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Automotive Emergency Brake
Concept Effects on Vehicle Dynamics, and a Sustainability and Investment Evaluation

Master's thesis in Automotive Engineering and Product Development

Andreas Håkansson
Håkan Winqvist

Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2014

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Department of Product and Production Development
Division of Product Development
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46(0)31-772 1000

Cover:
The Autoliv Logotype

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Preface

This master's thesis was carried out at the division for Special Safety Products at Autoliv Sverige AB, Vårgårda, Sweden, during the spring of 2014. The research was carried out in collaboration with the department of Product and Production Development at Chalmers University of Technology, Gothenburg, Sweden.

A number of people have provided important support throughout the project. We would first like to thank our supervisors Jörgen Kjellén at Autoliv Sverige AB and Hans Johannesson at Chalmers University of Technology. Mr. Kjellén and Professor Johannesson have provided continuous and valuable support throughout the entire project. We would also like to thank Christian Svensson and Erik Neander at Autoliv. Mr. Svensson and Mr. Neander not only initiated the project but also helped guide the project in the right directions during the initial work that was done. We would finally like to thank all engineers in the Vacuum Emergency Brake project at Autoliv for the helpful advice that was given during the project.

Andreas Håkansson and Håkan Winqvist
Vårgårda, Sweden, May 2014

List Of Abbreviations

ABS – Anti-Lock Braking System

CoG – Center of Gravity

EBIT – Earnings Before Interest and Taxes

IRR – Internal Rate of Return

NPV – Net Present Value

R&D – Research and Development

ROI – Return On Investment

TTM – Time To Market

VEB – Vacuum Emergency Brake

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Abstract

Braking acceleration for automobiles is normally limited by the available friction and normal force between the tires and the road. Autoliv is developing a vacuum assisted braking device that aims to overcome this limitation during emergency situations. There was uncertainty regarding how the Vacuum Emergency Brake would affect turning behavior and how positioning and geometry would affect the braking performance. There was also a need for an objective investment as well as sustainability evaluation to aid decision-making in the product development project that had been initiated. The outermost aim of this master's thesis was to create understanding and results that could be used in the continued development of the Vacuum Emergency Brake.

Models were key in the process towards answering the research questions in order to meet the aim of the project. These models were created and used in order to quantitatively evaluate the different areas of the Thesis. Models were consequently created for evaluation of vehicle dynamics, investment economics and sustainability, where vehicle dynamics was the most comprehensive area of research. 6 000 full vehicle rigid body simulations were carried out to create a sample that could be used for analysis of tradeoffs between chosen objectives. The objectives were chosen to evaluate the performance of the Vacuum Emergency Brake, the effects on existing brakes and the effects on the turning capability of vehicles. Software was subsequently used to analyze the data that was produced with the simulations.

The analysis showed that the Vacuum Emergency Brake has significant effects on the turning behavior of vehicles. The system is sensitive to changes in geometry, which demands careful analysis when implementing a Vacuum Emergency Brake. The effects that geometry changes have on turning capabilities can however be used when designing. Possible issues caused by packaging constraints can in fact be avoided by means of small geometry changes in the design of the Vacuum Emergency Brake. It was also concluded that the logic with which the Vacuum Emergency Brake is used highly influences the design configurations and that a thorough understanding of this logic must be had when designing. In addition to the area of vehicle dynamics it was discovered that the product development project could be expected to be profitable. Additionally, a sensitivity analysis showed that changes in Research and Development costs have a greater impact on the rate of return than the sales volume, when varied around approximates that were arrived at. A sustainability analysis lastly resulted in indications that the Vacuum Emergency Brake could provide large benefits when it comes to social sustainability.

Keywords: Automotive Safety, Rigid Body Simulations, Investment Evaluation, Sensitivity Analysis, Tradeoff Analysis, Multi-Objective Optimization

Table Of Contents

Table Of Figures

Table Of Tables

Table Of Equations

1 Introduction

This chapter introduces the reader to the subject of the thesis together with a declaration of the purpose of conducting the research. Additionally, the problem is discussed from different stakeholders' viewpoints and a number of specific research questions are presented.

1.1 Background

Autoliv Sverige AB (hereinafter Autoliv) is a leading actor in the field of automotive safety products, with a vision "To substantially reduce traffic accidents, fatalities and injuries". (Autoliv, 2013) In order to achieve this, a mission "To create, manufacture and sell state-of-the-art automotive safety systems" is stated to guide and inspire further work in the automotive safety field.

In 2012, pedestrians accounted for 17 % of the fatalities in Swedish traffic accidents (Trafikanalys, 2013). The braking capacity of a vehicle in an emergency situation is crucial to avoid injuries related to this type of accidents (Rosén & Sander, 2009). Advanced Emergency Braking Systems can detect many predictable accidents and avoid or at least mitigate them by braking autonomously (ADAC, 2011). There is however a risk with these systems, if they are sensitive and activates too early, they might instead cause accidents. (Jacobson et al., 2012) In situations where the hazard is discovered too late, or the speed is too high, the vehicle cannot stop even if the braking capability in the current system is used to the maximum limit.

A need for increased braking performance is therefore identified. Braking force is currently limited to the available friction and normal force in the tires' contact points with the road. (Jacobson et al., 2012) The normal force, the coefficient of friction or a combination of the two needs to be increased to gain braking performance. Regarding the coefficient of friction, trade-offs between friction and other aspects such as rolling resistance and longevity exist. Suitable compromises between tire properties are well developed and implemented. An area of research that is not as well developed is increasing the total normal force acting on the vehicle. (Fuchs, 2009) Solutions to increase normal force in a near-crash event have been proposed but not yet realized in production cars.

Autoliv is developing a system for improved braking performance with increased total normal force when an inevitable crash is detected.[1] It has been successfully tested and approved for further development. There are however uncertainties concerning how this solution affects vehicles and how it could be optimized in terms of for instance vehicle dynamics and packaging. In addition to strictly technical aspects, uncertainties and needs exist regarding a basis for decision both when it comes to sustainability as well as the financial viability of the invention[2].

[1] Christian Svensson, Director, Test and Design, Autoliv Development AB, December 19th 2013.

[2] Jörgen Kjellén, Project Coordinator, Special Safety Products, Autoliv Sverige AB, January 15th 2014

1.2 The Vacuum Assisted Emergency Braking System

The system that intends to overcome the braking limitations is vacuum assisted and the total available normal force acting on the vehicle is locally increased by means of low pressure that is sealed from the atmosphere.[3] This local increase of normal force then adds to the normal force from the mass of the vehicle and the total normal force is thus increased. The low-pressure zone is equipped with a material providing high friction and it provides braking force as it is being forced against the road surface. By providing this increase in normal force without adding the corresponding mass to the vehicle, gains in braking performance can be yielded.

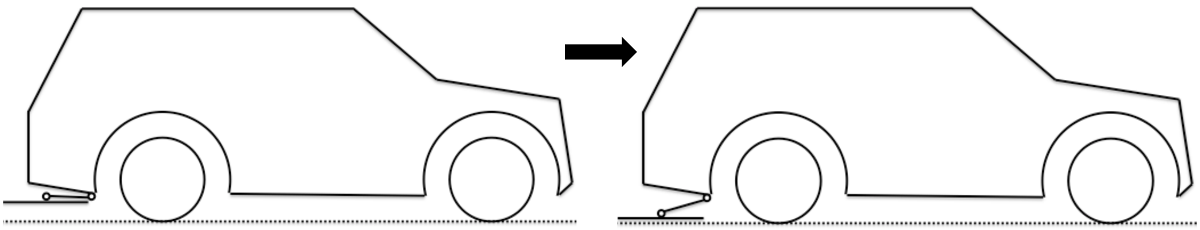

Figure 1 – Schematic image of the Vacuum Emergency Brake in a vehicle

The Vacuum Emergency Brake (hereinafter VEB) is activated prior to a collision.[3] A plate covered with rubber is launched towards the road as illustrated in Figure 1. Low pressure is created in the VEB contact patch by means of a vacuum tank. Figure 2 below illustrates the VEB schematically.

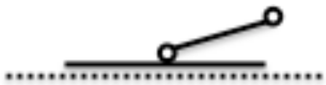

Figure 2 – Schematic image of the VEB unit

The vacuum acts over the area of the VEB and forces the VEB towards the road.[3] This then creates an additional braking force that increases the total braking performance of the vehicle. The gain in braking performance comes both from the friction between the VEB and the road, but also from increased normal force between the tires and the road. The normal force between the tires and the road is increased as a result of the reaction force from the VEB linkage.

1.3 Purpose

The purpose of the master´s thesis is (i) to create an understanding of, and provide an objective evaluation of the emergency braking system. The thesis aims to (ii) provide insight for Autoliv's continued development of the system based on answers to a number of research questions. Moreover, the thesis aims to (iii) evaluate the emergency braking system with respect to sustainability aspects. The outermost aim of the thesis is however to (iv) deliver a number of recommendations with the purpose of providing a basis for development decisions and further research in the topic.

[3] Christian Svensson, Director, Test and Design, Autoliv Development AB, December 19th 2013

1.4 Limitations

A number of limitations have been identified in consensus with available resources and relevance to the topic in order to guide the thesis work in the direction of the overall scope. (I) Only variants of the existing emergency braking system has been evaluated and (II) no detailed development of components has been carried out. (III) No evaluation of component designs and material selection was made and furthermore, (IV) research was to the furthest possible extent performed using relative measures to simplify analysis and the creation of models. Additionally, (V) no vehicle model specific analysis was carried out.

1.5 Problematization

The overall purpose of the master's thesis has been approached from the viewpoint of the most important stakeholders. Five main stakeholders were identified: Autoliv, shareholders, society, customers and consumers. These stakeholders have been dominating the problem formulation.

The problem directly affects the competitive position of Autoliv.[4] The company has expressed the need of analytical mapping of the implications an emergency braking system would have on vehicle dynamics. In addition to the technical aspects, Autoliv has the long-term target of increasing market shares by exceeding the relative increase in light vehicle production globally. (Autoliv, 2013) That is, increasing market shares by organically growing more rapidly than customers. Since the target is organic growth, the financial viability and the economical sustainability of the emergency braking system is of interest for Autoliv, as well as for shareholders.

The emergency braking system aims to increase the braking acceleration and thereby reduce the number of accidents.[4,5] Autoliv's vision to reduce accidents emphasizes the emergency braking device's importance both for Autoliv and for social sustainability in society. (Autoliv, 2013) Additionally, society would benefit from saved lives as a result of the emergency braking system. A severe pedestrian traffic injury costs society approximately $500 000 and pedestrian fatalities cost $2 700 000 per casualty (Trafikkontoret, 2008). This further consolidates the urgency of the topic for society as well as emphasizing the possible impact on sustainability, both with regard to social and economical sustainability. Besides having potential to be economically sustainable for society, the cost of an accident indicates that there is a market opportunity that would benefit several of the mentioned stakeholders, such as Autoliv and shareholders.

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[4] Erik Neander, Global Development Manager, Special Safety Products, Autoliv Sverige AB, November 13th 2013

[5] Christian Svensson, Director, Test and Design, Autoliv Development AB, November 22nd 2013

The effect that the emergency braking system has on vehicles is of most importance and the way that such a system affects vehicle dynamics was unknown.[6] Regardless of the performance of the isolated emergency braking system, it cannot under any circumstances affect the performance of other vehicular measures negatively. The potential of the system has been proven in an isolated manner but the problem's diverse nature required analysis of several variables simultaneously. Physical testing of such aspects was therefore not a viable option. In order to confirm that the system would function as intended without the negative consequences, deeper analysis was required. These technical problems are either directly or indirectly critical areas of interest for all stakeholders and by thoroughly investigating the set of research questions presented below, the value for all stakeholders can be exploited to the largest possible extent.

1.5.1 Research Questions

Four research questions based on the problem formulation were composed in order to guide the project activities. The thesis aims to fulfill its purpose by answering the following research questions.

1. How does the Vacuum Emergency Brake affect vehicle dynamics?
2. What implications does position and packaging have on the performance of the emergency braking system?
3. What financial implications could be expected from the product development project?
4. What is the social, economical, and environmental sustainability of the emergency braking system?

[6] Christian Svensson, Director, Test and Design, Autoliv Development AB, December 19th 2013

2 Theoretical Framework

The theoretical framework aims to present the research that has been done prior to addressing the research questions. The research questions have been used as guiding elements when choosing what literature to study. Furthermore, the theoretical framework is to be treated as an introduction to the problem field and additional more detailed information has been used when carrying the project out. All references to the presented theory are listed in chapter 8, References.

2.1 Mechanics

Basic mechanics are based on Newton's three laws of motion. (Grahn & Jansson, 2002) Newton's laws of motion are the foundation for all mechanical reasoning. Grahn & Jansson (2002) state the laws as follows:

1. An object without external influence of forces will remain at rest or at a constant speed.
2. Change per unit time of the linear momentum of an object is proportional to the acting force and acts in the same direction.
3. For all forces, an equal force in the opposite direction exists so that the mutual force between two objects are of the same size, but with opposite direction.

According to Newton's second law, $F = ma$. (Grahn & Jansson, 2002) This relationship between acceleration a, force F and mass m has been used extensively throughout the thesis. Further elaboration regarding Newton's laws of motion will however not be presented in this report.

The concept of friction has been used throughout the thesis. Frictional force appears when two objects are in contact with each other and an additional force is applied. The frictional force is reversed from the applied force and is proportional to the normal force between the two objects. (Grahn & Jansson, 2002) The frictional force then provides drag that opposes the applied force. Equation 1 and Figure 3 below explains and illustrates the information above.

$$F_f = \mu N$$

Equation 1 – Frictional force

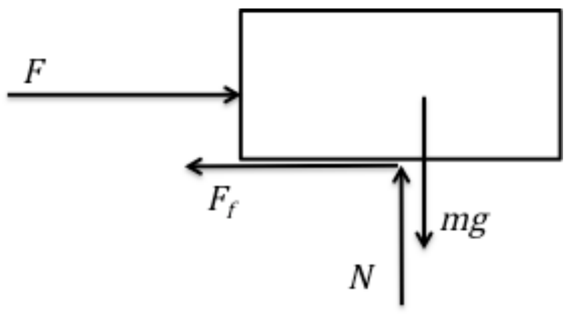

Figure 3 – Frictional reaction force

Where F_f is the frictional force, N is the normal force between two objects and μ is the coefficient of friction between the same two objects. (Grahn & Jansson, 2002) The coefficient of friction mainly depends on the characters of the surfaces, such as surface roughness.

Free body diagrams are used to derive equations and expressions to use in simulations and calculations. (Grahn & Jansson, 2002) A free body diagram is often a figure where forces are analyzed and noted. Equilibrium expressions are then created and addressed to perform analysis of the system. Free body diagrams use Newton's third law and whenever bodies are separated before the equilibrium expressions are created, these forces have to be accounted for. Figure 3 above shows a simple example of how this can be been done.

2.2 Vehicle Dynamics

In order to create an understanding of the phenomena involved in vehicle dynamics, a knowledge foundation was built up around basic vehicle dynamics theory. Since the thesis work was focused towards vehicle performance in braking- and braking-in-turn maneuvers, the longitudinal- and lateral dynamics and tire properties were important factors to consider (Jacobson et. al, 2012).

All calculations performed on vehicles are based on the ISO 8855 coordinate system, which has positive X in the longitudinal driving direction, Positive Y to the left and positive Z upwards (Jacobson et. al, 2012). This is illustrated in Figure 4 below:

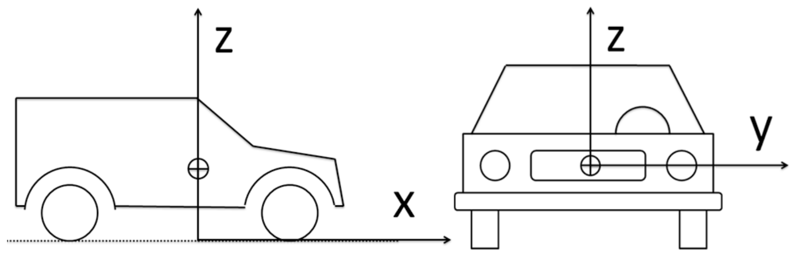

Figure 4 – ISO 8855 Coordinate system, side- and front view respectively

2.2.1 Longitudinal Vehicle Dynamics

Longitudinal vehicle dynamics are dynamics that affect the vehicle in the X direction as defined in the preceding section. (Jacobson et. al, 2012) Two of the most prominent aspects of longitudinal vehicle dynamics are longitudinal load transfer and the braking system. Load transfer has a critical impact on the dimensioning of braking system components. An ideal brake distribution between front and rear would be in direct proportion to the normal forces on each axle as defined in Equation 2 below. The free body diagram in Figure 5 defines the variables in the equation.

$$\frac{F_{xf}}{F_{xr}} = \frac{F_{zf}}{F_{zr}}$$

Equation 2 – Ideal brake distribution

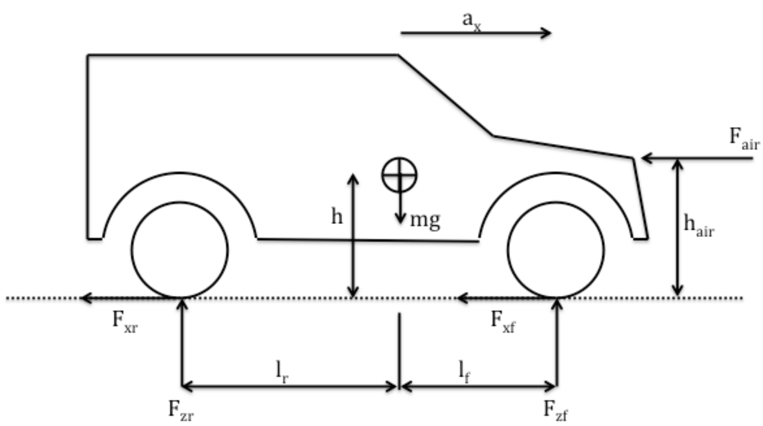

Figure 5 – Free body diagram of an entire vehicle

Changes to the normal forces F_{zf} and F_{zr} in Equation 2 occur either due to positive or negative acceleration. During a braking event an increase in the front normal load F_{zf} and a decrease of F_{zr} will take place due to this acceleration, as defined above. It is therefore important to compensate for load transfer when dimensioning brake systems on vehicles. (Jacobson et. al, 2012) Current braking systems not only compensate for load transfer, but are also front biased in order to avoid an instable behavior. If the front wheels are locked and sliding the maneuverability of the vehicle is affected, making the car less steerable, but stable[7].

2.2.2 Brake System

Dimensioning of the components in the braking system is done to match the weight- and load distribution that occurs in normal driving of vehicles. (Jacobson et. al, 2012) Furthermore, the braking acceleration that vehicle brakes are capable of achieving is typically limited by road friction since the available braking torque normally is enough to lock the wheels. This over dimensioning of brakes is done in order to ensure that external factors rather than the braking system itself are limiting the acceleration.[7] Increasing the normal loads F_{zf} and F_{zr} consequently demands increased maximum braking torque to keep external factors as limiting factors.

The equations for the braking torque for one wheel are stated below. It can be seen that the difference in braking torque and the normal force are in direct proportion to each other. (Mägi & Melkersson, 2006)

$$T_e = r_{wheel}\mu_{road}F_z$$

Equation 3 – Required braking torque

$$\Delta T_e = r_{wheel}\mu_{road}\Delta F_z \rightarrow \frac{\Delta T_e}{T_e} = \frac{\Delta F_z}{F_z}$$

Equation 4 – Relation between braking torque and normal force

Equation 4 above shows that if the normal load F_z increases due to load transfer, the required braking torque will increase with the same relative amount. In addition to the increased demands on braking torque, increased normal load will also increase the temperature build-up in the brakes during braking. The highest temperature is reached at the end of the braking event and is determined as defined in Equation 5. A complete explanation of the variables can be found in Appendix IX – List of Variables.

$$T_b = \frac{T\omega_0 t_b}{cm} = \frac{T\omega_0}{2A}\frac{t_b}{c\rho H}$$

Equation 5 – Temperature increase due to braking

[7] Mathias Lidberg, Associate Professor, The Department of Applied Mechanics, Chalmers University of Technology, Lecture notes, March 19th 2013

2.2.3 Lateral Vehicle Dynamics

Yaw is a key factor to consider when evaluating lateral vehicle dynamics.[8] *Yaw rotation* explains how the vehicle is turning around its vertical axis. Yaw rate describes the angular velocity around the vertical yaw axis. A vehicle that is following a circular path with a given radius will have a yaw rate corresponding to this path. Yaw rate is also defined in Equation 6 below.

$$\omega_z = \frac{v_x}{R}$$

Equation 6 – Yaw rate

When a vehicle is cornering with a constant speed (steady state cornering) no variations in yaw rate occur. (Jacobson et. al, 2012) If the vehicle is oversteering the yaw rate will be higher and for understeering it will be lower. It can be seen as when the vehicle is understeering the turning radius increases.

Yaw rate occurs as a result of several forces that together create a moment M_z around the yaw axis. (Jacobson et. al, 2012) Every force in the system that is offset from the yaw axis will affect the magnitude of the yaw rate. All conventional forces that affect yaw rate are illustrated in a one-track (one side of a vehicle) model of a turning vehicle in Figure 6. Basic expressions for lateral force, F_y, and yaw moment, M_z, for small deviations from steady state cornering are derived from this figure in Equation 7 and Equation 8.

$$\sum F_y = m(\dot{v} + ur) = F_{yf} + F_{yr}$$

Equation 7 – Lateral force

$$\sum M_z = I_z\dot{r} = l_f F_{yf} - l_r F_{yr}$$

Equation 8 – Yaw moment

$$m = Mass\ of\ the\ vehicle$$
$$I_z = Yaw\ Inertia\ of\ the\ vehicle$$

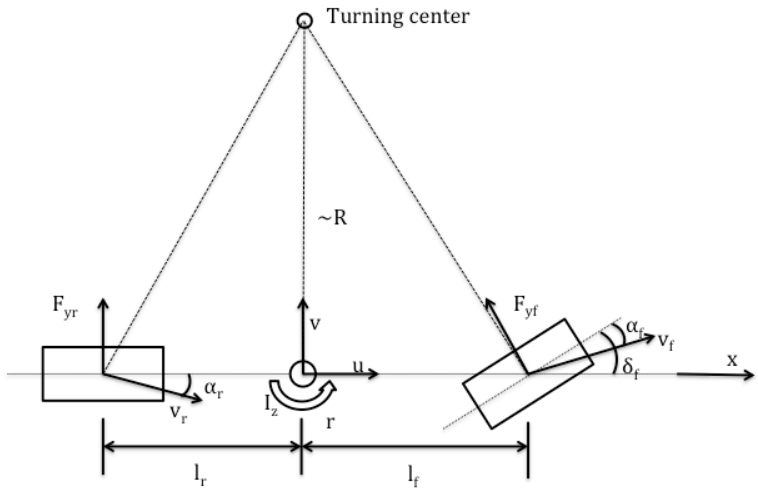

Figure 6 – One-track model of a turning vehicle with steerable front wheel

Changes in yaw rate can be used for evaluation of how the vehicle is behaving in turning motions[9]. As mentioned, additional forces will affect the yaw rate and an added VEB could therefore potentially affect the yaw rate. Tires are conventionally the only components that transmit the forces that affect the yaw rate. Tire properties are covered in the following section.

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[8] Mathias Lidberg, Associate Professor, The Department of Applied Mechanics, Chalmers University of Technology, Lecture notes, April 11th 2013

[9] Mathias Lidberg, Associate Professor, The Department of Applied Mechanics, Chalmers University of Technology, Lecture notes, March 21th 2013

2.2.4 Tires

Tire properties are important to consider when evaluating vehicle dynamics. (Pacejka, 2006) There are conflicting objectives in tire properties and the primary task of transmitting force is often connected to secondary effects, such as high friction and low rolling resistance. The most important properties and effects of tires are further described below.

The amount of force a tire can handle is limited by the friction properties of the tire. (Jacobson et. al, 2012) Illustrated in Figure 7 is a friction circle where it can be seen how the available friction can be utilized by the tire.

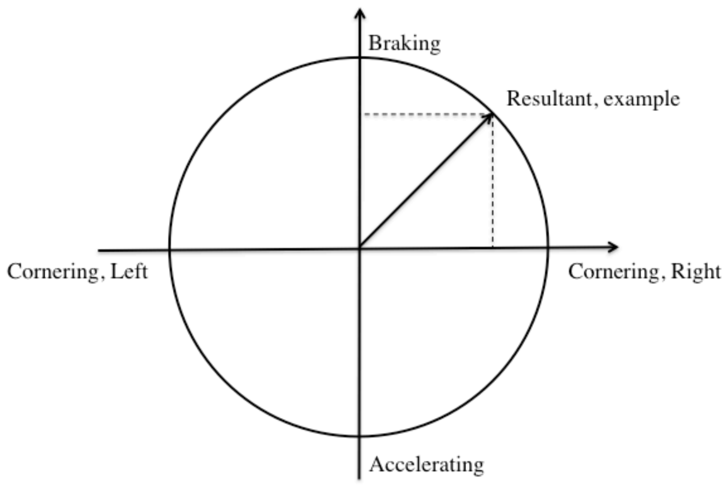

Figure 7 – Friction Circle for Tires

It can be seen that there is a tradeoff in available friction for braking when cornering and vice versa. (Jacobson et. al, 2012) When friction is needed for cornering the amount available for braking is lower. The example resultant illustrates a distribution between available friction for cornering and braking when the tire is used to its friction limit.

2.3 Dynamic Simulations

The simulation tool Adams® has been used to perform dynamic rigid body simulations. This chapter introduces the underlying principles used by Adams®. This is done in order to increase the trustworthiness of the results by declaring these principles and thus creating an understanding of drawbacks and possible sources of error.

2.3.1 Rigid Body Principles

Rigid body dynamics theory is used to describe how simulations can be built up and how the vehicle can be studied as a system. (Hahn, 2002) It is mainly used where mathematical models based on free body diagrams become very complex due to a large number of components and many degrees of freedom. This kind of simulations provide an overall understanding of how changes affect the vehicle and it also gives a visual representation of how the system works.

The definition of a rigid body is an assembly of particles that do not move with respect to each other. (Hahn, 2002) It means that deformation of bodies have no influence on the behavior of the overall system. A rigid body dynamics simulation consists of assemblies of bodies, which are connected with for example springs, dampers and friction elements or joints, links and bearings. Forces and loading conditions can then be applied. Desired motions of bodies are selected to correlate with the simulated system.

2.3.2 Analytic Method

Hahn (2002) divides rigid body simulations into four main categories depending on how they are set up and what they are aiming to analyze. The term time history is used in each of these categories and refers to sequences that depend on time, such as velocities, positions and accelerations.

1. In a *kinematic analysis* all model parameters are known and the focus is to see the system motion when forces and torques are applied from already determined time histories. Initial conditions must be specified in order to get a converging solution from the nonlinear differential equations that the simulation is based on.
2. *Inverse kinematics* is, as the title implies, used when the aim is to get the time histories based on the stipulated motions.
3. *Parameter identification* is used when the time histories for each rigid body are measured together with the time histories for torques and forces involved.
4. A *Control synthesis* analysis is performed when desired motions of selected bodies are chosen. The results from these simulations are control strategies for the system.

2.3.3 Applied Engineering

In order to replicate real life situations, simulation scenarios are created when a full vehicle analysis is performed. Such a simulation scenario is for example braking when turning. (Jacobson et. al 2012) These driving events are used for evaluation of the vehicle as a system or for analysis of different subsystems.

An engineering model is used in a similar way as a free body diagram is used for derivation of expressions by hand, but for functions to fulfill the purpose. (Hahn, 2002) The creation of an engineering model depends on what the purpose is with the model and parameters out of interested are excluded. Hahn (2002) states that the process of setting up a correct engineering model is highly depending on the skill level of the user. Hahn (2002) also points out the importance of basic knowledge about the system that is being simulated in order to draw the right conclusions.

2.3.4 Problems With Rigid Body Dynamics

Rigid body dynamics software such as Adams® are tools capable of simulating complex systems and situations. It is however important to know the drawbacks and limitations of such software to be able to use them properly. Featherstone (1987) mentions three main types of sources of errors: round-off error, truncation error and modeling error. These three types differ from each other and are briefly explained below. Round-off errors occur for example when numbers of different size are compared. (Featherstone, 1987) Scaling is mentioned, since for example weight and inertia will be scaled differently than volume. Truncation error can be described as the error occurring when numerical integrations are made as approximations to exact mathematical integrations. This is often a tradeoff between accuracy and efficiency in terms of simulation time and used computer capacity. The modeling error is down to the user of the simulation software and basic knowledge of the system is important to avoid faulty simulations. The model might converge to a solution, but the user must be able to understand the results and evaluate if they are reasonable. Assumptions such as frictionless joints, disregarded internal systems and temperature dependencies will be made by the modeler and affect the results. Featherstone (1987) also mentions the sensitivity problem, which is when small errors at one place are amplified to larger errors, potentially at other places.

2.4 Optimization

Optimization is a term that describes how the most beneficial system configurations can be decided mathematically. (Papalambros & Wilde, 2000) Systems can be configured in the best way, given certain constraints, by constructing a model and solving it with respect to these constraints and a single or multiple objectives. The objective determines what is going to be minimized when solving the optimization problem.[10] Additionally, tradeoff analysis can be performed using optimization theory in the case of optimization problems with several objectives. This is done in order to create an understanding of how conflicting objectives affect each other.

2.4.1 Systems And Analytical Models

Systems can be defined as tasks being performed by a number of objects that somehow transform input to output. (Papalambros & Wilde, 2000) When conducting optimization, the level of complexity in the system is important. The level of detail is reflected in the modeler and the modeler also determines the system boundaries of the model.

A model is a set of relations that are composed to create an abstraction of a real system (Papalambros & Wilde, 2000). Analytical models can be defined in several ways, such as mathematical models or simulation models[10]. Models rely on elements that are crucial for the notation of the optimization problem and the distinction between them is of vital importance.[10] (Papalambros & Wilde, 2000) These elements are *objectives*, *constraints*, *variables*, *parameters* and *constants* as described in Appendix V – Optimization Terminology. When modeling, there has to be a clear distinction between variables and parameters and the decision of whether to classify a measure as a parameter or a variable is up to the modeler. The distinction between parameters and variables is therefore undoubtedly subjective.

