ventilation resistance. In this thesis the last notation will be used, or sometimes it will be referred to as "ventilation moment" to avoid confusion with "aerodynamic drag" or "aerodynamic resistance", which is usually considered to be a force in the longitudinal direction.

3.2.1 Ventilation resistance origins

Ventilation resistance moment, similarly to aerodynamic drag force, see chapter 2.2, has two origins:

- Pressure component, produced by the non-uniform normal pressure distribution around the wheel;
- Viscous component, originating from the surface friction acting on different rotating parts.

In the case of the wheel, the rotating parts are: the tyre, the rim, and the brake disc; and therefore the ventilation moment acting on wheel is dependent on the shape and size of these components.

3.2.2 Ventilation resistance measurements

Measuring ventilation resistance in CFD is relatively easy. It can be done by simply selecting different parts of the wheel and integrating normal and tangential stresses over the surfaces, to calculate the ventilation moment around the axle of rotation.

In the case of wind-tunnel testing it is not that easy, because the mechanical components of forces and moments have to be separated from aerodynamic. Moreover, inertial, thermal and other changes must be taken into account.

Currently there are two documented methods describing ventilation-moment measurements in wind tunnels, both require changes to a standard wind-tunnel set-up. The first one uses a power approach, and involves changing the drivetrain of the vehicle to permit measurement of the power requirement to rotate the wheel [18]. The second, that is going to be discussed here in more detail, uses the approach studying forces, and involves measurement of traction force between the wheel and the wheel drive unit [33].

4. Experimental set-up

In this chapter an experimental set-up used to measure the ventilation resistance moment of wheels with different rims is briefly discussed. For more detailed descriptions see [33], [34].

4.1. The wind tunnel set-up

The Volvo wind-tunnel is equipped with a five-belt moving ground system with an advanced boundary layer treatment system. A general description, advantages and disadvantages of such a set-up were discussed in section 2.5.2; a more detailed description can be found in [8].

As it has been discussed, with such a set-up the wheels are rotated by wheel drive units, see Figure 14. In order to measure ventilation-resistance moment it was decided use load cells inside WDUs to measure the traction force produced in the contact patch of each wheel, and then isolate the part responsible for overcoming ventilation resistance. Knowing the force and the length of the lever arm, which in this case is the radius of deformed wheel, the ventilation moment can be calculated.

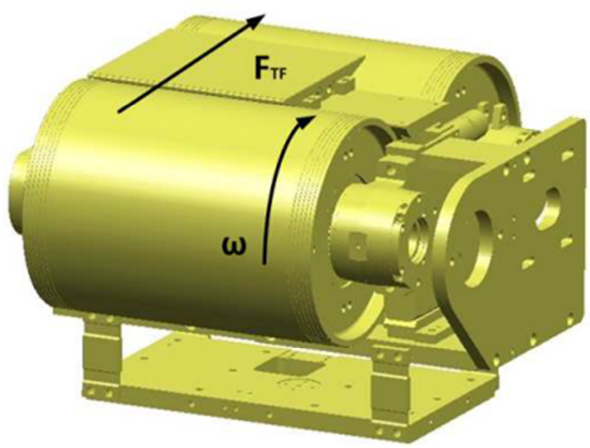

Figure 14. Wheel drive unit (courtesy of Volvo Car Corporation)

In a standard set-up, when only investigating aerodynamic drag and lift forces, traction force measurements are usually ignored. This is for two reasons: firstly, since both vehicle struts and wheel drive units are connected to the same balance, this force is internal and thereby has no effect on drag or lift forces acting on a vehicle; secondly, since the WDUs are rotating the wheels, the power supplied to it is used to overcome not only ventilation resistance, but all other resistances and losses associated with wheel and tyre rotation:

- Rolling resistance moment
- Inertial resistance moment
- Losses in bearings

- Losses in brakes
- Losses associated with drive-shaft and gearbox
- Losses due to slip in a contact patch of the wheel

Since the objective of this test was to measure ventilation resistance, all other resistance forces mentioned above must be either removed or measured. For this reason a modified wind-tunnel set-up is required.

To begin with, the drive-shafts were disconnected and the brake pads removed. The shock absorbers were removed and replaced with restraint posts with threaded rods, hence allowing a fixed wheel position inside the wheelhouse, see Figure 15.

