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Development of a New Cost-Efficient Procedure for Evaluation of Wheel Design Aerodynamic Performance

Master's thesis in Product and Production Development

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Gothenburg, Sweden 2017

MASTER OF SCIENCE THESIS

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PREFACE

The project presented in this 30 ECTS master's thesis was performed at the Product and Production Department at Chalmers University of Technology, Gothenburg. The project was launched in January and finished in June, 2017.

The project was mainly carried out at Volvo Car Corporation (Volvo Cars) in Torslanda, Sweden, interspersed with several internal study visits and meetings with the involved departments. The result presented in this report has been made possible by continuous dialogue with and support from fellow students and colleagues. I would, firstly, like to express my gratefulness and thank Lorina G. Modin, Lead Engineer and tutor, Volvo Car Company, for the continuous support, helpful advice and for giving me the opportunity of performing this project.

I also want to express my thankfulness towards the representatives from the involved departments at Volvo Cars; Linda Josefsson, Senior Analyst, Aerodynamic Dept., Ole-Kristian Bjerke, Expert Senior Designer, Exterior Design Dept., Johan Järbrink, Manager, Wheels & Tires Dept., Jens Bergqvist, Lead Engineer, Wheel Dept., Andreas Andreen, Lead Engineer, Wheel Dept. and Martin Ödlund, Analyst Engineer of Additive Manufacturing, Concept Center.

In addition, I would like to show my appreciation towards Professor Johan Malmqvist, supervisor and examiner, Chalmers University of Technology, for all valuable knowledge and input throughout the project.

Lastly, I want to express my gratitude to all those who in any manner directly or indirectly put a helping hand for completing this project.

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Viktor Robertsson

ABSTRACT

The Worldwide Harmonized Light Vehicle Test Procedure (WLTP) is developed by the European Union (UNECE) with the intention to perform more representative *emission level*, *fuel consumption* and *electric range* tests on passenger cars (Mock et al., 2014). To cope with upcoming regulations, one of the recognized issues by Volvo Cars is the wheel's aerodynamic influence on the vehicle's total aerodynamic drag which correlates with the vehicles fuel consumption.

Previous research has shown that the vehicle's wheels and wheel housings can affect up to 25% of the vehicle's aerodynamic drag and consequently increase its fuel consumption (Vdovin, 2013). Volvo Cars has conducted studies within the area of wheel aerodynamics, but it has been concluded that there is still a need for a more comprehensive understanding of the wheel designs' influence on the aerodynamic drag.

This project developed a base wheel solution which allowed different interchangeable wheel design features to be tested in the wind tunnel facility at Volvo Cars in Torslanda, Sweden. The base wheel solution, made out of aluminium, is used as a platform on which the interchangeable wheel design features can be securely mounted. The wheel design features are manufactured using an additive manufacturing technique and fastened onto the base wheel with two snap-fit geometries.

The developed solution was tested and verified in the wind tunnel facility at Volvo Cars, with satisfying results. The wheel design feature's snap-fit geometry proved to be adequate for performing full-scale wind tunnel tests.

In addition to the developed physical aerodynamic evaluation tool, the consequences of implementing an early aerodynamic evaluation activity into the current wheel development process was investigated. A proposal of implementing a design-build-test activity was developed in order to reduce the risk of costly late iterations of the wheel design and development.

Compared to the current procedure, the proposed procedure of implementing the developed base wheel solution and the additive manufactured wheel design features will reduce the cost with approximately 60-80% for each complete set of wheels. Further, the required time for prototype manufacturing is reduced to 10 days, corresponding to a reduction of almost 80% compared to the current procedure with milled wheels.

Table of Contents

Nomenclature

3D – Three Dimensional
AM – Additive Manufacturing
CAD – Computer Aided Design
CFD – Computational Fluid Dynamics
CO_2 – Carbon Dioxide
ETRTO – The European Tyre and Rim Technical Organisation
FEM – Finite Elements Method
g CO_2/km – Measurement of Emissions (gram carbon dioxide per kilometre)
NEDC – New European Driving Cycle
VLM – Vehicle Line Management
Volvo Cars – Volvo Car Corporation
WLTP – Worldwide Harmonized Light Vehicle Test Procedure
RPM – Rounds Per Minute
SPA – Scalable Platform Architecture
SLS – Selective Laser Sintering

1. Introduction

Volvo Car Corporation (Volvo Cars) is a Swedish automotive manufacturer within the premium car segment, owned by the Chinese company Zhejiang Geely Holding since 2010 (Volvo Cars, n.d.). Similar to other automotive manufacturers, Volvo Cars are currently facing challenges concerning forthcoming environmental regulations and legislations in an ever increasing competitive market. This master thesis is meant to investigate and facilitate for Volvo Cars to confront some of these challenges. The following chapter will introduce the context and prerequisites of the master thesis project.

1.1 Background

In order to certify a vehicle for the European market, the vehicle must, by law, undergo laboratory tests for emissions and fuel consumption. The present testing cycle for assessing a passenger car's fuel consumption and emissions is called the New European Driving Cycle (NEDC). It has been in use since 1996 and is mandatory for all types of passenger cars (Eichhorn, Mayer, & Richter, 2014).

Due to technological advancements and a shift towards lowering vehicle emissions, a lot has changed since the testing cycle was introduced and it is currently being criticized for its unrealistic laboratory testing procedure and misleading fuel-consumption and emission test results (Rabe, 2016). According to Transport & Environment, a non-governmental organisation, the difference between the laboratory tests and real-world CO_2 emissions have increased substantially from 9% in 2001 to 42% in 2015 and is expected to reach 50% by 2020 (Archer, 2016). This causes an unjust representation of the vehicle manufacturers due to misleading numerical values for the vehicle's emissions and fuel economy, which ultimately leads to dissatisfied consumers.

The Worldwide Harmonized Light Vehicle Test Procedure (WLTP) is developed by the European Union (UNECE) with the intention to perform more representative *emission level*, *fuel consumption* and *electric range* tests on light-duty vehicles (passenger cars and light commercial vans) (Mock et al., 2014). WLTP will compared to its predecessor NEDC, evaluate different car configurations (including optional accessories and equipment) in order to obtain more accurate emission and fuel-consumption values for different vehicle arrangements (ACEA, n.d.; Cooper, 2016). To cope with upcoming regulations, one of the recognized issues by Volvo Cars is the wheel's influence on the vehicle's total aerodynamic drag which correlates with the vehicles fuel consumption. There is a need within the organisation to develop a procedure which validates the wheels' influence and therefore ensures that the development process can provide with support to meet these upcoming requirements (Lorina G. Modin, personal communication, 2017-01-19).

Previous research has shown that the vehicle's wheels and wheel housings can affect up to 25% of the vehicle's aerodynamic drag and consequently increase its fuel consumption (Vdovin, 2013). Today's development approach, within Volvo Cars, is based on engineering know-how and limited research (Lorina G. Modin, personal communication, 2017-01-19). There is a demand and need within the organization for a more comprehensive understanding of the wheel designs' influence on the aerodynamic drag.

In order to approach the issue regarding WLTP introduction as well as stricter mandatory allowed CO_2 emission levels in the EU, which will be deployed in the near future, several changes in Volvo Car's product development process need to be carried out. The current process for wheel development lacks an appropriately scheduled aerodynamic evaluation. The wheel has not been aerodynamically evaluated until the verification production prototype is built, where any changes in design would be financially unsustainable. The current procedure of evaluating the wheel's aerodynamic performance uses milled prototypes of the wheel design, which is both a costly and time-consuming approach. It is evident that it is necessary with a well defined and clear process to approach the issues.

1.2 Purpose and Goal

The purpose of this master's thesis is to develop a solution that evaluates the aerodynamic performance of different wheel designs. Further, the thesis shall define and develop an aerodynamic evaluation process for passenger car wheels, which can be implemented in future projects at Volvo Cars.

The goal of the thesis is to find a solution which is more time-efficient and less costly compared to the current evaluation method in order to, in the future, reduce the wheel's aerodynamic drag and therefore the vehicle's emissions.

The intended deliveries of the master thesis are a base wheel and a solution for interchangeable features. These tools can be used to perform full-scale wind tunnel tests to determine what wheel design features that are beneficial from an aerodynamic perspective.

The final result is intended to serve as a proposal on how an aerodynamic wheel development process shall be conducted with the use of the developed tool. The resulting process will be compared and measured with and against the current approach, based on key measurements such as required time, cost and risk reduction.

1.3 Project Stakeholders

The content of this master thesis involves several departments within Volvo Cars. The three main stakeholders are the *Wheel-*, *Exterior Design* - and *Aerodynamic Department*. Where the Wheel Department provides with the project's main supervisor, Lorina G. Modin, who ensures that the results are kept relevant, and of interest, for future wheel projects. The Exterior Design Department supports with design expertise and their main interest is to ensure that the outcome will support them in future development of aerodynamic wheels. Lastly, the Aerodynamic Department supports the thesis with necessary knowledge and their experience of wheel aerodynamics and their expertise of the wind tunnel testing facility.

Other concerned stakeholders of the project are Volvo Cars' wheel suppliers, customers and the vehicle line management (VLM) team. The latter is in charge of deciding future vehicle projects and their content.

The master thesis is performed at Chalmers University of Technology for the Product and Production Development Department, that supports with an examiner and supervisor, Professor Johan Malmqvist. The university's main purpose of involvement is the content of the thesis and its results, with respect to product development novelty as well as the student's proof of use of studied product development methodology knowledge.

1.4 Delimitations and Project Scope

The thesis will be delimited to consider the following aspects:

- The final concept shall only consider passenger car wheel design parameters – tires are excluded.
- Develop a physical aerodynamic evaluation tool and process, not a computational simulation analysis.
- The project shall be finished in June 2017.

This master's thesis is meant to investigate the area of wheels for passenger cars and its design parameters. The area of tires, as well as other types of vehicles' wheels, are not in the scope of the project in order to confine the thesis' workload. In terms of the development process as a whole, this thesis will focus its study on the possibilities to implement the *aerodynamic evaluation process* in the current wheel development process.

1.5 Disposition of report

The following section describes the disposition and context of the report.

Introduction
The initial chapter presents the prerequisites of the master thesis, including a brief background and explanation of the aim and purpose of the project as well as the involved stakeholders and the delimitations conducted for the project.

State of the Art / Theoretical Framework
This chapter aims to provide with a sufficient amount of knowledge to allow the reader to further understand the process of the thesis in the following chapters. Fundamental wheel knowledge and terminology as well as essential information about the current state of the wheel development process is presented. Further, the chapter briefly explains fundamental aerodynamics and Volvo Cars' wind tunnel facility's composition.

Methodology
This chapter describes the methodology used in the development process of the master thesis. Further, it explains and motivates the choice of the specific method or tool by referring to relevant literature.

Results
The results reached in the master thesis are presented in this chapter. Further, it elaborates the development of the tool and the steps taken in order to reach the final concept and its results. In addition, underlying reasons and affecting factors are described to facilitate the understanding of the progress of the development work.

Process Development
This chapter describes the implementation consequences of the aerodynamic evaluation procedure for the current wheel development process. Further, proposals for improving the current process are described, based on the studied literature and experience gained through the performed project.

Discussion
This chapter elaborates the validity of the results and the process of the conducted work. Further, it includes a discussion about the methods used and the overall performance of the conducted project.

Conclusions
The conclusions from the performed master thesis and its results are presented in this chapter.

Recommendations for Further Work
Recommendations for further development as well as proposals for future projects, based on the knowledge gained from the performed master thesis, are presented in the final chapter.

Appendix
In addition to the report, further information about the wheels and its composition as well as enlarged visualizations of the developed concepts and results are presented in this section. The content of the appendices is presented below.

- Appendix A visualizes a large illustration of the current process, which is presented in a smaller format in chapter 3.
- Appendix B includes additional information about the rim and its composition.
- Appendix C describes the composition of the wheel disc and its composition.
- Appendix D presents additional photos of the base wheel prototype.
- Appendix E is a table of the different wheel design features that were of interest to evaluate in future research.
- Appendix F includes photos taken during the wind tunnel test and the final prototype.

2. Current State of Art and Theoretical Framework

In order to facilitate the understanding of the remainder of this master's thesis, this chapter contains and summarizes the current state of art of Volvo Car's wheel development process as well as basic technical knowledge about the wheel and its composition. Further, fundamental aerodynamics is reviewed and a brief summary of the current state of aerodynamic experience acquired within the organization is presented. Lastly, the chapter contains a description of the wind tunnel facility, its composition and how a test is performed. The provided information is of essential value for different decisions during the development work of the aerodynamic evaluation tool and process.

2.1 Current Wheel Development Process

In order to evaluate and implement a new process into the wheel development process, it is of importance to investigate the current development process and its involved tasks. Due to the classified content of Volvo Cars wheel development process, a generic version will be briefly described and is illustrated in figure 2.1.

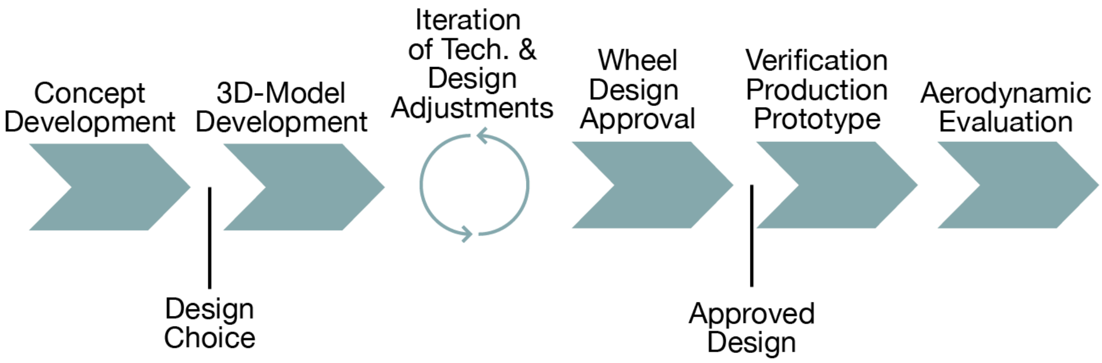


Figure 2.1: Generic Version of the Current Wheel Development Process.

Prior to the concept development activity, a request from the vehicle line management team need to be delivered to the departments involved in the wheel development. The request specifies the wheel dimensions and for what type of vehicle it is suppose to be assembled with. Thereafter, the actual development of the wheel begins.

The initial step is to develop several alternatives of the design, called the concept development phase. A choice of the basic design is thereafter made and the development of a digital 3D model is initiated. Based on the 3D model, several iterations are performed in order to fulfil technical and appearance requirements, e.g. fatigue strength requirements.

Once the wheel fulfils the requirements, the wheel is approved and the first physical prototypes of the wheel are manufactured, called a verification production prototype. These physical prototype wheels are thereafter being used for several different tests, where one is to evaluate its aerodynamic performance.

With the WLTP in mind, there are several issues that needs to be taken care of. The aerodynamic performance of the wheel is evaluated late in the development process. This implies that expensive manufacturing tools have already been made and even minor changes in the wheel design would be costly. Further, there is a lack of appropriate aerodynamic input in the initial activities of the development process of the wheel. This is the phase in the development process where there are great possibilities to influence the decision of the overall design.

2.2. Theoretical/Academic Product Development Process Guidelines

Ulrich and Eppinger (2012) defines a process as “a sequence of steps that transforms a set of inputs into a set of outputs” (p.12). Further, a product development process relates to the order of organizational and intellectual activities an organization follows and uses when developing their products. A generic product development process is visualized in figure 2.1

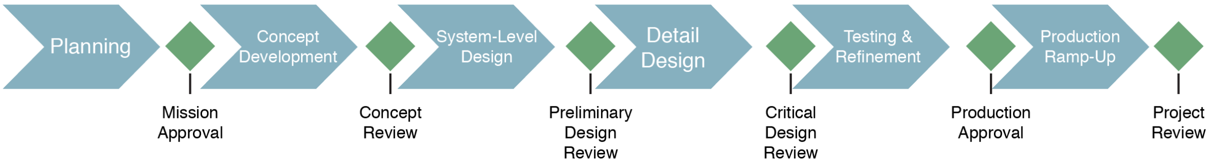


Figure 2.1: Generic Product Development Process Flow of Activities (Adapted from Ulrich & Eppinger (2012)

The green boxes in figure 2.2 represents mandatory review or decision gates, whose purpose are to evaluate and approve the continuation of the project, based on the results of the previous activity. Dependent on the intended product, there can be variations of the number of iterations in between the activities. Iterations refer to a process flow which allows activities to be repeated several times until the desired result is achieved (Ulrich & Eppinger, 2012). The process employed in quick-build products, where the process flow iterates design-, build- and test-activities, is an example of a process flow which allows several designs to be verified and tested in a time-efficient and structured manner prior to determining the final concept.