2.4.2 Formal Mathematical Optimization Models

A formal representation must be established in order to quantitatively solve an optimization problem. (Papalambros & Wilde, 2000) In this formal representation, the objective is expressed in terms of design variables and the objective function is minimized with respect to a set of constraints. The general formal expression for optimization problems is presented in Equation 9 below.

$$
\begin{aligned}
&\text{minimize } f(\mathbf{x}) \\
&\text{subject to } \mathbf{h}(\mathbf{x}) = \mathbf{0}, \mathbf{g}(\mathbf{x}) \leq \mathbf{0} \\
&\qquad\qquad \mathbf{x} \in \mathcal{X} \subseteq \Re^n
\end{aligned}
$$

Equation 9 – Formal single-objective optimization formulation

Where $\mathbf{h}(\mathbf{x})$ are equality constraints and $\mathbf{g}(\mathbf{x})$ are inequality constraints. Furthermore, $\mathbf{x}$ is a vector of design variables that belongs to $\mathcal{X}$, which in turn is a subset of the n-dimensional real space. (Papalambros & Wilde, 2000) This formal mathematical optimization model can then be solved mathematically.

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[10] Steven Hoffenson, Phd, The Department of Product and Production Development, Chalmers University of Technology, Lecture notes, September 9th 2013.

2.4.3 Multi-Objective Optimization

There are differences between single-objective optimization as described above, and multi-objective optimization. (Deb, 2005) A multi-objective optimization result is a set of optimal solutions rather than a single optimal solution. A multi-objective optimization problem also has more than one objective function. When optimizing towards several objectives simultaneously, a notation different than the single-objective notation described earlier is needed.[11] Multi-objective optimization is denoted as in Equation 10 below.

$$\begin{aligned}&\text{minimize } \{w_1 f_1(\mathbf{x},\mathbf{p}), w_2 f_2(\mathbf{x},\mathbf{p}), \dots, w_M f_M(\mathbf{x},\mathbf{p})\}\\ &\text{subject to } \mathbf{h}(\mathbf{x},\mathbf{p}) = \mathbf{0}, \mathbf{g}(\mathbf{x},\mathbf{p}) \leq \mathbf{0}\end{aligned}$$

Equation 10 – Formal multi-objective optimization formulation

By solving the optimization problem with different values for the weights w_1 to w_M, a *Pareto set* is obtained. (Papalambros & Wilde, 2000) A Pareto set only includes solutions that are not dominated by other solutions and every one of these solutions is optimal in some way. A non-dominated solution is therefore a solution that cannot be improved in one objective without becoming worse in another[11]. Figure 8 below demonstrates how an algorithm has been used to create the Pareto set. The Pareto set of points is illustrated with red points connected by means of a surface to aid the visibility of the set.

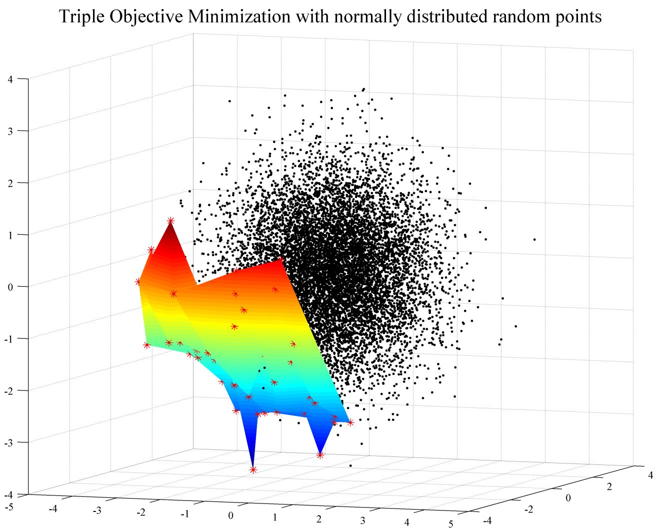

Figure 8 – Example of a Min-Min Pareto set in multi-objective optimization

[11] Steven Hoffenson, Phd, The Department of Product and Production Development, Chalmers University of Technology, Lecture notes, September 30th 2013.

The goal in multi-objective optimization is to minimize all objectives simultaneously. (Deb, 2005) In the case of single-objective optimization, one particular solution would have been arrived at. All objectives can however not be minimized at the same time when optimizing several objectives simultaneously. When optimizing several objectives simultaneously, the Pareto set is therefore created objectively with no regard to the relative importance between the objectives. That is, all points in the Pareto set are optimal depending on the relative importance between the objectives. This relative importance is represented by the weights w_1 to w_M in Equation 10. If the objective represented by the objective function f_1 had been most important, w_1 would have been assigned the highest number and so forth. High-level information is used to decide the values for these weights that are based on in-depth knowledge about the problem or the specific situation. After establishing the weights, a single optimal solution from the Pareto set can be arrived at.

2.4.4 Problems With Optimization

There are a few inherent problems with optimization. Firstly, optimization is always going to be influenced by the modeler. (Papalambros & Wilde, 2000) Subjectivity is therefore a risk when performing optimization. The interpretation of reality when constructing the abstraction of it, or the model, is going to influence the result of the optimization. Also, as mentioned, the choice of whether to treat quantities as parameters or variables is dependent on the modeler, but also on available information and the scope of the problem that optimization is carried out on. Secondly, multi-objective optimization with weighted objectives can disregard convexities in the Pareto set. This is illustrated in the figures below.

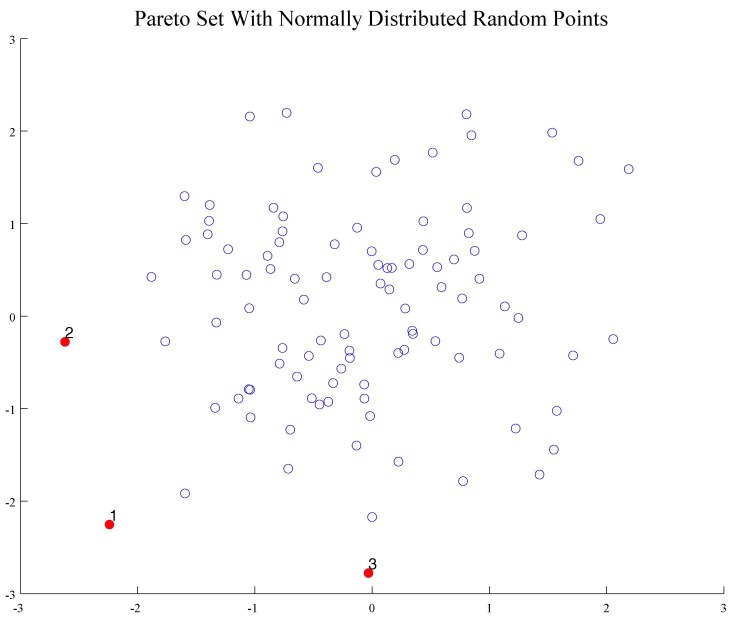

Figure 9 – A Min-Min Pareto set without convexities

Figure 9 shows a plot with normally distributed random points in two dimensions. No convexities are present in this double objective optimization example. Figure 10 does however show one distinct convexity.

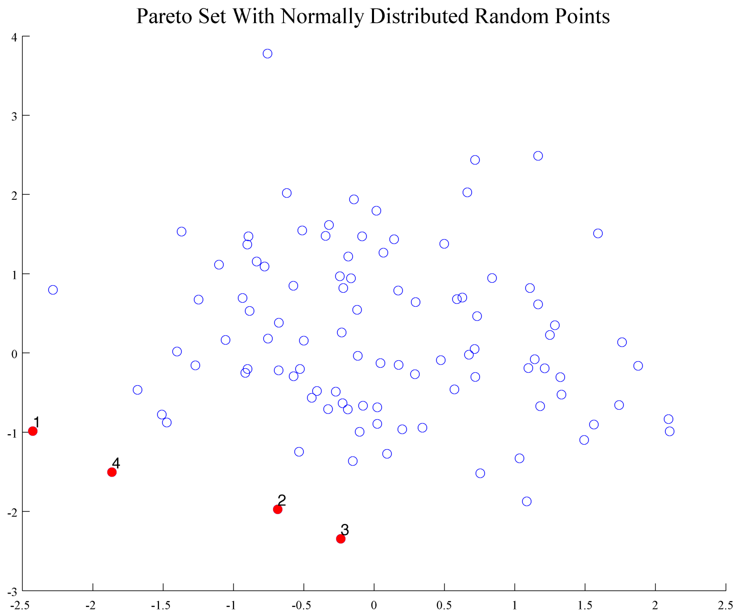

Figure 10 – A Min-Min Pareto set with one distinct convexity – point 2

It can be seen that point 2 in Figure 10 could have been disregarded in a multi-objective optimization problem. Point 2 lies inside a convex part of the *Pareto front* and would therefore have been impossible to identify with certain methods of optimization. (Papalambros & Wilde, 2000) For example point 4 would however have been found, as it is not inside a convexity.

2.5 Economic Investment Evaluation

This subchapter introduces the reader to economic evaluation of investments. The topic areas that are presented below have been chosen to give a good fit between the scope of the thesis and the presented theory. Consequently, the level of abstraction is on a level higher than that of a pure economic analysis, with focus on areas that can provide a rough indication and work as a basis for decision rather than absolute precision.

2.5.1 Investment Evaluation Fundamentals

Whenever a decision on whether or not to invest in Research and Development (hereinafter R&D) of an invention has to be made, an evaluation of the investment is needed (Granstrand, 2010). Investment evaluation is a continuous activity that needs to be carried out throughout the R&D process and especially when facing *go*, or *no-go*, milestones. (Ulrich & Eppinger, 2012)

2.5.2 Net Present Value

Economically successful products generate more cumulative cash inflow than cumulative cash outflow (Ulrich & Eppinger, 2012). That is, the Return On Investment (hereinafter ROI) is positive. (Ulrich & Eppinger, 2012; Granstrand, 2010) A common evaluation tool for investment is the Net Present Value (hereinafter NPV). There are a number of established evaluation methods alongside the NPV, such as Payback Time and Internal Rate of Return (hereinafter IRR).

$$NPV = \sum_{t=0}^{H} \frac{ICF_t}{(1+r)^t}$$

Equation 11 – Net Present Value

ICF_t in Equation 11 represents the incremental cash flow during the period t. (Granstrand, 2010) H is the horizon within which the evaluation is carried out, and r is the discount rate. All future cash flows are discounted to the present value using the discount rate when calculating the NPV. The simple rule of evaluation using NPV is that the investment should be made if the NPV is positive, and that the investment should not be made if the NPV is negative. In order for the NPV to be useful in decision-making, the drawbacks of using NPV need to be addressed. First, the discount rate r needs to be accurate according to the demands of the company in which the evaluation is carried out. Second, the NPV for different values of r need to be analyzed in order to create an understanding of the sensitivity of the analysis. And third, the future cash flows need to be understood. These issues will be elaborated in the following sections.

2.5.3 Discount Rate And The Internal Rate of Return

The basic principle behind the discount rate is that money tomorrow is worth less than money today. (Granstrand, 2010; Ulrich & Eppinger, 2012) The discount rate is adjusted to the level of risk of the investment and it reflects the cost of capital. Additionally, the discount rate is an interest rate for delaying ROI.

By calculating and finding the discount rate that gives an NPV of zero, the IRR is found. (Granstrand, 2010) The IRR rule dictates that the investment should be carried out if the IRR is larger than the expected opportunity cost of capital in the company in which the evaluation is performed. In the case of Autoliv, the IRR is adjusted from case to case, taking strategic aspects into account[12].

2.5.4 Cash Flow

Cash flows are as mentioned fundamental in investment evaluation. (Granstrand, 2010) The NPV is calculated using cash flow that will take place with the project subtracted from cash flow that will take place without the project. That is, only the cash flows that can be derived from the project are being evaluated (Brealey et al., 2004). Using investment depreciation as a tax shield is an example of cash flow that does not necessarily take place in the project, but can be derived from it, as it lowers tax outflow from the total profits. (Granstrand, 2010)

Total revenues and total costs should be included when conducting NPV analysis (Copeland et al., 2005). Total Revenues are defined as volume sold multiplied by price (Hansson et al., 2006). Therefore, forecasting of volume and price is of major importance. It is also important to note that the uncertainty about markets and the dynamic nature of markets have to be taken into account when analyzing future sales volumes (Granstrand, 2010).

The future price of products can be estimated by analyzing costs. (Granstrand, 2010) By combining findings from analysis of costs and markets, the NPV can be calculated, resulting in an indication of the value of the R&D project that Autoliv is running.

[12] Jörgen Kjellén, Project Coordinator, Special Safety Products, Autoliv Sverige AB, April 2nd 2014

2.5.5 Problems With Economic Analysis

There are a few inherent risks with conducting economic analysis, especially during early stages of R&D projects when the sources of error are many. (Granstrand, 2010) Economic analysis is however of help when planning R&D projects.

Granstrand (2010) argues that there are three fundamental types of problems in analysis of investments. These problems are associated with values, time and uncertainty. (Granstrand, 2010) The problem with values is an issue simply because people consider value in different ways. This goes both for the modeler of the economic model as well as for future customers. Time is a problem since activities taking place in different periods of time have to be compared and evaluated. The last problem, uncertainty, has to do with the fact that complete knowledge of future events cannot be had. Uncertainty also affects the problems related to values and time. One way of managing the uncertainty related to these problems is described in section 2.5.6 below.

2.5.6 Sensitivity Analysis

Sensitivity analysis in an investment evaluation model can be carried out by varying input data. (Jovanović, 1999) The sensitivity is analyzed by registering the change in output that these input changes result in. One example based on this theory is presented in Table 1 below.

Input Variable	Discounting Factor $k_1 = 10\%$	$k_2 = 15\%$	…	k_n
p_1	NPV_{11}	NPV_{12}	…	NPV_{1n}
p_2	NPV_{21}	NPV_{22}	…	NPV_{2n}
…	…	…	…	NPV_{3n}
p_m	NPV_{m1}	NPV_{m2}	NPV_{m3}	NPV_{mn}

Table 1 – General structure of a sensitivity analysis

An understanding of the sensitivity that the NPV has to variation in p is attained by identifying the k for which the NPV is zero for each p. (Jovanović, 1999) The sensitivity can then be compared between different input parameters. The knowledge that is acquired by performing a sensitivity analysis can be used as input in decision-making regarding the evaluated investment.

2.6 Sustainability

Sustainability and Corporate Social Responsibility are becoming increasingly important in business and are being recognized as driving factors for profit. (Hill & Seabrook, 2013) The most widespread definition of sustainability as defined by the Brundtland Commission is presented below. (World Commission on Environment and Development, 1987)

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"

Sustainability can be divided into three separate dimensions that each should be managed in order to achieve sustainable development according to the Brundtland Commission's definition. (Elkington, 1997) These dimensions are closely related to the dimensions of Corporate Social Responsibility and are specified as: Social sustainability, Environmental sustainability and Economic sustainability. (Elkington, 1997; Hill & Seabrook, 2013) These sustainability dimensions will be explained in the subsequent chapters.

2.6.1 Environmental Sustainability

Close to 87 % of the automotive energy consumption can be derived from using the vehicles (Mcauley, 2003). Reducing fuel consumption is therefore a major challenge in automotive design. (Mayyas et al., 2012) One of the most effective ways to reduce the environmental impact of vehicles is to minimize the amount of used material, and consequently weight, with reduced fuel consumption and thus the overall environmental impact of vehicles as a result.

2.6.2 Economic Sustainability

In order for products to be sustainable, the products have to be economically worthwhile[13]. Methods to evaluate R&D projects has been elaborated thoroughly in previous sections of the Theoretical Framework and for the VEB project to be a valuable investment, it has to offer an acceptable ROI (Granstrand, 2010).

2.6.3 Social Sustainability

Social sustainability is one of the cornerstones in sustainability and it aims to ensure the well-being and health of people.[13] As mentioned, pedestrian accidents account for roughly 17 % of fatalities in Swedish traffic accidents. (Trafikanalys, 2013) Fatalities and severe injuries caused by road traffic accidents bring costs for the society. Rosén and Sander (2009) point out the high dependency of impact speed and the severity of accidents when moving vehicles hit pedestrians. The fatality risk when being hit in 50 km/h is twice of that in 40 km/h and up to five times higher than the fatality risk in 30km/h (Rosén & Sander, 2009).

[13] Steven Hoffenson, Phd, The Department of Product and Production Development, Chalmers University of Technology, Lecture notes, October 16th 2013.

3 Methods

The methods that were used to achieve a reliable and repeatable result are presented in this chapter. The overall working procedure is described, followed by an explanation of the method of scientific inquiry. Furthermore, a discussion of the quality of the research and the general applicability is provided to explain known potential sources of error.

3.1 Overall Procedure

The master's thesis was carried out in several subsequent as well as overlapping steps and the research questions were used as guiding elements during the thesis work. Proven quantitative models were used throughout the thesis in order to ensure quality and repeatability. These models were based on a theoretical framework that was created by studying relevant literature. Using these models helped collect the data that the analysis was based on. This data was then analyzed in order to explore the research questions and ultimately fulfill the purpose of the thesis.

The effects of the emergency braking system on vehicle dynamics was evaluated using the commercial software packages Matlab®, Adams® and Microsoft Excel®. The theory that was used is presented in the literature review above, and software specific models such as Matlab® scripts are included in the Appendix. In addition to effects on vehicle dynamics, packaging constraints were analyzed in a similar manner. Proven optimization theory was used to analyze tradeoffs between relevant objectives with respect to constraints such as positioning and packaging limitations.

Quantitative methods combined with qualitative methods and assumptions were used to evaluate the financial aspects of the emergency braking system. Additionally, a sensitivity analysis was carried out in order to create an understanding of how specific input variables affect the value of the investment. Appropriate evaluation methods for such analysis are explained in the literature review. The same approach was used to evaluate the sustainability of the VEB. Sustainability was quantified using cost as the measure whenever possible.

Empiric data that has been gathered by Autoliv was used as reference in the analysis that was carried out. Practically all analysis was however based on data that was created during the project. When data for analysis was needed, simulations were carried out to create the data.

3.2 Method Of Scientific Inquiry

The method of scientific inquiry that has been used throughout the study can be considered to be both *inductive* and *deductive.* (Wallén, 1996) Inductive in the way that data was gathered as a basis for general and theoretical conclusions and deductive in the way that imaginable sources of causes for effects were varied in order to draw conclusions. It can even be argued that the adopted inquiry is *hypothetically deductive,* as the unknown effects were explored empirically. That is, models with theoretical relationships were used to search for empirical consequences.

Research already carried out by Autoliv is mainly done in an inductive way where observations from experiments and tests have been analyzed and the results are used to improve the concept. Data has mainly been gathered through physical testing[14]. When using data that has been measured for a different purpose, the validity of the results could be compromised. (Wallén, 1996) The validity of the data that is used for analysis directly affects the reliability and quality of the results. The quality of the research is further discussed in the subsequent chapter.

3.3 Quality Of The Research

The *quality* and *objectivity* of the research conducted in the master's thesis can be qualitatively evaluated with respect to *reliability*, *validity* and *general applicability*.[15] The reliability of the methods that have been used to gather and analyze data is considered to be satisfactory as nothing but proven facts were used to build models and conduct analysis. Use of secondary data could however have affected the outcome of the analysis and lowered the reliability (Wallén, 1996). The secondary data that was used was however collected with the same product in mind, which could increase the validity of the information (Eriksson & Wiedersheim-Paul, 2008).

Objectivity of the results was accomplished by a quantitative approach. The nature of the problem that is treated in the master's thesis did not require extensive qualitative analysis. Therefore, to increase the general applicability and ensure reliability of the results, quantitative analysis was performed to the largest possible extent. (Wallén, 1996) The analysis is supported by empirical simulation data where literature cannot provide useful information. The reliability of the results can however be compromised when conducting analysis based on data that originally has been collected for a different purpose, which can reduce the validity of the data that was used to produce some results.

[14] Christian Svensson, Director, Test and Design, Autoliv Development AB, December 19th 2013.
[15] Bengt Berglund, Professor, Technology Management and Economics, Lecture Notes, February 2012.

3.4 General Applicability

General applicability is an important factor in all scientific research results. (Wallén, 1996) The general applicability can be divided into *empirical* and *theoretical* general applicability. The empirical general applicability is low as the empirical data used to conduct analysis is specific for the concept that is evaluated in the thesis. The theoretical general applicability is affected by assumptions, limitations and simplifications. (Wallén, 1996) Provided an identical set of assumptions, limitations and simplifications, the theoretical general applicability of the results is theoretically high. Assumptions are however likely to be affected by the researchers. Assumptions that are made are described throughout the report and should therefore not affect the theoretical general applicability, provided that these assumptions remain the same while repeating the analysis.

Eriksson and Wiedersheim-Paul (2008) define general applicability as results that are only valid in the case of the study, which resembles the definition for empirical general applicability given by Wallén (1996). That is, according to the viewpoint of Eriksson and Wiedersheim-Paul (2008), the results of this study are not generally applicable as previously stated when discussing the empirical general applicability. Wallén (1996) does however present a more versatile view on general applicability and the results of this study can according to Wallén's reasoning be considered to be theoretically generally applicable.

4 Results
This chapter presents the results of the work that was carried out in the project. It begins with the results from the early efforts of understanding the system followed by rigid body simulations. Then, the reader is taken through how the results from the many simulations were analyzed with the approach of evaluating tradeoffs. Lastly, the findings from the investment evaluation and the sustainability analysis are presented.

4.1 Analysis Of Logged Data From Physical Testing
Logged data from physical testing carried out by Autoliv was analyzed in order to direct the research in the most crucial direction and to consolidate the first research question. The existing prototype of the VEB was mounted behind the rear axle on a front engine, rear wheel driven automobile[16]. Different scenarios were tested: braking followed by turning and turning followed by braking, with and without the VEB respectively.[17] The tests were persistently carried out with an entry speed of approximately 45 km/h to ensure comparability between the results. Data from these tests were analyzed after being provided by Autoliv.

The relationship between longitudinal acceleration and yaw rate was evaluated in order to guide the direction of the project. Increased longitudinal deceleration is the benefit and sole purpose of incorporating the VEB and yaw rate indicates how well the vehicle turns as described in the theoretical framework, hence the comparison between the two. Functions of the form in Equation 12 below were fitted to the data in each of the four cases, where a is the acceleration and c is a constant term. This was done in order to create a unified quantitative expression for the relationship between yaw rate and acceleration in all four cases.

$$Yaw\ Rate = c + a^2$$

Equation 12 – Function that was fit to data from physical testing

Figure 11 below illustrates the result from one of the four cases. It shows how yaw rate varies with longitudinal acceleration for the case of turning followed by braking. This was done for the test scenarios both with and without the VEB in order to arrive at a general expression for how Yaw Rate varies with longitudinal acceleration. The three remaining scenarios can be found in Appendix I – Analysis of Data from Physical Testing.

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[16] Christian Svensson, Director, Test and Design, Autoliv Development AB, January 8th 2014

[17] Dan Bråse, Research Engineer, Autoliv Development AB, February 3rd 2014

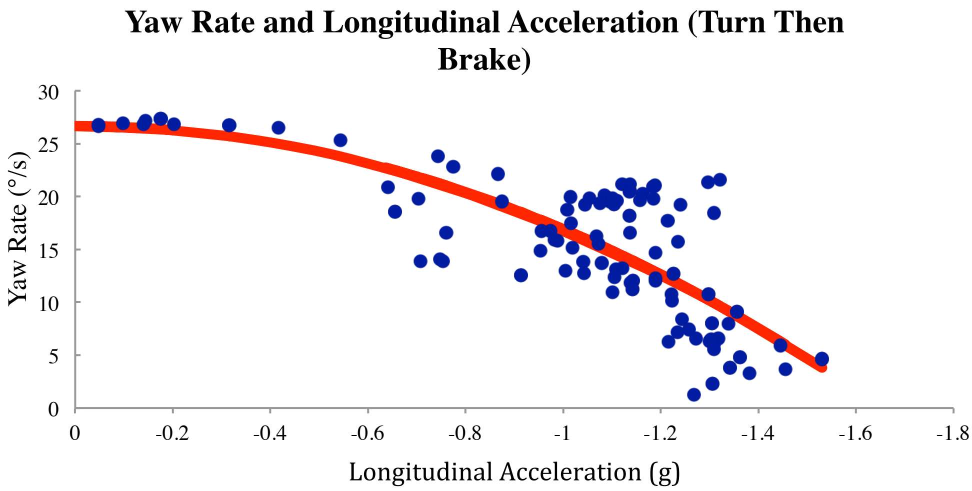

Figure 11 – Curve fitted to data points from physical testing

The average coefficient for *a* and the constant term *c* in Equation 12 were then used to generally express the relationship between yaw rate and acceleration in the tests that were carried out. This composed relationship is illustrated in Figure 12 below. The analysis clearly shows that yaw rate does vary with acceleration. The yaw rate decreases on average 3 % per 0.1 g of acceleration between 0.1 g and 1.2 g, with a 50 % decrease between 0.1 g and 1 g of deceleration. This can be explained by tire properties as illustrated in Figure 7 in the Theoretical Framework. It shows how the resultant friction force limits the turning capacity of a vehicle and that a large braking acceleration consequently provides lesser available friction for cornering. The theory corresponds well with the findings presented in Figure 12.

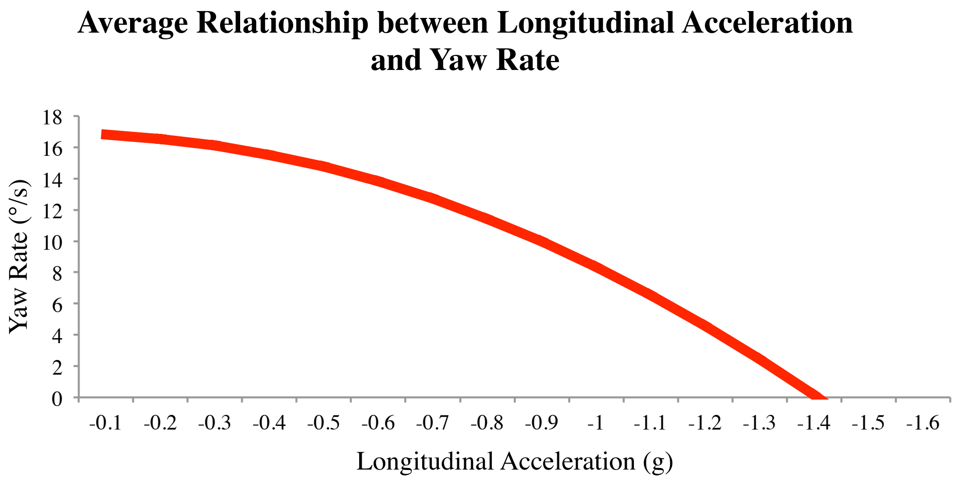

Figure 12 – Average relationship between longitudinal acceleration and yaw rate

This initial evaluation of existing logged data confirmed that there in fact was a need for closer research related to vehicle dynamics as stated in research question 1, and more specifically yaw rate. The few tests that were carried out with the physical prototype were however not considered to be a large enough sample to properly draw conclusions regarding how the VEB affects vehicle dynamics. A simulation model was therefore constructed in order to enable quantitative analysis of the effects on vehicle dynamics. The simulations that later were carried out using this model are explained in detail in sections 4.3 and 4.4.

4.2 Static System Modeling

Free body diagrams with corresponding equations for static equilibrium were created in order to increase the understanding of the system. The mechanical system constituted by the vehicle and the VEB is statically underdetermined, so the system of equations had to be solved numerically. The system was therefore divided into two sides, the vehicle side and the VEB side, as presented in the two following subchapters. This separation enabled solving the system by varying the angle of the VEB and comparing the force *F* in the VEB linkage.

4.2.1 Vehicle Side

Figure 13 below shows the mechanical system on the vehicle side of the system. The added force *F* with the angle *v* that was varied can be seen in the figure. All calculations were done under the assumption that the system has reached a static state.