Figure 15. Modified suspension [33]

After fixing the wheels inside wheelhouses the entire vehicle was lifted up using struts to have almost no contact between wheels and WDUs. This was done to minimise rolling resistance moment as much as possible, and at the same time maintaining the contact required to keep the wheels rotating.

4.2. Minimising losses

The initial rolling resistance moment was minimised and the part left was measured. Due to distributed inertial forces discussed in chapter 3.1, the tyre radius was changing with increase of rotational velocity, increasing the vertical load in the contact patch. In order to compensate for this change the vehicle ground clearance was altered to maintain constant and relatively low rolling resistance. Moreover, since the tyre deformation in the contact patch was negligible there were no temperature fluctuations for the tyre itself and of the air inside, therefore the tyre inflation pressure and rolling resistance coefficient could be considered constant [35].

The inertial resistance moment was considered to be zero, since all measurements were conducted at constant speed steps from 80 km/hour to 200 km/hour with a step increment of 20 km/hour.

Losses associated with brakes, drive-shaft and gearbox were considered to be zero since the brake pads were removed and shafts disconnected. Losses due to slip in the contact patch were also neglected since the contact patch area was small.

Lastly, resistance moment in bearings was estimated with a dynamometric screwdriver and considered to be constant [36].

4.3. Test objects

The set-up described was used to measure ventilation resistance of wheels with different rim designs. In order to ensure the same tyre characteristics and deformations, and to minimise other possible errors associated with changing of wheels during the test, a decision was made to use a set of previously developed modular wheels [37]. Each of the wheels was a five spoke, 17´´ aluminium rim, and a number of inter-changeable add-on parts manufactured using selective laser sintering (SLS) rapid prototyping was used, see Figure 16.

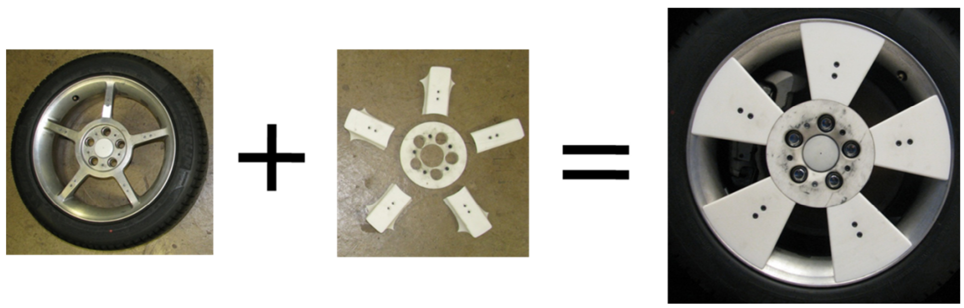

Figure 16. Modular wheel system

Since changing the rim configuration was possible without dismounting or changing the wheel, the time between testing different designs was minimal.

Due to the limitations of the geometry of the base rim all wheel designs were limited to five spokes and 17´´ diameter. Designs investigated can be seen in Figure 17. As can be seen the designs differ in size and shape of the spokes, and in the area coverage from inner to outer radii. One design has no openings at all, see Figure 17(b), and two designs have three-dimensional blade spokes, Figure 17(d, e), one designed to guide the air out from the wheelhouse and the second one to pump air in.

One design that deserves special attention, the high drag profile, see Figure 17(k), was introduced to have a reference point and enable comparison between different configurations.