In general terms, there are several ways of approaching the issue of improving an already established product development process. Key areas of interest for such are evaluating the composition of the involved project team members, investigating the amount and timing of the iterations as well as possibilities to use computational complimentary tools. The following subchapters presents how such evaluations and investigations can evolve and improve an already existing process.

2.2.1 Project Team Composition

According to Ulrich & Eppinger (p.8, 2012) one reason behind unsuccessful product development projects are the lack of cross-functional representation in the project team. Where project decisions are taken without involving relevant organisational functions, e.g. technical experts, design or marketing. To cope with such issues, it is necessary to allocate and involve persons from the concerned organisational functions in the project.

2.2.2 Iterations and Timing – Failure Risk Reduction

A product development team’s knowledge about the issue and level of influence of the design can be described with the chart below (figure 2.2), also known as the designer’s dilemma (Sobek, 2014). Where the level of influence is high in the initial part of the project, but the team’s knowledge about the issue to solve is low. As time passes, the team gains understanding of the issue, but the design freedom decreases as decisions are made during the progress of the project.

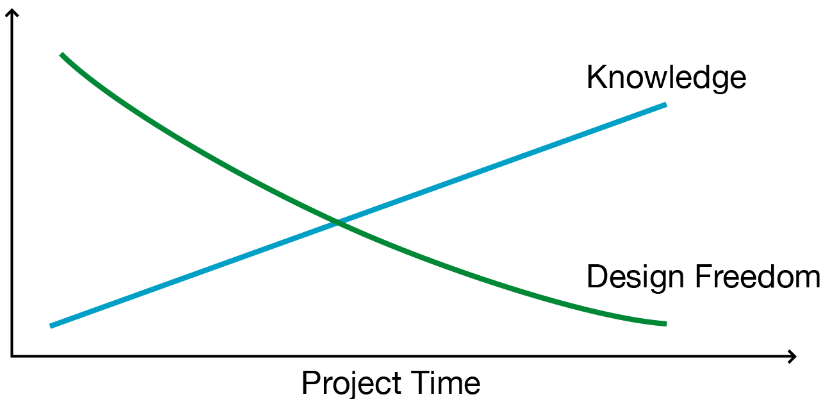


Figure 2.2: Designer's Dilemma, Knowledge Increases as the Design Freedom Decreases

In order to avoid costly delays or even cancellations of projects, due to uncertain or non-verified results, it is recommended to integrate testing activities in the development process. By allowing iterations in a Design-Build-Test process as a part of the development process, the risk of not meeting the requirements is reduced. Further, by implementing the design-build-test process as an initial activity in the development process, the probability of success increases (Ulrich & Eppinger, 2012). In addition, the risk of having to iterate back once the final concept is established is reduced, since it allows the development team to discover and manage issues in a state of development process where changes are more allowed and less costly. Put simply, early test iterations allow the derivative of the knowledge curve in the designer's dilemma chart to increase, reducing the gap between the two curves. In terms of risk reduction, several iterations increase the probability of success. Figure 2.3 illustrates the advantage of building prototypes of the product, as it increases the probability of success. The activity allows the product's properties to be tested prior to e.g. building expensive manufacturing tools or moulds.

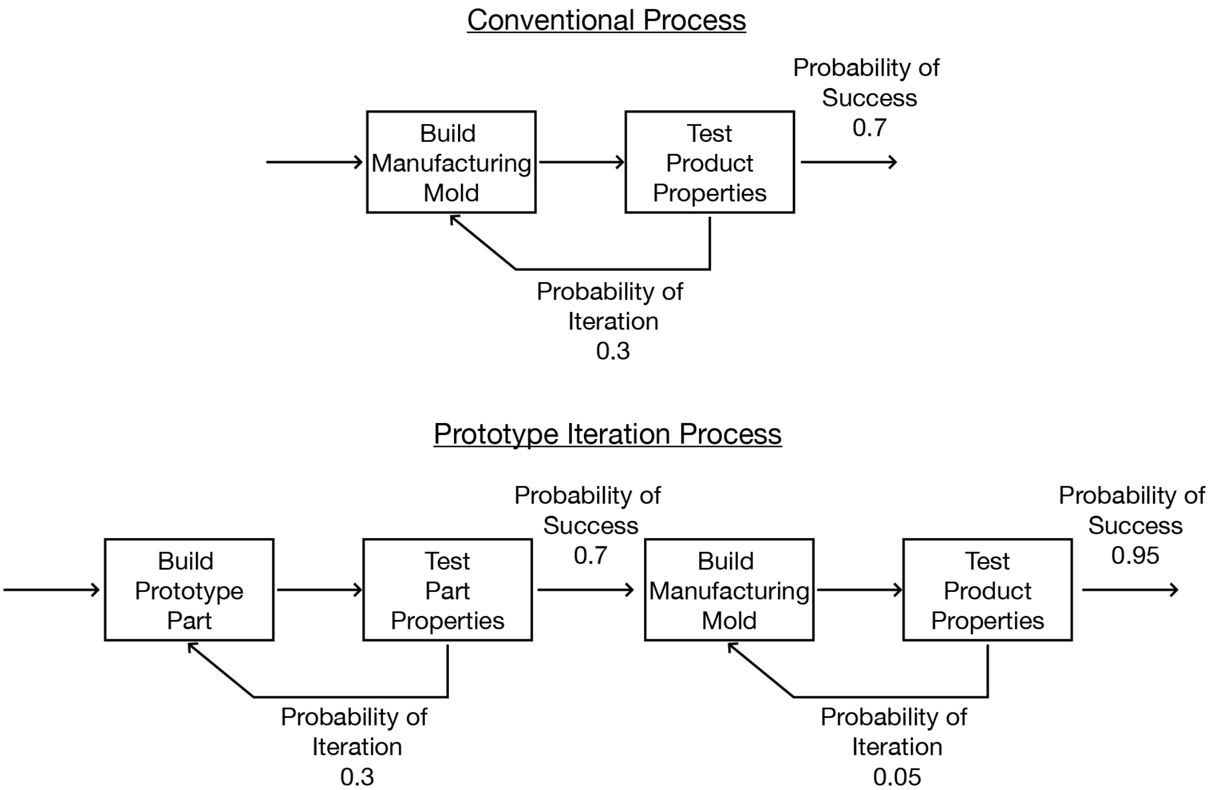


Figure 2.3: Benefit of Prototype Iterations (Ulrich & Eppinger, p. 298, 2012)

In addition, the time and cost required to build a prototype and test its properties is, in general terms, less than having to iterate back to manufacturing a completely new mould if the product would fail the testing.

2.2.3 Computational Supplements

Historically, there are numerous indications on computational tools that have improved the product development process and its results. One example is the implementation of computer aided design (CAD) tools, which have revolutionized how products are designed and engineered (Ulrich & Eppinger, p.220, 2012). The use of computational tools, have increased the efficiency of the product development process and reduced the time-to-market.

2.3 Wheels

The vehicle wheel assembly is the only component that connects the vehicle's axles with the ground, allowing the vehicle's power to be translated into a forward movement. The assembly mainly consists of two main parts; *the tire* and *the wheel*, which are being mounted onto the wheel hub in order to connect it with the rest of the vehicle.

Currently, the most common type of wheels for passenger cars are cast or forged aluminium alloy wheels. Compared to other materials, the aluminium alloys allow a large design freedom and beneficial possibilities of mass production. There are other alternate materials that are currently being investigated and developed for automotive purposes, where carbon fibre is the most common alternate material among several vehicle manufacturing companies (Astrén, 2012). Due to both cost and the limitations in mass production, Volvo Cars' Wheel Department does not see any disruptive breakthroughs for the carbon fibre wheels in the near future and are therefore still focusing on developing and manufacturing aluminium alloy wheels (Lars Lindblad, personal communication, 2016-07-03). Compared to pure metal wheels, alloy wheels have the advantage of offering greater strength characteristics without compromising the weight of the wheel and according to Volvo Cars the appearance of aluminium alloy wheels are highly appreciated by both their customers and their designers.

The wheel is surrounded by several parts when mounted on the vehicle, a brief overview of the surrounding components of the wheel is visualized in Figure 2.4. The wheel itself, however, is composed by two components; the rim and the disc (See Figure 2.5). Individual descriptions for the rim and the disc are presented in Appendix B and C.

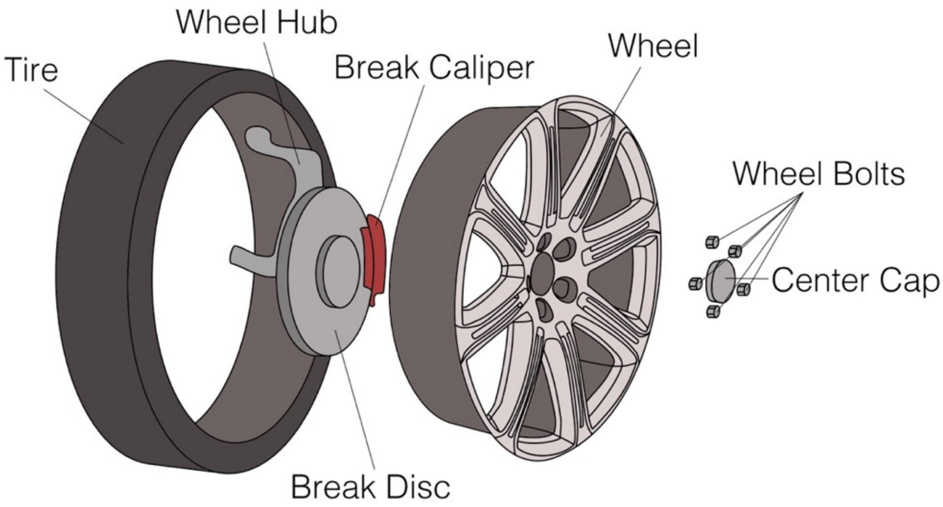


Figure 2.4: Surrounding Components of the Wheel

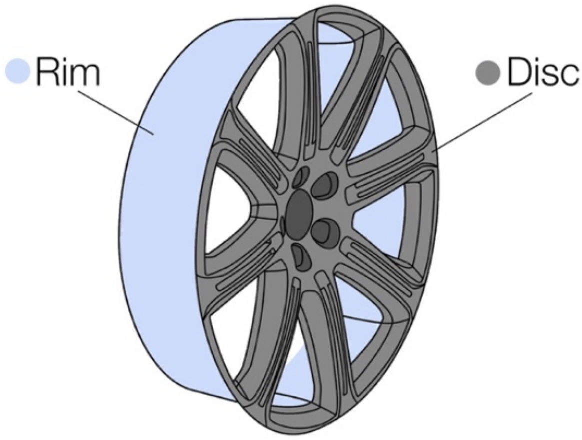


Figure 2.5: Wheel Components

Commonly used dimensions in terms of the wheel are the wheel width, the wheel diameter and the wheel offset, all dimensions are illustrated in Figure 2.6. Whereas the latter, the wheel offset, is the dimension from wheel centre to the mounting surface of the back of the disc, a geometric distance which affects the wheel's position on the wheel axle and conclusively the width of the vehicle wheel base.

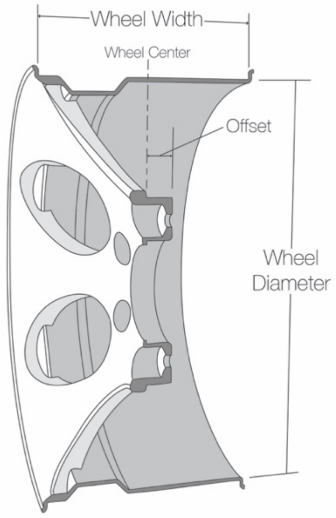


Figure 2.6: Common Wheel Dimensions

In terms of general guidelines for the wheel and its performance, one of the most important factors is the weight of the wheel. It is of interest to keep the weight to a minimum, consequently keep the total vehicle weight low, in order to reduce the rolling resistance and therefore the environmental impact. In addition, according to Koenigsegg (n.d) by minimizing the rotational unsprung mass of the wheel, it allows both shorter breaking distances and faster acceleration allowing greater handling properties.

2.4 European Vehicle Emission Targets

According to the European Commission (2017), cars are responsible for 12% of the total emissions of CO_2 within the EU. In order to reduce the environmental impact, the EU has set mandatory emission reduction targets for a car's allowed g CO_2/km, where the target for 2015 was 130g CO_2/km. By 2019 there will be an excess emission premium of 95€ for every exceeding g CO_2/km that the vehicle manufacturer has to pay for each sold car. The target value will be further reduced to 95g CO_2/km by 2021, implying that every saved or decreased g CO_2/km will be extremely important for vehicle manufacturers in the near future.

To put into context and facilitate the understanding, the consequences can be exemplified as follows: if a vehicle manufacturer sells 100,000 cars each year and every car exceeds the targeted value with only 1g CO_2/km, the vehicle manufacturer would have to pay an excess emission premium of 9.5 million euro.

2.5 Fundamental Aerodynamics

The field of aerodynamics consists, in general terms, of analysing the motion of air around an object. During acceleration an object is subjected to gravity and drag, whereas the drag is caused by the forces created by displacement of the fluid medium that surrounds the object (George, 2009). The amount of drag an object experiences is correlated with the velocity it moves through the medium, e.g. air, consequently higher velocity equals a larger drag. The acceleration (a) of a free falling object (see figure 2.7) can be described by rewriting Newton's second law as the gravitational force (F) minus the drag (D) divided by its mass (Hall, 2015a):

$$a = \frac{F-D}{m} \quad (Equation\ 1)$$

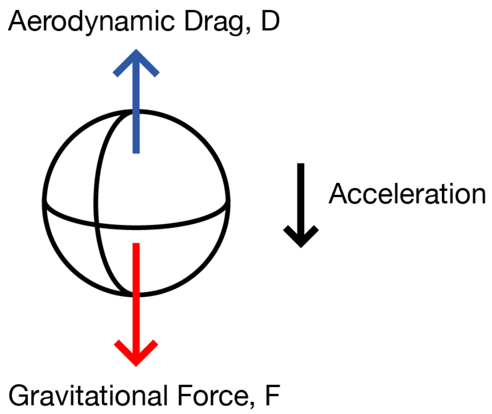


Figure 2.7: Forces Acting on a Free Falling Object

In terms of vehicle aerodynamics, the acting forces are applied differently and the gravitational force is replaced by a resultant driving force (See figure 2.8). But, in general terms the same theory can be applied. This implies that a vehicle can only accelerate until the drag equals the driving force of the vehicle. Simply put, as a vehicle accelerates, the air resistance increases and therefore limits the vehicle's speed.

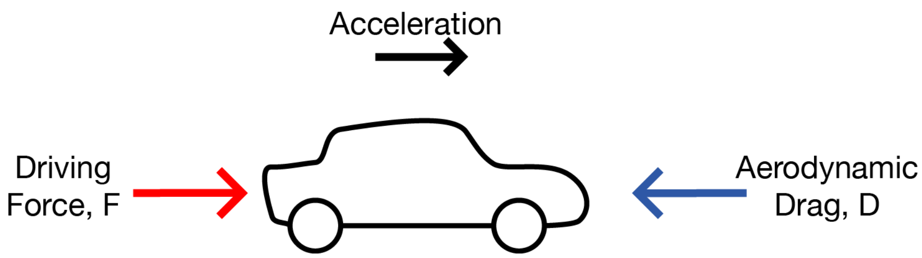


Figure 2.8: Simplified Vehicle Aerodynamics

The key factor for understanding the vehicle's aerodynamics and its drag, is the drag coefficient, C_d. The drag coefficient describes the object's ability to move through air and is dependent on the drag (D), the square velocity (v) of the vehicle, the density of the surrounding fluid (ρ) and the area (A). Where the area (A) is the area of the object which is perpendicular to the direction of the air flow (Hall, 2015b). C_d is determined by the following equation:

$$C_d = \frac{2D}{A \times v^2 \times \rho} \quad \textit{(Equation 2)}$$

To put into context, as mentioned earlier increased velocity equals higher drag, and by applying it to vehicle aerodynamics it implies that a vehicle travelling in 60 km/h is exposed to four times greater drag forces than a vehicle travelling in 30 km/h. Passenger cars have a C_d coefficient of approximately 0.3-0.4 (Odum, 2001), and by reducing the drag coefficient by 0.01 a car can improve its range and fuel economy with approximately 0.09 kilometres per litre (George, 2009). To put into terms of g CO_2/km, the decrease of 0.01 C_d would correspond to a reduction of approximately 0.5 g CO_2/km.