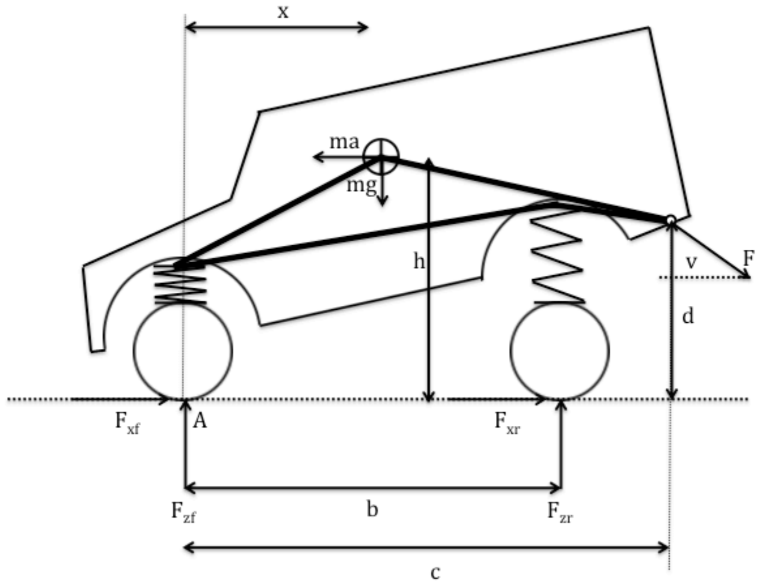

Figure 13 – Free body diagram of the complete vehicle-VEB system

Equation 13, Equation 14 and Equation 15 below were subsequently defined in line with the theory presented in section 2.1. Moreover, the directions of the forces in Figure 13 were used when formulating the equations below.

$$\uparrow: F_{zf} + F_{zr} - mg - Fsin(v) = 0$$

Equation 13 – Vertical forces

$$\leftarrow: ma - F_{xf} - F_{xr} - Fcos(v) = 0$$

Equation 14 – Horizontal forces

$$\curvearrowright A: mgx - mah - F_{zr}b + Fcos(v)d + Fsin(v)c = 0$$

Equation 15 – Moment around front wheel contact patch

The normal load distribution between the front and the rear axle was assumed to remain the same after the addition of the VEB unit. This was done in order to preserve the brake load distribution in conformance with the theory that was presented in chapter 2.2. This boundary condition is presented in Equation 16 and Equation 17, where B_f and B_r are the constants that define how the load is distributed between the front and the rear axle.

$$F_{zr} = B_r\big(mg + Fsin(v)\big)$$

Equation 16 – Rear brake load

$$F_{zf} = B_f\big(mg + Fsin(v)\big)$$

Equation 17 – Front brake load

As the height of both the Center of Gravity (hereinafter CoG) as well as the VEB mounting height varies during the braking process, expressions were created for these heights as can be seen in Equation 18 and Equation 19. The system is as mentioned assumed to have reached static equilibrium and angles are assumed to be small. The kinematic relationships for the CoG height and the VEB mounting height are illustrated in Figure 14 and Figure 15 below. The not already introduced variables k_f and k_r are the respective front and rear total suspension spring stiffness.

$$h = h_0 - \left(\frac{F_{zr}}{k_r} + \frac{\left(\frac{F_{zf}}{k_f} - \frac{F_{zr}}{k_r}\right)(b-x)}{b}\right)$$

Equation 18 – CoG height

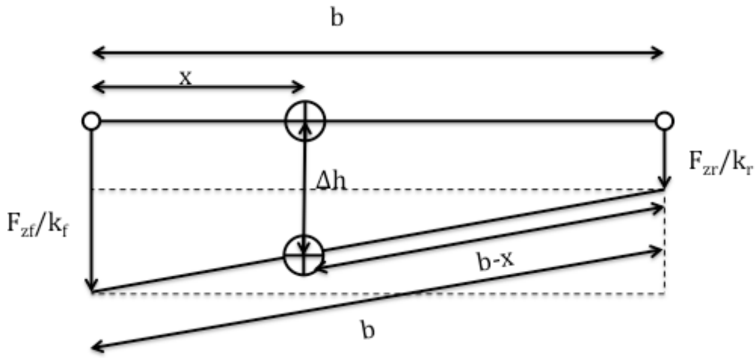

Figure 14 – CoG height displacement

$$d = d_0 - \frac{\frac{F_{zr}c}{k_r} + \frac{F_{zf}}{k_f}(b-c)}{b}$$

Equation 19 – VEB mounting height

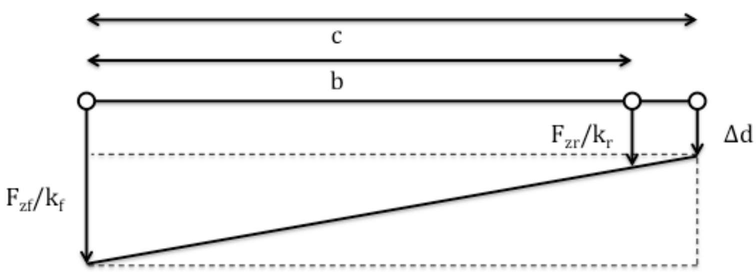

Figure 15 – VEB mounting height displacement

An expression was then created for the magnitude of the braking acceleration of the vehicle. Equation 20 below presents how the acceleration was calculated. It should be stated that the braking acceleration was calculated using the initial CoG height h_0 to simplify the calculation. The effects that this simplification has on the acceleration did however prove to be negligible.

$$a = -\frac{mg\left(x - bB_f\right) - \rho A\left(bB_f + c\right) + \mu_t\left(bB_f + c\right)\dfrac{mg\rho A}{\mu - \mu_t}}{m\left(h_0 + \dfrac{bB_f + c}{\mu - \mu_t}\right)}$$

Equation 20 – Expression for braking acceleration

4.2.2 Vacuum Emergency Brake Side

As with the vehicle side of the vehicle-VEB system, the VEB side was also treated separately. The VEB side free body diagram was constructed as presented in Figure 16 below with the equivalent force expressions in Equation 21 and Equation 22. The mass of the VEB corresponds to approximately 0.5 % of the normal load that the vacuum produces so the VEB was assumed to be massless in the calculations.

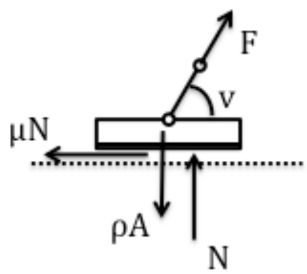

Figure 16 – Free body diagram of the VEB unit

$$\uparrow: Fsin(v) - \rho A + N = 0$$

Equation 21 – Vertical forces

$$\rightarrow: Fcos(v) + \mu N = 0$$

Equation 22 – Horizontal forces

4.2.3 Solving The System Of Equations

Expressions for *F* were subsequently created so that the linkage angle *v* could be found. The angle *v* was found by matching the vehicle side *F* to the VEB side *F*. Simplification of Equation 13 through Equation 19 on the vehicle side gave the quadratic equation for *F* as presented in Equation 23 below.

$$F^2\left(\frac{\cos(v)\sin(v)}{b}\left(\frac{B_r c}{k_r} + \frac{B_f(b-c)}{k_f}\right)\right) - F\left(sin(v)\left(ma\left(\frac{B_r(b-x)}{bk_r} - \frac{B_r}{k_r} - \frac{B_f(b-x)}{bk_f}\right) + bB_r + c\right) + d_0\cos(v)\right) - m\left(ah_0 + g(bB_r + x)\right) = 0$$

Equation 23 – Vehicle side F

The same was done on the VEB side of the vehicle-VEB system. Solving Equation 21 and Equation 22 for F on the VEB side gave an expression for F on the VEB side. This expression is presented in Equation 24 below.

$$F = \frac{\mu \rho A}{\cos(v) + \mu \sin(v)}$$

Equation 24 – VEB side F

Matlab® was then used to solve the underdetermined system of equations. The vehicle side and the VEB side were therefore solved separately, with values for v ranging from 0 to π radians. Static equilibrium was subsequently found by matching the VEB side F with the vehicle side F, thus solving the system of equations numerically. That is, v was found by finding the v that gave the same F on both the vehicle and the VEB side of the system.

4.2.4 Example Case Vehicle

An example vehicle was modeled in order to further increase the understanding of the system and to get tangible results. Reasonable vehicular parameters were defined to obtain data that could be analyzed. These parameters are defined under *Vehicle Data* in Appendix II – Static System Modeling Matlab Code. VEB specific parameters such as the VEB-to-road contact patch area and obtainable pressure were assumed to be the same as the physical prototype mentioned in section 4.1. Additionally, the sliding friction was assumed to be 75 % of the static friction. This resulted in that the available friction between the VEB and the road was always 75 % of the available friction in the tire-to-road contact patches, assuming no sliding of tires.

Values for the VEB mounting location were then specified within reasonable and arbitrary limits. The tire-to-road coefficient of friction was varied between 0.1 and 1 and the system of equations was subsequently solved for every value of the coefficient of friction in this range. Figure 17 below presents the desired angle between the VEB linkage and the road in order to achieve the desired boundary conditions for the vehicle that is specified in Appendix II – Static System Modeling Matlab Code.

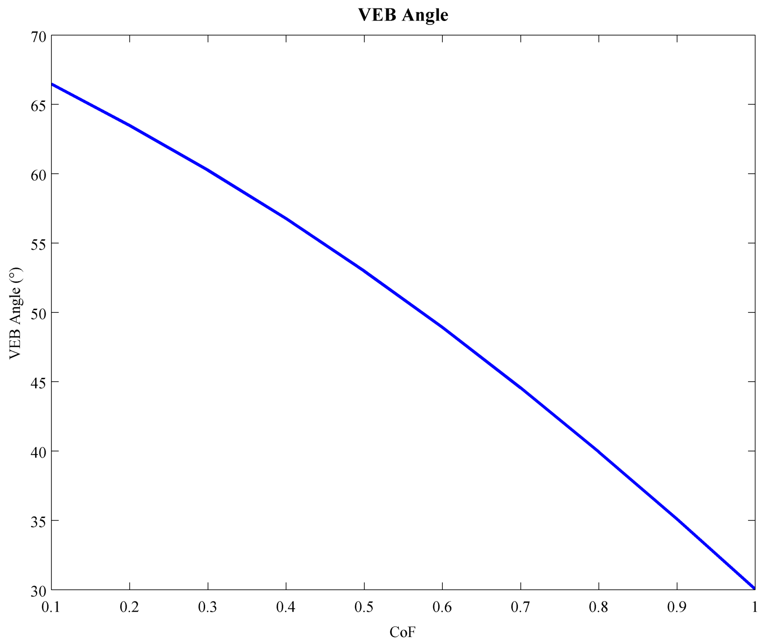

Figure 17 – Desired VEB angle for different coefficients of friction, 65 % front axle load

It can be seen that the desired angle between the road and the VEB linkage changes greatly with the coefficient of friction. It is important to note that this angle corresponds to the angle that the system has arrived at after the vehicle has reached static equilibrium. That is, other systems such as suspension springs and dampers could potentially have affected the system during the time in which the vehicle has reached static equilibrium.

An angle that varies with the coefficient of friction practically means that the length of the linkage connecting the VEB to the vehicle varies as well. The VEB angle in Figure 17 above and the linkage length in Figure 18 below are examples of this for a single vehicle with a single VEB configuration.

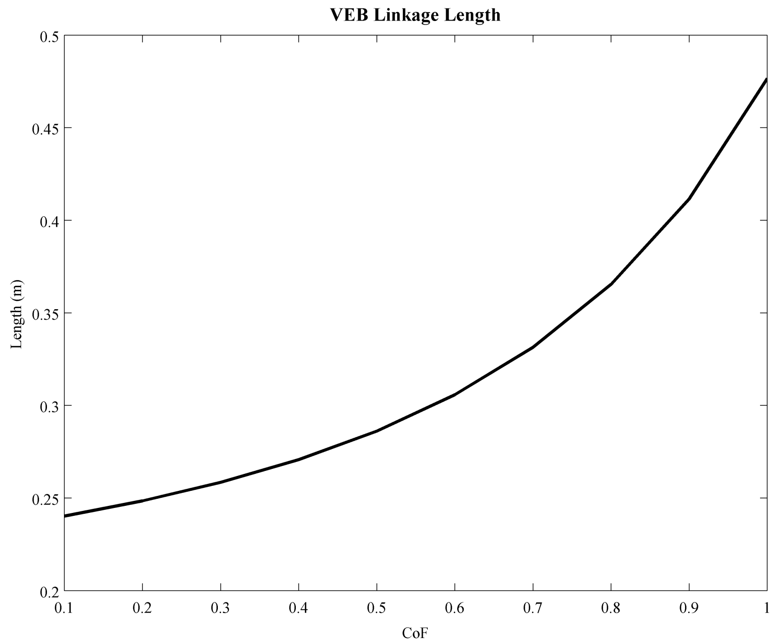

Figure 18 – Linkage length for different coefficients of friction, 65 % front axle load

The exemplified case has a VEB mounting height of 250 mm and the VEB unit is attached close to the rear axle of the vehicle. Also, the desired normal load distribution is assumed to be 65 % at the front axle and 45 % at the rear axle. An increase in the distribution to a more extreme 85 % at the front axle and 15 % at the rear axle yields an entirely different result as illustrated in Figure 19 and Figure 20 below.

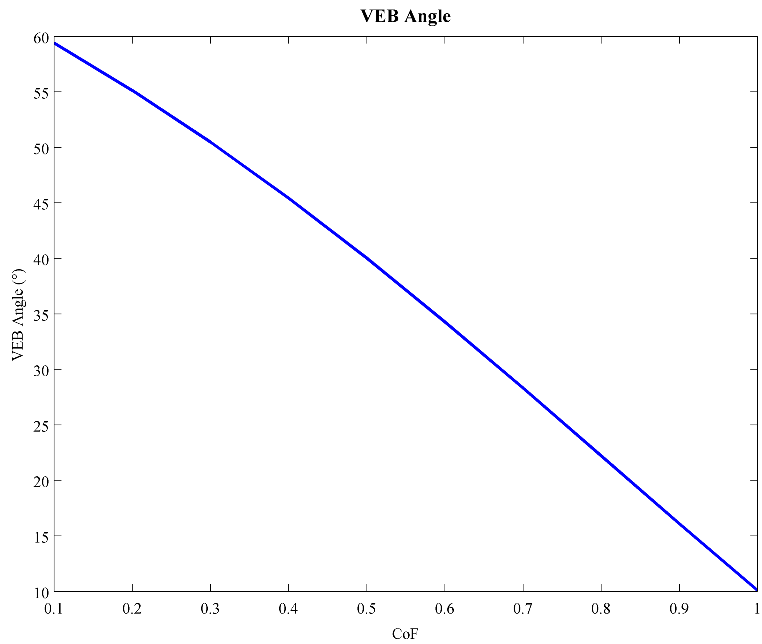

Figure 19 – Desired VEB angle for different coefficients of friction, 85 % front axle load

When comparing the results that are illustrated in Figure 19 with those in Figure 17 it can be observed that the difference between the desired angles at low coefficients of friction is small, with an approximately difference of 9 %. As the coefficient of friction increases, it can however be seen that the desired angle is 67 % lower in the case of the vehicle with a desired load of 85 % on the front axle. The small angles that are arrived at in the case could also bring additional challenges, as illustrated in Figure 20 below.

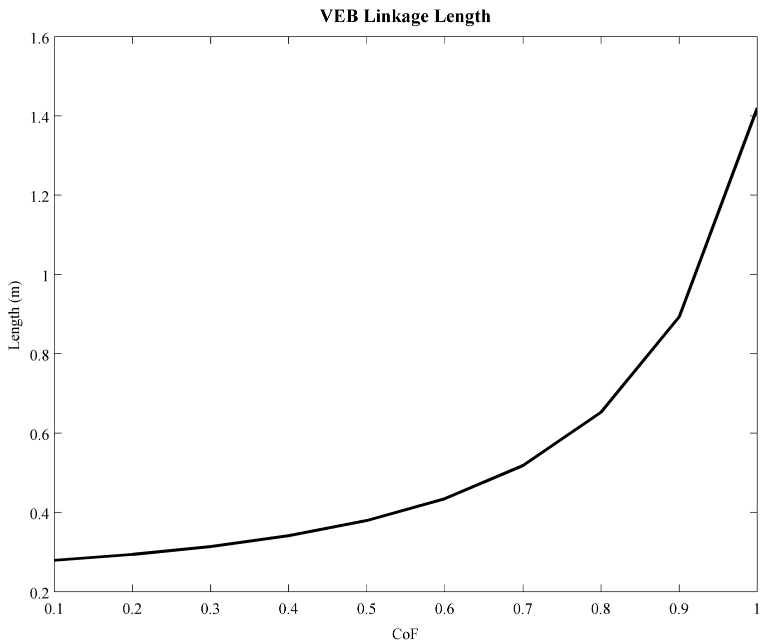

Figure 20 – Linkage length for different coefficients of friction, 85 % front axle load

As the coefficient of friction is increased, the heavily decreased VEB linkage angle results in a linkage length that grows exponentially. Increased linkage lengths might have implications on packaging of the VEB unit among with potential problems regarding the weight of the linkage. Moreover, the desired angles that the static modeling resulted in does as mentioned correspond to the desired VEB linkage angle when the system has reached static equilibrium. That is, the results from the static system analysis do not provide any information regarding how the vehicle-VEB system acts dynamically. Therefore, the research called for analysis of the dynamic aspects of the system, which is described in the following chapters.

4.3 Dynamic Simulations

Adams® was used to perform dynamic simulations when gathering information for the evaluation process. The VEB system is a new system that cannot be found in the simulation software. As a result, the creation of a new model was necessary in order to analyze the concept with dynamic simulations. This section explains how the model was build and how the simulations were carried out. The overall simulation method was a kinematic analysis where torque and forces were applied to a system with known properties, as described in section 2.3.2.

4.3.1 Simulation Model

The VEB unit was modeled as a new subsystem that was attached to an example vehicle that existed and was already modeled in Adams®. This example vehicle is included in the Adams® software package and it is a complete vehicle model with advanced tire models. The example vehicle also has all properties and relationships between bodies defined. After creating the VEB model, full vehicle simulations could be carried out with the VEB attached.

Before creating the model of the VEB, its functions were identified so that the model could be modeled correctly. Key factors that were identified are the plate that slides on the ground and a linkage that can move relative to the ground and to the moving vehicle. A number of relationships between these bodies were then identified and corresponding connections between the bodies could be defined in conformance with the simulation software. The modeled VEB subsystem is illustrated in Figure 21.

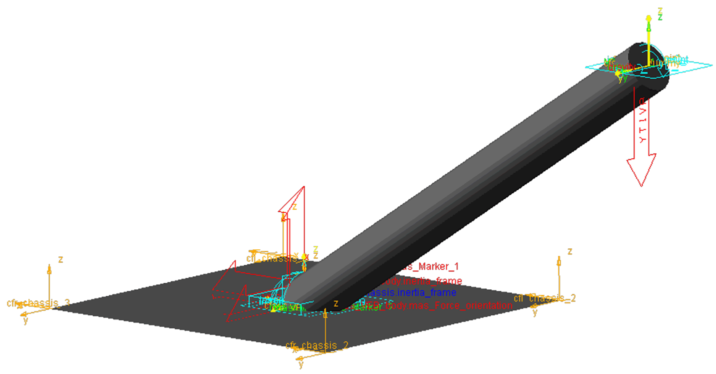

Figure 21 – The modeled VEB

A linkage was connected to the vehicle using a hinge joint that allows the linkage to follow the vehicle as it is moving. A plate sliding on the ground was then constrained to the linkage with several combined joints that removed the necessary degrees of freedom. In order for the VEB model to provide the frictional force that adds braking acceleration, expressions for the frictional force had to be created. The force expressions use normal force from the vacuum and the current speed relative to the ground as input parameters. The normal force generated from the vacuum is activated when the brakes are applied and the time from when the brakes are applied until the force in the VEB is fully developed is 0.1 seconds. This is illustrated in Figure 22.

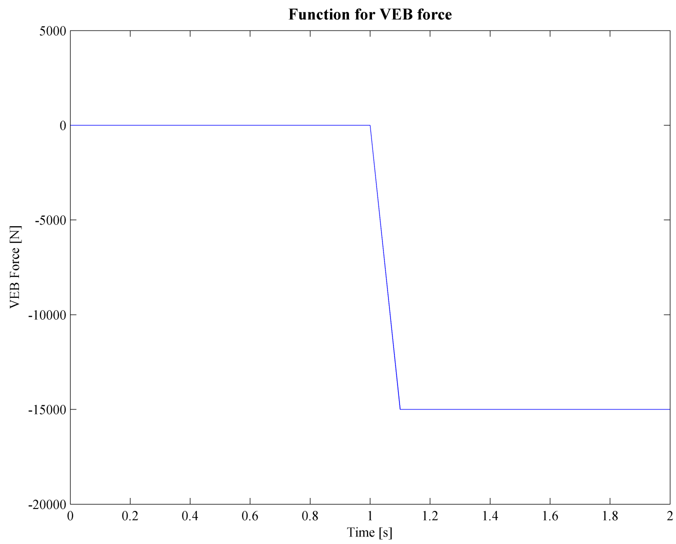

Figure 22 – Step function for the VEB normal force

As seen in Figure 22 the VEB normal force is zero until activation. The force delay of 0.1 seconds is the assumed time it takes for the vacuum to reach its peak value. Furthermore, it is important to note the simplification that the VEB constantly is sliding on the ground in the modeled system and no kinematic events take place in order for the VEB to reach the ground. That is, the only event that takes place when activating the VEB is the activation of the force from the vacuum. The drop from the stand-by position to the ground is therefore not accounted for in the model. A more detailed description of how the model and the force expression were created in Adams® can be found in Appendix III – Simulation Model.

4.3.2 Design Variables

Three factors were identified as key design parameters during the modeling of the static system in section 4.2. These three factors have significant impact on the vehicle-VEB system and they are also possible to alter with the design. These factors are expressed as design variables and are listed in Table 2 and explained afterwards.

Design Variables	Denotation
Longitudinal position of the VEB attachment	VEB X Position
Vertical height of the VEB attachment	VEB Z Position
Length of the linkage between the VEB and the vehicle	Link Length

Table 2 – Overview of design variables

The design variable VEB X Position indicates the distance between the front axle and the attachment point of the VEB. VEB Z Position correspondingly indicates the height of the attachment point from the ground and Link Length is specified as the length of the VEB linkage in the x direction. By defining the Link Length in such a way, the simulations were practically possible to carry out, as contact between the VEB and the road could be ensured in every VEB configuration in the design space. All results that are presented further down the report are however presented as the actual length of the linkage, and not in the X direction.

Large ranges for the allowable values for the design variables were then defined. Next, 3 000 configurations of the design variables in these ranges were sampled using Latin Hypercube sampling. Every one of these 3 000 configurations was later simulated in order to create the data that was used in the tradeoff analysis in section 4.4. The ranges are illustrated in Figure 23 below.

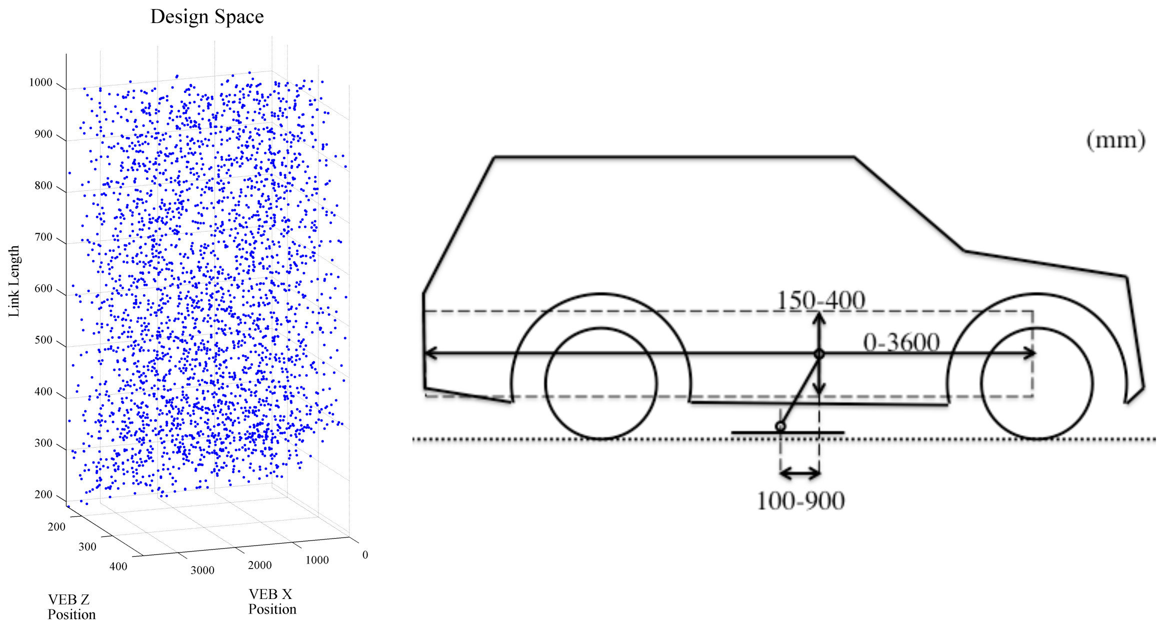

Figure 23 – Design Space sampling and schematic illustration on a vehicle

The scatter plot to the left in Figure 23 shows all 3 000 configurations that later were simulated. This design space was selected to cover a large span of designs, on the verge of being unrealistic. The parameters that were selected for variation in the simulations are all parameters that can be changed when implementing the design in a vehicle platform.

4.3.3 Simulation Output Measurements

Three simulation output measurements were identified to be critical when evaluating how the VEB affects vehicle dynamics. These measurements were defined in line with the theory presented in section 2.2 and are listed in Table 3.

Simulation Output Measurements
Yaw Rate
Acceleration
Brake Load Distribution

Table 3 – Simulation output measurements

Tradeoffs between objectives based on these measurements were later analyzed to evaluate the influence of the VEB on vehicle dynamics. The result of the tradeoff analysis can be reviewed in section 4.4.

Test simulations were used to define how measurements would be carried out. Limitations in the software combined with an evaluation of different ways to measure led to a number of measurement methods that were practically possible to perform. The average value for the yaw rate was selected in favor of peak values, in order to be able to do a relevant comparison in the trade-off analysis later on. Additionally, the minimum acceleration was selected as a measurement for the brake performance. For the brake load distribution, the values at the end of the simulations were selected to avoid recording initial fluctuations. The test simulations showed that the brake load distribution stabilizes after a while, which indicated that the value at the end of the simulation would give the most accurate reading.

4.3.4 Simulations

In order to perform the tradeoff analysis between the simulation output measurements, two separate scenarios were simulated for every one of the 3 000 sampled design configurations, resulting in a total of 6 000 simulations. Table 4 presents an overview of the strategy for the simulations that were made.

Overview of Simulations

Simulation Scenario	Output Measurements	Number of Simulations
• Braking in a straight line • 50 km/h entry speed	• Acceleration • Brake Load Distribution	3 000 (one for every design configuration)
• Braking-in-turn • 50 km/h entry speed • 27 meter turning radius	• Yaw Rate	3 000 (one for every design configuration)

Table 4 – Overview of simulations

Both simulation scenarios presented in Table 4 were tested on road surfaces with identical properties. The same turning radius and speed as for the comparison with logged test data are used. This makes the results comparable to the real life testing already performed. Furthermore, the findings in section 4.2 suggest that road friction is a highly influencing parameter. It was despite that kept constant in all simulations, as it is a parameter that cannot be affected by the design of the VEB, but is rather reflected in the external conditions such as type of road surface and weather conditions.

No Anti-Lock Braking System (hereinafter ABS) has been created and no driver simulator has been used. This was done so that the pure effects of the VEB on vehicle dynamics could be analyzed without interference of other systems. This eliminates the risk of having systems that hide effects on vehicle dynamics that the VEB causes. Furthermore, a brake force that stops the vehicle with a deceleration of around 1 g without locking any of the brakes when the VEB is not active have been used in all simulations. Depending on the position of the VEB some brakes might lock up at particular scenarios, resulting in sliding tires. That is then an effect from the VEB and should therefore be included in the results.

The strongest relationship that was found after performing the simulations is seen in Figure 24. It shows how the difference in yaw rate normalized to a reference vehicle without a VEB varies with the VEB X Position. It can be seen that the VEB X Position clearly affects the yaw rate. The width of the curve does however indicate that the yaw rate is affected by other design parameters as well.

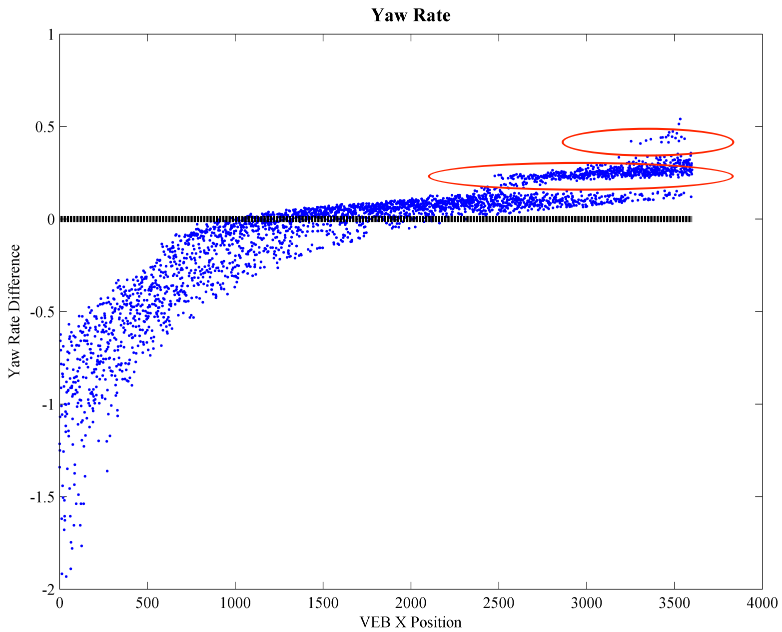

Figure 24 – Yaw rate as a function of VEB X Position

Two gaps in yaw rate marked with red can be seen in the plot when the car is understeering. The first gap is identified to occur when the inner front wheel starts sliding due to being locked and the second gap when both front wheels are locked and sliding. A simulation of the reference vehicle without a VEB was performed to verify this theory. The spring stiffness was varied in steps and the yaw rate output it resulted in was recorded for every increase in stiffness. Figure 25 shows the result of this and it can be seen that a similar gap occurs when reaching a certain point.

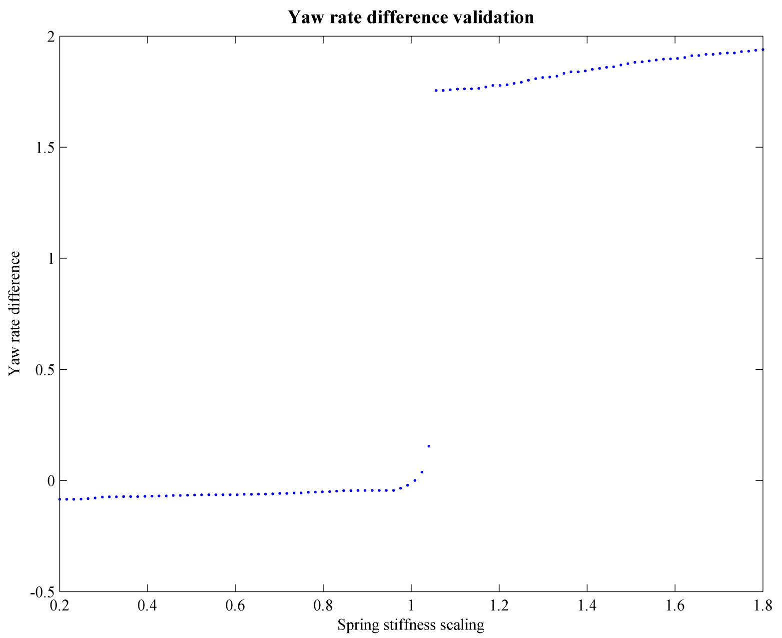

Figure 25 – Spring stiffness varied to test the effects on yaw rate

4.4 Tradeoff Analysis

The results from the dynamic simulations are analyzed in this chapter. All analysis is performed in relative measures to ensure objectivity and, to the furthest possible extent, general applicability. Tradeoffs were analyzed between the three simulation output measures: yaw rate, acceleration and brake load distribution. These threes output measures were compared for every single simulated VEB configuration.