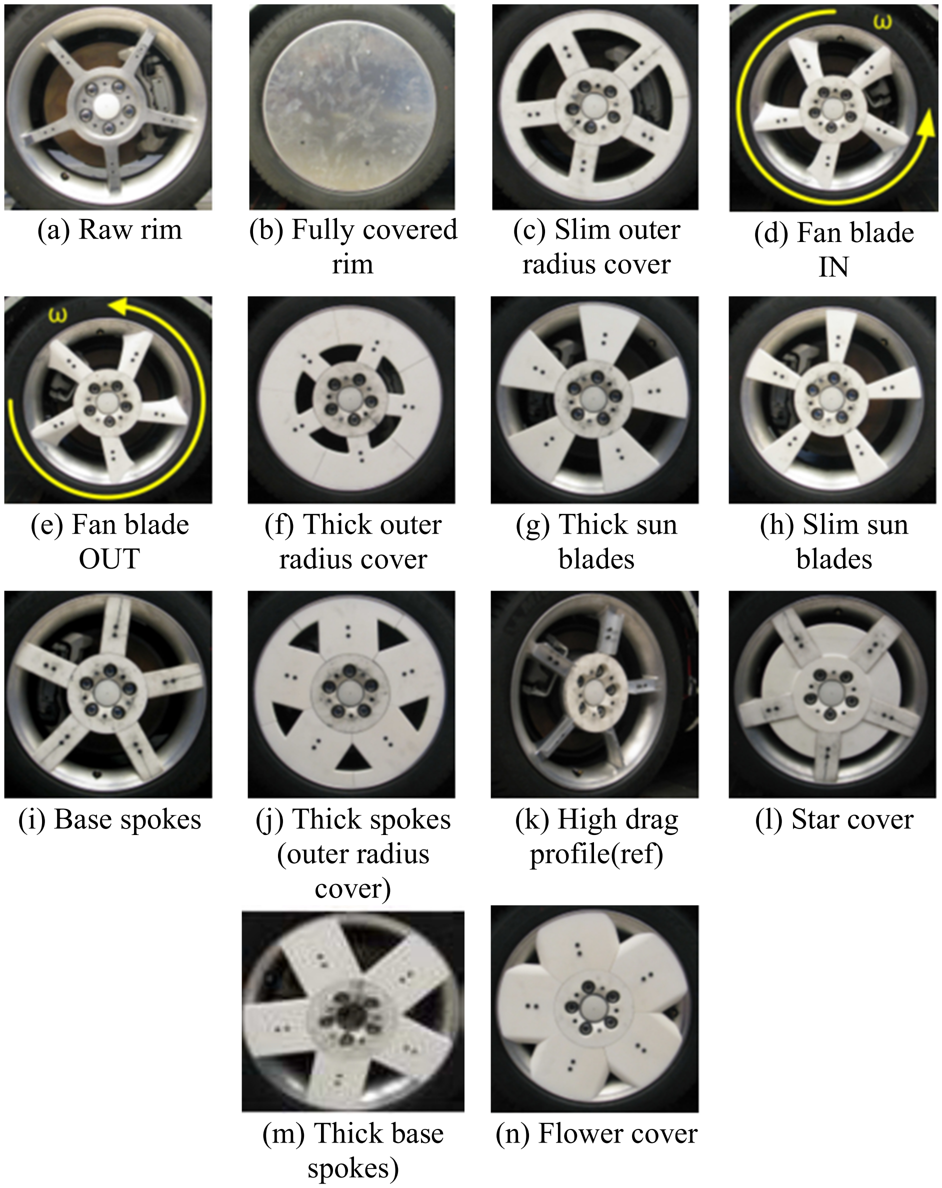

Figure 17. Rim designs investigated in Paper II

5. Results and discussions

5.1. Introduction of ventilation drag coefficient

Since the force measured during the experiment was part of the traction force responsible for overcoming ventilation resistance F'_{trac} , it is possible to replace ventilation resistance moment with equivalent resistance force F_{vent} counteracting vehicle movement. This force can be added to driving resistance force, see equation 1, in order to include effect of ventilation resistance:

$$F_x = F_a + F_R + F_G + F_D + F_{vent} \tag{2}$$

The ventilation resistance moment can be calculated using equation 3:

$$M_{vent}(V) = F'_{trac}(V) \cdot r(V) \tag{3}$$

$r(V)$ is the dynamic tyre radius, that changes with speed, see Figure 18.

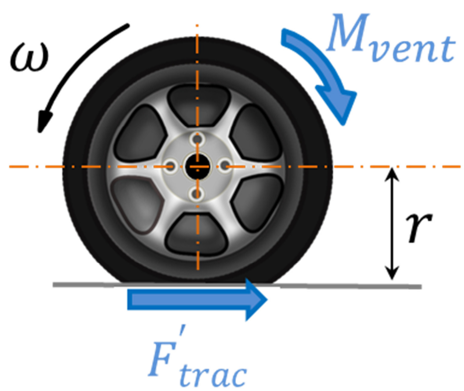

Figure 18. Ventilation resistance measurement

The power required to overcome ventilation resistance moment can be written in two forms:

$$P_{vent}(V) = M_{vent}(V) \cdot \omega(V) \tag{4}$$

and

$$P_{vent}(V) = F_{vent}(V) \cdot V \tag{5}$$

Equations 3 and 4 allow representing the equivalent ventilation resistance force in terms of traction force measured during the experiment F'_{trac}, see equations 6-9.