This thesis focuses on passenger car aerodynamics and more specifically on the area of the passenger car wheels. 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 represent as much as 25% of the drag resistance (Vdovin, 2013). The difference between an aerodynamic optimized wheel and a poorly designed wheel is in general terms a 0.005-0.015 increase of the overall C_d (Pirooz Moradnia, personal communication 2017-05-04).

Two of Volvo Cars' wheels are presented in figure 2.9. The wheel to the left is an 18" wheel which has shown to have preferable aerodynamic properties, due to its large coverage of the disc area. The wheel to the right has been proven to perform poorly in the aerodynamic evaluations, mainly due to the shape of the spokes (Linda Josefsson, personal communication 2017-03-03).

Figure 2.9: Volvo 18" Ailos Wheel and 16" Oden Wheel (Volvo Cars, n.d.)

With respect to the aerodynamics of the vehicle's wheel, the complexity of calculating the aerodynamic influence from the rotating wheel is increased. In addition to the aerodynamic drag created by the vehicle's exterior design, the wheels create an additional contributing aerodynamic resistance, commonly referred as ventilation resistance.

By evaluating the wheel as a separate part, it is easier to comprehend the complexity. When a wheel rotates, the wind velocity on the top part of the wheel is twice the speed compared to the relative velocity at the centre of the wheel (*Figure 2.10)* (Zhiling, 2009). Whereas the velocity of the wind closest to the ground is close to zero. Due the large variation of wind speed on such a small area it is complicated to comprehend and estimate the wind flow around rotating wheel geometries, without performing full-scale wind tunnel tests.

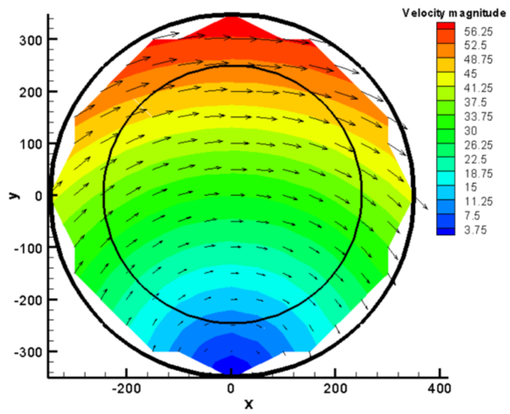


Figure 2.10: Relative Wind Velocity on a Rotating Wheel (Wheel Rotation is Counter Clockwise) (Zhiling, 2009).

2.6 Current Aerodynamic Wheel Knowledge

The current method for evaluating the wheel's aerodynamic performance is by conducting complete vehicle tests in the wind tunnel and compare the resulting C_d coefficients between the different setups (Linda Josefsson, personal communication, 2017-03-03). Compared to the previously explained aerodynamics, which is developed foremost by the airplane industry with its streamlined designs, the passenger car suffers from the additional aerodynamic effects caused by the rotating wheels. The wheels increase the complexity that is difficult to comprehend and translate into computational fluid dynamics (CFD) analysis, mainly due to the uncertainty of the behaviour of the air flow which is created when the wheel is rotating at high speeds. It is also shown how a simple change of rim design can lead to a decrease of the total aerodynamic drag of the vehicle (Vdovin, Lofdahl, & Sebben, 2014). One example of such improvement is believed to be to cover the outer radial part of the wheel, see figure 2.11.

Figure 2.11: Increased Outer Radial Cover Allows Improved Aerodynamic Characteristics

Volvo Cars has executed several studies within the area. The most recent was performed by Qui Zhilling, et al. (2010), in order to achieve knowledge of the aerodynamic characteristics for wheel designs. Their studies were, though, limited to basically two dimensional design changes of the wheel and the resulting guidelines have been proven to be insufficient for the Exterior Design Department when developing previous aerodynamically optimized wheels.

Due to the aerodynamic turbulence that occurs around the rotating wheel, there are presently no adequate sophisticated computational fluid analysis software tools available. Presently, the Aerodynamic Department uses current available computational tools in order to estimate the wheel's aerodynamic performance in advance. But, as shown in figure 2.12, an example of a prognosis of the wheels' aerodynamic performance, the prognosis differs from the actual measured value from the wind tunnel tests with almost 10%. Which, put into context, means that the current estimation method is not accurate enough.

The development of a more sophisticated computational fluid analysis software is initiated, but in order to facilitate the development of such, more physical wind tunnel tests are considered as necessary (Christoffer Landström, personal communication 2017-02-22).

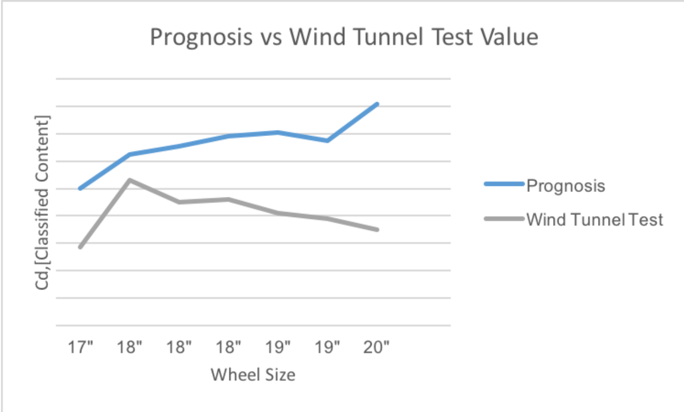


Figure 2.12: Example of C_d Prognosis Values Compared to Actual Test Values

2.7 Volvo Cars Wind Tunnel

Volvo Cars wind tunnel facility and test centre is located in Torslanda, Göteborg, with the main purpose to simulate real-world conditions and especially evaluate vehicle behaviour at high speeds. An illustration of the wind tunnel facility and its composition is visualized in figure 2.13.

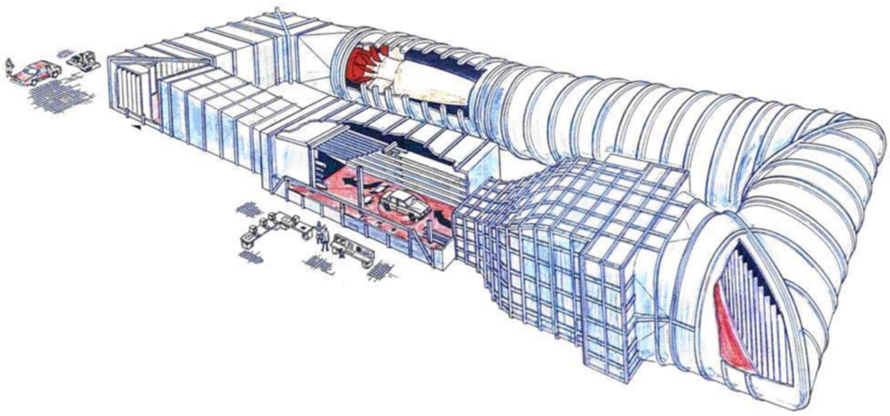


Figure 2.13: Volvo Cars Wind Tunnel Facility (Sternéus, & Walker, 2007)

The wind tunnel has been operational since 1986 and it is a full-scale facility of a closed-return type with a slotted wall test-section and equipped with a five-belt moving ground system. In 2006, the facility was upgraded to the current state, with a fan power of 5 MW, allowing wind speeds up to 250 km/h in the test section and a turn table allowing the vehicle to be exposed to winds from different angles (Sternéus, & Walker, 2007). The moving ground system consists of a centre belt, which simulates the speed of the moving ground, and four drive units that allows all four wheels to rotate in the corresponding speed of the wind.

Figure 2.14: A Volvo C30 in the Current Setup of the Volvo Wind Tunnel Facility (Volvo Cars, 2005)

A Volvo C30 is positioned on the turn table with a 30-degree angle towards the wind direction in the Volvo Wind Tunnel facility in figure 2.14 and a schematic visualization of the wind tunnel and its composition is displayed in figure 2.15.

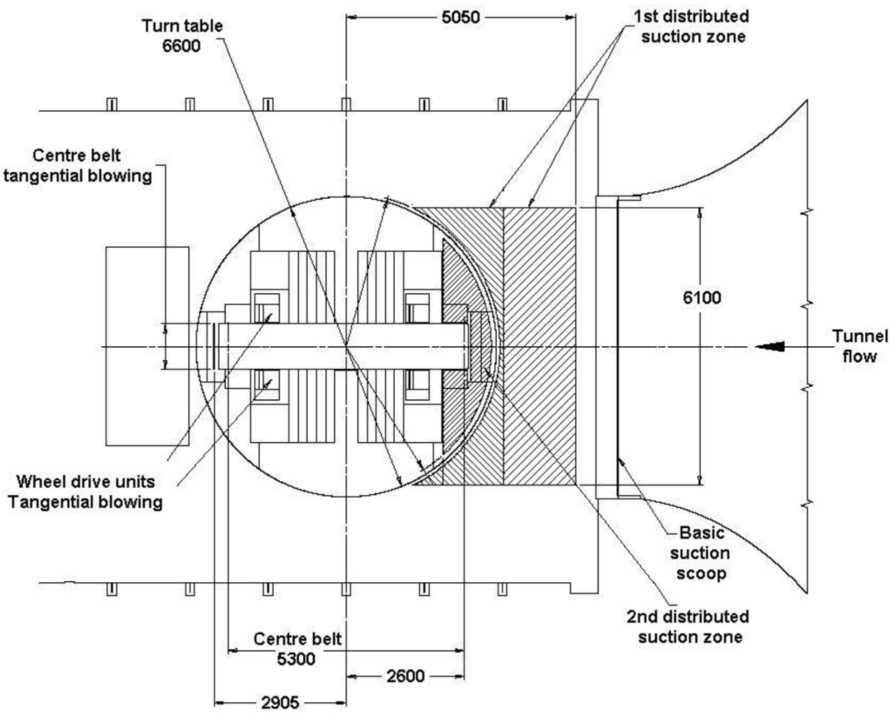


Figure 2.15: Schematic View of the Volvo Wind Tunnel Test Section Area (Zhiling, 2009)

2.7.1 Wind Tunnel Test Procedure

The initial step prior to performing the wind tunnel test, is to prepare the test object and ensure that the vehicle is set up correctly and mounted onto the turn table, with each wheel positioned on the corresponding wheel drive units (figure 2.15). The vehicle is thereafter attached to four scale sensors, which are positioned underneath the car. The sensors are connected to a large scale, positioned underneath the turn table, with the purpose of measuring the forces provoked by the vehicle during the test in x-, y- and z- direction, with a precision of 1N in every direction (Linda Josefsson, personal communication 2017-02-21).

Prior to the test it is of importance to let the wheels rotate in at least 140 km/h in order to ensure that all four wheels have the same deformation and therefore the equal aerodynamic properties (Linda Josefsson, personal communication 2017-05-16). Thereafter the test can be performed, where the large 5 MW fan accelerates the wind to the required velocity, maximum 140 km/h, and the vehicles wheels as well as the centre belt rotate accordingly. The outcome of the test is specific numerical values for the vehicle's aerodynamic drag count, C_d. The level of accuracy of measurement for the aerodynamic drag coefficient is $C_d \pm 0.001$.

As mentioned earlier, the current approach of estimating a wheel design's aerodynamic performance, computational fluid software is used, but the results differ with approximately 10% compared to the actual, measured value. Furthermore, the current process for measuring a wheel's aerodynamic influence is by performing full vehicle tests, where the only change between the test cycles are different wheels mounted on the vehicle. Thereafter, the resulting C_d coefficients for each of the different vehicle wheel setups can be compared. This implies that the wheel is required to, at least, withstand the acting forces during the test. Currently, the different wheel setups are being evaluated late in the development process since that is when the wheel have reached the required performance to undertake wind tunnel testing.

2.8 Summary of the Current State of Art and Theory

The current development process for wheels do not include the Aerodynamic Department and their input. Further, the wheel's aerodynamic performance is only considered once the verification prototype is built, a stage in the development process where any changes of the design would be financially unsustainable. Theory suggests that the development team shall consist of representatives of all concerned areas of expertise in order to be successful. In addition, a design-build-test activity of a prototype is posed as a solution for increasing the project's probability of success. The use of computational tools is also considered as a possible enhancement, but the current computational fluid dynamic (CFD) analysis tools are not adequately sophisticated to evaluate the wheels' aerodynamic properties. Therefore, must the intended solution be used during full-scale tests in the wind tunnel facility at Volvo Cars.

3. Methodology

In order to reach the desired results, the master thesis have implemented and used several tools and methodologies correlated with product development, foremost in accordance with Ulrich & Eppinger's (2012) literature. The purpose and brief descriptions of each method are presented in consequential order below and illustrated in figure 3.1.

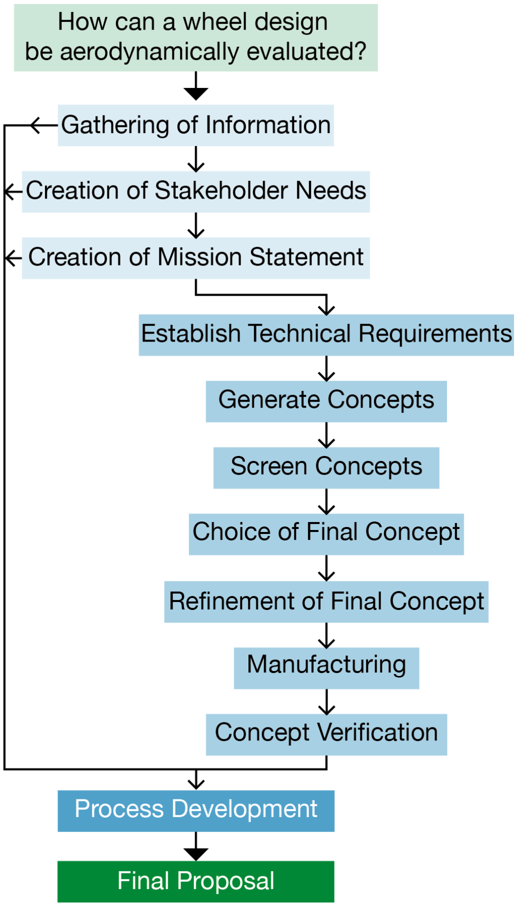


Figure 3.1: Methods and Tools Used in the Project

3.1 Information Gathering

During the first two months, thirteen meetings and interviews were held with the involved departments' representatives in order to gather various project related information, their expectations and miscellaneous input. According to Ulrich & Eppinger (2012, p.77), interviews are the most cost and time efficient method for collecting primary data. The interview structure used during the meeting depended on the agenda of the meeting. The meetings called by the student were foremost performed in a semi-structured manner. A semi structured interview facilitates the gathering of relevant information and keep the interview on the intended topic (Wallgren, 2015). Each interview lasted approximately one hour. An introduction of the topic of the meeting was presented as an initial step. Thereafter, an open discussion with the interviewees was performed and all topics were noted and documented into a meeting protocol.

In addition to the meetings held by the student, several presentations were attended, which were held by any of the representatives from the involved departments with the intention to clarify certain issues or present the current state of art and an unstructured interview approach was more suitable.

Supplementary information was gathered through studies of previously performed work, foremost presented as company publications, and literature within the field of wheel aerodynamics in order to further enhance the understanding of the issue. Lastly, product and process development related literature were also studied to enhance knowledge about the state of art and knowledge within the field.

3.2 Creation of Stakeholder Needs

In order to comprehend the issue, it was necessary to investigate and determine the involved stakeholders' needs and their ulterior purpose for pursuing this project. With the gathered information from interviews, meetings, presentations and literature studies, the different departments' needs were elicited and compiled into a stakeholder needs list.

3.3 Creation of Mission Statement

The following and simultaneously performed activity was to determine the goal for the thesis, as well as the scope. Due to conflicting desires among the involved departments, it was important to determine a common understanding of the expected outcome and ensure the relevance of the results for each department. In accordance with Ulrich & Eppinger (2012, p 67), a mission statement can be used as a tool in order to determine, specify and communicate the intended direction of the project. The use of mission statement was intended to communicate and clarify the master thesis' goals and scope. Therefore, the mission statement was modified, where the product's primary and secondary markets were replaced with primary and secondary area of application to properly fit the thesis goals.

3.4 Function Structure and Technical Requirement Specification

With a common understanding of the aim and scope of the project, the following step was to determine the required functions of the solution. By interpreting the information gathered through conversations, meetings and interviews with involved stakeholders, their needs could be translated into a list of the required and desired functions for the solution. With the purpose to further clarify and facilitate the understanding of the issue to solve, the functions were categorized and put into a function structure.

The initial development of the solution needed additional investigations of the functions and a technical requirement specification was developed in order to further clarify the respective functions. The requirement specification assigns each function with a verification method, main stakeholder, priority classification and target value with the purpose of facilitating the forthcoming development.