4.4.1 Multi-Objective Optimization Problem

A multi-objective optimization problem was formulated to enable a comprehensive tradeoff analysis of the three measures mentioned above. Every simulation output measurement represents one objective in the tradeoff analysis. Each objective has to be minimized in order to comply with optimization theory as mentioned in the theoretical framework, so the objectives were expressed relative to a reference vehicle. Both simulation scenarios in Table 4 were therefore simulated without the VEB. The simulation output from these reference simulations were recorded and each of the 6 000 simulations were compared to the result from these reference simulations. Two different expressions were used to calculate this relative difference. The expression used for Yaw Rate and Brake Load Distribution is presented below.

$$Relative\ difference = \left|\frac{Simulated\ reference\ value\ from\ vehicle\ without\ VEB - Simulated\ value\ from\ VEB\ equipped\ vehicle}{Simulated\ reference\ value\ from\ vehicle\ without\ VEB}\right|$$

Equation 25 – Relative difference for Yaw Rate and Brake Load Distribution

The absolute value was used as the sign of the difference is not considered. That is, the optimization problem only seeks to minimize the difference, regardless of an increase or decrease. A slightly different expression was used to calculate the relative difference for the objective Acceleration. This expression is presented below.

$$Relative\ difference = \frac{Simulated\ reference\ value\ from\ vehicle\ without\ VEB - Simulated\ value\ from\ VEB\ equipped\ vehicle}{Simulated\ reference\ value\ from\ vehicle\ without\ VEB}$$

Equation 26 – Relative difference for Acceleration

The absolute value of the difference is not used in the case of Acceleration as stated in the expression above. This is done in order to preserve compliance with optimization theory and at the same time optimize the performance of the VEB. Minimizing the percentage difference between the reference vehicle and the VEB equipped vehicle maximizes the performance of the system. The performance of the system is maximized as a large negative difference gives a large negative acceleration in the VEB equipped vehicle. An overview of the objectives is presented in Table 5 below.

Overview of Optimization Targets for Objectives

Simulation Output	Objective		Effect
Yaw Rate	$f_1(\mathbf{x}, \mathbf{p})$	Minimize absolute difference between VEB vehicle and reference vehicle	Turning Behavior Maintained
Brake Load Distribution	$f_2(\mathbf{x}, \mathbf{p})$	Minimize absolute difference between VEB vehicle and reference vehicle	Front to Rear Load Distribution on Brakes Maintained
Acceleration	$f_3(\mathbf{x}, \mathbf{p})$	Minimize difference between VEB vehicle and reference vehicle	Negative Acceleration Maximized

Table 5 – Overview of optimization targets for the different objectives

When expressing the objectives as explained above, the optimal solution for the VEB would be a solution that has exactly the same yaw rate and exactly the same brake load distribution as the reference vehicle without the VEB, but the largest possible negative acceleration. The fact that there are tradeoffs between these objectives did however indicate that such a solution did not exist. The multi-objective optimization problem was therefore formulated so that these tradeoffs could be analyzed. Weights that specify the relative importance between the objectives were also added to enable finding the optimal solution later on. The formal optimization problem that this formulation resulted in is presented below.

$$\begin{aligned}&\text{minimize } \{w_1 f_1(\mathbf{x}, \mathbf{p}), w_2 f_2(\mathbf{x}, \mathbf{p}), w_3 f_3(\mathbf{x}, \mathbf{p})\}\\ &\text{subject to } \mathbf{g_1}(\mathbf{x}, \mathbf{p}), \mathbf{g_2}(\mathbf{x}, \mathbf{p}), \dots, \mathbf{g_8}(\mathbf{x}, \mathbf{p})\end{aligned}$$

Equation 27 – Formal multi-objective optimization formulation used in the tradeoff analysis

The formulation above includes the weights denoted w_n for each objective. Depending on the relative importance between the objectives, the optimal solution could be found by varying the values of the weights, as shall be demonstrated further down the report. The optimization formulation also includes parameters, $\mathbf{p}$, and design variables, $\mathbf{x}$. Parameters are variables such as road surface friction and road surface roughness that cannot be altered with the design of the VEB, whereas design variables are defined as variables that can be changed when designing the VEB. These have been introduced earlier and can be reviewed in Table 2.

The design variables were used as input in the simulation model explained in chapter 4.3 to create output in the three measures mentioned above: yaw rate, brake load distribution and acceleration. That is, the objective functions f_1, f_2 and f_3 were represented by the simulation model.

4.4.2 Constraints

A number of constraints were added to the optimization problem in order to limit the feasible set of solutions. The tradeoff analysis that is presented further down the report deals with both constrained and unconstrained sets of both input and output data. The input data is constrained in terms of design constraints and the output data is constrained in terms of solution constraints, as described in the following two subchapters. It should be noted that the constraints that are stated are highly arbitrary and depend entirely on the application. The constraints presented below are therefore merely to demonstrate one possible scenario.

4.4.2.1 Design Constraints

When selecting a position for the VEB unit, the available space will be limited by other components and systems in the vehicle, which is described in section 4.5. A reasonable approximation about the packaging possibilities was assumed and used in the constrained optimization.

The tradeoff analysis presented in chapter 4.4.3 utilizes the design constraints presented in Table 6 below when it is specified that constraints have been used. Despite that these constraints are vehicle dependent, no particular vehicle was kept in mind when choosing these arbitrary values for the constraints.

Design Constraints		Min	Max
$g_1(x, p)$	**VEB X Position (mm)**	1800	2500
$g_2(x, p)$	**VEB Z Position (mm)**	150	300
$g_3(x, p)$	**Link Length (mm)**	200	700

Table 6 – Design constraints

Combining the design constraints presented in Table 6 gives a constrained design space with only the feasible designs according to these constraints. Figure 26 below illustrates the constrained Design Space arrived at by combining the arbitrary design constraints. The allowed Design Space is illustrated in green inside the total simulated Design Space in red.

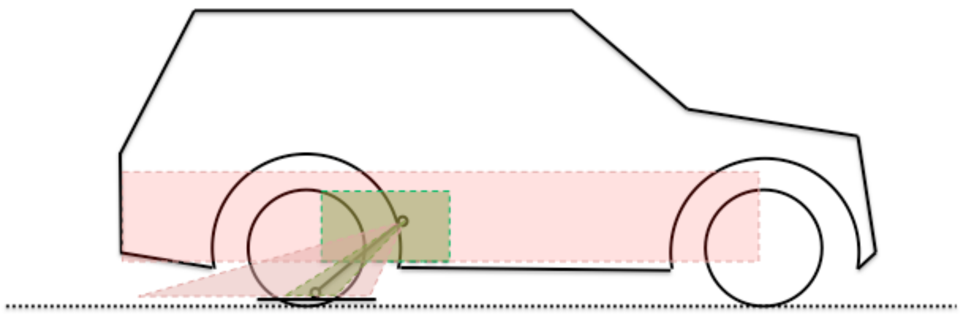

Figure 26 – Constrained Design Space in green and the entire Design Space in red

In addition to design constraints, the tradeoff analysis also depends on constraints with respect to the solution. Design constraints are the result of packaging limitations whereas solution constraints limit the effects that the VEB has on the vehicle. Solution constraints are presented in the following subchapter.

4.4.2.2 Solution Constraints

As mentioned, solution constraints limit the allowable effects that the VEB can have on certain measures. A number of example constraints for the Solution Space are presented in Table 7 below, where Yaw Rate Difference, Acceleration Difference and Brake Load Distribution Difference are the most prominent ones as described earlier.

Solution Constraints

$\mathbf{g_4(x, p)}$	**Maximum Absolute Yaw Rate Difference**	10%
$\mathbf{g_5(x, p)}$	**Maximum Braking Acceleration Difference**	-50%
$\mathbf{g_6(x, p)}$	**Maximum Absolute Brake Load Distribution Difference**	20%
$\mathbf{g_7(x, p)}$	**Maximum Front Load Difference**	40%
$\mathbf{g_8(x, p)}$	**Maximum Rear Load Difference**	30%

Table 7 – Solution constraints

Two extra constraints, $\mathbf{g_7}$ and $\mathbf{g_8}$, that limit the allowable load increase on brakes were added. As opposed to $\mathbf{g_6}$, Brake Load Distribution Difference that is specified as a relative difference, $\mathbf{g_7}$ and $\mathbf{g_8}$ limit the absolute brake load increase. This was done in order to enable constraining the solution with respect to how over-dimensioned the brakes on a particular vehicle are. The example constraints presented in Table 7 assume that the brakes are able to handle a 40 % load increase on the front wheels, and a 30 % load increase on the rear wheels.

Constraint $\mathbf{g_4}$ specifies the Maximum Absolute Yaw Rate Difference. As mentioned earlier, it is the magnitude of the difference that is of interest and not the sign of the difference, hence the absolute value. The same goes for constraint $\mathbf{g_6}$, whereas constraint $\mathbf{g_5}$ in essence limits the poorest performance of the VEB, as explained in chapter 4.4.1.

As with the design constraints, the solution constraints are highly subjective and are only incorporated to exemplify. Constraints would have to be determined by the vehicle manufacturer while integrating a VEB unit in a vehicle.

4.4.3 Tradeoff Analysis

The results of the dynamic simulations are presented in Figure 27 below. The total simulated Design Space is presented to the left. Every blue dot in the Design Space in Figure 27 represents one unique combination of the design variables. Two simulations were done for every configuration in the Design Space and every configuration has a corresponding marker in the Solution Space to the right in the figure.

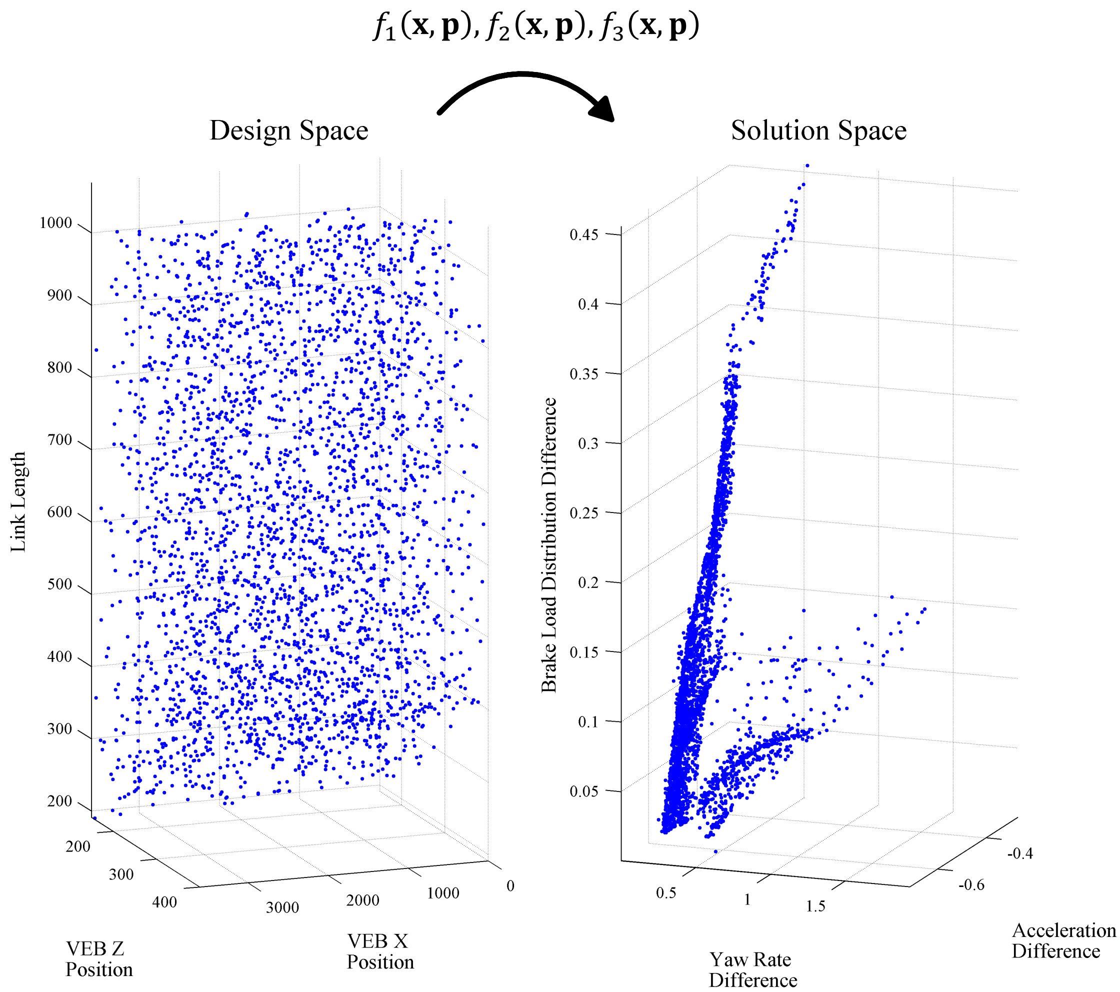

Figure 27 – Unconstrained Design Space and Solution Space

The Solution Space is the output that is arrived at by transforming input from the Design Space. The simulation model that essentially is a large number of mathematical equations accomplishes this transformation. The transformation process is illustrated in Figure 28 below.

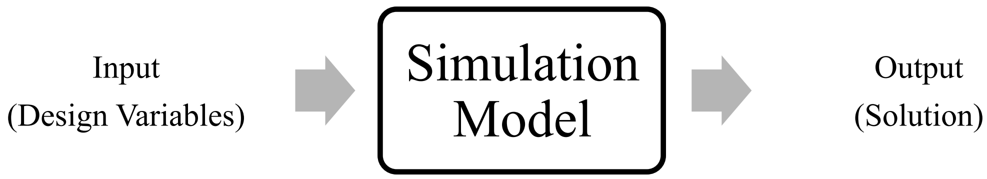

Figure 28 – Schematic representation of input to output transformation

This transformation process was then repeated for every one of the 6 000 simulations using Adams®. Yaw rate, acceleration and brake load distribution were measured in every one of these simulations. These values were then compared to the reference simulation run without the VEB and the percentage difference was calculated as described in section 4.4.1. The Solution Space on the right in Figure 27 shows the result of this. A point in the Solution Space represented by for example simulation x can be used as an example of how to interpret the result. This example can be viewed in Table 8 below.

Objective	Solution Space Value	Effect
Yaw Rate Difference	0.1	Simulation x gave an average value of the Yaw Rate that was 10 % higher or lower than the reference vehicle without the VEB.
Brake Load Distribution Difference	0.05	Simulation x gave 5 % higher or lower load on the front or rear axle than the reference vehicle without the VEB.
Acceleration Difference	-0.6	Simulation x gave 60 % better braking acceleration than the reference vehicle without the VEB.

Table 8 – Example of how to interpret the Solution Space

The Solution Space results that were exemplified above are then connected to some values for the design variables such as VEB X Position. These design variables were used when simulating the hypothetical simulation x.

Optimization theory was applied on the Solution Space after the simulations were completed. This was done in order to sort the Pareto set out, as explained in chapter 2.4.3. Figure 29 below shows the Design and Solution Spaces with the Pareto set marked in red.

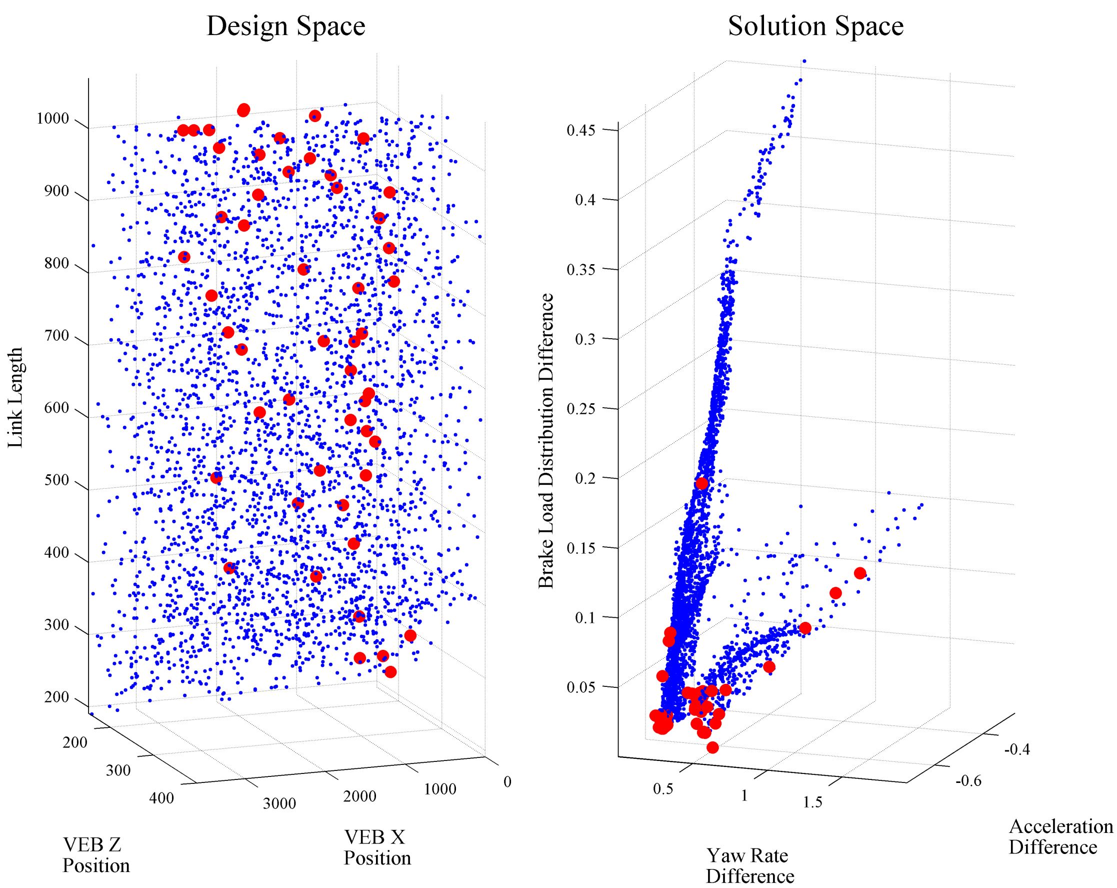

Figure 29 – Design Space and Solution Space with the Pareto set marked with red

No constraints have been added when creating the Pareto set in Figure 29. The sorting algorithm presented in Appendix VI – Optimization Sorting Program was used to arrive at the Pareto set in the Solution Space. The design variables that correspond to these Pareto solutions were then backtracked. These backtracked design variables are marked with red to the left in Figure 29 above. Consequently, each Pareto solution marked with red corresponds to a design marked with red.

By identifying the Pareto set, non-dominated and therefore most beneficial designs were found. Weights, that were presented briefly, were now introduced in order to successfully distinguish the single most beneficial design – the optimum. The weights and therefore also the optimal design are however highly dependent on the application. One vehicle manufacturer might not tolerate any compromise when it comes to the braking performance of the system, whereas another might not tolerate any raw rate change as a result of the VEB. These two manufacturers would therefore distribute the weights differently and thus arrive at different optimal designs. Figure 30 below shows the optimal design in pink when the weights are evenly distributed among the objectives. By distributing the weights equally, the objectives Yaw Rate, Acceleration and Brake Load Distribution are consequently considered equally important when finding the optimum.

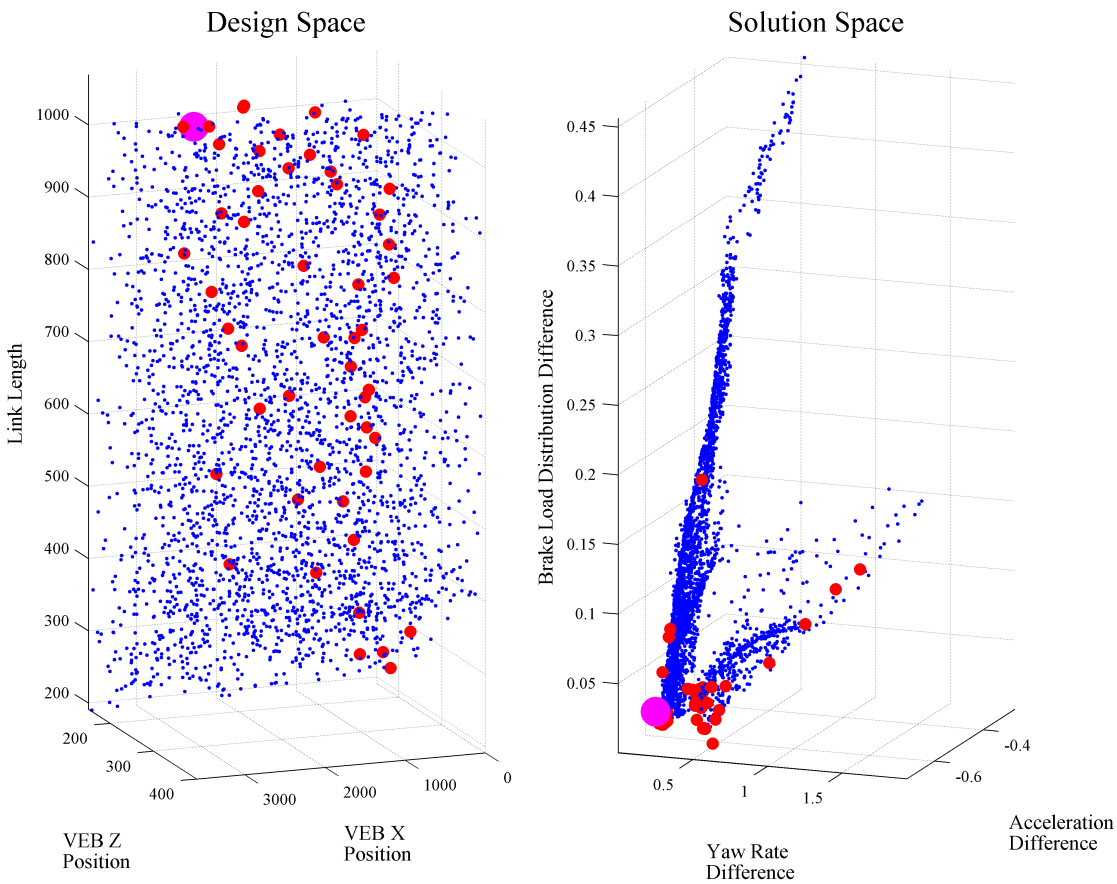

Figure 30 – Unconstrained optimal design when all weights are equal

When optimizing with equal weights, a single solution point marked in pink to the right in Figure 30 above is found. That very solution comes from the simulation that was carried out with the VEB configuration as presented by the pink marker in the Design Space to the left in Figure 30. This example therefore shows that if no limitations are considered and that if Yaw Rate, Acceleration and Brake Load Distribution are equally important, the VEB should be configured as in Table 9 below.

Optimal Configuration

VEB X Position	2311 mm
VEB Z Position	155 mm
Link Length	986 mm

Table 9 – Optimal VEB configuration – No constraints and equal weights

Table 9 does however only present the optimal design for a single case. Other optimums are found when introducing constraints and varying the importance weights for the different objectives. These optimums are compiled in Table 10 below. The Design and Solution Spaces for these optimums can be viewed in their entirety in Appendix IV – Dynamic Simulations.

Optimal VEB Configurations

	With Constraints				**Without Constraints**			
Important Objective	**Yaw**	**Acc.**	**Brake Load**	**All Equal**	**Yaw**	**Acc.**	**Brake Load**	**All Equal**
VEB X Position (mm)	1847	1893	2109	2109	1847	12	2110	2311
VEB Z Position (mm)	152	156	159	159	152	183	182	155
Link Length (mm)	375	674	620	620	375	225	875	986
Illustrated in Section	4.4.4.1	4.4.4.2	4.4.4.3	4.4.4.4	4.4.4.5	4.4.4.6	4.4.4.7	4.4.4.8

Table 10 – Optimal VEB configuration for various criteria

Figure 31 shows an illustration of what “With Constraints” and “Without Constraints” in Table 10 practically means. The allowed Design Space for “With Constraints” can be seen in the green area to the left in the figure below and the ranges for the values can be reviewed in Table 6. The optimal solutions were then evaluated only inside the green area of the total simulated Design Space for “With Constraints”. Correspondingly, the entire simulated Design Space as can be seen to the right shows that the entire simulated Design Space was evaluated when optimizing “Without Constraints”.

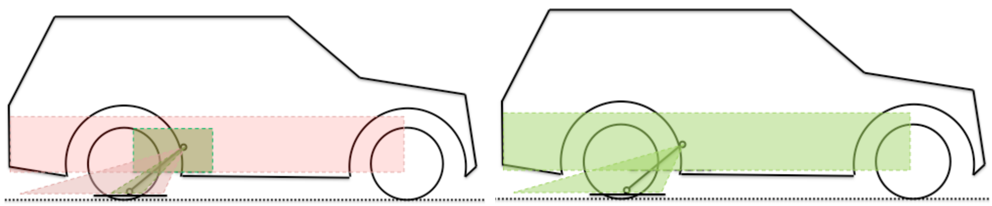

Figure 31 – Schematic images for “With Constraints” and “Without Constraints”

It is worth noting that some VEB configurations are represented several times in Table 10. As an example, when Yaw Rate is considered the most important objective, the optimal configuration is the same with and without constraints. Although when Acceleration is considered most important, the optimal VEB configuration is not the same with and without constraints. This indicates that the packaging of the VEB limits the acceleration performance of the VEB. This decrease in performance must then be accepted unless additional packaging space can be accommodated, provided that the increase in braking acceleration is worth it.

Every optimum presented in Table 10 above was then analyzed in detail in order to increase the understanding for changes that take place and how objectives tradeoff. This analysis is presented in the following subchapters.

4.4.4 Optimal Design Simulation Results

All optimal configurations that were identified for different compositions of constraints and objective importance were simulated individually. The results from these simulations were then compared to a reference simulation run without the VEB unit.

Figure 32 shows the measured yaw rate in the same simulation scenario that was used in the tradeoff analysis. The reference simulation run is plotted with a dashed red line and it shows how the yaw rate develops over time in a braking-in-turn scenario. It should be stated that the simulation stops recording data when the speed of the vehicle in the X direction reaches a value of zero, which is why the plots not always have a yaw rate of zero at the simulation end.

Most lines from the optimal VEB configurations are lumped together as can be seen in Figure 32. These lines follow the overall pattern of the reference run and the average yaw rate during the simulation is close to the reference run in most cases. The peak yaw rate does however exceed the reference run's peak yaw rate in two cases. Both of these two cases are the ones that have acceleration as the most important objective. The VEB simulation that resulted in the largest deviation of yaw rate by far was the one without constraints and acceleration as the most important objective. This very configuration is illustrated in Figure 40 in section 4.4.4.6 where the position and linkage length of the VEB can be observed visually.

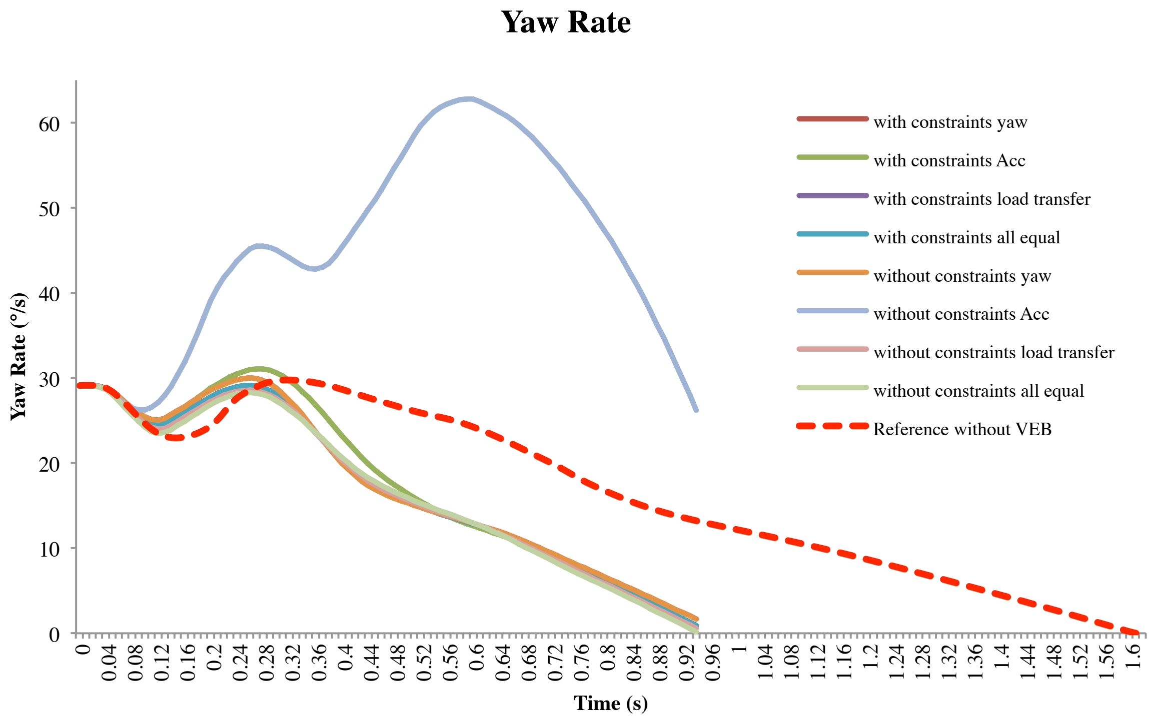

Figure 32 – Yaw rate simulation results for optimal designs

Figure 32 above shows an important result of the tradeoff analysis – namely that there in fact are several VEB configurations that provide a close to identical turning capability, or yaw rate, as the reference vehicle. The same applies to Figure 33, where the maximum braking acceleration was plotted for each of the optimal VEB configurations in a straight-line braking event.