$$F_{vent}(V) \cdot V = P_{vent}(V) = M_{vent}(V) \cdot \omega(V) \tag{6}$$

$$F_{vent}(V) \cdot V = F'_{trac}(V) \cdot r(V) \cdot \omega(V) \tag{7}$$

$$F_{vent}(V) \cdot V = F'_{trac}(V) \cdot V \tag{8}$$

$$F_{vent} = F'_{trac} \quad (9)$$

As can be seen the equivalent ventilation resistance force is equal to part of the traction force responsible for ventilation resistance moment. Similarly to the aerodynamic drag force, F_{vent} can be written in the form of:

$$F_{vent} = \frac{1}{2} C_{D(vent)} A \rho V_{rel}^2 \quad (10)$$

where $C_{D(vent)}$ can be called ventilation drag coefficient, analogous to aerodynamic drag coefficient $C_{D(AD)}$. This coefficient can be calculated using equation 11:

$$C_{D(vent)} = \frac{F'_{trac}}{\frac{1}{2}\rho V_{rel}^2 A} \quad (11)$$

The dimensionless ventilation drag coefficient $C_{D(vent)}$ can be used to evaluate ventilation resistance moment effects relative to aerodynamic drag force, since equation 2 can be re-written in the following form:

$$F_x = \gamma ma + f_R mg \cos\alpha + mg \sin\alpha + \frac{1}{2}\left(C_{D(AD)} + C_{D(vent)}\right) A \rho V_{rel}^2 \quad (12)$$

In the equation 12, it can be observed, that the last term includes both aerodynamic drag and ventilation resistance, and therefore represents total aerodynamic resistance of the vehicle.

5.2. *Ventilation resistance for wheels with different rim designs*

All rim designs described in section 4.3 were tested: aerodynamic drag force and ventilation resistance moment were measured and represented in the form of aerodynamic drag coefficients $C_{D(AD)}$ and $C_{D(vent)}$. Some of the most interesting results for 6 different rim configurations are summarized here, the rest can be found in Paper II.

5.2.1 Ventilation resistance

In Figure 19 one can see ventilation resistance versus vehicle speed for the 6 selected configurations. $C_{D(vent)}$ is presented as a percentage difference from the reference design: the High drag profile rim design, Figure 17(k). The configurations compared are Fan blade out, Thick outer radius cover, Fully covered rim, Base spokes and Star cover, see Figure 17(e, f, b, i, l) respectively.