3.5 Concept Generation Methods

Several concepts were developed using primarily handmade and digital sketches. The concepts were either based on external or internal search, as described by Ulrich & Eppinger (2012, p 120), with the intention of exploring both new and existing concepts and solutions.

The base wheel concept generation primarily used sketches and external search, due to its technical requirements and the use of external expertise was considered as vital. The idea generating activity for the wheel design features used both internal and external searches. The design feature concepts were further explored by building physical mock-ups in order to facilitate the understanding of the implications of the different concepts, as suggested in Ulrich & Eppinger (2012, p 105).

3.6 Concept Screening

In order to objectively evaluate and select one or more concepts to proceed with in the development the Pugh Concept Selection matrix was used. This tool is commonly used in product development processes and referred to in Ulrich & Eppinger (2012, p150) as an efficient evaluation matrix which scores the concepts based on predetermined criteria. The criteria used in the matrix were based on the elicited needs and functional requirements of the solution. Each of the concepts were individually scored either with a minus, zero or plus dependant on their perceived performance compared to a chosen reference solution. The result is a total score for each concept which was used to objectively either reject or proceed with in the development.

3.7 Choice of Final Concept

With a reduced number of concepts, further evaluation of the proceeding concepts was necessary to perform in order to select a final concept to proceed with. Since two of the proceeding concepts required adjustments on the base wheel design, the wheel supplier was contacted in order to gather their input on the suggested concepts. Further, the concepts were developed in Computer Aided Design (CAD) in order to, in detail, investigate their respective mounting solution on to the base wheel. Based on the input from the base wheel supplier and the CAD investigation a final concept for further development could be chosen.

3.8 Concept Refinement

When a final concept had been chosen, the consequent activity was to further develop and improve the concept using CAD with the CATIA v5 software. This activity was performed in order to find a suitable design of the design features and evaluate the geometry with respect to the base wheel geometry. Further, the CAD software was used in order to check the assembly possibilities and restrictions.

3.9 Manufacturing

In order to produce physical models of the developed concept, the internal workshop, Concept Center, at Volvo Cars was contacted. By delivering the developed 3D geometries of the concept they could provide necessary manufacturing techniques. The base wheel geometry was adjusted and material was extracted by milling, on site at Volvo Cars. The design features were manufactured with a selective laser sintering (SLS) technique at GT Prototyper AB, an additive manufacturing sub-supplier to Concept Center. The material used for the prototypes was a polymer called PA2200.

3.10 Concept Verification - Wind Tunnel Test

The final step of the aerodynamic tool development was to test and verify its functionality and properties. As a prerequisite for the aerodynamic vehicle wheel evaluation it is, as earlier stated, necessary to be perform a full-scale test in a wind tunnel. A formerly aerodynamically evaluated Volvo S90 was used in the test performed at the wind tunnel facility at Volvo Cars in Torslanda, due to its already known aerodynamic properties and performance.

The test was performed (as described in *Chapter 2.7.1 Wind Tunnel Test Procedure*) with a wind speed of 140 km/h and four different wheel designs were tested: three variants of the design features and one with a fully covered wheel design. Each of the configurations were tested twice in order to assure the reliability of the measured C_d.

3.11 Process Development

Based on interviews, the conducted literature study of process development and the evaluation of the current development process a proposal of the aerodynamic evaluation process was developed. The results from the performed concept verification were also considered as fundamental for the development of the aerodynamic wheel evaluation process. The process development as such, was performed by discussing alternatives with the involved stakeholders based on the experience from the performed development and manufacturing of the base wheel and the design features.

The proposed aerodynamic evaluation process for wheels was developed and presented graphically and with a descriptive text of the timing of the activities as well as the related costs in order to clearly communicate its purpose and implications.

4. Results

The results of the master thesis are presented in the following chapter. The initial task was to determine and clarify the goal and scope of the project, followed by sequential development of the base wheel and the design-features mounting solutions. In addition, the manufacturing and testing of the developed solution is presented.

4.1 Interviews and Defining the Project Aim and Scope

The initial phase of the project was characterized by diverse expectations and different desired results from the involved departments at Volvo Cars. It was considered important to collect all the different expectations and needs from involved departments; *the Aerodynamic, Design* and *Wheel Department* in order to determine the goal and scope of the master thesis. By collecting the opinions from the concerned departments through semi-structured and unstructured interviews or meetings, it was possible to clarify the issues. The respective needs of the involved stakeholders are presented in table 4.1 below.

Table 4.1: Stakeholder Needs

Need	Cause	Department
Clear and comprehensive aerodynamic design guidelines	Unclear and vague design input from the Aerodynamic Department.	Exterior Design Department
Knowledge about specific aerodynamic impact caused by different design features	Inconsistent directives and inadequate aerodynamic knowledge regarding specific wheel design features.	Exterior Design Department
Verified test data of different wheel designs	Inadequate knowledge, due to insufficient amount of performed tests. Unmanageable to answer the Design Department’s requests.	Aerodynamic Department
Efficient wind tunnel wheel design test procedure	The wind tunnel facility is already being used at its maximum capacity and the WLTP introduction will further increase the need for wind tunnel tests.	Aerodynamic Department
Standardized aerodynamic wheel development process and activities.	Non-existing standard process for aerodynamic wheel development. Currently, each individual project uses individually unique procedures.	Wheel Department
Early verification activity of the aerodynamic performance	Too late verification of the wheel’s aerodynamic performance – financially unsustainable to adjust the wheel design at that stage.	Wheel Department

As seen in table 4.1, there are some differences in between the needs of the stakeholders. The Aerodynamic Department desires to perform more tests in order to enhance their knowledge within the area of wheel design. Related to that desire is the Exterior Design Department, which lacks clear and comprehensive guidelines on how to approach an aerodynamic wheel design.

Design guidelines which the Aerodynamic Department is responsible of delivering. The Wheel Department desires a process or a flow of activities to implement in future aerodynamic wheel projects, in order to be able to plan the holistic approach of the wheel development project. The Aerodynamic Department also recognizes the need for an efficient test procedure in order to be as resourceful as possible of the wind tunnel facility capacity.

During the meetings with the involved stakeholders it could be concluded that the work necessary to be performed in order to achieve a comprehensive solution for the above listed needs would in fact not be possible to perform within the limited time of the master thesis. It was therefore necessary to determine a common goal for the master thesis and its scope.

4.2 Mission Statement

In order to restrict the work load of the master thesis it was needed to reach a common agreement of what the initial development work should include. With the gathered information and additional meetings with the involved departments a mission statement was developed (see table 4.2) to state and communicate the goal and scope of the thesis for the involved stakeholders.

Table 4.2: Mission Statement: Aerodynamic Evaluation Tool for Wheel Design

Mission Statement: Aerodynamic Evaluation Process for Wheel Design	
Product Description	An aerodynamic evaluation process where a physical tool is used in order to evaluate the aerodynamic performance of the wheel design.
Benefit Proposition	Enhanced aerodynamic wheel design knowledge
Key Business Goals	• Serve as a platform for multiple tests • Project cost reduction • Reduced manufacturing time • Time-efficient assembly • Reduced aerodynamic influence for future wheels
Primary Application	Wind tunnel tests for aerodynamic wheel design research
Secondary Application	Wind tunnel tests for early aerodynamic evaluation of project wheel designs
Assumptions and Constraints	Full-scale wind tunnel tests Modular – allow interchangeable wheel design features Withstand load of the vehicle
Stakeholders	Aerodynamic Department Exterior Design Department Wheels & Tires Department

It was agreed to develop a tool, a base wheel, that together with the interchangeable wheel design features allow evaluations of a wheel's aerodynamic performance to be performed. The tool should allow all types of wheel designs to be tested. Further, the master thesis main task would be to develop a base wheel as well as investigating the possibilities and consequences of implementing an aerodynamic evaluation procedure, with the usage of the developed tool, into the current wheel development process.

In addition, it was concluded that benefits of developing such a tool could be favourable from both a cost and time perspective by simultaneously enhancing the knowledge within the area. In addition, it was determined that the primary use of the solution would be for research purposes in order to improve the aerodynamic design guidelines. The secondary application of the solution should be for future aerodynamic wheel projects and the developed project designs would be possible to test and be verified in an early phase of the development.

4.3 Function Structure

Due to the lack of comprehensive design guidelines on how to design an aerodynamic wheel and especially the limited knowledge of each design feature's specific aerodynamic influence, it was evident that the master thesis needed to develop a tool which the Exterior Design Department and Aerodynamic Department could use to further enhance their knowledge. In order to facilitate the understanding of the required functions, a list of the necessary functions was developed (see figure 4.1). Each of the required (red boxes) or desired (green boxes) functions are listed below the function categories (blue boxes).

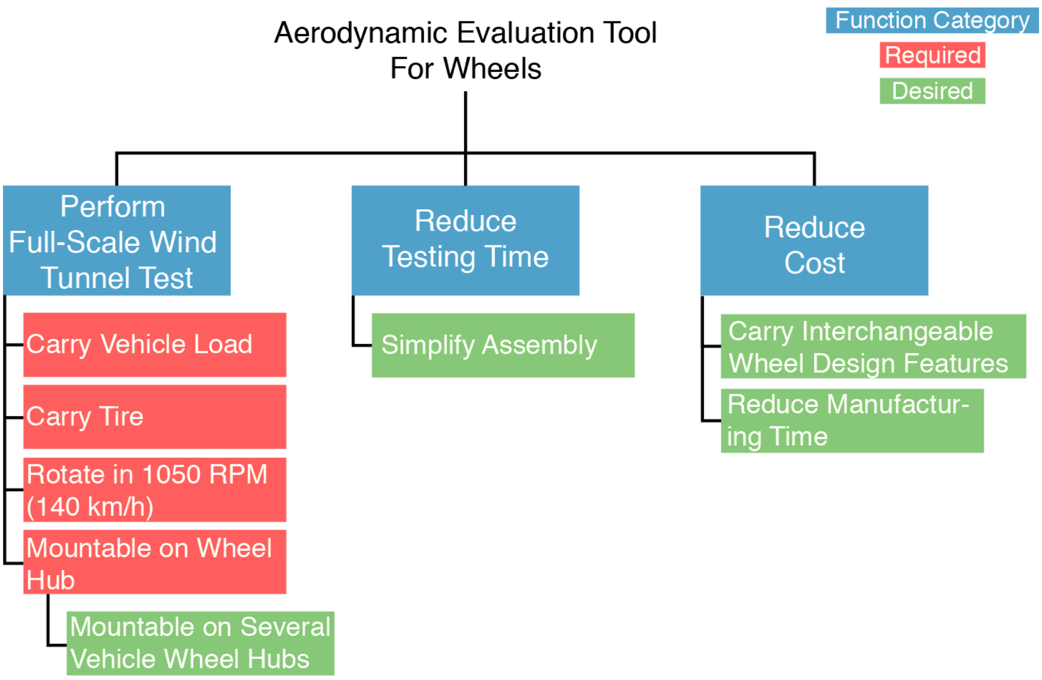


Figure 4.1: Function Structure with Required and Desired Functions for the Aerodynamic Evaluation Tool

Since the current approach of evaluating and measuring the aerodynamic properties of a vehicle, and its wheels, is by conducting full-scale tests in the wind tunnel, it is required that the intended solution is used with the same conditions. It was also recognized that a solution which could be mounted on several different vehicles' wheel hubs was desirable.

As mentioned earlier, the time spent in the wind tunnel needs to be used efficiently due to the limited capacity of the facility. Therefore, it is desirable to have a solution which enables a fast assembly and disassembly of the wheel designs. Further, as for all product development projects, cost is an issue of interest and all of the functions which could allow lower costs are considered as desirable.

4.4 Functional Requirements

In accordance with the above described required functions, the need for a wheel which has the required functions and allows as many as possible desired functions was of initial interest for the development work. To further understand the consequential requirements of the different functions, it was necessary to further break them down respectively into a requirement specification list (see table 4.3). The functions are listed with their respective category (required or desired), target values for the intended solution, verification method, priority and their main stakeholder.

Table 4.3: Function Requirement Specification List

Requirement (R/D)	Target Value	Verification	Priority (1-3)	Stakeholder
Perform Full-Scale Wind Tunnel Test				
R1: Carry Vehicle Load	N/A	FEM & Prototype Test	1	N/A
R2: Carry Tire	N/A	CAD & Prototype Test	1	N/A
R3: Rotate in 1050 RPM (140 km/h)	N/A	FEM & Prototype Test	1	N/A
R4: Mountable on Wheel Hub	Fit 1 Vehicle	CAD	1	N/A
D1: Mountable on Several Wheel Hubs	Fit >2 Vehicles	CAD	1	Wheel Dept.
Reduce Testing Time				
D2: Simplify Assembly	1 min/wheel	Mock-ups, CAD & Prototype test	2	Aerodynamic Dept.
Reduce Cost				
D3: Carry Interchangeable Features	N/A	Mock-Ups, CAD & Prototype test	1	Aerodynamic, Design & Wheel Dept.
D4: Reduce Prototype Manufacturing Time	< 6 weeks	Prototype Manufacturing	3	Wheel Dept.

The required functions are connected to restrictive requirements, such as material and geometry requirements that are based on fundamental strength and fatigue requirements and restrictions in order to fulfil its function as a vehicle wheel, where the target values are confidential. These requirements were considered to serve as basic requirements for the future solution and not to restrict the concept development, only serve as requirements once the concept is determined.

The desired functions, however, allow the solution to alter in between different approaches. It was therefore of interest to rate the level of importance of the functions in order to guide the development. The most prominent desired function was concluded to be interchangeable design features of the wheel, due to the possibilities of allowing several different designs without having to manufacture a new wheel for each test, evidently saving costs. It was also concluded that a solution which would be able to fit several, or all vehicles included in Volvo Car's fleet was of great interest. A one-size-fits-all solution was considered as a desired function which would further reduce costs and time required for development. Lastly, the desire to have a short manufacturing lead time as well as easy to assembly were, in this phase of the project, considered as functions that need to be further investigated once the overall wheel concept was determined. Where the latter, needs to take into account the time required for assembly as well as how the assembly shall be performed.

4.5 Base Wheel Concepts

The initial concept development activity was to evaluate the possibilities of fulfilling the desired functions: *interchangeable design features* and *fit several vehicles*. Studies of current solutions and current wheel design alternatives were conducted. Based on the investigation, two possible solutions were developed and they are presented briefly in the following sub-chapters.

4.5.1 Split Wheel

The split wheel concept was inspired by a particular wheel design, which allowed the wheel disc to be separated from the rim. Similar to bead lock wheels, the disc geometry is fastened to the rim by bolts on the outer circumference (see figure 4.2).

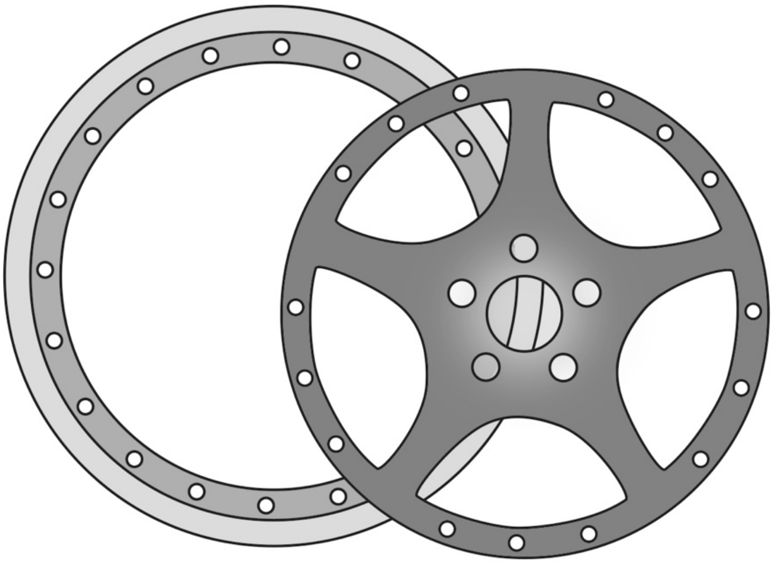


Figure 4.2: Split Wheel: Disc Separated from Rim

The identified benefit of the split wheel includes the possibility to change the disc geometry, allowing it to vary wheel offset in order to fit and be mounted on different vehicles without having to manufacture a complete new wheel. Further, the disc geometry could vary in design without affecting the surrounding rim and rim track. The recognized disadvantage was the evident need to dismount the wheel from the vehicle in order to change the wheel design. Another disadvantage was that design of the disc needed to take into account the basic strength and fatigue requirements each time a new design needed to be developed, increasing the complexity of developing the shape of the disc.