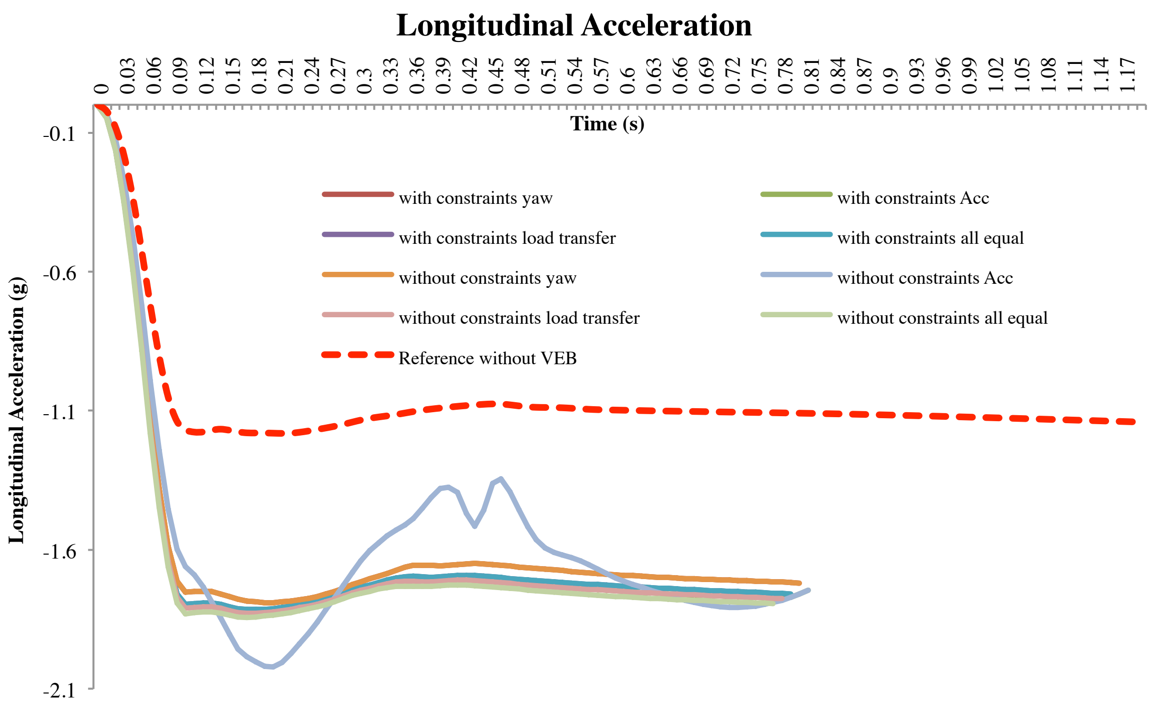

Figure 33 – Longitudinal acceleration simulation results for optimal designs

Most simulation runs in Figure 33 above show a significant improvement in braking acceleration from the reference simulation run with gains of over approximately 50 %. It is however worth noting that these absolute numbers do not provide any useful information as the maximum acceleration easily could be increased merely by increasing the surface area of the VEB. An interesting finding is however the small differences between the optimal configurations. Only the results from the simulation run with acceleration as the most important objective combined with no constraints deviates greatly from the other simulation results. All other simulations resulted in braking accelerations within approximately 5 % from each other. One important outcome from these simulations is that although the simulation run marked with "without constraints Acc" in the legend in Figure 33 is optimal when it comes to acceleration being the most important objective, it has the longest stopping distance. Therefore, it might be desirable to incorporate another VEB configuration that provides a shorter stopping distance. The tradeoff analysis did however aim to minimize the acceleration and hence the configuration that is illustrated in section 4.4.4.6 was arrived at. This is further discussed in chapter 5 - Discussion.

The simulation event with a straight-line braking process that was used to measure the acceleration was also used to measure the brake load distribution. Figure 34 below illustrates how this brake load distribution varies over time for every optimal solution.

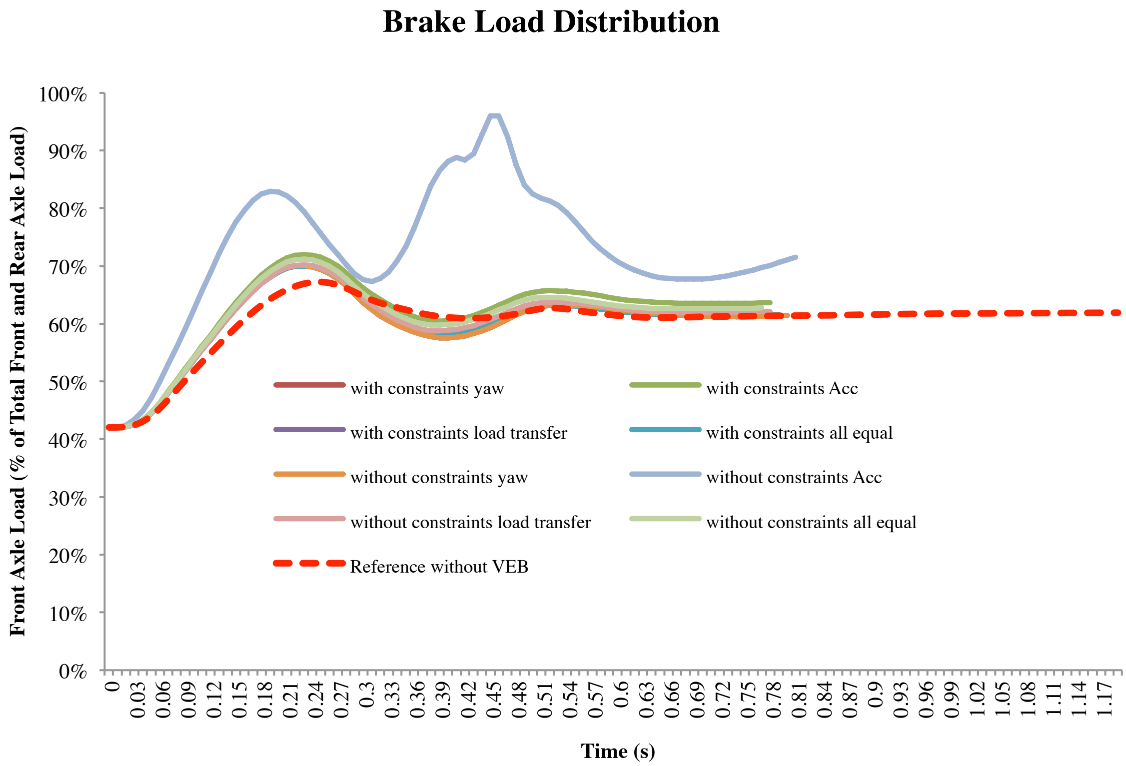

Figure 34 – Brake load distribution simulation results for optimal designs

The dashed red line in Figure 34 shows the percentage of the total wheel load that is loading the front wheels on the reference vehicle. If the front wheels are loaded with 60 % of the total load the rear wheels are consequently loaded with 40 % of the total wheel load. The optimization method used to perform the tradeoff analysis aimed to minimize the difference in this distribution from the reference vehicle so that the brakes would experience the same load distribution both without the VEB activated as well as with the VEB activated.

Figure 34 also shows that the brake load distribution varies cyclically between the front and the rear axle. This occurs both in the reference run as well as with simulations with the VEB. It can also be understood that the VEB amplifies this cyclic load distribution slightly in most cases. The optimal design without constraints and acceleration as the most important objective does however stand out, just as with the yaw rate in Figure 32 and the acceleration in Figure 33. This configuration results in a brake load distribution of a hefty 95 % at the front and 5 % at the rear at most.

On an aggregated level it can be observed that the simulation results that were produced by simulating the different optimal VEB configurations resulted in very similar results in most cases. All optimal designs are in fact very similar and the following subsections show the actual full vehicle simulations models for each of the optimal designs. It can be seen that the arbitrary constraints presented in 4.4.2.2 that were used to exemplify happened to coincide well with the unconstrained optimal designs. This could also be a factor that gave such similar results in Figure 32 through Figure 34 above.

4.4.4.1 Optimal Design With Constraints, Yaw Rate Most Important

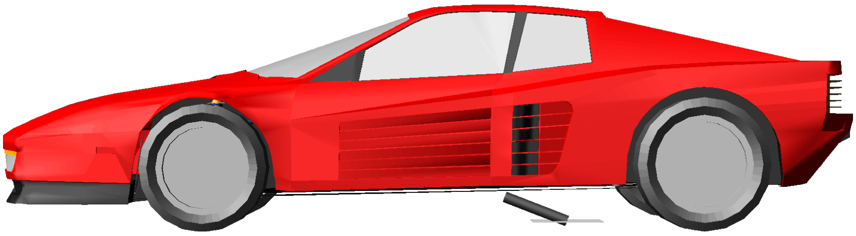

Figure 35 – Schematic Image. Constrained, Yaw Rate Most Important

4.4.4.2 Optimal Design With Constraints, Acceleration Most Important

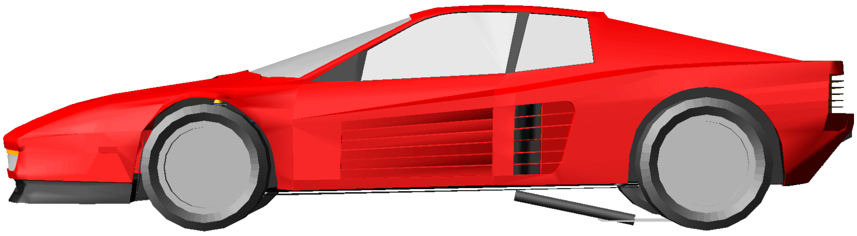

Figure 36 – Schematic Image. Constrained, Acceleration Most Important

4.4.4.3 Optimal Design With Constraints, Brake Load Distribution Most Important

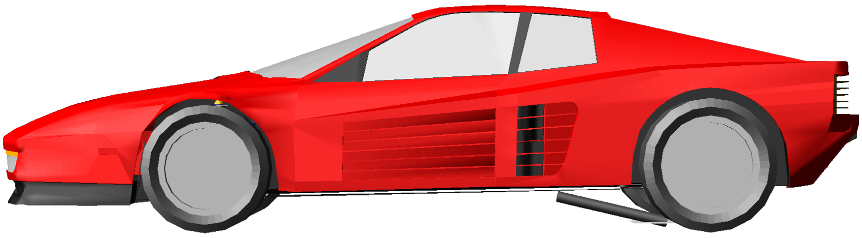

Figure 37 – Schematic Image. Constrained, Brake Load Distribution Most Important

4.4.4.4 Optimal Design With Constraints, All Objectives Equally Important

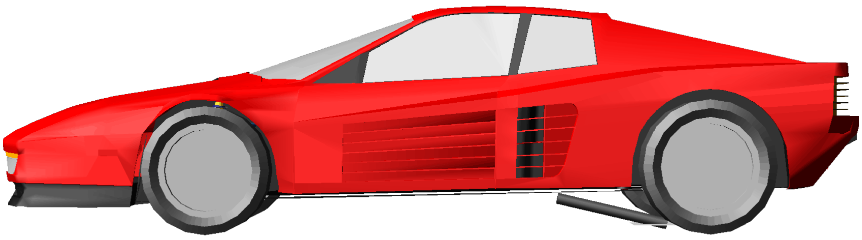

Figure 38 – Schematic Image. Constrained, All Objectives Equally Important

4.4.4.5 Optimal Design With No Constraints, Yaw Rate Most Important

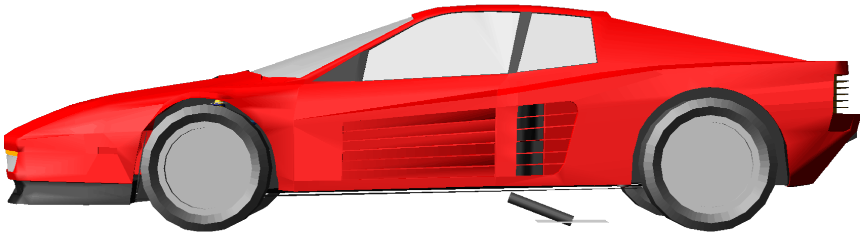

Figure 39 – Schematic Image. Unconstrained, Yaw Rate Most Important

4.4.4.6 Optimal Design With No Constraints, Acceleration Most Important

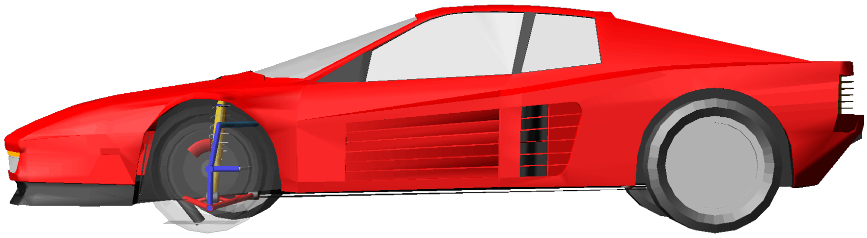

Figure 40 – Schematic Image. Unconstrained, Acceleration Most Important

4.4.4.7 Optimal Design With No Constraints, Brake Load Distribution Most Important

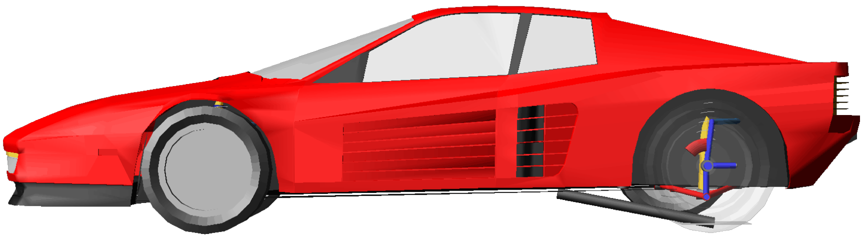

Figure 41 – Schematic Image. Unconstrained, Brake Load Distribution Most Important

4.4.4.8 Optimal Design No Constraints, All Objectives Equally Important

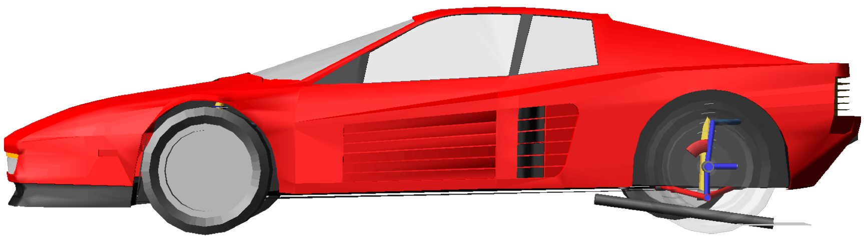

Figure 42 – Schematic Image. Unconstrained, All Objectives Equally Important

4.4.5 High Speed Braking Followed By Turning

To test the performance of the VEB system in another scenario than the ones used for optimization, a scenario where the vehicle brakes at high speed and then turns was simulated. The vehicle and VEB configuration used in the evaluation is the one that gave the best results when all objectives are equally important and when no constraints were used as illustrated in 4.4.4.8.

The scenario is a vehicle traveling at a straight line in 108 km/h when the brakes are applied. After 0.5 seconds the steering wheel is turned 180° in 0.1 seconds. The behavior of the vehicle during the maneuver is studied. The VEB is activated at the same time as the brakes are applied (t = 0). Figure 43 illustrates the levels of longitudinal and lateral acceleration.

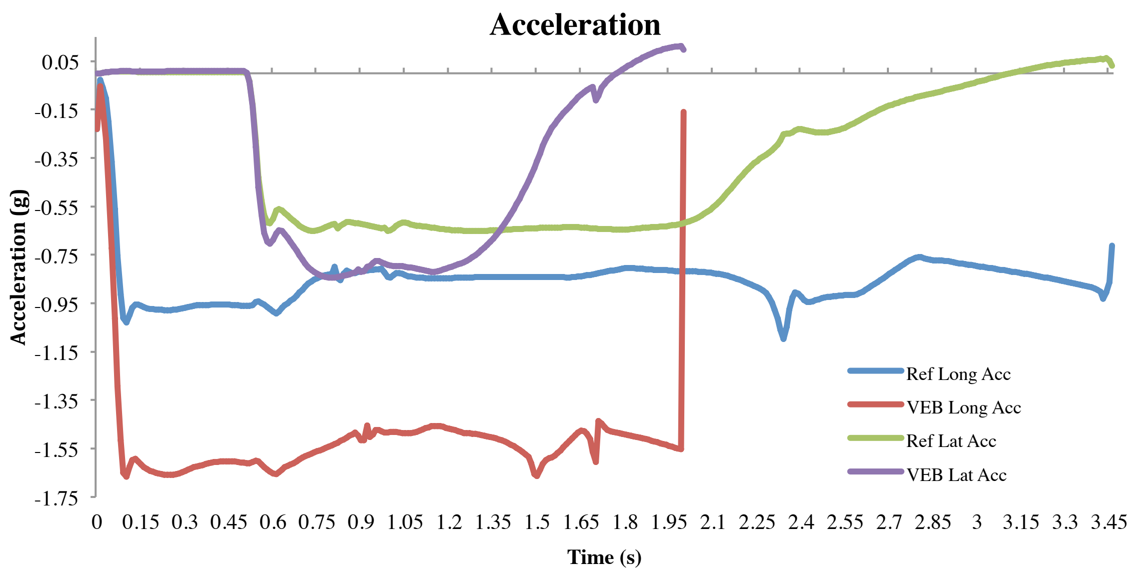

Figure 43 – Acceleration levels with and without VEB

It can be seen that the levels correspond well to the other scenarios tested. The same levels of acceleration gain with the VEB can be seen. The level of longitudinal acceleration drops when the vehicle starts turning, which is expected. This can be explained with the friction circle described in section 2.2.4. The amount of friction that the tire can handle in the contact point is limited. Since the drop in longitudinal acceleration is smaller than the increase in lateral acceleration it can be seen that the tire is not on the limit in the straight line braking. In addition to acceleration, yaw rate was evaluated to study the turning behavior of the vehicle in the high-speed scenario. The results from the yaw rate evaluation are displayed in Figure 44.

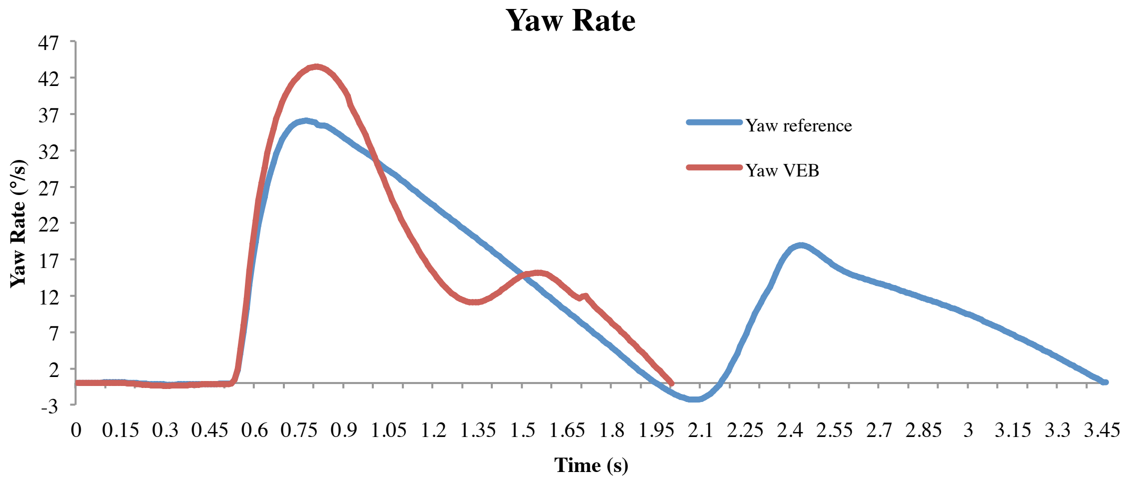

Figure 44 – Yaw rate difference with and without VEB

It can be seen that the vehicle is significantly more stable when braking with the VEB. Without the VEB the yaw rate drops to zero, indicating understeering and lost grip at the front axle. When a VEB is used the yaw rate does not fluctuate as much. The fluctuation in yaw rate when braking with a VEB is approximately 19 % of the fluctuation compared to a vehicle with a VEB. This indicates that the stability increases with a VEB and that there could be other areas of use, such as controlled high-speed maneuvering.

4.5 Affected Systems

The results from the dynamic simulations indicated a need to study which subsystems and components that affect and are affected by the VEB as design variables had great impact on the results. The VEB X Position proved to be a critical factor for the yaw rate as described in section 4.3.4. Brake load distribution was furthermore clearly affected by the length of the VEB linkage. The following subchapters deliver analysis of how critical systems are affected by the VEB. The most critical system was identified to be brakes and in conformance with the findings in the tradeoff analysis, general packaging will be discussed as well.

4.5.1 Brakes

Data from the simulations were used to determine the brake torque demand. Calculations showed a maximum normal force increase of 73 % at the front wheels and 141 % at the rear wheels in the two VEB configurations that gave the highest increase in normal force for each axle. Presented below in Table 11 is the force difference when the VEB vehicle was compared to a reference vehicle without the VEB.

Increased demand on braking torque

Important Objective (Unconstrained)	Front Increase [%]	Rear Increase [%]
Acceleration	47.3	-4.4
Brake Load Distribution	14.5	13.6
Yaw	20.3	22.7
All Equal	13.7	10
Max Front Increase	73	-
Max Rear Increase	-	141

Table 11 – Brake torque demand increase for different scenarios

The numbers in Table 11 suggest that design decisions can lead to large changes in braking torque demand. The results are based on the assumption that all parts in the braking system (such as mounts, brake lines and brake calipers) are assumed to be sufficiently stiff to withstand additional forces. This might however not be true in all cases, which makes it important to thoroughly analyze the brakes of vehicles intended for a VEB as another step in the product development chain.

In addition to brake torque demand, the brake temperature increase was evaluated under the assumption that disc brakes are used. The temperature in the brake rotors was calculated for the four unconstrained optimal configurations using the dimensions of the braking system in the simulated vehicle. The results can be found in Table 12. It can be seen that most calculated temperatures with the VEB are close to the reference temperatures without the VEB. This is due to the decreased time to stop the vehicle, as can be seen in Equation 5. It can however be seen that the temperature can increase rapidly if one axle gets a significant increase in normal load.

Increased Temperature

Important Objective (Unconstrained)	Front Temp [°C]	Front Increase [°C]	Rear Temp [°C]	Rear Increase [°C]
Acceleration	97	32	107	-3
Brake distribution	75	10	127	17
Yaw	79	14	137	27
All Equal	74	9	123	13
Max Front increase	113	48	-	-
Max Rear increase	-	-	269	159
Reference without VEB	**65**	-	**110**	-

Table 12 – Temperature increase in brake rotors for different configurations

4.5.2 Packaging

The result from the simulations and tradeoff analysis indicated that a suitable mounting position for the VEB was in the regions around and in front of the rear axle, which can be seen in section 4.4.4. Existing components on current vehicles that could be affected by this are for example the fuel tank, hybrid electric batteries, rear suspension components and the propeller shaft on rear- and four-wheel drive vehicles.[18] These components are often located in the same region as the VEB could be located on current production vehicles. Of the listed components only the rear suspension and propeller shaft need to have the exact position they have due to mechanical couplings and transmission of torque.

Another important aspect of packaging is the actual space needed for the VEB unit. The available space in a smaller vehicle could be limited and the higher ground clearance of a sport utility vehicle could be problematic since the results from the simulations indicate that a low mounting position would be beneficial in most cases. Smaller vehicles are however often front wheel driven, which gives a larger freedom to relocate other components that could interfere with the VEB.[18] Larger vehicles have more space, but are on the contrary rear- or four-wheel driven to a larger extent, meaning that components such as propeller shafts need packaging space in the potential VEB region as well.

[18] Sixten Berglund, Engineer, Powertrain Engineering, Volvo Group, Lecture Notes, December 2nd 2013

4.6 Investment Evaluation

The VEB product development project was evaluated financially in order to answer Research Question 3. Methods were used to evaluate the investment and to provide insight when it comes to how sensitive the investment is for variation of certain input variables. That is, input variables were varied and the NPV as introduced in the Theoretical Framework was calculated for each case. Three main variables were varied in order to obtain an understanding of the relative importance between the three. These variables are: sales volume, R&D cost and the Time To Market (hereinafter TTM).

The sensitivity analysis that was briefly introduced above was carried out to reduce the effects of uncertainties to the furthest possible extent. That is, no exact answer was sought after in favor of understanding based on an objective evaluation that can be used when making investment decisions.

4.6.1 Problem Structure

A problem structure based on the NPV investment analysis method was constructed in order to create an overview of how the investment would be evaluated. Figure 45 illustrates the structure with which the investment evaluation was tackled.

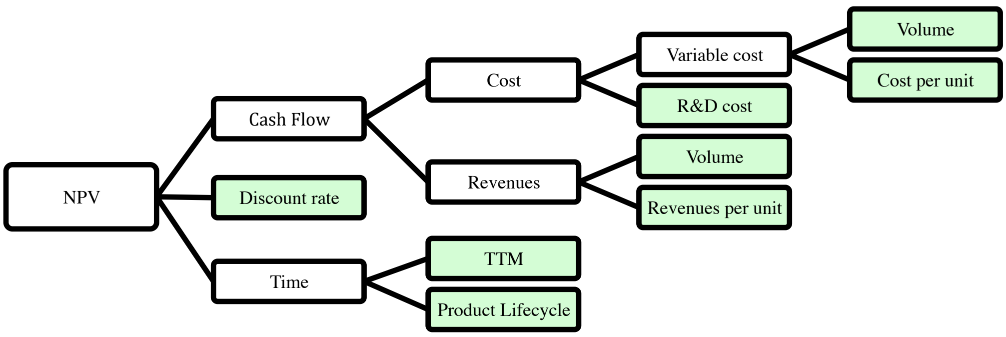

Figure 45 – Problem structure for the investment evaluation

The results from the investment evaluation were consequently arrived at by approaching the problem from the blocks marked with green in Figure 45. The results are described in detail in the following chapters.

4.6.2 Assumptions And Clarifications

A large number of assumptions were made in order to enable the evaluation of the investment. Whenever assumptions had to be made, measures were taken to ensure some amount of validity in the assumptions. In addition to uncertainties, assumptions were also handled by means of the sensitivity analysis.

A number of assumptions that affect the overall evaluation were made in order to reduce complexity and align the investment evaluation with available resources when it comes to time. These assumptions are presented in the bulleted list below.

- Synergies from the investment were not considered
- Patent life was assumed not to affect the forecasted sale volume
- Already spent resources were considered to be sunk costs
- No specific discounting factor was used. The IRR was evaluated in the sensitivity analysis
- When varying the TTM in the sensitivity analysis, R&D Costs were assumed distributed equally among the years before market introduction
- Market penetration was assumed to be identical regardless of TTM

As mentioned, sales volume, R&D costs and the TTM were varied in the sensitivity analysis. These three factors were identified as the main drivers for cash flow magnitude and cash flow timing. The baseline magnitude and timing around which the sensitivity analysis would be varied did however need determining. This was to the furthest possible extent done using data from Autoliv as described in the following sections.

4.6.3 Volume

Historical data compiled by IHS Incorporated (2012) regarding sales was analyzed in order to create an understanding of the total future sales. The data holds information when it comes to sales volumes for sales segments *A* through *Others* as listed in Figure 46 below. (IHS, 2012) This historic data was combined with data regarding volumes until 2019. The investment evaluation was carried out with a 20-year horizon and the future volumes between 2019 and 2034 consequently had to be approximated. A regression model was created in order to roughly approximate sales between 2019 and 2034 based on data between 2002 and 2019. Each sales segment was approximated separately as can be seen in Figure 46. The approximations were carried out using the regression model and Microsoft Excel® Solver. The Coefficient of Determination for the fit ranged between the poorest fit of 0.983 and the best fit of 0.999 and the forecast that was arrived at can be seen in Figure 46 below. Fitting the functions to only historic data yielded an entirely different result as can be seen in Figure 73 in Appendix VII – Economic Analysis. The near-future forecasts were however assumed to be reliable and it was hence more adequate to fit the functions to historic data combined with the near-future forecasts.

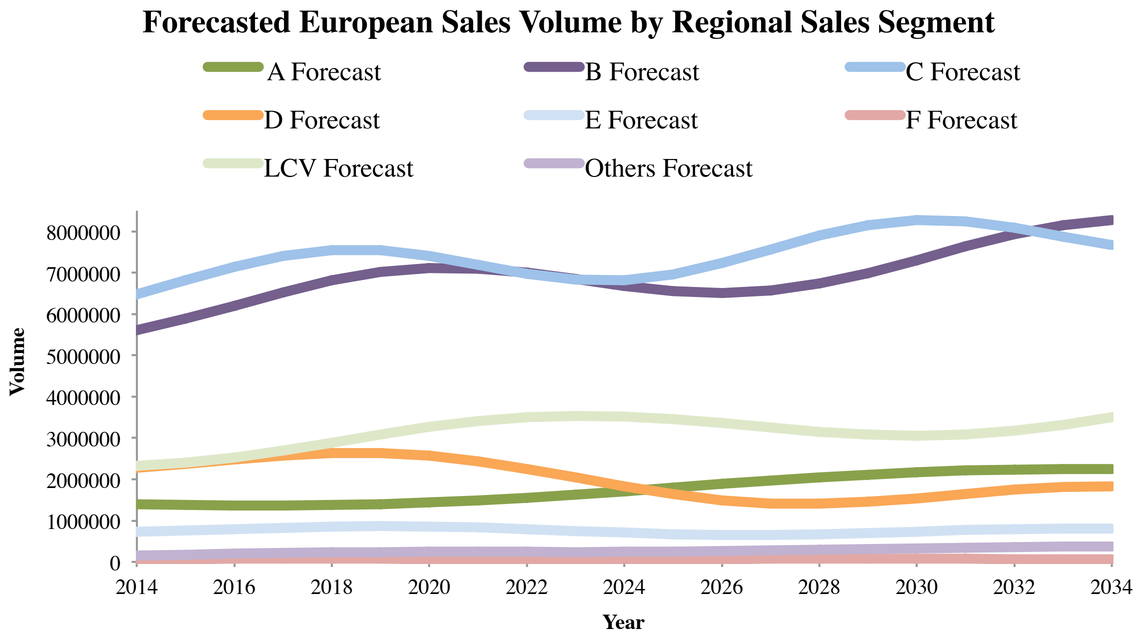

Figure 46 – Forecasted European sales volume by regional sales segment

Figure 46 illustrates how sales are expected to develop between 2014 and 2034 according to the forecast that was made. As an example, segment B with a typical vehicle model being the Opel Corsa is expected to exceed the sales of segment C in the future, with a typical vehicle model being the VW Golf. Combining the results from the individual segments in Figure 46 gives the total forecasted sales volume for Europe as illustrated in Figure 47 below.

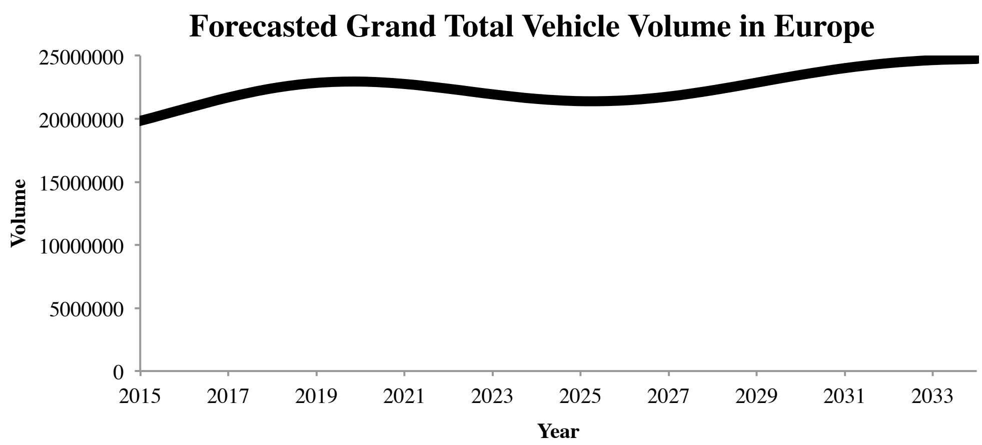

Figure 47 – Forecasted total European vehicle sales volume

Figure 47 shows that the long-term sales can be expected to increase slightly over time in a cyclic manner. For reference, the corresponding illustration for fitting the functions to only historic data can be found in Figure 74 in Appendix VII – Economic Analysis. After the long-term forecast for all European sales had been created, it was used to approximate the expected sales volume for the VEB.