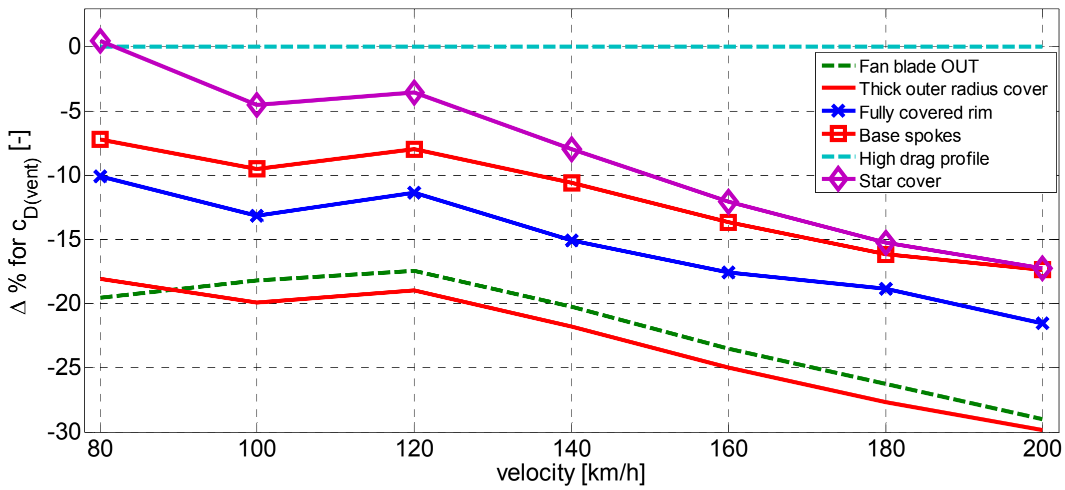

Figure 19. Ventilation resistance comparison for different rim configurations

It will be seen that the best design in terms of ventilation resistance moment was the Thick outer radius cover, since it had the lowest $C_{D(vent)}$ throughout almost the entire velocity range. A possible reason for this may be that the exposed parts of spokes in this configuration have lower relative speed, since the spoke length was shorter and they are positioned closer to the centre of rotation of the wheel. This meant that the leading edge of the spoke was subjected to a lower pressure, compared with the Star cover configuration, for example.

The second best configuration, Fan blade out, had aerodynamically shaped wheel spokes designed to pump the air out from the wheelhouse, thereby reducing pressure inside. The smooth corners on the leading edge of the spokes may have also contributed to lower ventilation resistance moment.

With regard to the other designs, as expected the High drag profile was proved to be the worst design, and the Star cover had the second worst performance out of all the 16 designs.

One configuration that deserves special attention is the Fully covered rim since it was already known for producing really good results for aerodynamic drag force [37]. Its performance in terms of ventilation resistance was slightly below average. This may have several explanations. Firstly, having no openings in the rim permits an attached flow on the outer side of the rim; this can result in increased surface friction. Secondly, with such a configuration the air cannot pass through the rim and the pressure inside the wheelhouse may be affected.

5.2.2 Aerodynamic drag force

Figure 20 shows the percentage difference between different wheel rim designs in terms of aerodynamic drag of the vehicle in relation to velocity.

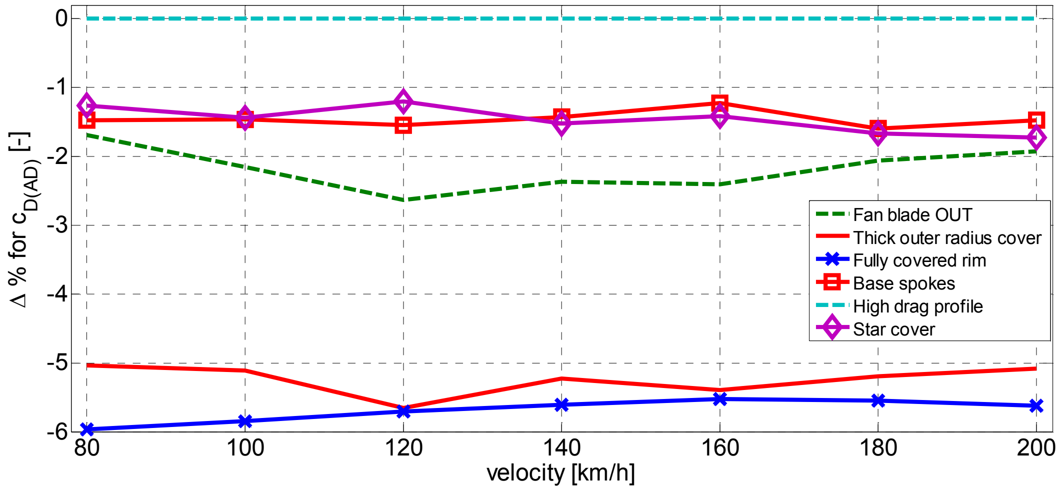

Figure 20. Aerodynamic resistance comparison for different rim configurations

As expected, changing the wheel rims did not have as significant effect on the aerodynamic drag of the vehicle as it had on ventilation resistance of the wheels themselves. Also, as predicted, the Fully covered rim design produced the lowest aerodynamic resistance, closely followed by the Thick outer radius cover. The importance of covering the outer radius of the wheel rim, in order to achieve lower aerodynamic drag force, has already been investigated [38], [39].

It should also be stated that there was no obvious correlation observed between aerodynamic drag force and ventilation resistance moment.

5.2.3 Total aerodynamic resistance

As described in section 5.1, since aerodynamic drag coefficient $C_{D(AD)}$ and ventilation drag coefficient $C_{D(vent)}$ are both dimensionless and defined in a similar way, it is possible to combine them. The unit obtained is a total aerodynamic resistance coefficient $C_{D(AD+vent)}$, it is represented in Figure 21.