4.5.2 Base Wheel

The second identified solution was to use a conventional wheel with a reduced material on the disc area of the wheel, thus, not modifying the rim geometry and the interface towards the tire. The material on the spokes, disc circumference and centre of the wheel would be reduced (on the area facing outwards) in order to allow interchangeable design features to be fastened on the wheel (see figure 4.3).

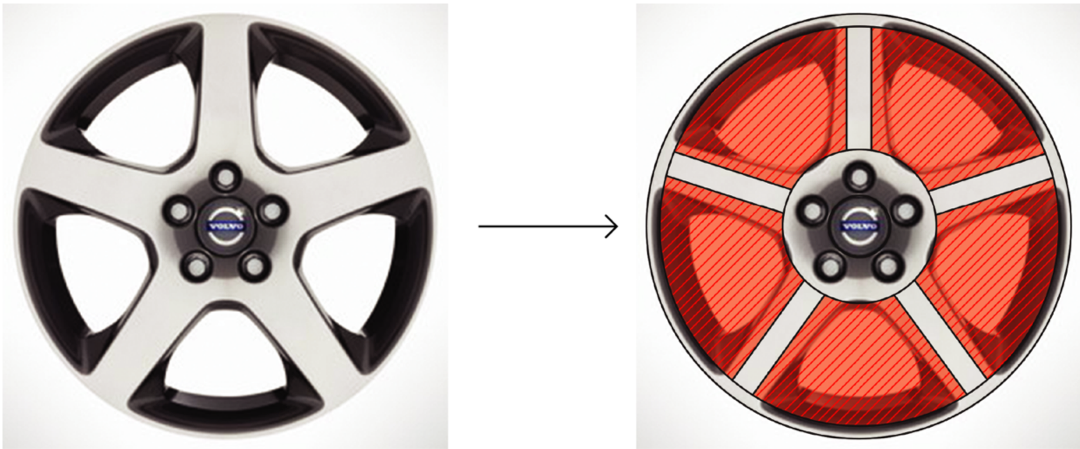


Figure 4.3: Material Reduction (marked in red) of Wheel

The thin spoke wheel, further defined as *base wheel,* would be used as a platform or base for separate interchangeable design features, as a standardized interface which the design features could be mounted on. Contrary to the split wheel, the base wheel would be able to still be mounted on the vehicle while the different design features could be exchanged. Further, the base wheel would be designed after the limiting requirements, e.g. carry vehicle load, allowing the design features to be manufactured and designed without taking those limiting requirements into account. The disadvantage however is that the disc geometry and therefore also the wheel offset would be invariable, limiting the solution to not be possible to be mounted on all vehicle types, due to the vehicle specific wheel offset.

4.5.3 Choice of Base Wheel Solution

In order to proceed the development, the two above described solutions were presented for the involved departments' representatives. While discussing the benefits and disadvantages of the two, it was concluded that the base wheel was favourable from a design, cost and time point-of-view. Whereas the primary judgement was based on the perceived fact that the base wheel would still be able to be mounted on the vehicle while exchanging the different design features. This is an important factor and appreciated property among the representatives, due to the limited availability of the wind tunnel. Further, the split wheel was considered as a too advanced solution due to the required milled or casted manufacturing process for the disc geometry. In addition, another concern was about the required developing time for each disc geometry, it was perceived to be more expensive than the base wheel solution. Therefore, the base wheel was considered as the best solution to proceed with.

4.6 Base Wheel Development

The following chapter describes the steps taken in order to develop the base wheel concept. The initial idea was a cast wheel, designed to allow interchangeable design features to be mounted onto it. Further, the base wheel needed to allow a large design freedom of the disc area in order to allow all possible configurations of shapes and designs of the different wheel design features to be mounted onto it. Examples of such wheel design features are visualized in figure 4.4 and the investigation and development of these will be further described in chapter 4.7.

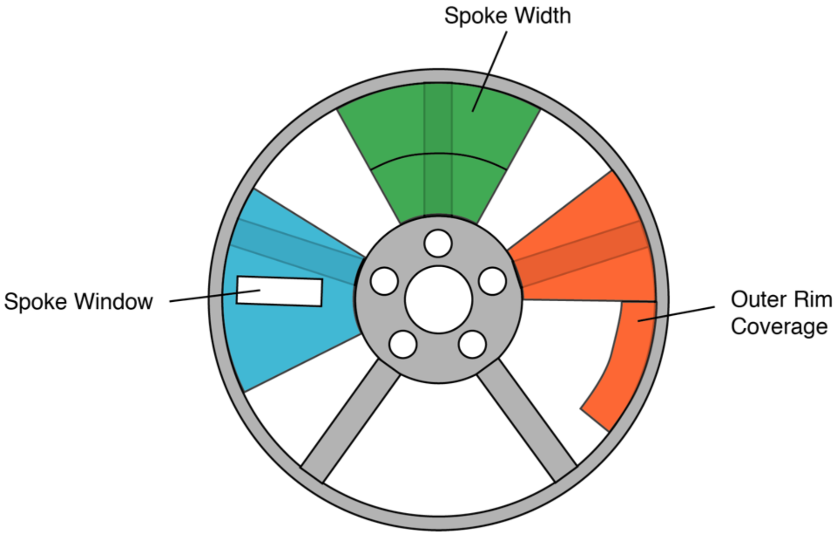


Figure 4.4: Examples of Interchangeable Design Features (blue, green and orange)

4.6.1 Choice of Base Wheel Dimension

Once the preliminary solution was set, several geometrical constraints needed to be taken into consideration and be decided upon, whereas one in particular was the size (diameter) of the wheel. Since the master thesis project was set to be finished in June 2017, it was agreed between the student and the involved stakeholders that the thesis was to focus on one wheel-size and find an appropriate solution which in the future could be applied on other wheel sizes.
In order to find dimensions for the base wheel that allowed the wheel to be mounted on as many vehicle types as possible, an investigation of Volvo Cars' offered range was performed. Based on currently predicted sales volumes for each vehicle segment: *small, medium, large and extra large vehicle type*, it was possible to comprehend the proportion of each wheel size's representation.

The choice of dimension was discussed with the involved departments and it was determined to proceed with an 18" sized wheel.

Since the solution was required to be used in a full-scale wind tunnel test, it was considered beneficial to find wheel dimensions that were possible to use on already aerodynamically tested vehicle models. The recently released SPA (scalable platform architecture) – models: Volvo S90, V90 and XC90, were considered as appropriate cars to conduct the wind tunnel test with.

The wheel offering for the SPA vehicles was therefore investigated in order to determine the remaining dimensions: *wheel width* and *offset.* Based on the current wheel offering, a wheel width of 8" and a wheel offset of 42 mm were chosen, where the latter was the minimum allowed wheel offset on the SPA vehicles. A minimum wheel offset allows the base wheel to have a maximum depth of the disc surface (see figure 4.5). This was considered as beneficial, since that allows the interchangeable features a greater area of design freedom (see figure 4.6).

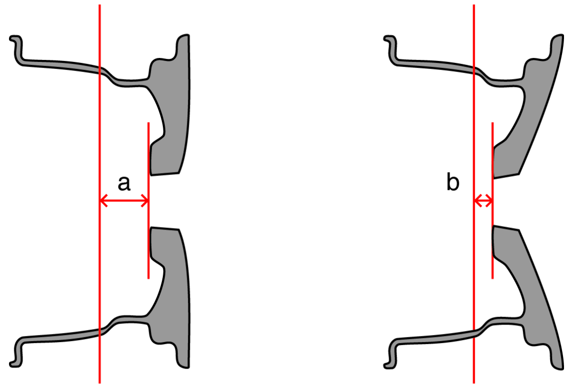


Figure 4.5: Cross-Section of Wheel. Smaller Wheel Offset Allows Larger Disc Depth

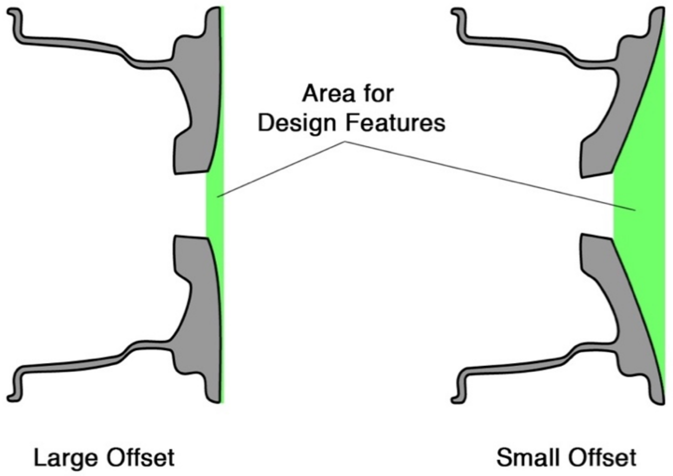


Figure 4.6: Cross-Section of Wheel with Corresponding Area for Design Features on Different Wheel Offsets

4.6.2 Choice of Base Wheel Manufacturing Method

Whilst the final dimensions of the wheel were set, the project faced a choice in between two paths to follow. The first option was to design and develop a complete wheel from scratch, requiring the rim track and spokes to be designed and verified using FEM tools, for strength calculations, and physical laboratory tests. Further, it also required to be manufactured either through milling or by manufacturing moulds and thereafter cast the wheel. A procedure which would require approximately 5-7 weeks.

The second option was to find an appropriate wheel, with identical dimensions, in Volvo Car's current production and thereafter contact the supplier and request their expertise regarding reducing the material on the specific wheel. Similar to the first option, the wheel needed to be machined by milling in order to obtain the final geometry. But, contrary to the first option, it required a maximum manufacturing time of approximately 10 working days and cost would be significantly reduced.

The identified benefit of designing a wheel from scratch, was the possibility to, in detail, design the wheel with respect to its task*; to serve as a platform for the design features*. But, the cost and time required to manufacture the wheel were considered too extensive for this master thesis and it was therefore decided to find an appropriate wheel in the current wheel offering.

4.6.3 Material Reduction and Base Wheel Requirements

A five-spoke wheel with the correct dimensions was found in Volvo Car's current wheel offering (see figure 4.7) and the responsible supplier was contacted in order to investigate the possibilities of reducing material of the chosen wheel.

Figure 4.7: CAD-Model of the Chosen Five-Spoke Wheel with Correct Dimensions

Since the wind tunnel conditions are in a controlled environment (e.g. wheels will not experience any lateral forces), the ordinary requirements of the wheel's strength and fatigue properties can be reduced. Based on still fundamental, but reduced, strength- and fatigue requirements (e.g. vehicle weight), the supplier delivered a 3D model of the reduced wheel geometry (See figure 4.8).

Figure 4.8: 3D model of the Wheel with Reduced Material

4.6.4 Manufacturing of Base Wheel

Volvo Cars' workshop, Concept Center, in Torslanda, was chosen as manufacturer of the base wheel, due to the low costs and availability. Based on the 3D model delivered by the wheel supplier, Concept Center could prepare the milling machine and extract material from the original wheel. The preparing and manufacturing of four base wheels took 10 days and the cost is of classified content and therefor not printed in this version. The final model of the base wheel assembled with tires can be seen in figure 4.9 and additional photos of the base wheel can be found in Appendix D.

Figure 4.9: Four Base Wheels Assembled with Tires

4.7 Design Features

The initially planned subsequent step for the project was to evaluate and investigate what design features that were of interest to assess and test from a design and aerodynamic perspective. In collaboration with the involved departments' representatives, the design features of interest were discussed. An example of such a design feature is described below. Similar discussions were held about other design features, but due to its classified content it is not printed in this version.

Position of Bend on Spoke

A wheel spoke can vary in multiple different designs, with altering cross-section shapes, width, depth etc. One spoke design feature that was of primary interest from an aerodynamic perspective was the position of the bend towards centre, since it correlates with how far the surface of the spoke is flat (see figure 4.10). The Design Department's main concern and perception with aerodynamic wheels are that it has to be completely flat. The intention was therefor to find a distance from the outer circumference of the wheel towards the centre of the wheel, that indicates where the aerodynamic benefits are less evident.

In order to determine the variants that were of interest, existing wheel design was investigated and three variants of the design with angled spokes were found in Volvo Cars' current wheel offering. The current wheel designs altered between either approximately 50 mm, 100 mm or 150 mm, measured from the outer circumference of the wheel, as indicated in figure 4.10.

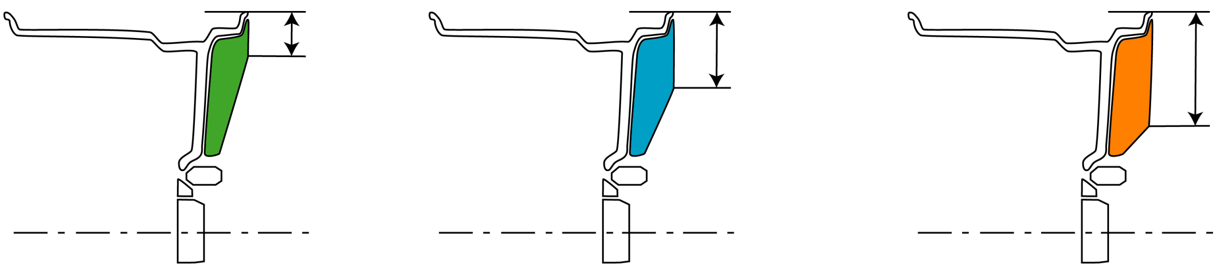


Figure 4.10 Position of Bend on Spoke, Seen from a Cross-Sectional View of the Wheel

Due to the limited time of the master thesis it was concluded that in this phase of the aerodynamic evaluation project, the master thesis should focus on *how the wheel design features should be manufactured* and *mounted onto the base wheel*, rather than deciding upon what type of features that shall be investigated. A full list of the discussed design features is presented in Appendix E, where each feature is listed with additional comments.

The following sub-chapters present the results of the development of the wheel design features.

4.7.1 Wheel Design Feature's Function Structure

A function structure chart was developed in order to facilitate the understanding of the issue. The design feature solution had three main function categories that needed to be considered for the forthcoming development. Each of the categories have corresponding required or desired functions, which are presented in figure 4.11.

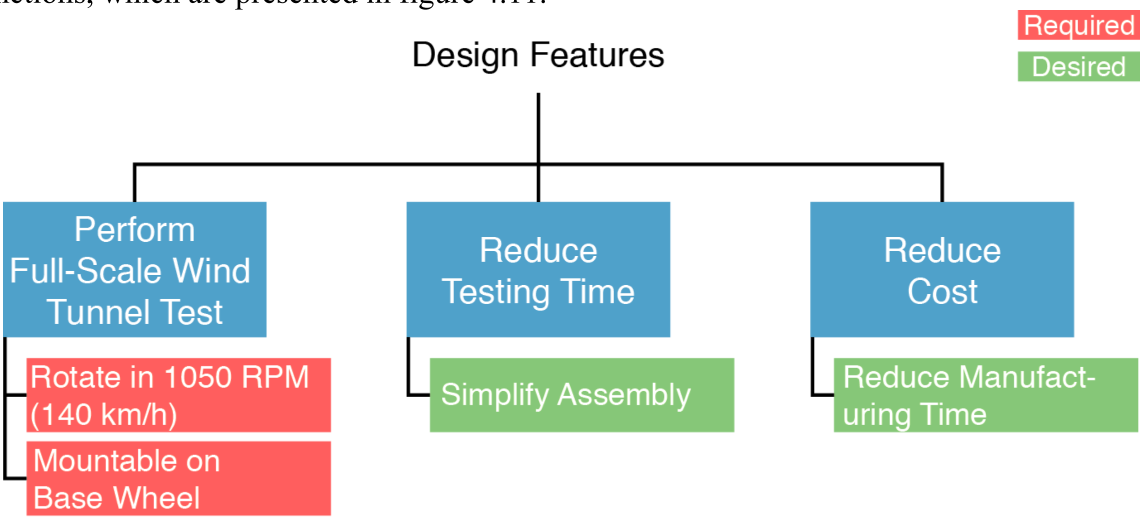


Figure 4.11: Design Features Function Structure

Similar to the functions of the base wheel, the design features are required to be able to rotate in 1050 RPM and consequently be mounted onto the base wheel. Functions that were considered as beneficial were either to decrease the required time for assembly and prototype manufacturing or by being manufactured in a cost efficient material.

4.7.2 Concept Development

The prominent area of conceptual elaboration was on how to fasten the design features on the base wheel. Initially, sketches of different alternative solutions were developed and these are presented in the following figures. The grey area in each sketch represents the cross-section of the base wheel spoke and the white figures represents the design feature.