The Inflatable Curtain is an existing Autoliv safety product and it was used as a reference when approximating the future VEB sales. The Inflatable Curtain was chosen as a reference since it was young enough for data to be available from market introduction, and mature enough for data to be available over a longer period of time[19]. Also, using an automotive safety product from Autoliv for the baseline volume was assumed to outperform using a generic product lifecycle. The great uncertainty involved with forecasting future volumes also dictated the evaluation to incorporate a sensitivity analysis as described earlier in the report.

The expected sales for the VEB are presented in green in Figure 48 below whereas the Inflatable Curtain sales are presented in purple. The horizontal axis shows the year from market introduction, without regard to the actual year this represents. It is stated like this since the market introduction year was varied between 2015 and 2025 in the sensitivity analysis, as presented in section 4.6.5.

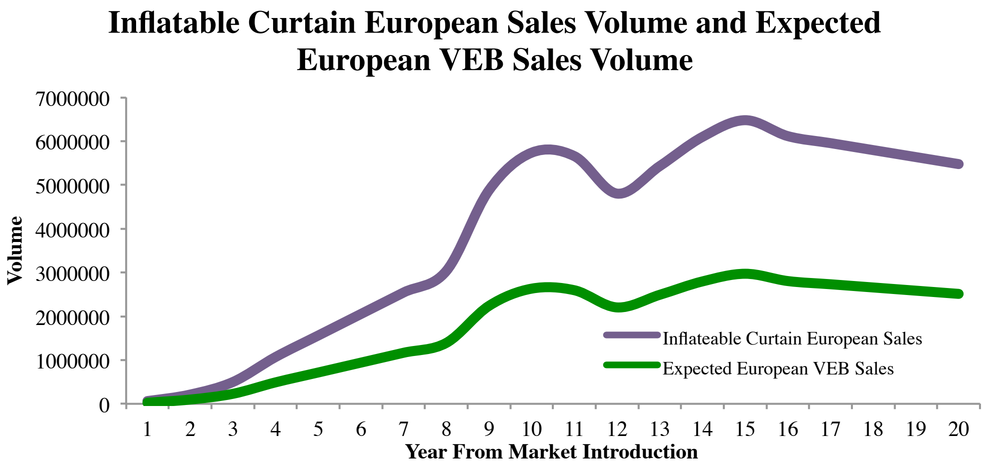

Figure 48 – European Inflatable Curtain sales volume in number of vehicles

The expected VEB sales volume was created under the assumption that the Inflatable Curtain is relevant for every vehicle, whereas the VEB was assumed to be relevant in segments C, D, E and F for cost and packaging reasons as explained in section 4.5. Furthermore, only European volumes are considered at all times. The average C, D, E and F fraction of the total European sales were calculated between year 2015 and 2034, according to the sales forecast as depicted in Figure 46 and Figure 47. Segments C, D, E and F are expected to sell on average 46 % of the total European sales volume between 2015 and 2034. Therefore, the past Inflatable Curtain sales volume was scaled with the factor 0.46 to obtain an approximate baseline VEB sales volume for the sensitivity analysis.

[19] Björn Wärn, Business Controller, Business Unit Control, Autoliv AB, April 23rd 2014.

4.6.4 Costs And Revenues

In addition to the expected future sales volume, values for expected costs and revenues needed to be arrived at in order to enable calculation of the NPV in the sensitivity analysis presented further below. The costs and revenues for the VEB were assumed to follow the same overall cost structure as the rest of Autoliv's product portfolio. Assumptions and estimations regarding values for Earnings Before Interest and Taxes (hereinafter EBIT) and the depreciation time are based on this cost structure and are presented in Table 13 below.

List of Assumptions

EBIT (Autoliv, 2014)	8.30%
Direct Material per Unit[20]	$50.00
Direct Material of Total Revenues (Autoliv, 2014)	53%
Cost Reduction per Year[21]	3%
Research and Development[22]	$5 000 000.00
Tax Rate	30%
Depreciation Time[22]	3 Years
Baseline Market Introduction Year[22,23]	2020

Table 13 – Breakdown of assumptions with respect to costs and revenues

4.6.4.1 Costs And Revenues Per Unit

The assumptions presented in the preceding subsection were subsequently used to create approximations for the costs and revenues related to the VEB. Unlike the approximated future sales volume in Figure 48, the costs and revenues per unit as presented in Figure 49 below assumes that the cost estimation holds true in 2015 and that the cost reduction per year as stated in Table 13 will take place regardless of when the VEB is introduced to the market. As an example, the cost for the VEB will be the same in 2020 regardless of the market introduction year.

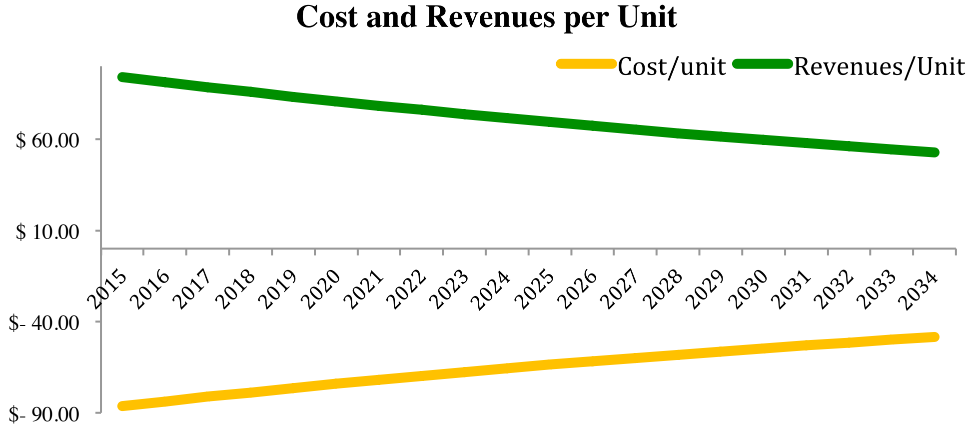

Figure 49 – Cost and revenues per unit

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[20] Erik Rydsmo, Supply Chain Engineer, Special Safety Products, Autoliv Development AB, March 31st 2014

[21] Erik Tönsgård, Sales Manager, Sales, Autoliv Sverige AB, April 22nd 2014

[22] Jörgen Kjellén, Project Coordinator, Special Safety Products, Autoliv Sverige AB, April 15th 2014

[23] Yogen Patel, Group Manager, Autoliv Development AB, April 15th 2014

4.6.4.2 Tax And Depreciation

The tax rate and depreciation time as presented in Table 13 were included in the calculation of the NPV to increase the comprehensiveness and give a more accurate result. Tax was treated as a cost and all profits were taxed. Furthermore, the depreciation time for investments was assumed to be three years from when the investment was made. The depreciation was then assumed to act as a tax shield that lowers tax outflow. Cash flows from depreciation with the corresponding tax shield were assumed to take place at the end of each one-year period.

4.6.5 Net Present Value Sensitivity Analysis

A sensitivity analysis was done in order to create an understanding of how the NPV of the investment varies when input variables are varied. This sensitivity analysis has been mentioned throughout the chapter and three main input variables were identified as drivers for the NPV of the investment as described in chapter 2.5. These three variables are the sales volume, the R&D costs and the TTM. Both the volume and the R&D costs were varied with factors ranging from 0.5 to 1.5 in increments of 0.1. Figure 50 demonstrates the undiscounted cash flow when varying the expected volume with these factors around the baseline volume that was specified in chapter 4.6.3.

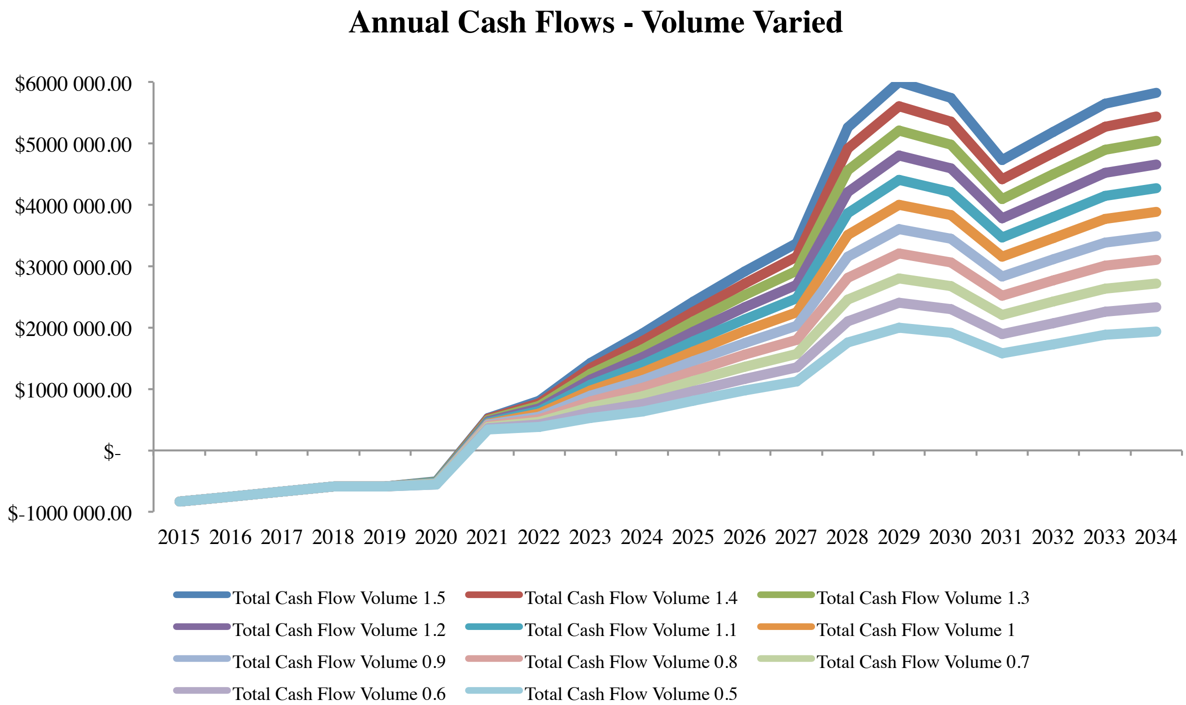

Figure 50 – Example of how the annual undiscounted cash flows are scaled using the scale factor

Figure 50 shows that the market introduction takes place in 2020 as specified in Table 13. 2020 was used as a baseline year for the market introduction when varying the volume and R&D cost. The annual undiscounted cash flows that take place when varying the R&D cost with the same scale factor are illustrated in Figure 51.

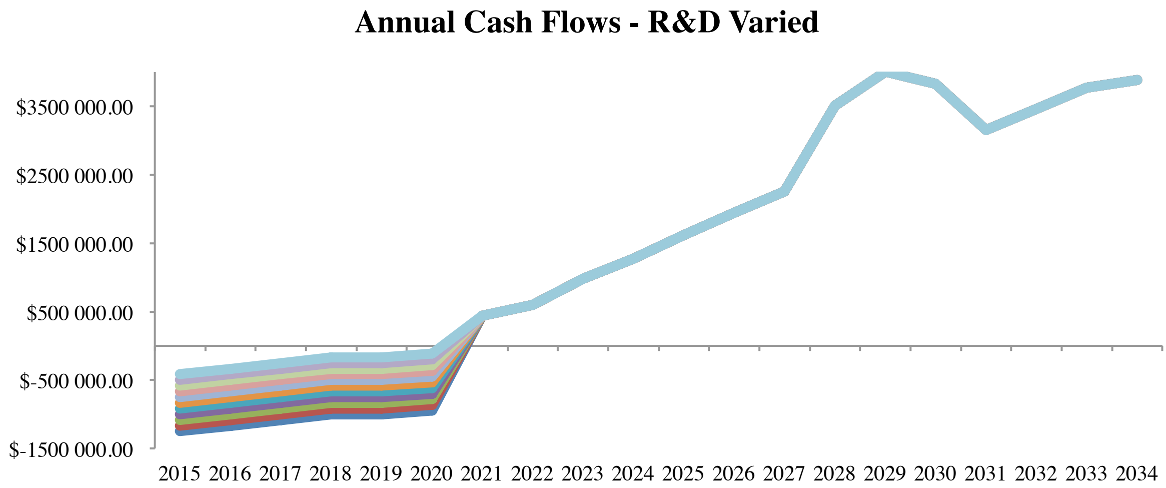

Figure 51 – Annual undiscounted cash flows when R&D costs are varied using the scale factor

As when varying the sales volume, a market introduction in 2020 is used as the baseline. Additionally, the assumption that there is available profit for the tax shield to reduce is clear in both Figure 50 and Figure 51. The profile for the sales volume after the market introduction was kept at its forecasted baseline in order to isolate the effects of R&D on the NPV in the sensitivity analysis.

When varying the TTM, the market introduction is varied from 2015 to 2025. The R&D costs are as mentioned divided equally among the years before market introduction, regardless of TTM. That is, if the TTM is ten years, one tenth of the total assumed R&D cost is spent every year.

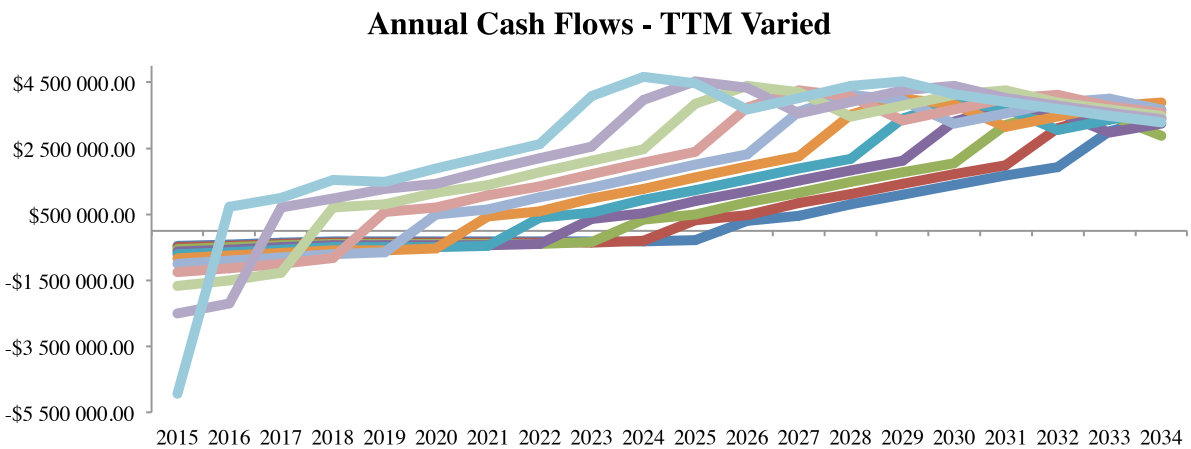

Figure 52 – Annual undiscounted cash flows when the TTM is varied

Figure 52 illustrates how this was implemented and the resulting annual undiscounted cash flows follow the same pattern as the baseline volume profile. After the annual undiscounted cash flows had been calculated, the NPV could be calculated for every case. Or put differently, the NPV was calculated for every line in Figure 50, Figure 51 and Figure 52 as described below. Although the NPV and IRR was used as the main method of evaluation, illustrations of the payback time for every of the 30 cases can be viewed in Appendix VII – Economic Analysis.

4.6.5.1 Identifying The Internal Rate Of Return

The sensitivity analysis was carried out in line with the theory presented in chapter 2.5.6. The NPV was calculated for every one of the cash flow curves presented above, resulting in a total of 30 evaluated cases. The IRR that gave an NPV of zero in each of these cases was then identified. Figure 53 below illustrates how the IRR varies with the scaling factor for the volume and the R&D cost.

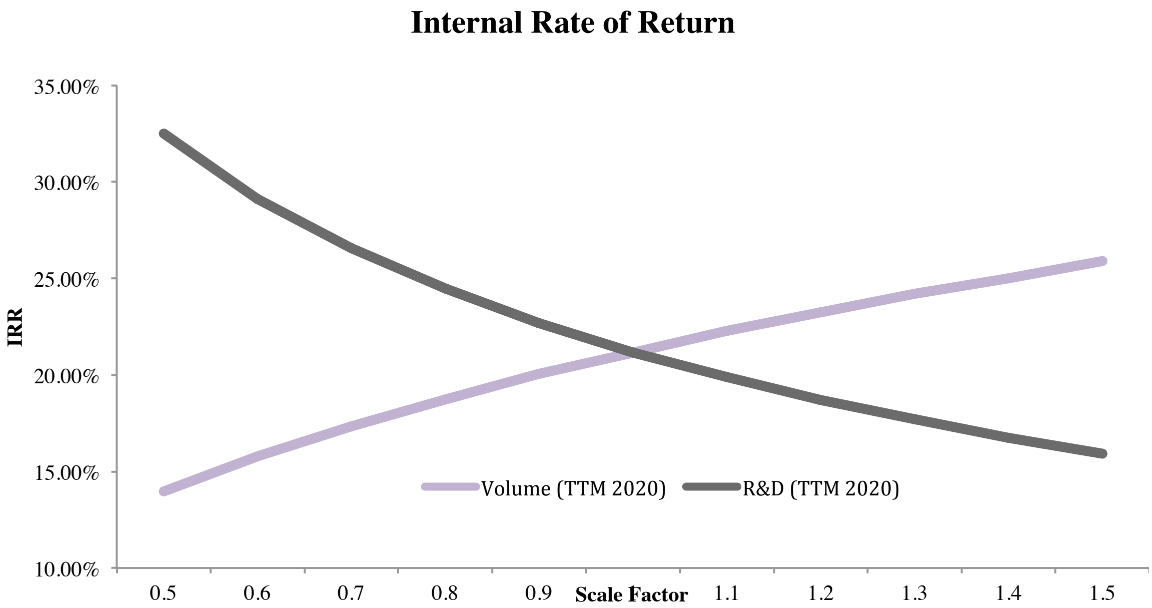

Figure 53 – IRR for varied sales volume and R&D costs

The lines in Figure 53 are crossed as a result of how the sensitivity analysis was formulated. The same scaling factor was used for both the sales volume and the R&D cost and a lower R&D cost obviously gives a higher IRR whereas a smaller sales volume gives a lower IRR. What is interesting is the slope of the curves and simply reading Figure 53 shows that a 10 % difference in sales volume affects the IRR more than a 10 % difference in the R&D cost. It is worth mentioning that this only holds true for the sensitivity analysis under the given assumptions.

Mean Derivative

Volume Varied	0.12
R&D Varied	0.17

Table 14 – Mean derivative for varied volume and R&D cost respectively

The mean derivative was used as a measure of the sensitivity and Table 14 above displays the mean derivatives for the curves in Figure 53. It can be seen that the NPV is approximately 33 % more sensitive to variation in R&D than sales volume. The likelihood of the variation in volume and R&D cost is however a factor that is not included in the sensitivity analysis.

The same approach was used when varying the TTM and the result is illustrated in Figure 54. For comparison, the mean derivative value is 0.22. The TTM is however varied by altering the number of years, whereas R&D and volume was varied with factors. A comparison does nevertheless show that varying for example the sales volume with 10 % roughly corresponds to varying the TTM with six months.

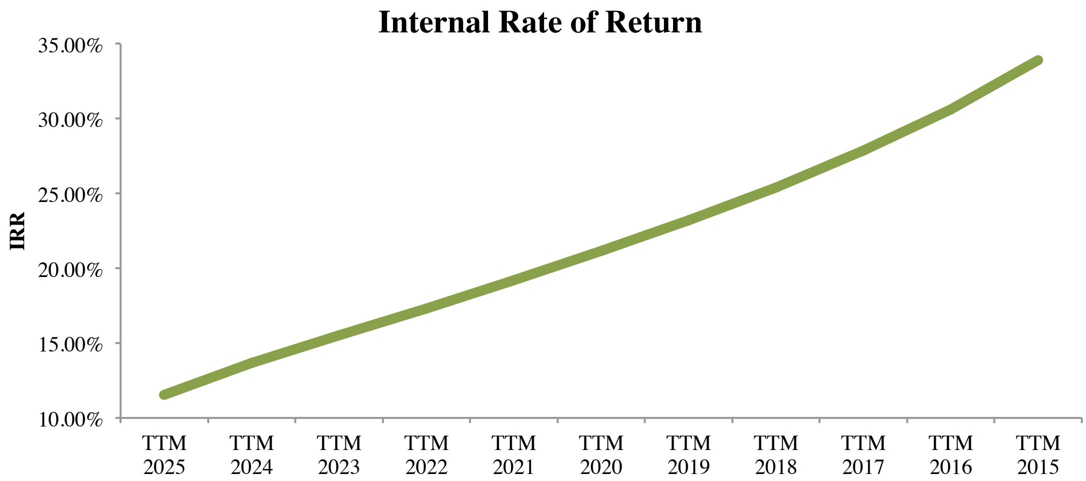

Figure 54 – IRR for varied TTM

It can be seen that the baseline sales volume, R&D cost and TTM all result in an IRR of approximately 20 %. When scaling the R&D or the sales volume down with 50 %, an IRR of roughly 15 % can be expected. Another example is a market introduction in 2022, which would give an IRR of approximately 17 %, given the assumptions that have been made.

4.7 Sustainability Analysis

The aim with the sustainability analysis was to study how the VEB unit affects the sustainability factors when seen as a product on the market. Relative measurements have been used to the furthest possible extent in this analysis as well. The economic sustainability is thoroughly described in section 4.6 and is therefore not treated in this section.

4.7.1 Environmental Sustainability

To estimate the total environmental effect of the system, the airbag has been used as a reference. 73 % of the environmental impact from an airbag comes from the user phase through fuel consumption. (Autoliv, 2014) Both an airbag and a VEB adds mass to the vehicle without serving a purpose apart from situations when they are used. The VEB is therefore assumed to have the same ratio of environmental impact as an airbag.

The increase in fuel consumption from the VEB was calculated in order to evaluate the environmental impact of the unit. The required force to drive a vehicle had to be calculated to enable the approximation of increased fuel consumption. The required force is defined in Equation 28 and Equation 29 below. (Jacobson et. al, 2012)

$$F_t = F_{acc} + F_{drag} + F_{roll} + F_{grad}$$

Equation 28 – Required driving force

$$F_t = ma + \frac{\rho}{2} A\, C_D v^2 + 0.01mgv + mgG$$

Equation 29 – Explained required driving force

The equations indicate that an increase in mass has an effect on all factors, except the aerodynamic drag. It is however assumed that the VEB unit is mounted in a hidden position when not in use and the drag is therefore neglected.

Matlab Simulink® has been used to build a full vehicle model and simulate driving cycles to make an approximation of the total effect that the VEB unit would have over the entire life cycle of a vehicle. The New European Driving Cycle was used to determine the fuel consumption. This driving cycle has been used to compare a typical vehicle with and without a VEB. It is however not a perfect replication of real life driving, but the use of relative measurements in this study makes it a useful indication of the potential impact the VEB would have on fuel consumption.

A representative vehicle for each segment has been modeled and tested using Matlab Simulink®. (Audi, 2014) (Mercedes-Benz, 2014) (Opel, 2013) (Volkswagen, 2013) The assumption that all vehicles are either gasoline or diesel driven has been made. The VEB unit was assumed to be identical on all vehicles and have a weight of 7 kg[24].

[24] Erik Rydsmo, Supply Chain Engineer, Special Safety Products, Autoliv Development AB, March 31st 2014

Overview of Environmental Impact

Objective	A-Segment	B-Segment	C-Segment	D-Segment	E-Segment	F-Segment	Total
Increase in CO_2 emissions, %	0.355	0.189	0.187	0.156	0.14	0.146	0.1955
Increase in CO_2 emissions (tons/Segment)	2290000	5050000	6780000	2590000	819000	97800	17626800
Increase in CO_2 emissions (tons/car)	172	110	114	114	114	172	795

Table 15 – Overview of environmental impact from the user phase

Based on the environmental impact during the user phase that is presented in Table 15 and the assumption that the overall environmental impact ratio is similar to an airbag, with 73 % from the user phase, the total environmental impact was approximated. The formula specified in Equation 30 was used to approximate the total environmental impact of the VEB.

$$Environmental\ Impact_{VEB} = \frac{Impact_{User\ Phase}}{Ratio_{User\ Phase}}$$

Equation 30 – Total environmental impact increase

Based on this equation, the total increase in CO_2 emissions was calculated for each sales segment as defined in section 4.6. An overview of the results is showed in Table 16 below. These results indicate the total CO_2 impact of the VEB and not only the impact from the user phase.

Overview of Environmental Impact

Objective	A-Segment	B-Segment	C-Segment	D-Segment	E-Segment	F-Segment	Total
Increase in CO_2 over life, (tons/segment)	3136986	6917808	9287671	3547945	1121917	133973	24146300
Increase in CO_2 over life, (tons/car)	236	150	156	156	156	235	182

Table 16 – Total overall environmental impact

In addition to the quantitative evaluation of the environmental impact of the VEB, the prevention and decreased severity of accidents that a VEB unit could provide could potentially also affect the environmental sustainability. It could lower the number of cars that are prematurely scrapped and therefore lower the overall energy and material needed to produce more vehicles.

4.7.2 Social Sustainability

The focus in this social sustainability study has been oriented towards pedestrian accidents since the logic for when and how to activate the VEB is not yet fully determined. Pedestrian accidents were only assumed to provide an indication of the potential of the VEB. Several other areas of application could however exist.

Most pedestrian incidents occur at speeds below 50 km/h, indicating that a VEB could be beneficial in these speeds. (Rosén & Sander, 2009) Speeds up to these levels occur in populated areas where pedestrians and motor vehicles are interacting with each other to a larger extent than on roads with higher speeds. Figure 55 illustrates the distribution of accidents, fatal accidents and the correlation to speed.

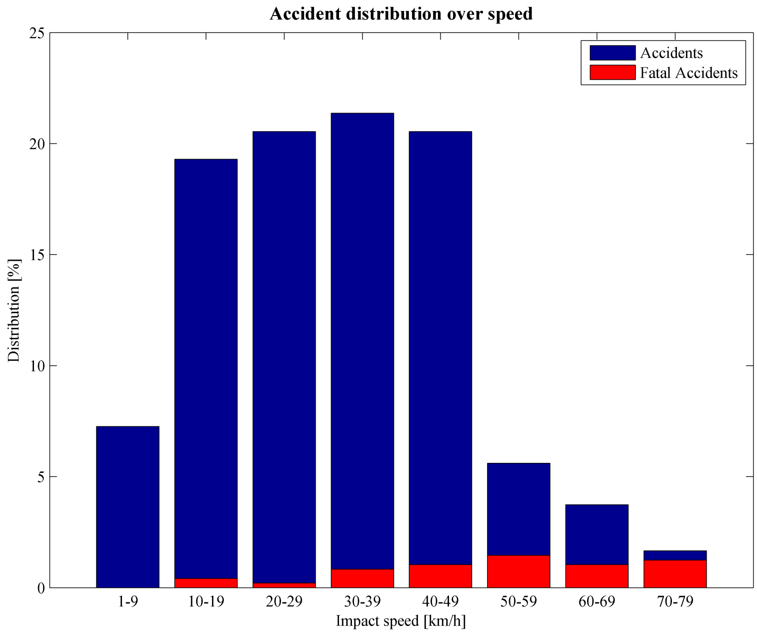

Figure 55 – Accident distribution over speed

Equation 31 defines how pedestrian fatality is related to the impact speed when a vehicle hits a pedestrian. (Rosén and Sander, 2009) This function is illustrated in Figure 56 and it was used to estimate the potential improvements that a VEB unit could provide.

$$P(v) = \frac{1}{1 + exp(6.9 - 0.090v)}$$

Equation 31 – Fatality risk function

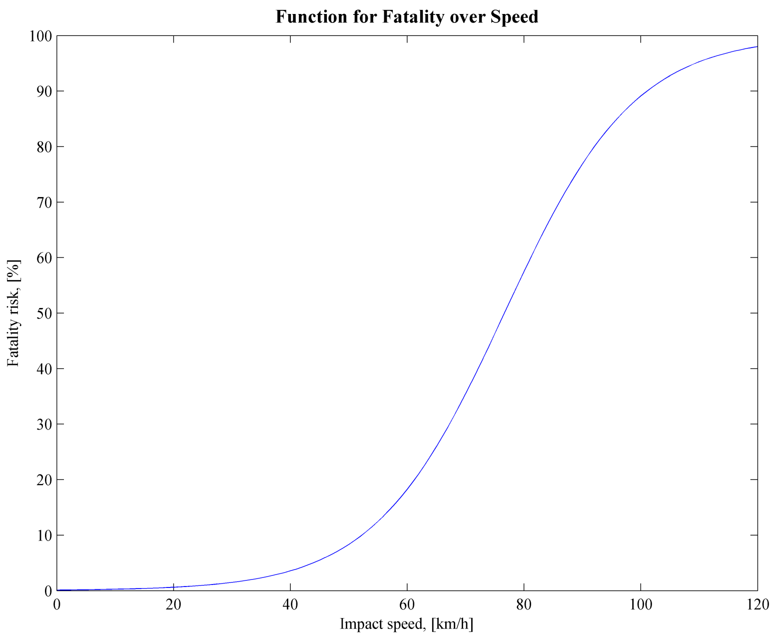

Figure 56 – Function for fatality over speed

An estimation based on the results from the dynamic simulations was that the VEB unit could lower the impact speed with 30% compared to a vehicle with no VEB. This simplification was made to give comparable results. The new impact speeds were calculated and used to rearrange the statistics from Rosén and Sander (2009). The number of fatalities has been calculated again based on the same ratios as illustrated in Figure 57. A shift towards a lower impact speed can be seen in the accident distribution statistics compared to Figure 55.