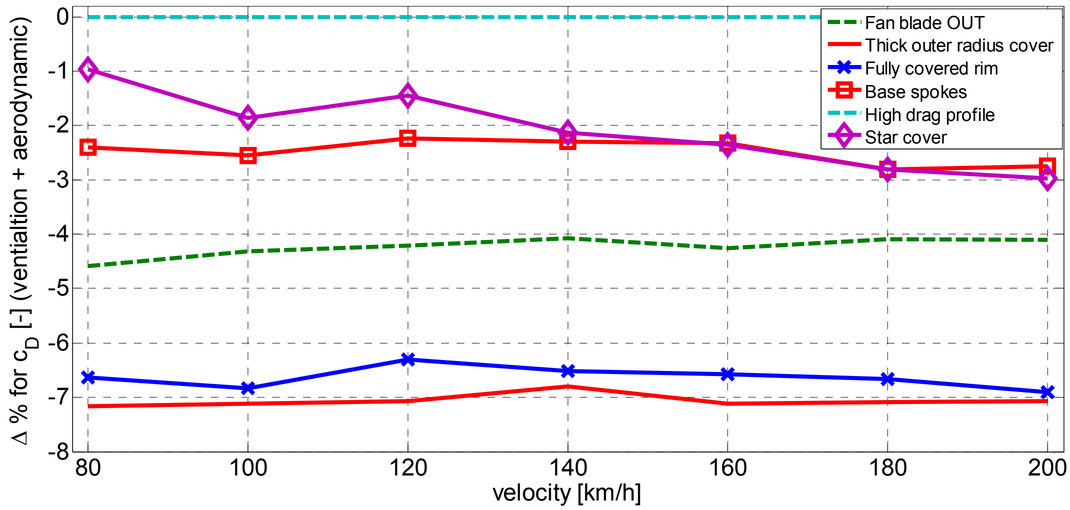

Figure 21. Total aerodynamic resistance comparison for different rim configurations

This graph, together with Figure 19 and Figure 20, shows the importance of ventilation resistance. One can see that the Fully covered rim has rather good overall results, but even though it has shown the best performance in terms of aerodynamic drag force, it was not the best design when it came to total aerodynamic resistance. This was due to the relatively high ventilation resistance moment generated by this configuration.

The best result was shown by the Thick outer radius cover, since it produced the lowest ventilation moment and performed rather well in terms of aerodynamic drag. This configuration was also better than the Fully covered rim from a brake cooling point of view, since it allowed air exchange through the rim.

The Fan blade out design that had relatively low ventilation drag coefficient, showed only intermediate results in terms of total aerodynamic resistance. Despite this fact, a better designed version of this configuration may have a lot of potential [19].

5.3. Alternative way to introduce ventilation resistance into driving resistance equation

Since the ventilation drag coefficient $C_{D(vent)}$ is highly dependent on vehicle velocity it is difficult to use equivalent ventilation resistance force F_{vent} in the form of equation 10 for driving resistance force (equation 12) calculations. In order to overcome this limitation an alternative form of equation 10 is suggested.

In Figure 22 one can see the calculated equivalent ventilation resistance dependency on the vehicle velocity for four wheels with different rims. With the exception of the High drag profile, Figure 17(k), which was a rather extreme and unrealistic design for a rim, all designs show linear dependency of the force studied to the vehicle speed. That allows the equation for F_{vent} to be written in the following form:

$$F_{vent} = \frac{1}{2} C_{vent} \rho V_{rel} \tag{13}$$

or

$$F_{vent} = \frac{1}{2}\left(\frac{C_{vent}}{V_{rel}}\right)\rho V_{rel}^2 \tag{14}$$