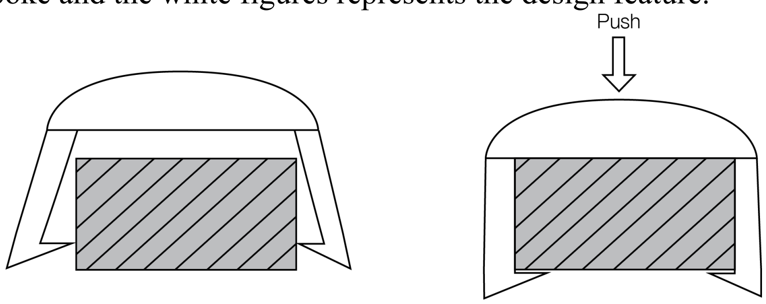


Figure 4.12: Snap-Fit Concept

The first concept, Snap-Fit (figure 4.12), uses a flexible material in order to allow it to bend the embracing clips prior to snapping into the fixed position on the base wheel.

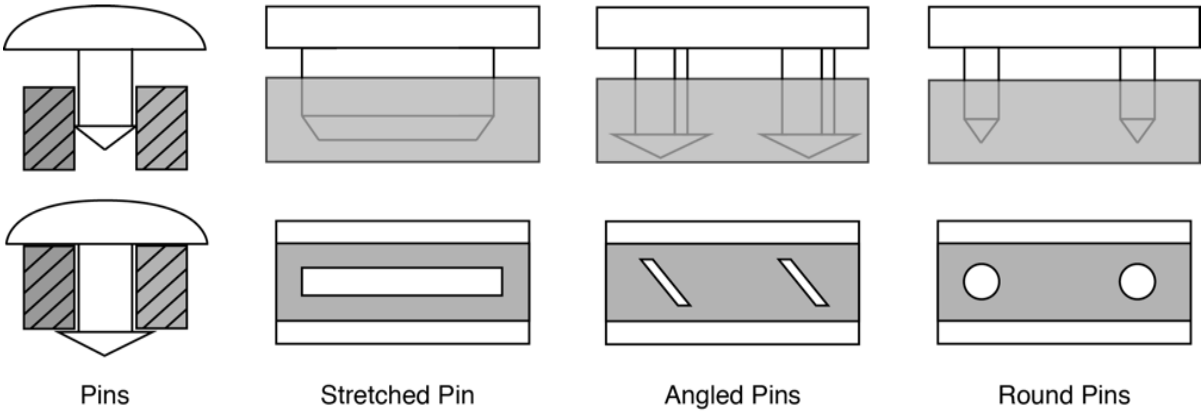


Figure 4.13: Pins Concept

The Pins concepts (figure 4.13) use similar mounting properties as the Snap-Fit concept, but by drilling holes in the base wheel spoke it allows the design features to instead be mounted with pins through the centre of the spoke. The pins thereafter expand when put into the correct position. Three alternative solutions of the pins were developed, where the stretched pin (left in figure 4.13) was developed with the intention to increase the coupling force. The second pin concept with two angled pins (middle in figure 4.13) was intended to reduce possible vibrations due to possible gaps in the fitting. The third concept was to use round pins (right in figure 4.13) similar to screws, but the elastic material and design would allow the pins to expand in all directions in order to snap-fit to the base wheel.

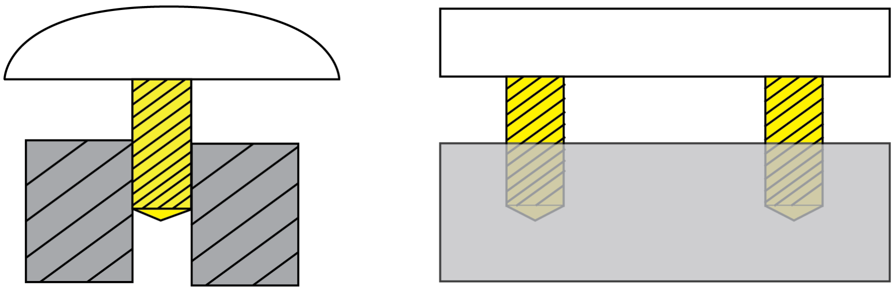


Figure 4.14: Screws

One of the more conventional solutions were to use two screws in order to mount the design feature on the base wheel's spoke (figure 4.14). Where the holes in the base wheel spoke were to be pre-drilled and threaded.

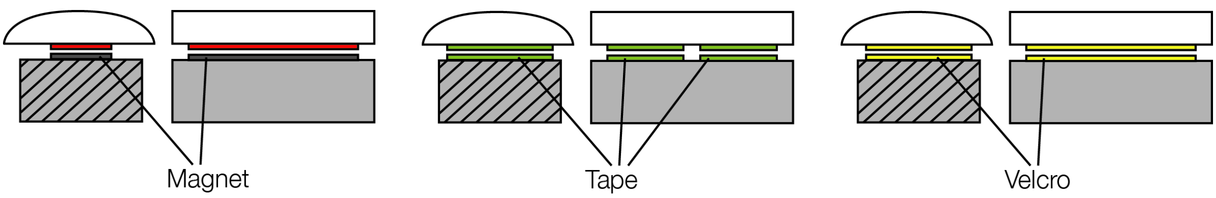


Figure 4.15: Magnet, Tape and Velcro – Fastening Concept

Based on everyday fastening solutions, three more unconventional concepts were developed, where the use of magnets, tape or Velcro would enable the features to be mounted on the base wheel (figure 4.15)

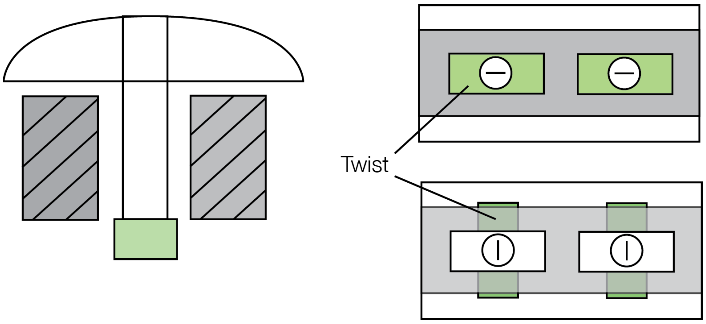
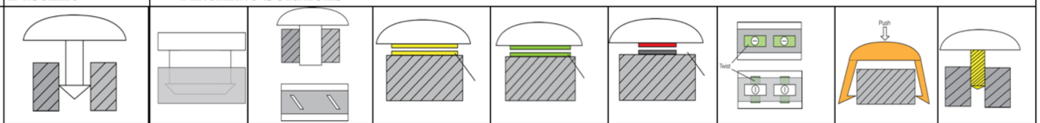


Figure 4.16: Twist Concept, 90 Degree Twist to Fasten the Design Feature

Lastly a concept which is developed as a mix between the pins and the screw concepts was developed. The Twist concept allows two pins to rotate 90 degrees in order to be mounted and fastened on the base wheel (figure 4.16)

4.7.3 Concept Selection

The following step in the concept development process was to evaluate and compare the developed concepts. By using a Pugh matrix, it was possible to assess the concept objectively, based criteria translated from the identified needs and described functions. The Pugh matrix is presented in figure 4.17.



	Baseline	Alternate Solutions							
PUGH MATRIX: FEATURES									
Criteria	Reference Solution: Pins	Stretched Pin	Angled Pins	Velcro	Tape	Magnet	Twist Pin	Snap - Fit	Screws
Manufacturing (Time)	0	0	0	-	-	-	-	0	0
Simplify Assembly	0	0	0	+	+	+	+	0	+
Robustness (Adhere on Base-Wheel)	0	+	0	-	-	-	+	+	+
Product Complexity (Cost)	0	0	-	-	-	-	-	0	-
Feasibility	0	0	0	-	-	-	+	+	+
Sum of all Positives	0	1	0	1	1	1	3	2	3
Sum of all Negatives	0	0	1	4	4	4	2	0	1
Sum of all Neutrals	5	4	4	0	0	0	0	3	1
Total:	0	**1**	-1	-3	-3	-3	1	**2**	**2**

Figure 4.17: Pugh Matrix for Fastening Concepts

Each of the concepts' score was based on an approximation of the performance for each criterion compared to a reference solution. The reference used in the matrix is the concept of having two expandable pins, a solution which was in advance considered as a promising solution, mainly due to its simplicity. By using criteria such as *product complexity* and *robustness*, the intention was to find plausible and promising concepts to proceed with and further develop. Based on the results from the Pugh matrix, three concepts were considered to be of interest for further development: *The Stretched Pin, The Snap Fit* as well as *The Screws.* Mainly since all of them were considered as to be more robust than the reference and due to their perceived feasibility. The adherent concepts with tape, Velcro and magnets were considered as less robust and therefore less feasible as solution for mounting the features onto the base wheel.

4.7.4 Concept Mock-ups

In order to further evaluate the selected concepts, full-size mock-ups of the concepts as well as the base wheel spoke were built. Cardboard was used to build the two fastening concepts and the spokes of the base wheel mock-up was made out of wood in order to represent a more robust material. By testing each concept onto the base wheel mock-up it was possible to gain further understanding of their properties. Photos from the mock-up build can be seen in figure 4.18.

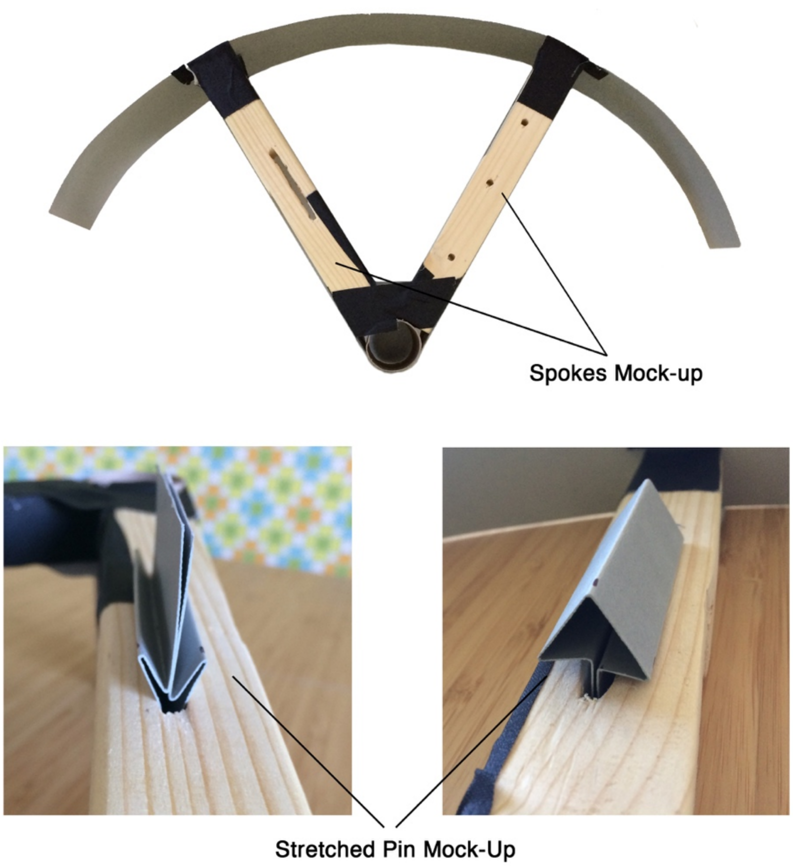


Figure 4.18: Photos of Base Wheel Spokes and Stretched Pin Concept Mock-ups

One of the most noticeable discoveries was that the fastening solution needed to be very geometrically precise in order be robust and securely fastened onto the base wheel. Further, it was also concluded that conventional screws were the most robust solution and seen from a development time perspective, it would require less effort when modelling the design features in CAD.

4.7.5 Further Development

Based on the experiences from the mock-ups, it was determined to proceed the development of the three concepts by constructing them in CAD, in the provided Catia V5 software. With the purpose to further compare their feasibility and ease of handling. But, prior to proceeding with the development, the supplier of the base wheel geometry was contacted in order to investigate the possibilities of making holes in the spokes and what effects that would have on the base wheel geometry.

Their response was that the base wheel spokes needed to be thickened in order allow the large hole required for the stretched pin concept. The stretched pin concept was therefore eliminated for further development.

In order to allow screws to be fastened in the base wheel spokes, the holes in the spokes would need to be threaded. But, since the wheel is made from an aluminium alloy, the threads would be easily worn out due to its soft material properties. Therefore, a new substituting concept to the screws was developed, where the screws were to be fastened into an underlying plastic piece, positioned behind the spoke (see figure 4.19). The plastic piece behind the spoke was intended to be thin enough to only hold a thread insert, to allow the screws to connect the two parts.

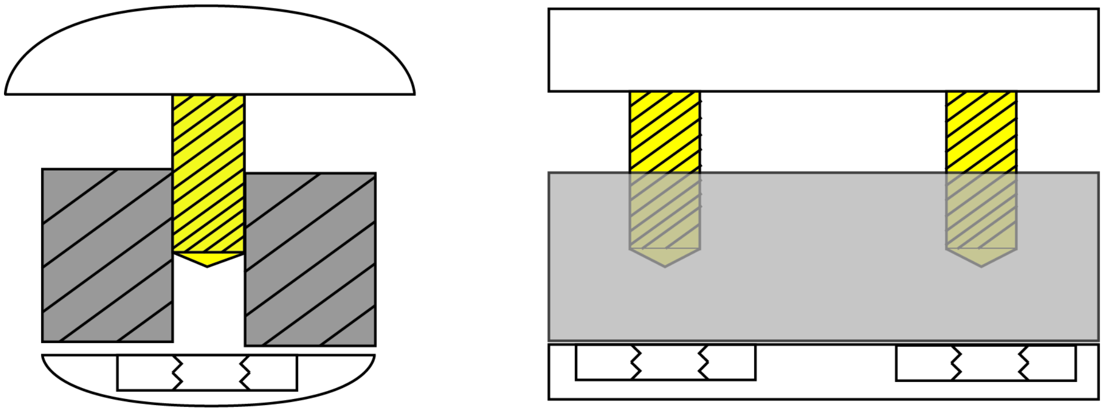


Figure 4.19: Screw Concept with Underlying Piece with Threaded Inserts

By proceeding the development in CAD, the two concepts, *Snap-fit* and *Screw,* could be visualized in a 3D environment and thereafter mounted onto the 3D geometry of the base wheel in order to further evaluate and assess their properties and geometries.

While assembling the screw concept on to the base wheel geometry, it was recognized that the base wheel geometry did not allow enough space between the back of the spoke and the brake calliper (see brake restriction in figure 4.20). Therefore, it was decided to proceed with the Snap-Fit concept, which did not interfere with the space on the back of the spoke.

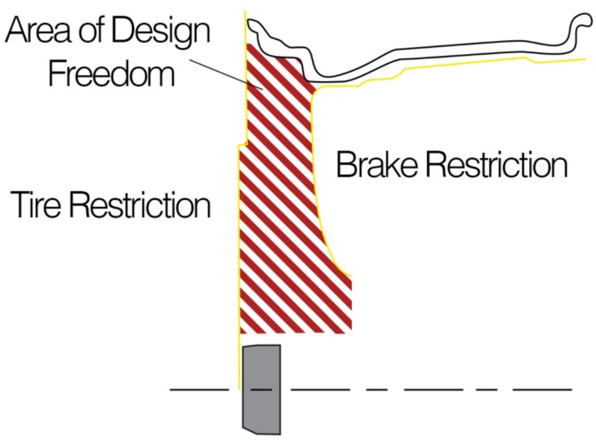


Figure 4.20: Restrictions for Wheel Design

4.7.6 Final Concept

The final concept for the snap-fit design was developed and designed using CAD in order to fit and match the base wheel geometry. The snap-fit geometry design was developed and adjusted in accordance with a snap-fit design manual provided by BASF (BASF, 2007). The snap-fit solution is visualized in figure 4.21.