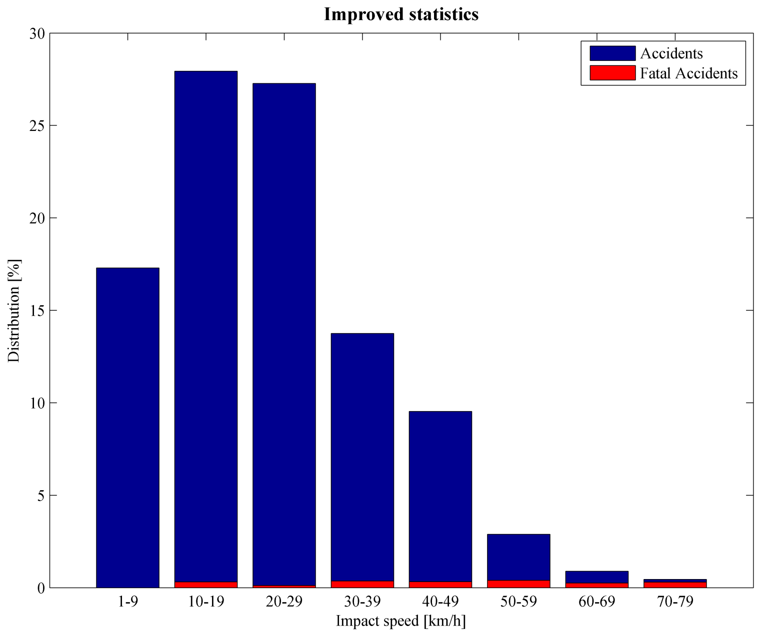

Figure 57 – Fatality over speed, improved statistics

It is important to note that the lowered risk comes from the potential to lower the impact speed. The VEB unit also does not improve the passive safety performance. Instead the lowered risk comes from the approximation of 30 % lower impact speed, where an accident in 60 km/h would instead have been an accident in 42 km/h with a VEB. The lowered fatality risk is illustrated in Figure 58.

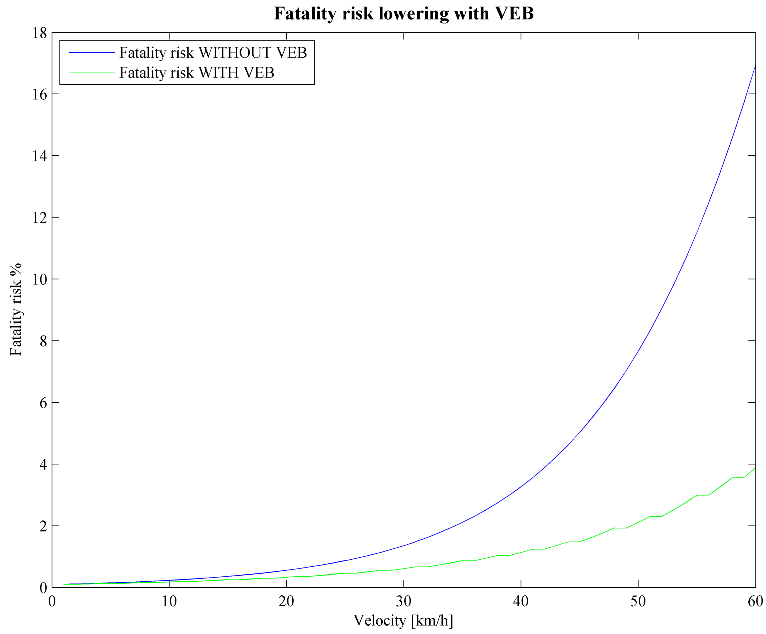

Figure 58 – Lowered fatality risk with VEB

When comparing the fatality risks for pedestrians when being hit by vehicles, it can be seen that the benefit from using a VEB increases with the impact speed. This fatality risk is approximately 350 % higher in the case of 60 km/h that would have been 42 km/h if the vehicle had been equipped with a VEB. Figure 59 shows how the chance of survival increases with a VEB.

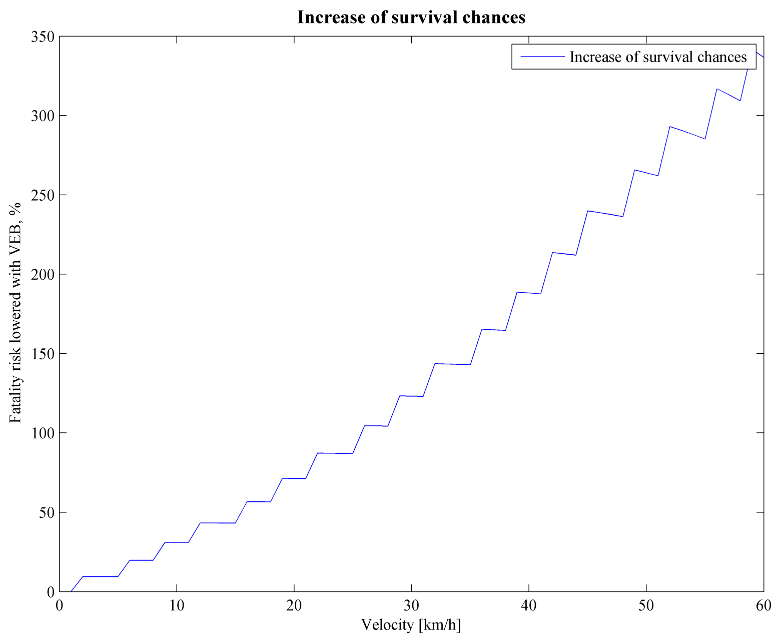

Figure 59 – The lowered fatality risk illustrated

A translation of the accidents into cost for the society has been made based on statistics. (Myndigheten för samhällsskydd och beredskap, 2012) The statistics are based on accident data from Sweden during 2005. Table 17 shows a comparison between the actual cost, the estimated cost if all vehicles involved would have had a VEB and the estimated cost if 1 % of the involved vehicles would have been equipped with a VEB.

Social sustainability benefits

Case	Fatal injuries	Severe injuries	Minor injuries	Property damage	Total cost
Cost No VEB [M$]	485	1325	387.7	1098.46	3295
Cost All VEB [M$]	162	441.5	129.2	366.154	1098
Cost 1% VEB [M$]	483	1320	386.5	1094.77	3284

Table 17 – Cost for society

The results show that there is potential for cost savings for the society if the VEB unit is implemented to a larger fraction of vehicles. An explanation of the calculations that were made when calculating the cost saving can be found in Appendix VIII – Sustainability.

4.7.3 Sustainability Tradeoff

It can be seen that there is a tradeoff within the sustainability aspect of the VEB. The addition of mass has a negative impact on the direct environmental sustainability in terms of increased fuel consumption and CO_2 emissions. The potential social sustainability benefits could however decrease the costs for society and an evaluation of the tradeoff needs to be performed. Estimated savings per added ton CO_2 have been calculated using Equation 32 below. A vehicle is estimated to be used for 20 years and values for savings and emissions are previously calculated.

$$\frac{Social\ savings\ per\ year\ [\$]}{Emission\ increase\ per\ year\ [ton\ CO_2]} \rightarrow \frac{\$\ (3295-3284)M}{(24146300/20)} \sim \frac{\$9}{ton\ CO_2}$$

Equation 32 – Social savings related to emissions

This illustrates a tradeoff that exists within the sustainability area. For each ton of CO_2 the VEB adds, the Swedish society could save $9. As a comparison, the price of carbon-offset rights has varied between $9 and $41 per ton over the last decade (Svensk Energi, 2013). Put into another perspective it is a saving of $11 million and an increase of emissions of less than 0.2 % from the vehicles with a VEB, if 1 % of all vehicles were equipped with a VEB. It is important to remember that the calculations are based on estimations and should not be seen as definite numbers, but rather an indication of potential effects.

5 Discussion

The results presented in chapter 4 call for a discussion regarding the reliability and validity as presented in chapter 3, Methods. As mentioned, several different approaches have been used to increase the validity and reliability. An example of this approach is the use of a reference vehicle when carrying the simulations out. This methodology is expected to primarily have increased the validity of the research and some amount of general applicability was hence achieved. The results can therefore be used in a more general context.

The different models that were used during the project present additional uncertainty when it comes to assessing the reliability of the results. Unknown errors in these models can exist and undiscovered errors could potentially have affected the results. Errors that affect the function of the models have been detected and fixed throughout the project. Errors that solely affect the result and not the function can however hypothetically still exist in all models.

An additional point of discussion when it comes to the reliability of the results is how average yaw rate was measured in the simulations that were used in the tradeoff analysis. The average measure was a result of a limitation when it came to practicalities. As several thousand simulations were done, it was not feasible to perform extensive analysis on each simulation run, so the average yaw rate measure had to be used. Another measurement that was considered early on was maximum yaw rate. Test runs did however reveal that the maximum yaw rate in some cases was smaller and in some cases larger than the initial yaw rate before activating the VEB. This fact dictated that the average yaw rate had to be used. A qualitative assessment of how well the average yaw rate would suit the research was made. The outcome of this assessment was that the average yaw rate would be a satisfactory measurement. Measuring the average yaw rate could however have lowered both the reliability and the validity of the research. No other practical way of conducting the research was however found, so the average yaw rate measure had to be accepted.

One very important note regarding the validity of the results is how minimum acceleration was measured in the rigid body simulations. The use of minimum acceleration is an important point of discussion as the validity truly is in the eye of the beholder. One alternative measurement would have been the stopping distance of the vehicle, as these two measurements not necessarily correlate perfectly. A subject that has emerged several times during the project, and although it is outside the scope of the project, is the logic with which the VEB is trigged. The validity of using the minimum acceleration as a measurement consequently depends on how the VEB is used. In case the VEB is used solely as a device to lower the impact speed of an inevitable crash, a large braking acceleration that is reached quickly might be preferable. Correspondingly, the minimum stopping distance might be preferred if the VEB is used to avoid a collision altogether.

Brake load is another interesting discussion topic that not directly affects the validity or reliability. Although the tradeoff analysis includes constraints for the maximum brake load, the research did generally not take brake dimensioning into account. Therefore, the results regarding the performance of the system do not necessarily mean that the same levels of performance can be achieved on any vehicle. The results can however be used to ensure that the front to rear brake load distribution is maintained at the same level as on the reference vehicle without the VEB, resulting in that the percentage load increase is the same both front and rear.

Although all simulation results were compared to a reference vehicle to normalize and produce results in relative differences, one single vehicle model was used. This could potentially have compromised the validity. It is important to note that vehicle specific analysis must be carried out for each vehicle when implementing the VEB. The simulation results that were produced in this project were the very first of their kind and how the results are used should reflect their purpose – to create awareness of how a VEB would affect vehicle dynamics.

The economic analysis of the VEB product development project called for a large number of assumptions. Although measures were taken to quantify the assumptions to the largest possible extent, the reliability is most likely affected. There are also many aspects such as for instance specific cash flows that were not considered. Also, the fact that the VEB is patented was not directly included in the analysis. Possible effects of the patent could however have been indirectly included when approximating the VEB sales volume as it was based on another patented safety product. Additionally, no consideration was taken to competition and game theory, which potentially can have affected the reliability.

Performing a sustainability analysis on a product as early in the development process as the VEB currently is has required a number of assumptions. The result of the sustainability analysis shall therefore be seen as an estimation of the potential benefits and drawbacks with the system. Estimating the increased fuel consumption based on increased mass gives fairly accurate results, but numbers for the environmental benefits of the VEB causing fewer vehicles to be prematurely scrapped have not been estimated.

The study of social effects from the VEB has been limited to pedestrian accidents. The case of pedestrian accidents was chosen since the strategy for how and when to use the VEB is yet to be determined. To fully analyze the gains a VEB could provide, the strategy must be known to provide a more reliable result where the lowered risk for passengers can be evaluated more exactly.

6 Conclusions

A number of conclusions can be drawn based on the research questions and the findings in the report. When it comes to vehicle dynamics, it can be concluded that the vehicle-VEB system is sensitive to big design changes. Large negative effects could be seen both regarding yaw rate and brake load distribution in many simulated cases. It can however be concluded that when design parameters are chosen carefully, this sensitivity can be used as an advantage. By positioning the VEB where it is physically possible, the linkage length can be altered to compensate for the effects of the overall position of the VEB. Furthermore, it could be observed that many different design configurations resulted in the same dynamic behavior of the vehicle. The VEB can therefore provide similar dynamic behavior in different vehicles with different packaging constraints.

When it comes to packaging it can be concluded that packaging constraints not only affect the magnitude of the braking acceleration of the vehicle, but how quickly the acceleration is increased. The design parameters therefore clearly have implications on the braking performance of the VEB. Another aspect that was realized was how the friction greatly affects the design parameters of the VEB. It was discovered that the length of the VEB linkage decreases exponentially with the friction between the tires, VEB and road. The target friction to aim the design towards when defining design parameters must consequently be chosen carefully.

The investment evaluation indicated that investing in the VEB project potentially is lucrative. The IRR proved to be more sensitive to changes in R&D expenditures than changes in sales volume under the assumptions that were made. Also, the IRR increases non-linearly when subject to reductions in R&D costs whereas the opposite hold true for increases in sales volume. In addition to these conclusions, it is also worth to mention that changes in the sales volume has a marginally larger effect on the pay-back time than changes in R&D costs.

From the sustainability analysis it can be seen that the negative environmental effects from a VEB are small compared to the potential benefits in social sustainability. A VEB provides chances of mitigating the effects of accidents or completely avoiding them, which would lead to significantly decreased costs for society. A well-defined strategy must however be determined in order to get a more detailed understanding of the social sustainability benefits.

7 Recommendations

A number of recommendations were arrived at after concluding the results. These recommendations are listed in an arbitrary manner without regard to the relative importance. The recommendations primarily aim to suit Autoliv specifically, but also the field in general. Finally, the recommendations should be reflected over as being subjective proposals based on quantitative findings.

1. Analyze how changes in road friction affect turning behavior.

2. Define exactly how and when the VEB will be used. The optimal design for a specific vehicle cannot be arrived at without an understanding of what is most important, for instance when it comes to how quickly the braking acceleration builds up. Also, a definition of how and when the VEB will be used would enable a more precise evaluation of the social sustainability impact of the VEB.

3. Investigate how ABS affects the vehicle-VEB system.

4. Perform simulations and calculations on specific vehicles with known detailed parameters to create an understanding of how for instance brakes are affected by the VEB.

5. Explore possible ways of integrating the VEB linkage in vehicle platforms.

6. An acceptable IRR for the VEB project should be defined so that the investment can be evaluated with respect to it. The investment evaluation should be revisited continuously as deals with customers are closed.

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9 Appendix

Appendix I – Analysis Of Data From Physical Testing

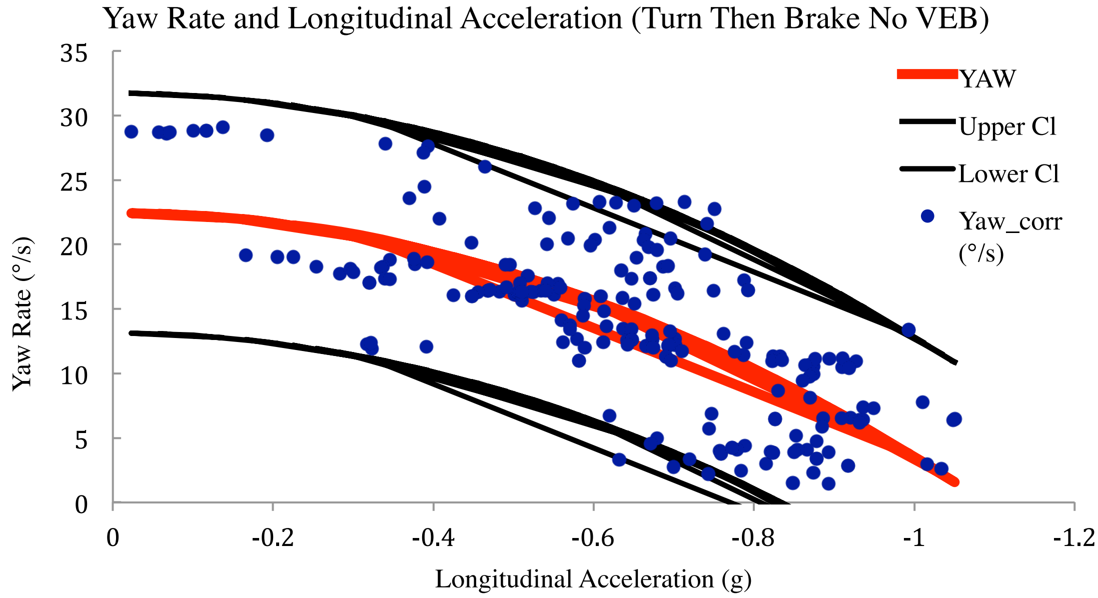

Figure 60 – Yaw Rate and longitudinal acceleration (Turn Then Brake No VEB)

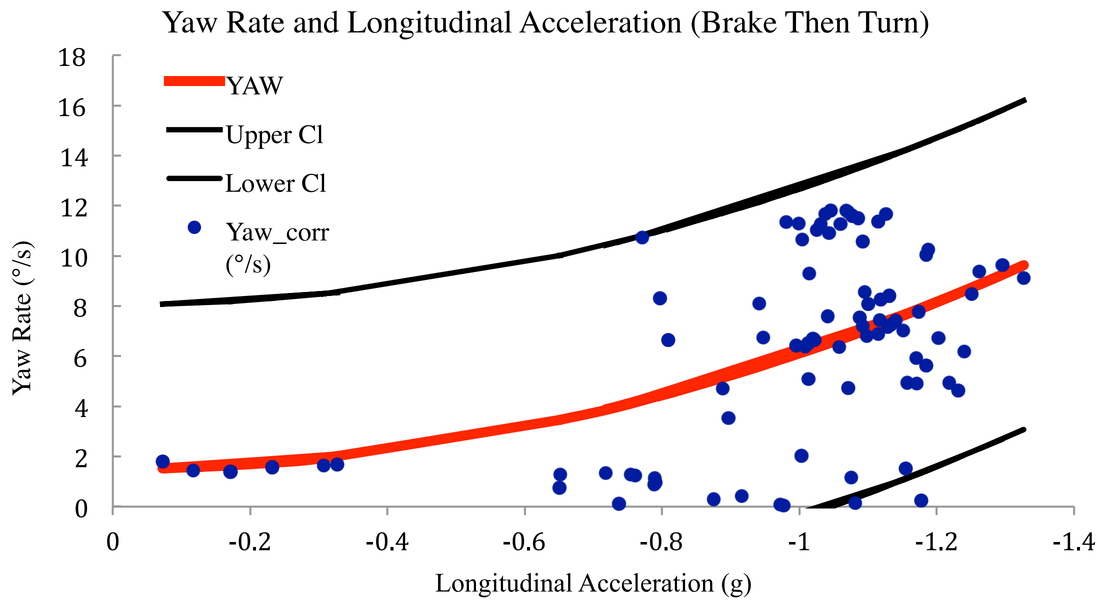

Figure 61 – Yaw Rate and longitudinal acceleration (Brake Then Turn) with VEB

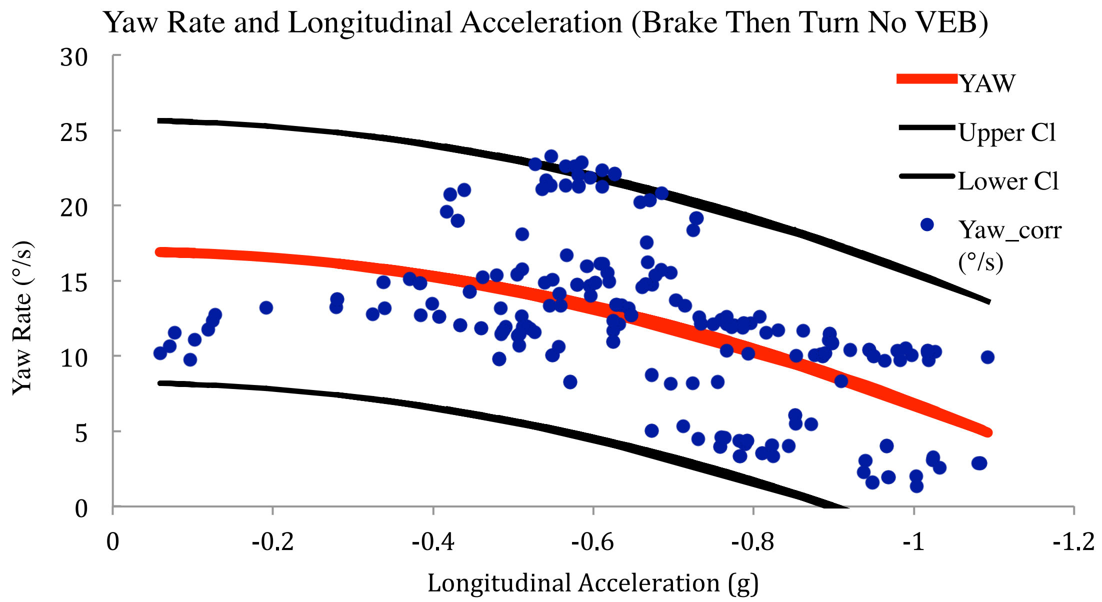

Figure 62 – Yaw Rate and longitudinal acceleration (Brake Then Turn) No VEB

Appendix II – Static System Modeling Matlab Code

```
%% Vehicle Data
kf=100000;  %N/m Both sides
kr=90000;   %N/m Both sides
m=1500;     %kg
g=9.81;     %m/s2
Bf=0.65;
Br=1-Bf;
x=1.2;      %m
b=2.7;      %m
c=2.75;     %m
h0=0.53;    %m
d0=0.25;    %m
p=50000;    %Pa
A=0.3;      %m2
VEB_mounting=0;     %m
v=0:(pi/10000):pi/2;    %rad
deg=v.*180/pi;          %∞
myt=linspace(0.1,1,10);
my=myt.*0.75;

%% Calculations
%initiate response vetors
angle=zeros(size(myt));
Fveb=zeros(size(myt));
h=zeros(size(myt));
d=zeros(size(myt));
l_linkage=zeros(size(myt));
a=zeros(size(myt));

%calculate the desired angle at each coefficient of friction
for j=1:length(myt)
   %Initiate response vectors
   Fveb_car=zeros(size(v));
   Fveb_veb=zeros(size(v));

   %calculate the acceleration
   a(j)=-(m*g*(x-b*Bf)-p*A*(b*Bf+c)+myt(j)*(b*Bf+c)*((m*g+p*A)/(my(j)-myt(j))))/(m*(h0+(b*Bf+c)/(my(j)-myt(j)))); %m/s^2

   %check each angle
   for i=1:length(v)
      %F2
      C1=-(cos(v(i))*sin(v(i))/b)*(Br*c/kr+Bf*(b-c)/kf);
      %F
      C2=m*a(j)*sin(v(i))*(-Br/kr-Bf*(b-x)/(b*kf)+Br*(b-x)/(b*kr)) + b*Br*sin(v(i)) + c*sin(v(i)) + cos(v(i))*d0;
      %
      C3=m*a(j)*h0 + b*Br*m*g + m*g*x;
      %Solve second order polynomial
      C=[C1 C2 C3];
      Fveb_car_temp = roots(C);
      %store forces in response vectors
      Fveb_car(i) = abs(min(Fveb_car_temp));
      Fveb_veb(i) = my*p*A/(cos(v(i))+my*sin(v(i)));
   end
   %find corresponding forces
   [min_difference, array_position] = min(abs(Fveb_car-Fveb_veb));
   %find the angle that gives corresponding forces
   angle(j)=deg(array_position); %∞
   %find the actual force that gives the correct result
   Fveb(j)=Fveb_car(array_position);
```

```
    %calculate front Fz difference for current friction
    delta_Fzf=Bf*Fveb_car(array_position)*sind(angle(j));
    %calculate rear Fz difference for current friction
    delta_Fzr=Br*Fveb_car(array_position)*sind(angle(j));

    %find equilibrium cog height
    h(j)=h0-delta_Fzr/kr-((delta_Fzf/kf-delta_Fzr/kr)*(b-x))/b;
    %find equilibrium VEB height
    d(j)=d0-(delta_Fzr*c/kr+delta_Fzf*(b-c)/kf)/b;
    %find the VEB linkage length that gives the right angle
    l_linkage(j)=(d(j)-VEB_mounting)/sind(angle(j));
end
```

Appendix III – Simulation Model

The model of the VEB was created as a subsystem in Adams® and attached to the existing demo vehicle. In order to attach the VEB to the car, a mounting point was created on the vehicle. A matching mounting point was created at the end of the VEB linkage. Figure 63 illustrates how it looks with the VEB attached to the rear of the simulation vehicle.

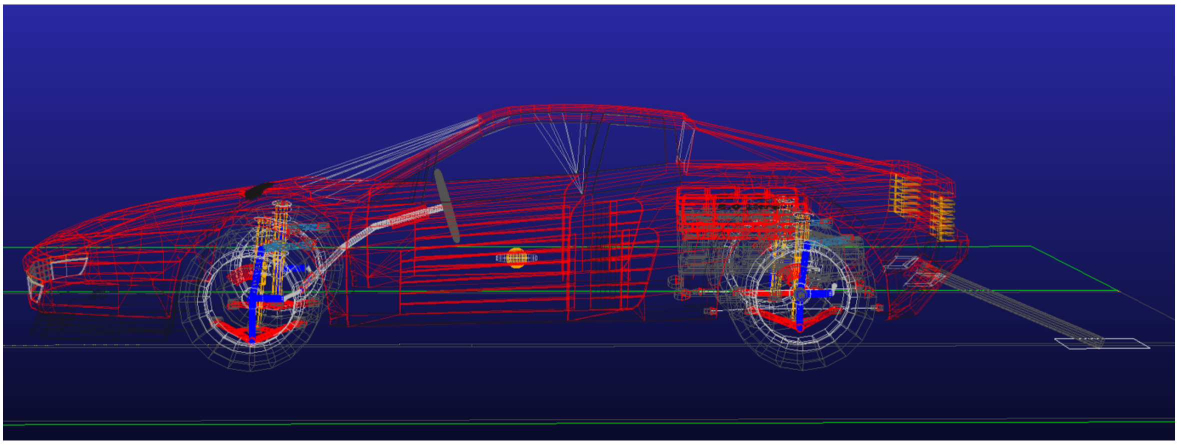

Figure 63 – Vehicle-VEB simulation model

A template with the bodies and joints was created first. The simplified VEB model consists of two bodies:

- The VEB plate which is in contact with the ground
- The VEB linkage which is connecting the VEB plate to the vehicle

Four joints were used to constrain the VEB and allow realistic movement. They are listed below:

- A *hinge joint* where the VEB linkage is attached to the car, to allow movement up and down when the body is pitching
- A *revolute joint* to attach the linkage to the plate, to allow for roll motion of the vehicle and still maintaining the VEB to the ground
- An *angular joint* to prevent the pate from rotating around the revolute joint
- A *planar joint* to ensure the VEB plate was in constant contact with the ground

A new subsystem could be created from the VEB template. Properties such as mass, inertia and forces are addressed in the subsystem. The forces in each direction are briefly expressed in the equations below.

$$F_z = STEP(TIME, 1,0,1.1, -15000)$$

Equation 33 – Vacuum Force

The force created to represent the vacuum is written as a step function to include a time ramp from activation until fully developed force. It could without any major revision be extended to include also a drop off in force due to leaks in the vacuum seal over time. In this case the force is zero the first second, and then it ramps up to a value of -15000N at a time of 0.1 seconds.

$$F_x = -F_z \mu_{dynamic} v_x(VEB_{Body}, VEB_{Ground})/v^*$$

Equation 34 – Force from friction in the X-direction

$$F_y = -F_z \mu_{dynamic} v_y(VEB_{Body}, VEB_{Ground})/v^*$$

Equation 35 – Force from friction in the Y-direction

The expressions for the friction forces use the force in the normal direction, the dynamic friction and the difference in speed between the objects as input to calculate the friction force during a dynamic maneuver. Figure 64 illustrates the VEB subsystem in the Adams® environment.