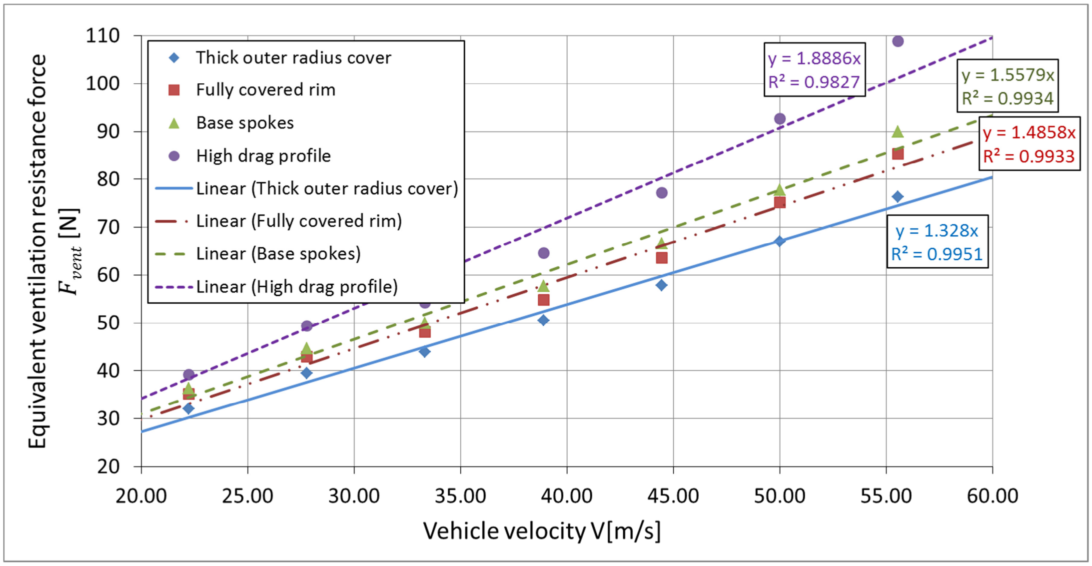

Figure 22. Equivalent ventilation resistance force vs vehicle velocity

C_{vent} can be called ventilation resistance coefficient and, based on the measurements conducted during the experiment, this coefficient may be considered to be constant for each specific wheel design. Based on the values for one of the worst designs in terms of ventilation resistance moment (Base spokes) and the best one (Thick outer radius cover), it can be concluded that this coefficient varies between 2.2 and 2.6 $\left[\frac{m^3}{s}\right]$.

Using the form of representation F_{vent} shown in equation 14 one can re-write the equation for driving resistance in the following form:

$$F_x = \gamma ma + f_R mg\cos\alpha + mg\sin\alpha + \frac{1}{2}\left(C_D A + \frac{C_{vent}}{V_{rel}}\right)\rho V_{rel}^2 \tag{15}$$

where C_{vent} is constant for a chosen wheel configuration. As one can see, by the addition of one small term it is possible to include ventilation resistance into the equation for driving resistance.

5.4. Example of power comparison

Multiplying both sides of equation 15 by vehicle velocity V, one can get total power requirement to overcome the different resistances. In Figure 23 an example of these power requirements can be seen for a typical modern vehicle.