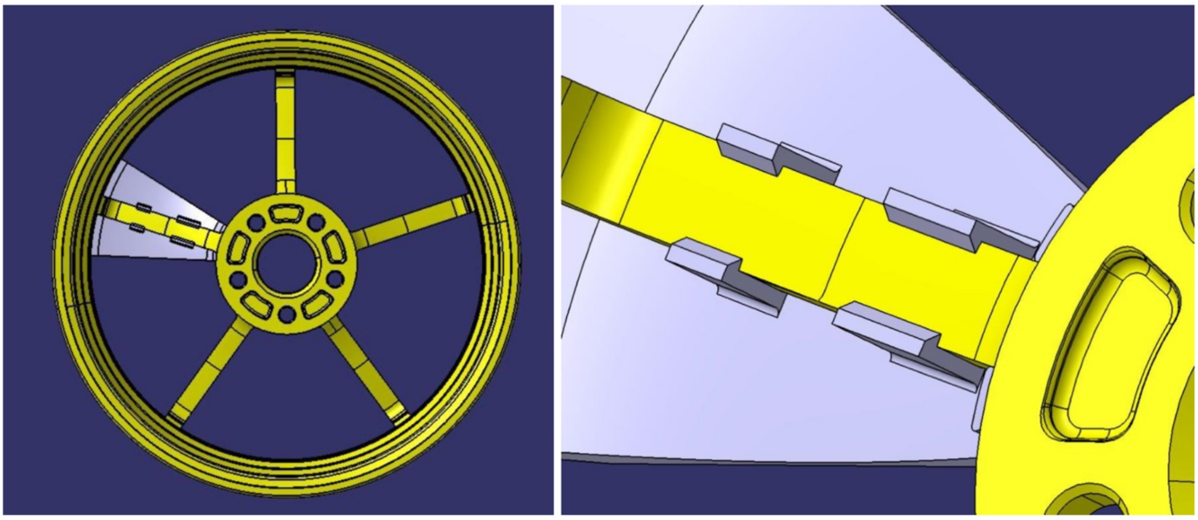


Figure 4.21: Snap-Fit Solution for Design Features (Grey Geometry) Mounted on the Base Wheel (Yellow Geometry)

Two snapping geometries were considered as fundamental in order to secure the feature onto the base wheel. Further, the design feature was equipped with supporting geometries towards the centre of the wheel in order to be easily mounted into the correct position (see figure 4.22)

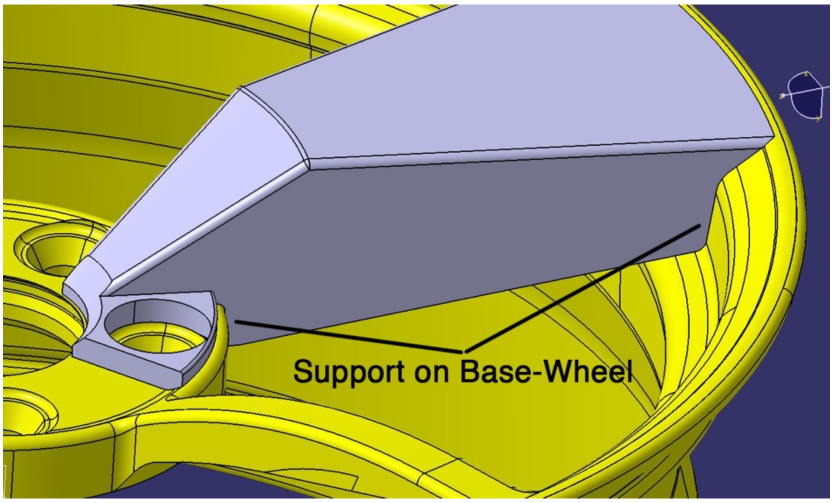


Figure 4.22: Supporting Geometry of Features against Base Wheel

The design feature should only vary one parameter when performing the aerodynamic evaluation in order to establish correct aerodynamic results of the specific parameter's influence. Due to the limited time of the thesis, only one wheel design feature was developed in CAD prior to the wind tunnel test. The chosen wheel design feature was the position of the bend, presented in chapter 4.7. The distance between the bend and the outer diameter of the wheel was either 50mm, 100mm or 150mm, which correlates with current distances on Volvo Cars' wheel designs. The developed CAD models of the wheel design features are presented in figure 4.23.

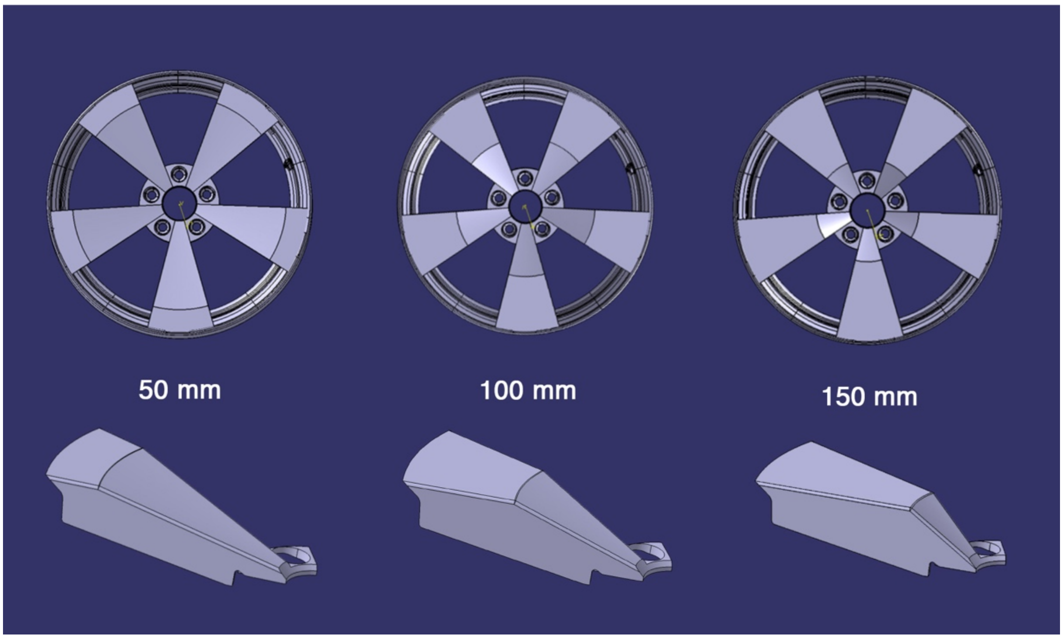


Figure 4.23: Design Features with Varying Bend Position (measured from the wheel's outer diameter)

The CAD-models were thereafter sent to Concept Center for manufacturing, where the selective laser sintering (SLS) technique was used in order to obtain the required level of detail as well the correct material properties. The material used was a nylon material called PA 2200, which can allow the snapping geometries to be flexible but still have the stiffness where its required. The final manufactured prototypes are visualised in figure 4.24 and additional photos of the final concept can be found in Appendix F.

Due to unexpected manufacturing inaccessibility at Concept Center, the manufacturing work was outsourced to GT Prototyper, in Ystad, Sweden, a supplier of additive manufactured parts. The three different wheel designs developed in this project were manufactured in approximately five days.

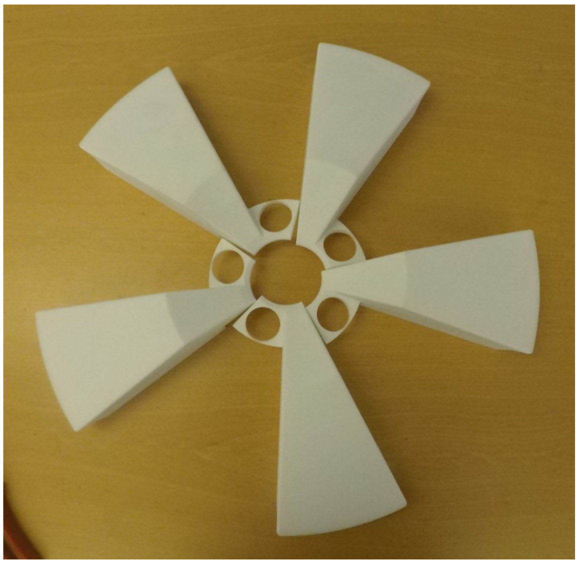


Figure 4.24: Photo of SLS Manufactured Prototypes of the Design

4.8 Concept Verification

The Wind Tunnel Facility at Volvo Cars was used in order to test and verify the properties of the developed concept, where a Volvo S90 was assembled together with the base wheels (See figure 4.25). As described in chapter 2.7.1, the test was performed with a constant wind velocity of 140km/h in order to reach desired properties of the air flow, with corresponding rotation of each wheel.

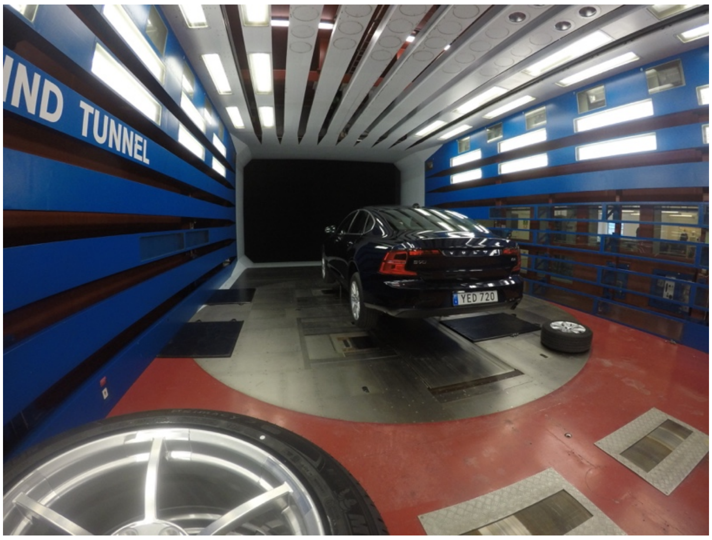


Figure 4.25: Volvo S90 in Volvo Wind Tunnel Prior to Test

In total ten tests were performed, where each variant of the features was tested twice in order to ensure the measured results validity. In addition to the test of the features, two tests with a fully covered disc design were performed in order to obtain a reference. The results are presented in table 4.4 below.

Table 4.4: Test Data from Wind Tunnel Test

Test #	Configuration	C_d
1	Fully Covered Disc	0,300
2	Fully Covered Disc	0,300
3	Base Wheel & Feature 150mm	0,312
4	Base Wheel & Feature 150mm	0,312
5	Base Wheel & Feature 100mm	0,313
6	Base Wheel & Feature 100mm	0,313
7	Base Wheel & Feature 50mm	0,314
8	Base Wheel & Feature 50mm	0,313

As presented in the table above, the difference in between the maximum bend position (150mm) and the minimum bend position (50mm) was 0.0015 – 0.002 C_d, where the latter performed less well. In other words, this means that it is beneficial to have the bend on the spoke closer to the centre of the wheel. Further, this particular design of the spoke allows the vehicle to reduce its emissions with approximately 0.1 g CO_2/km compared to having the bend 50mm from the outer rim circumference.

Figure 4.26: Design Feature (150mm) Mounted on the S90 in the Wind Tunnel Facility

The spoke design features with the bend positioned 150mm from the outer rim diameter can be seen in figure 4.26. During the assembly of the features it was realized that the snap-fit geometry was able to break and the damaged features were fastened with tape for additional support (as seen in figure 4.26).
The total duration of the wind tunnel test was five hours, where each of the performed tests required approximately two minutes. The remainder of the time was spent preparing the test and the vehicle as well as assembling and disassembling the wheel setups. The assembly and disassembly of the design features was recorded on film and acquired approximately one minute per wheel.

4.9 Concept Cost and Time

The manufacturing cost for a complete set of base wheels and one setup of a wheel design, using the SLS manufacturing technique, reduces the costs with approximately 60-80% (numerical values are confidential and therefore not printed in this version), compared to milling the complete wheel design. The cost for the design features is depending on the geometry of the features due to geometrical limitations of the SLS machines. Therefore, the price may vary depending on how many SLS manufacturing boxes that need to be used for manufacturing the features.

In terms of required time for manufacturing the developed solution, the total duration from finished 3D geometry of the base wheel to final physical model is approximately 10 working days. Where the 3D geometry needs to be prepared and the supporting structures for the base wheel need to be manufactured prior to milling the base wheel geometry. The wheel design features were as described manufactured with a SLS technique, which allows a rapid manufacturing and similar to the costs, the time required is depending on the geometry. This project's design features were manufactured within five working days. Further, compared to milling the complete wheel, the manufacturing of the base wheel as well as the design features can be performed in parallel, allowing the total manufacturing time to be ten working days.

4.10 Evaluation of Project Results

The initial performed activity in this project was to comprehend the stakeholders' needs and thereafter determine a common goal and purpose of the project, which stated that the master thesis shall deliver *an aerodynamic evaluation process where a physical tool is used in order to evaluate the aerodynamic performance of a wheel design.* The developed base wheel and the developed mounting solution for the wheel design features enable an evaluation of the aerodynamic performance of different wheel designs to be performed. The purpose of serving as a tool for evaluation is therefor considered to be fulfilled.

In terms of stakeholder needs, the developed evaluation tool for wheel designs can be used in order to establish comprehensive aerodynamic guidelines as well as determining specific characteristics for a wheel design feature. Evidently, it can be used to achieve verified test data of different wheel design as requested by the Aerodynamic Department. Further, the developed assembly solution for the wheel design features was considered as an efficient solution which met the stated target value of approximately 60 seconds per wheel. A complete comparison of the results for the developed evaluation tool and the stated requirements are presented in table 4.5.

Table 4.5: Requirement Specification Fulfilment

Requirement (R/D)	Target Value	Verification	Fulfilled (Y/N)
Perform Full-Scale Wind Tunnel Test			
R1: Carry Vehicle Load	N/A	FEM & Prototype Test	YES
R2: Carry Tire	N/A	CAD & Prototype Test	YES
R3: Rotate in 1050 RPM (140 km/h)	N/A	FEM & Prototype Test	YES
R4: Mountable on Wheel Hub	Fit 1 Vehicle	CAD	YES
D1: Mountable on Several Wheel Hubs	Fit >2 Vehicles	CAD	NO*
Reduce Testing Time			
D2: Simplify Assembly	1 min/wheel	Mock-ups, CAD & Prototype test	YES
Reduce Cost			
D3: Carry Interchangeable Features	N/A	Mock-Ups, CAD & Prototype test	YES
D4: Reduce Manufacturing Time	< 6 weeks	Prototype Manufacturing	YES

* The developed base wheel only fits on SPA models.

In terms of requirement fulfilment, the developed solution fulfils all but the desired possibility to be used on several different vehicles. But, the developed solution can be adjusted in order to fit other vehicle segments in Volvo Cars' offering besides the vehicles built on the SPA platform.

5. Process Development

In addition to the developed base wheel solution, this master thesis has analysed the consequences of implementing an aerodynamic evaluation process into the current wheel development process. With respect to the studied literature, there are several adjustments that can be implemented into the current wheel development process in order to enhance its results, with focus on time, cost and risk reduction. A generalized and simplified version of the current process is visualized in figure 5.1.

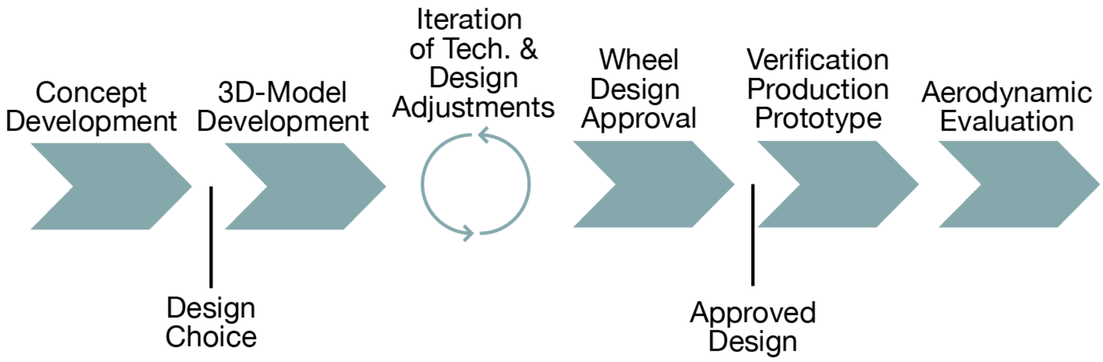


Figure 5.1 Simplified Illustration of Current Wheel Development Process

Firstly, it was recognized that the Aerodynamic Department did not have any influence or involvement in the early design development phase of the wheel projects. An absence of relevant aerodynamic knowledge was identified within the current development team. It is therefore suggested that once the vehicle line management (VLM) requests an aerodynamic wheel design or a targeted aerodynamic value for the wheel, the Aerodynamic Department shall be included in the development team for the specific wheel project. This would enhance the knowledge within the development team and the aerodynamic input can be considered earlier in the wheel development process, allowing the design to be adjusted accordingly in a less costly manner compared to the current approach.

Further, aerodynamic wheel design is still considered as an area that needs further research and there is, currently, a risk of not knowing the aerodynamic influence of specific design features. It is therefore suggested to use the developed base wheel solution to perform the research in order to gain the desired comprehensive aerodynamic wheel design guidelines.

In addition, since aerodynamic wheels are already of importance for the company, there is a need to verify the aerodynamic properties for the near future wheels as well, in parallel with the proposed research. It is therefore suggested that future aerodynamic wheel projects shall implement and plan a design-build-test activity into the current wheel development process, which will be further described in the following sub-chapter.

5.1 Design-Build-Test Activity

As described in chapter 2.2, it is posed that by implementing a design-build-test activity of a prototype early in the development process, the risk of costly and time-consuming late iterations in the development process decreases. The developed base wheel solution allows such an activity to be performed with the project specific wheel design mounted onto the base wheel in order to verify its aerodynamic performance. The following section describes each required activity in order to perform the design-build-test activity and an illustration of a generalized development process is visualized in figure 5.2.

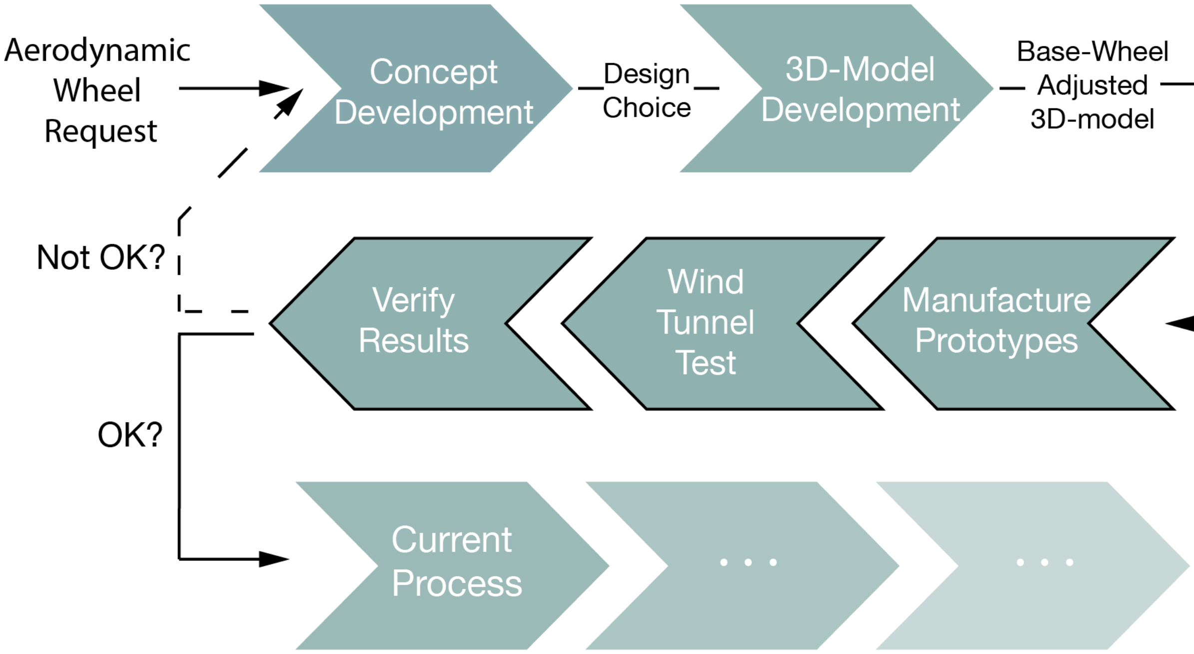


Figure 5.2 Aerodynamic Wheel Design Evaluation Process, Implemented with a Design-Build-Test Activity

Concept Development
Similar to the current process, the initial step is to select a design of the wheel, but by including the Aerodynamic Department the choice of design can be influenced by their expertise and aerodynamic input.

3D model of Wheel Design
A 3D geometry of the wheel design needs to be developed in order to be able to manufacture the prototype. Where the construction of the design needs to adapt or consider the base wheel geometry and apply the snapping geometries.

Manufacturing of Wheel Design
The finished 3D model of the wheel design feature shall thereafter be sent to the additive manufacturing supplier, whom manufactures the geometries. The required time for manufacturing is dependant on the number of parts as well as the geometry itself, but in general it requires 5-7 working days. In terms of costs, four complete wheels manufactured with the SLS technique is dependant on the geometry and suitability for packaging in the SLS machine.

Wind Tunnel Test
Perform the wind tunnel test, with at least two tests of each wheel design and use a flat wheel disc design as reference. Each individual test requires approximately two minutes and by considering assembly and test preparations, one timeslot (6 hours) in the wind tunnel facility is adequate for performing testing approximately 3-5 wheel designs.

Verify Results
Compare the results with aerodynamic target values or requirements. If the results are coherent with the targeted values, proceed as with the current wheel development process. If not, allow further aerodynamic input on the design and perform a second iteration of the design-build-test activity. When the aerodynamic properties are of agreement with requirements, the wheel development process can proceed as usual.

The total duration for the proposed design-build-test activity is difficult to estimate, due to uncertainties regarding the time for developing and choosing the wheel design as well as the time necessary for developing the 3D model. But, what can be determined based on the experiences gained throughout the performed master thesis, is the duration for manufacturing, testing and verifying the aerodynamic performance of the wheel. In other words, when the design of the wheel is chosen and the CAD model is developed, the remaining activities; *manufacturing, wind tunnel testing* and *verifying of the results* can be performed in approximately eleven working days.

6. Discussion

The master thesis has developed a base wheel, a mounting solution for the wheel design features, a proposal on how a future aerodynamic wheel development process can be executed and performed a wind tunnel test of a specific wheel design feature. The results of the performed project are considered to fulfil the stated goal and purpose. But, there are areas of concern that need to be discussed and further elaborated, which are presented in this chapter.

Overall, the methods used in this project are considered to be sufficient and appropriate, but the planning of the project as well as determining deliveries for each week could have been improved in order to improve the project efficiency. The lack of experience in building physical prototypes as well as time-consuming bureaucracy, commonly found in larger companies, resulted in several unpredicted late deliveries. Where the most prominent consequence was that the base wheel prototypes and the spoke design features were delivered the day before the wind tunnel testing and there was therefor no time to prepare and evaluate the assembly prior to the test.

Other adjustments that would have been beneficial from a product development perspective, would be to perform a design-build-test activity in order to evaluate the interface between the base wheel and the wheel design features. This would have allowed the snap-fit geometry to be properly tested and further adjusted to be more robust and match the physical base wheel geometry prior to the wind tunnel test.

Considering the results of the project, with respect to the environmental benefits, the developed solution allows Volvo Cars to have the possibility to further test and verify other wheel design features. This would reduce the aerodynamic drag and therefore decrease the vehicle emissions. Furthermore, the use of SLS manufactured interchangeable wheel design features instead of milling the complete wheel design from aluminium is assumed to reduce the environmental impact of the manufacturing. The environmental benefit has not been verified and no life cycle assessment has been performed due to the limited time of the master thesis.

Lastly, it should be discussed if the outcome of the project would have differed if it was performed by a team, instead of one student. It has been identified during the progress of the project that a lack of a project team member has made it more difficult to develop and discuss different concepts as well as objectively reflecting on the results. Even though the student has had several informal conversations and discussions with both the supervisors as well other involved stakeholders of the project, it is still necessary to recognize that a second full-time team member might have improved the progress and the concluding results of the project.

7. Conclusions

The performed project has reached the intended results, by developing and delivering a tool on which wheel designs can be evaluated from an aerodynamic perspective. Several results and discoveries have been reached throughout the performed project with corresponding conclusions which are presented in this chapter.

Firstly, the area of wheel aerodynamics is complex. Evaluations of the corresponding aerodynamic effects for different wheel designs features are necessary to perform in order to enhance the knowledge within the field. Therefore, it is considered as necessary to perform a large study of the field, with full-size wind tunnel tests of the different wheel design features. The results of this master thesis have shown to be an efficient procedure for performing such.

It is also recognized that the use of the base wheel and additive manufactured interchangeable wheel design features is less costly and require less time than the alternative of milling each wheel design. The resulting procedure is shown to reduce the manufacturing time for the required testing parts with approximately 80%.

In terms of cost reduction, the developed solution can reduce the costs with approximately 60-80% compared to the alternative of milling the complete wheel. Further, it is necessary to enlighten that the base wheel geometry can be re-used in order to test different designs in several projects, with the restrictions of the wheel having the same geometrical limits. Allowing the costs to be further reduced if the same base wheel can be used.

The base wheel solution allows a design-build-test activity to be performed in order to test and verify the wheel's aerodynamic properties in an efficient manner. If implemented into the current development process, it would acquire approximately 11 working days for manufacturing and testing. Which, compared to the current procedure of milling the wheel design allows the development time to be reduced to approximately 4-6 weeks, which in turn represent 10-15% of the total process duration. Further, the implementation of the design-build-test activity allows the wheel design to be assessed in an early stage of the process and therefore the risk of aerodynamically unsuitable wheels can be reduced.

The proposed early involvement of the Aerodynamic Department and their provided expertise in the wheel development process is considered to be of essential value for the forthcoming aerodynamically optimized wheels.

Lastly, the performed wind tunnel tests have proven that a minor design variation influences the C_d of the whole car. In addition, it is proven that the level of influence of the variation of the design features is measurable in the wind tunnel.

8. Recommendations for Future Work

The conducted master thesis is considered to have reached its predetermined goals, by delivering a solution which is both more cost-efficient and less time-consuming than the current evaluation procedure. There is, however, further work that needs to be considered for forthcoming development and implementation of the developed solution.

Firstly, the developed base wheel solution with the use of an existing wheel design was chosen due to the limited time of the master's thesis. It was recognized during the project that in order to achieve the largest design freedom of the disc area, the development of a customised wheel would be preferable. Therefore, it is suggested to develop and design a base wheel with simpler spoke design in order to facilitate the snap-fit design and its assembly.

The performed project has shown that the use of a base wheel and additive manufactured design features is a suitable solution for performing wind-tunnel tests. The design features' snap-fit mounting points do need further adjustments in order to not break during assembly. It is suggested to redesign the snap-fit geometry and thicken its material. Another alternative solution, discussed with Martin Ödlund at Concept Center, is to put the design features in water directly after the SLS manufacturing in order to obtain more elastic material properties of the nylon.

The base wheel prototype developed in this project has proven to be sufficient enough to perform the wind tunnel tests, but additional fatigue calculations need to be performed in order to determine how many additional tests that can be performed with the same base wheel.

In terms of wheel aerodynamics, the master thesis has only performed one test of the wheel design features and further tests of different features and their combination need to be assessed in order to obtain comprehensive design guidelines. Further, the thesis has not considered all type of design features to its full content, it is therefore suggested to build and evaluate different design features and their interface towards the base wheel in CAD. This is in order to investigate any limiting properties of the base wheel that can restrict the possibilities of mounting some design features on the base wheel. In addition, the developed snap-fit solution of the design features has only considered the spoke as a fastening geometry. It can be of interest to further evaluate the base wheel for alternative mounting opportunities that are more suitable for other types of design features, e.g. rim track design.

In order to further evaluate the wheel designs' aerodynamic influence, it can be of interest to evaluate additional wheel dimensions. The developed base wheel solution is considered to be adaptable and applicable to any wheel size since it does not interfere with any of the restrictive geometries of the wheel.

The performed verification of the concept showed a decrease of 0.002 of the vehicle's C_d, which in turn corresponds to a reduction of approximately 0.1 g CO_2/km. It is necessary to clarify that even though the result of this specific test implies a rather small environmental improvement, it is still considered that by conducting further tests within the field, superior environmental improvements can be reached.

Lastly, future extensive research and tests can enhance Volvo Car's competitive edge with attractive and unique aerodynamically optimized wheel designs.

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Appendices

Appendix A: Illustration of Current Wheel Development Process

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Appendix B: The Rim

The rim, or rim track, is the cylindrical surface on which the tire is mounted on and its design is mainly dependent on the vehicle weight and tire dimension. The European Tyre and Rim Technical Organisation (ETRTO) has developed a geometric standard with the purpose to facilitate the development and choice of rim track. The standard is considered and a part of the wheel development process at Volvo Cars in order to ensure that the requirements are being considered properly. Volvo Cars outsources the actual development and choice of rim track design to the suppliers of the wheels, mainly due to their unsurpassable technical experience and knowledge within the area. However, Volvo Cars still preserves the right to affect the choice of rim track in order to reach the desired design of the wheel. The area of such involvement is the visible part of the rim track, more precisely, the appearance of the surface in between the spokes of the wheel. There are mainly three types of rim tracks that are of interest for the following report: *technical, concave* and *convex rim track* (See Figure B.1).

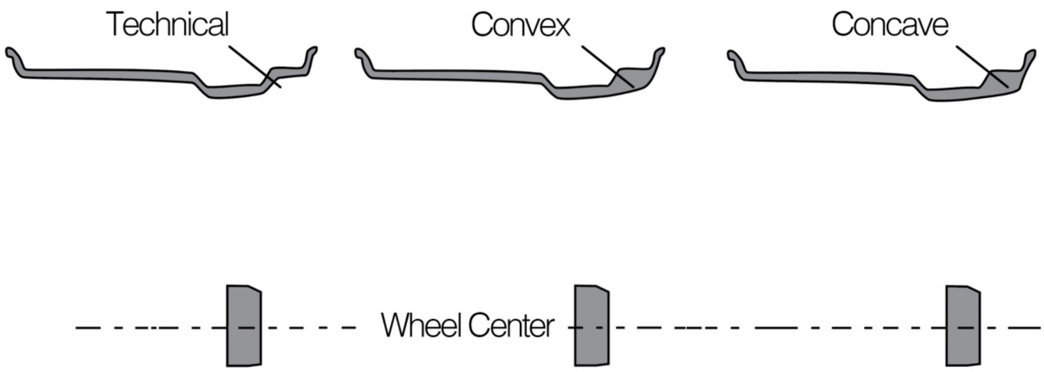

Figure B.1: Cross-section of Three Types of Rim Track Design: Technical, Convex and Concave.

These three configurations can individually change in appearance in infinite modifications, especially in terms of radius on the curvature, position of the bend inwards etc.

Appendix C: The Disc

The second part associated with the wheel is the wheel disc (see figure C.1), also referred to as the A-surface, which is the most significant and visible surface of the wheel, in terms of the design of the wheel. This is the surface which the Design Department develops and determines internally at Volvo Cars prior to the choice of supplier and manufacturer of the wheel. Associated features with the a-surface are; the spokes, windows, wheel bolts and centre cap, all of which are visible on when mounted onto the car.

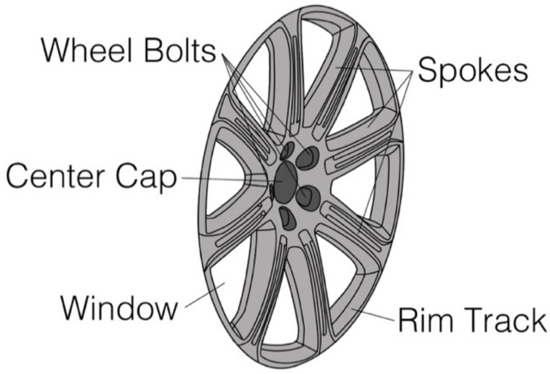

Figure C.1: The Disc and associated features

As previously mentioned, the wheel is surrounded by several parts and there are two surrounding components that sets certain restrictions for the design of the a-surface of the wheel that needs to be considered; *the tire* and *the brake* (See figure C.2). The surrounding tire sets the allowed protrusion of the a-surface and on the opposite side, the inside of the disc area, the brake and hump restricts the thickness and depth of the wheel spokes, visualized in figure C.2.

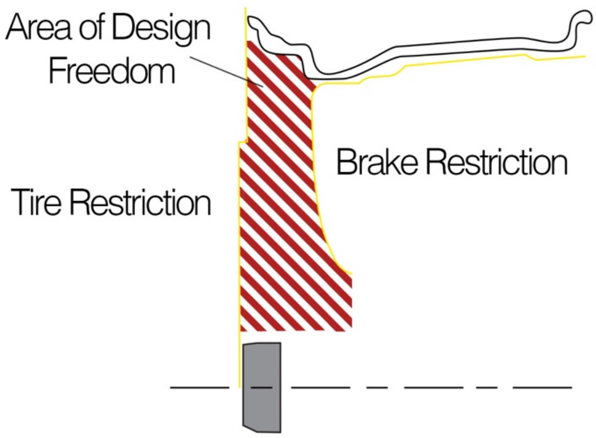

Figure C.2: Restrictions for Wheel Design

Presently the most common design of the disc is with either five, eight or ten spokes. Examples of current Volvo Cars wheel designs are displayed in figure C.3. The spokes are the part of the wheel which are connecting the rim with the centre of the wheel, allowing the rotational forces produced by the engine to be transformed into a rotational force which in turn allows the vehicle to move.

Figure C.3: Five, Eight and Ten Spoked Volvo Cars Wheels [1], [2] [,3]

Image references:

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Appendix D: Photos of Base Wheel

Photos of Base-Wheel

Appendix E: Design Features of Interest for Aerodynamic Evaluation

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Appendix F: Photos of Final Concept in the Wind Tunnel Facility

Photos from Wind Tunnel Testing