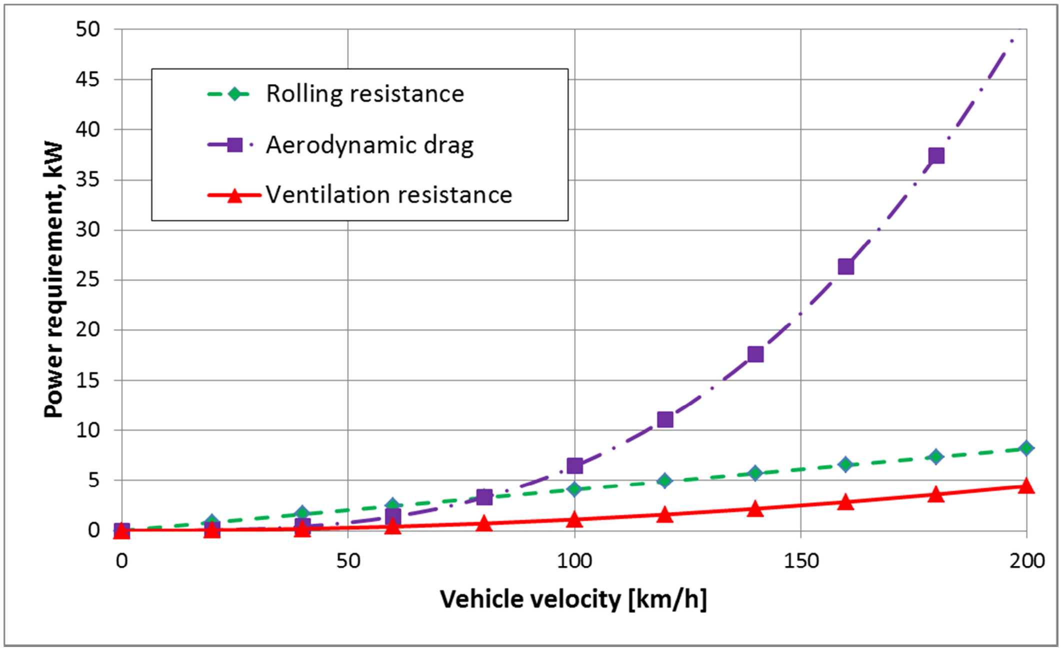

Figure 23. Power requirement to overcome different resistances

Obviously the contribution of ventilation resistance to the overall power requirement is not as significant as, for example that coming from rolling resistance; but as can be seen for highway velocities, ventilation resistance plays an important role and should not be neglected.

5.5. Limitations

In the experiment the focus was solely on measuring the effects of different rim designs on the ventilation resistance moment of the wheels. As described in section 3.2.1, this moment depended on design of the entire wheel, including brake disc and tyre, therefore it is recommended for future investigations to test rim and tyre combinations, since different tyre design can lead to significant differences in results.

Unfortunately, due to limitations of the modular wheel system available, it was only possible to test 17´´ wheel rims. Investigating ventilation resistance dependency on wheel rim size should also be investigated.

It should also be noted that in some cases ventilation resistance may be partially measured during rolling resistance tests, and later be included in rolling resistance coefficient. Therefore before applying equation 15 one should check how the rolling resistance was defined. Nevertheless, since there is no oncoming airflow during the rolling resistance test, the ventilation resistance magnitude in real life may be significantly different and should not be neglected.

Another thing to consider that the ventilation resistance addressed in this thesis may only be a part of the total aerodynamic resistance moment: the part that originates from the rotating wheels. Since there are more rotating parts subjected to the airflow, for example shafts or fans, the total aerodynamic resistance moment may be significantly higher, especially if taking into consideration cooling fans of the vehicles.

6. Conclusions

The investigation has shown that there are different methods available to measure ventilation resistance moment in the wind tunnel. All methods require measuring or eliminating numerous resistance moments and power losses associated with them. Most importantly, rolling resistance moment should be taken care of. In order to do that, it is necessary to make certain modifications to a standard wind-tunnel test procedure. With a modified set-up it is entirely possible to measure the ventilation resistance moment. One of the methods was described in the Paper II and some of the results were presented.

The magnitude of the ventilation resistance, and more importantly the power required to overcome it, shows that this phenomenon has a significant influence on the total aerodynamic resistance of the vehicle and should not be neglected.

It has been confirmed that ventilation resistance depends on the design of the wheels. The rims with a thick outer radius, that were known to have a relatively good performance in terms of aerodynamic drag force, have shown the best results in terms of ventilation resistance. Moreover it was found that this configuration was slightly more efficient than a fully covered rim, when comparing total aerodynamic resistances. Another wheel rim configuration that should be mentioned, and that may have certain potential, is the one with aerodynamically designed 3-dimensional spokes.

In sections 5.1 and 5.3 two different methods of including ventilation resistance effects in the equation for driving resistance force were presented. Equation 15 should be preferred, since the ventilation resistance coefficient C_{vent}, which is used in this equation, depends only on the tyre and rim configuration used, and is independent of vehicle velocity.

7. Future work

To continue the investigation of ventilation resistance moment it is suggested conducting a series of numerical studies, using CFD codes that are available. This will allow not only the correlation of numerical results to experimental data from the wind tunnel, but also investigation of the individual contributions of tyres, rims and brake discs to the ventilation resistance of wheels.

As discussed in section 5.5, it is possible to extend ventilation resistance investigations from wheels to all other parts of the vehicle rotating in the air. For example, rotating cooling fans consume a lot of power to drive the air through the cooling package, and the majority of this power is being consumed overcoming ventilation resistance.

Another suggestion for the continuation of this project would be to test other rim sizes and more sophisticated 3D configurations of the wheel rims. Furthermore, the dependency of ventilation resistance magnitude to tyre/rim combinations could be investigated.

Lastly a more detailed investigation of the airflow inside the wheelhouse and around it can be conducted in order to evaluate interaction between ventilation resistance and underbody flow.

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