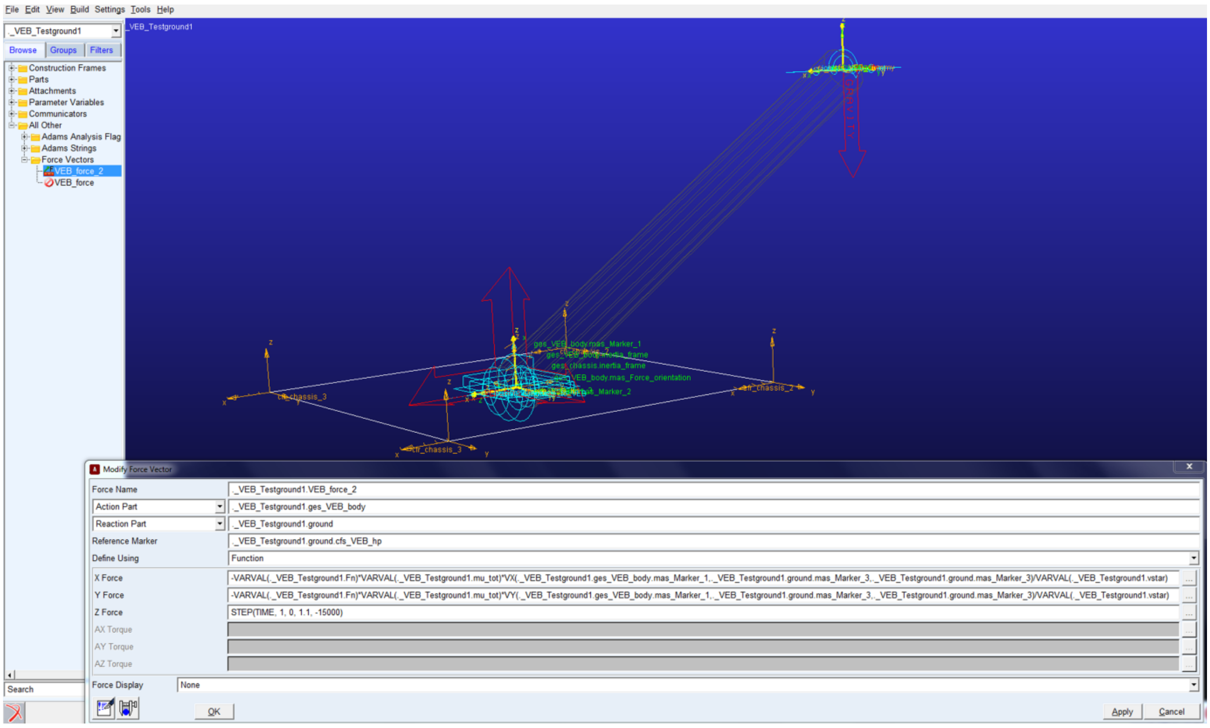

Figure 64 – Detailed image of the VEB simulation model

Appendix IV – Dynamic Simulations

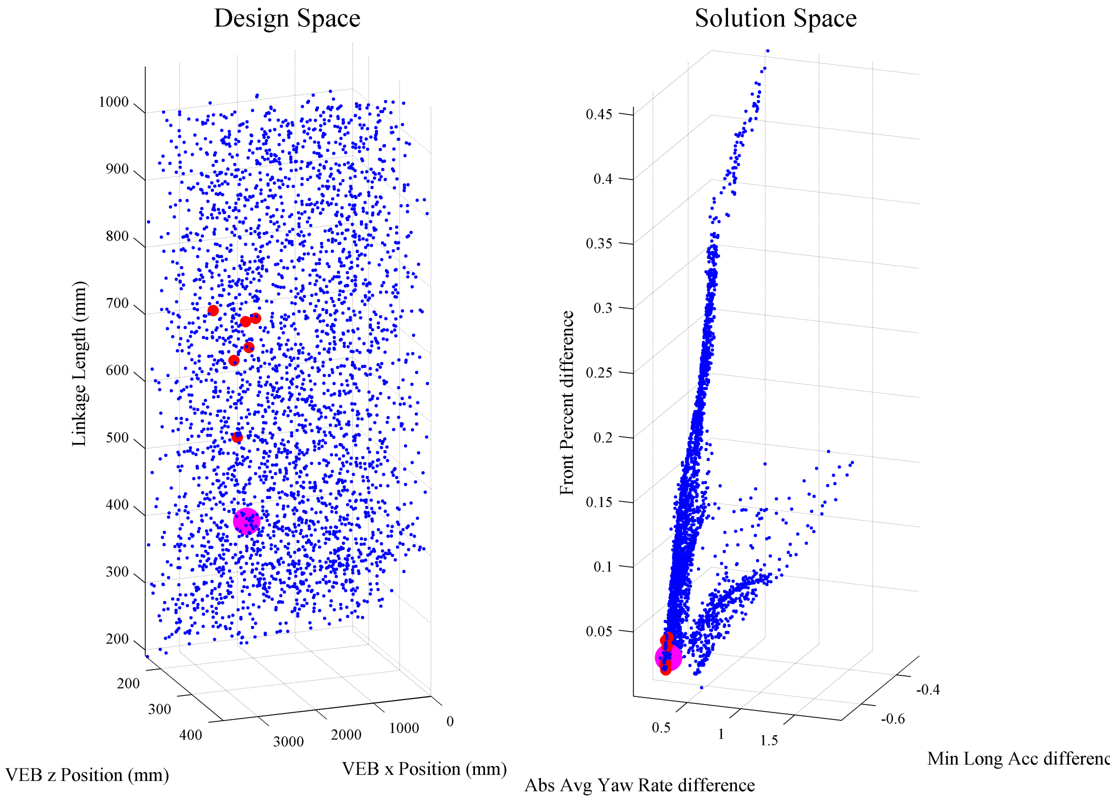

Figure 65 – Constrained, Yaw Rate most important

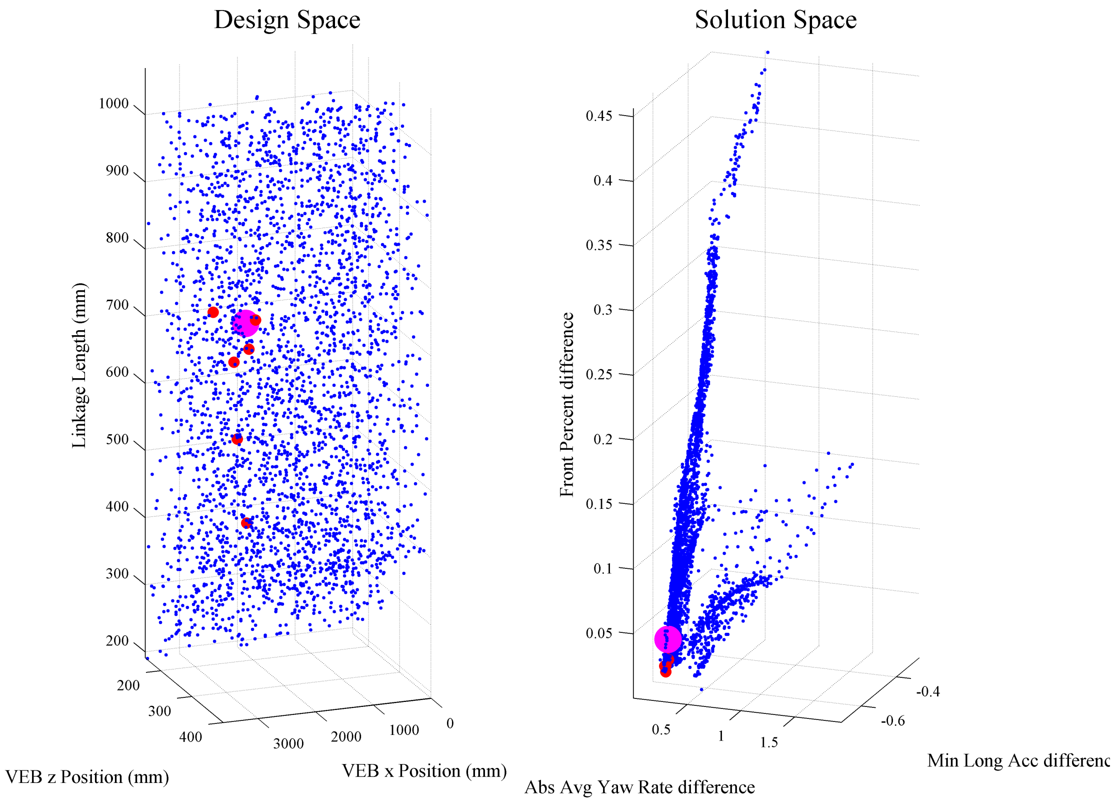

Figure 66 – Constrained, Acceleration most important

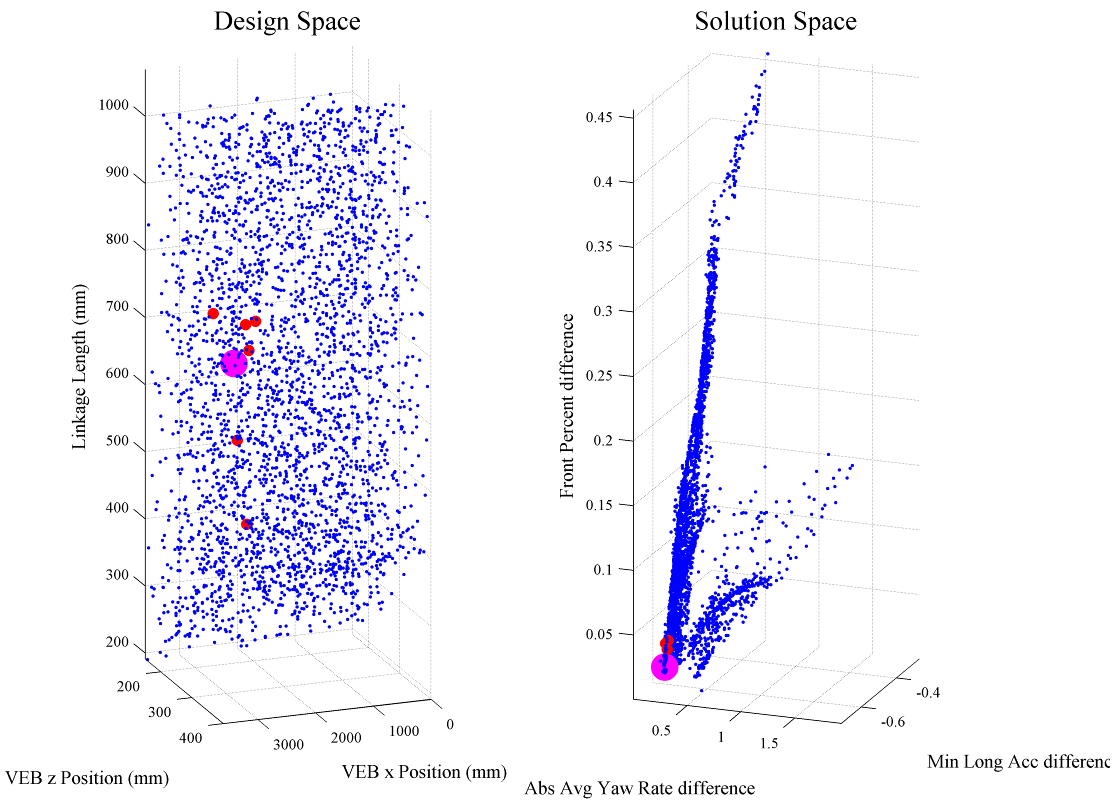

Figure 67 – Constrained, Brake Load Distribution most important

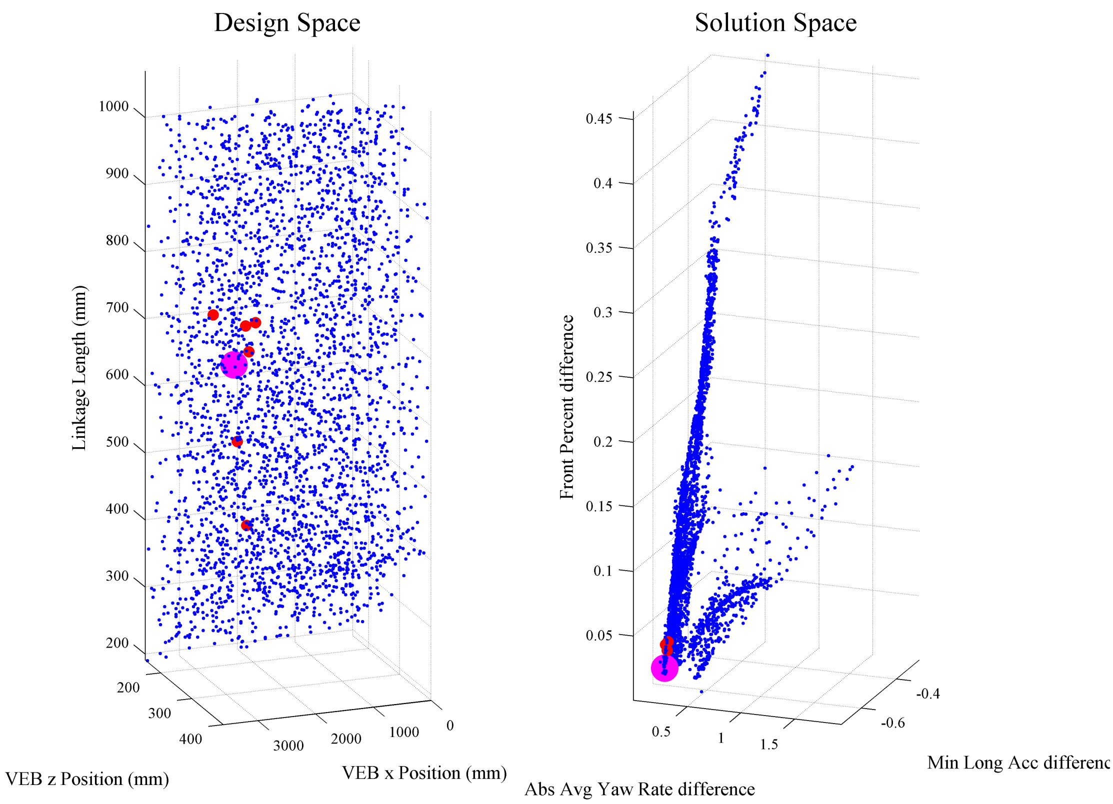

Figure 68 – Constrained, all objectives equally important

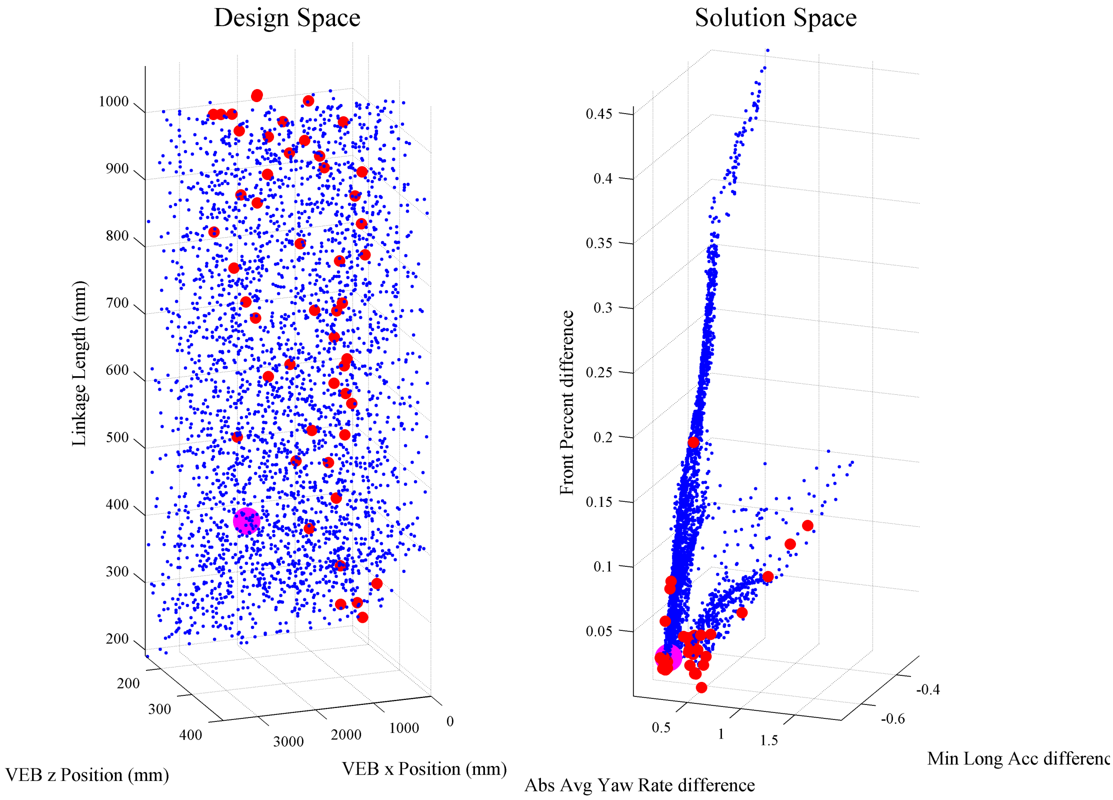

Figure 69 – Unconstrained, Yaw Rate most important

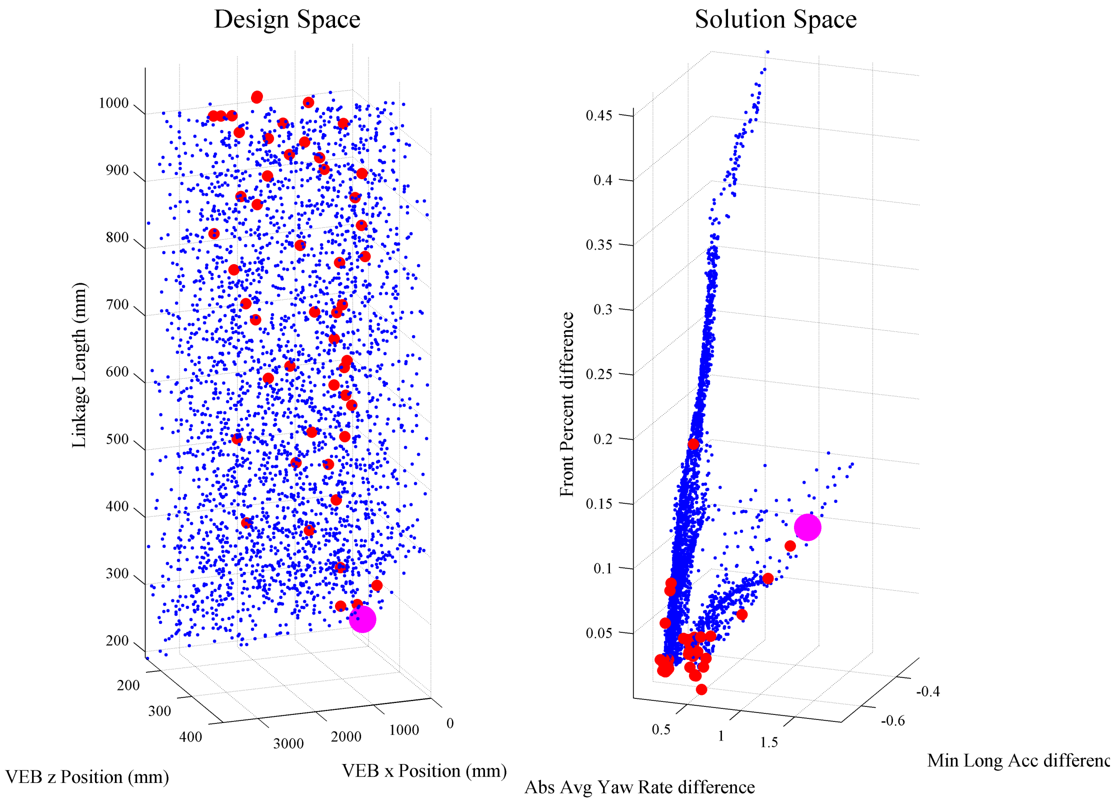

Figure 70 – Unconstrained, Acceleration most important

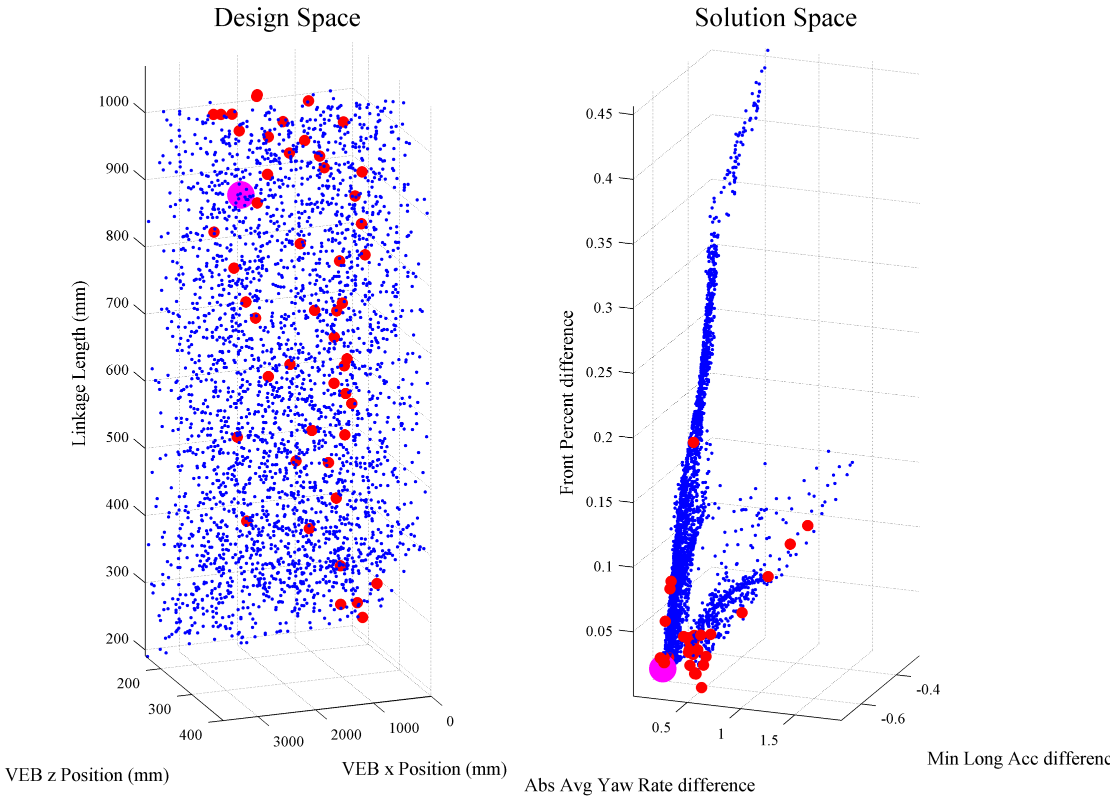

Figure 71 – Constrained, Brake Load Distribution most important

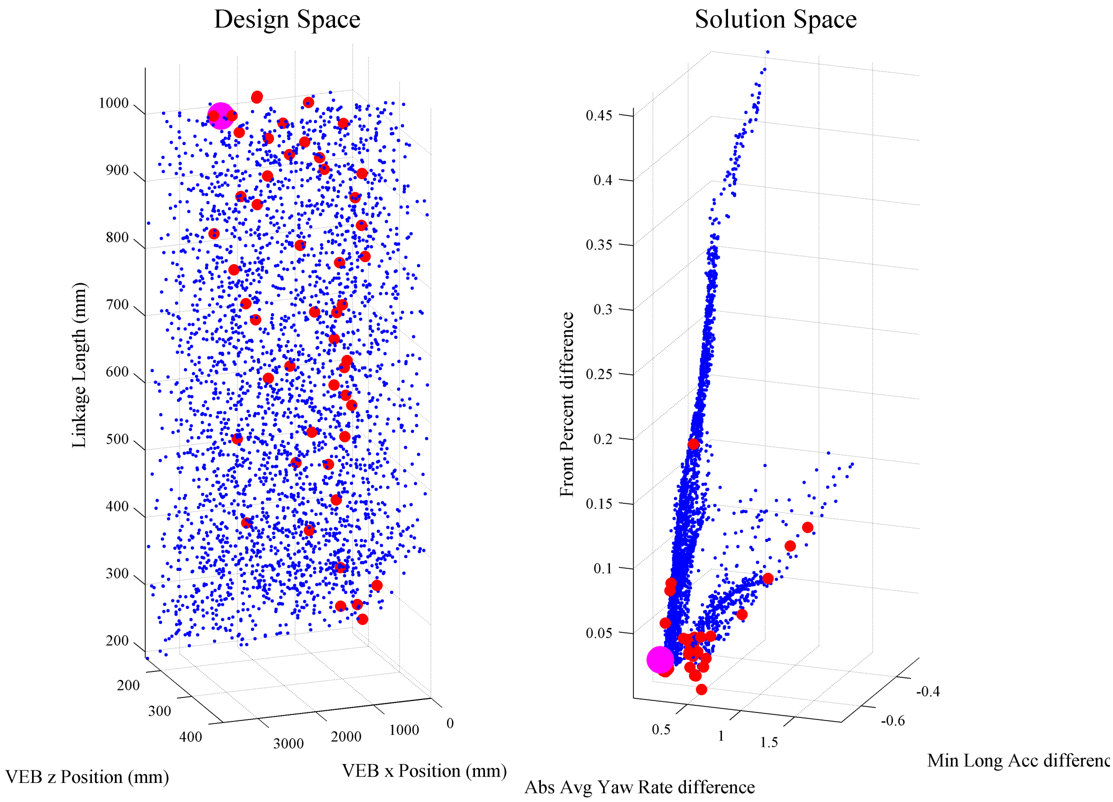

Figure 72 – Constrained, all objectives equally important

Appendix V – Optimization Terminology

Objectives	A single or multiple objectives determine what is going to be minimized when solving the mathematical model.[25]
Constraints	Restrictions that limit the problem space.[27]
Variables	Specifies the different states of the system. (Papalambros & Wilde, 2000) Different values of the variables are tested when solving mathematical models numerically to find the optimum.
Parameters	Parameters are assumed fixed when solving mathematical models[27]. The application of the model decides the parameters that are fixed (Papalambros & Wilde, 2000).
Constants	Typically natural constants that the modeler cannot influence. (Papalambros & Wilde, 2000)

[25] Steven Hoffenson, Phd, The Department of Product and Production Development, Chalmers University of Technology, Lecture notes, September 9th 2013.

Appendix VI – Optimization Sorting Program

```
function P = pareto(datapoints)
%Calculates the pareto optimal set from a 3xN matrix
%% Identification of Pareto Set
%Assign Starting point and assume that it is Pareto optimal
P = datapoints(1,:);
for i=2:length(datapoints)
  %Add point to test
  P_test=datapoints(i,:);
  %Initiate variables to keep track of what has been done to the point
  xyz_add=0;
  erased=0;
  check=0;
  dominated=false;
  removed=false;
  %Compare the point with all other points in the Pareto set
  for j=1:size(P,1)
    %Compensate the for loop if an existing point has been removed
    j=j-erased;
    %If all objectives are smaller
    if P_test(:,1) < P(j,1) && P_test(:,2) < P(j,2) && P_test(:,3) < P(j,3)
      %and if the point has been added
      if xyz_add > 0
        %Remove the current j-point
        P(j,:)=[];
        %Keep track of that a pareto point has been removed
        erased=erased+1;
      %and if the point has not been added
      elseif xyz_add == 0
        %Replace the current pareto point with the test point
        P(j,:)=P_test;
        %Keep track of that the point has been added
        xyz_add=xyz_add+1;
      end
    %If one or two objectives are smaller
    elseif P_test(:,1) < P(j,1) || P_test(:,2) < P(j,2) || P_test(:,3) < P(j,3)
      %and if the point has not already ben added, and if it is not
      %dominated
      if xyz_add == 0 && dominated == false
        %add the test point at the end of the pareto set
        P((size(P,1)+1),:) = P_test;
        %Keep track of that the point has been added
        xyz_add=xyz_add+1;
        %Keep track of the position of that particular point
        check=size(P,1);
      end
    %If all objectives are bigger
    elseif P_test(:,1) > P(j,1) && P_test(:,2) > P(j,2) && P_test(:,3) > P(j,3)
      %Keep track of that it is dominated to avoid comparing it to
      %any other pareto points than the current one
      dominated=true;
      %And if the test point has been added and if it has not been
      %done yet
      if xyz_add>0 && removed == false
        %Remove the semi-dominated point
        P(check,:)=[];
        removed=true;
      end
    end
  end
end
```

Appendix VII – Economic Analysis

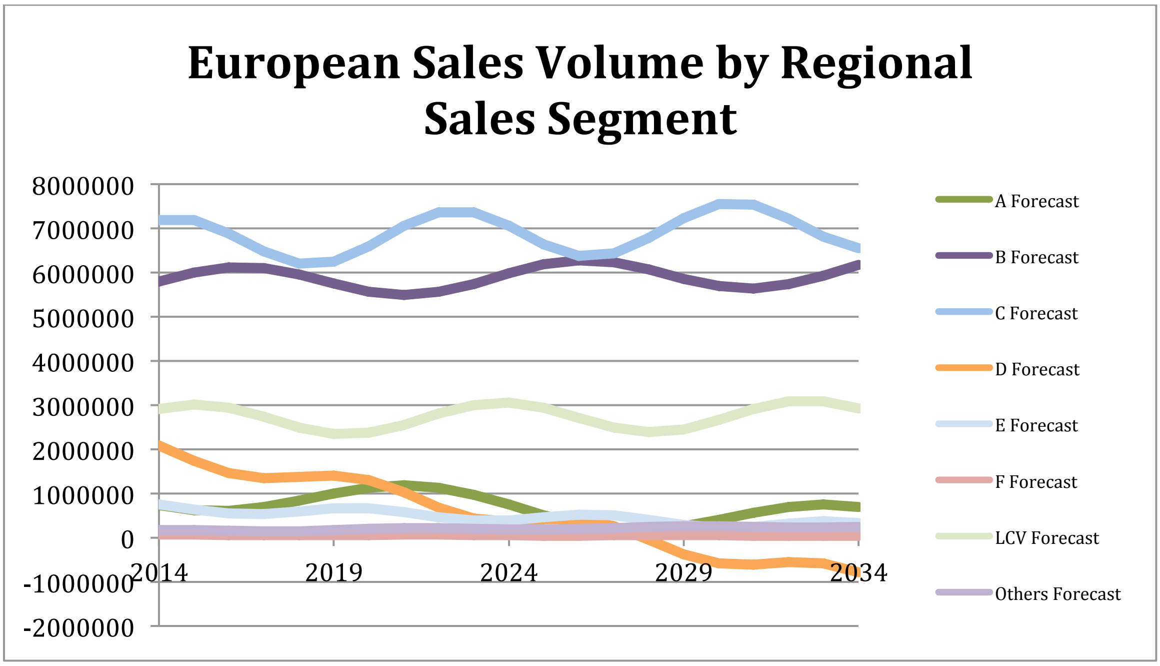

Figure 73 – Forecasted European sales by segment. Only historic data.

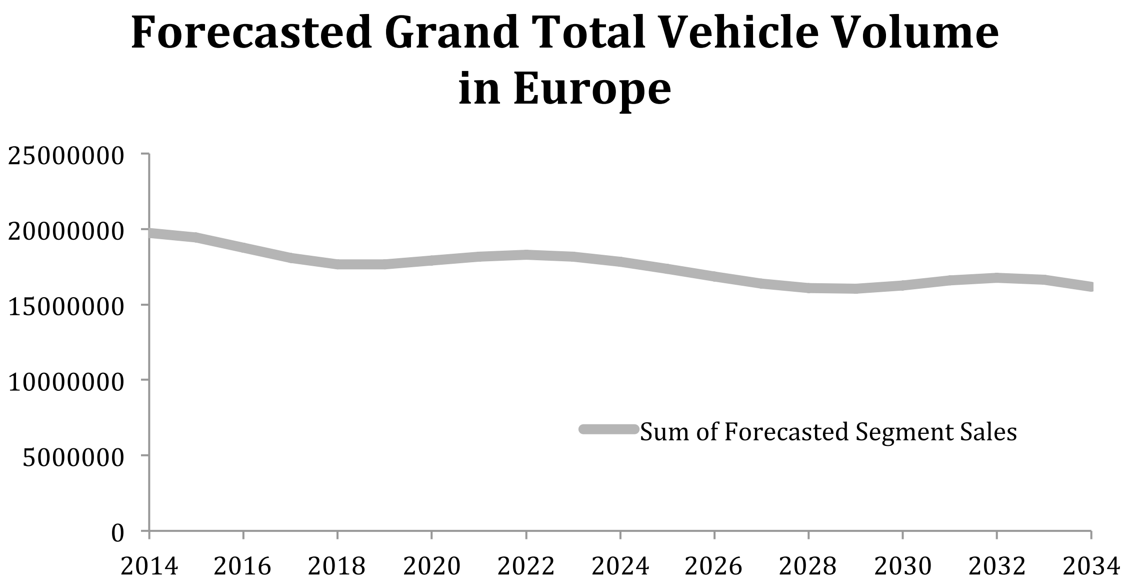

Figure 74 – Forecasted grand total European vehicle sales volume. Only historical data.

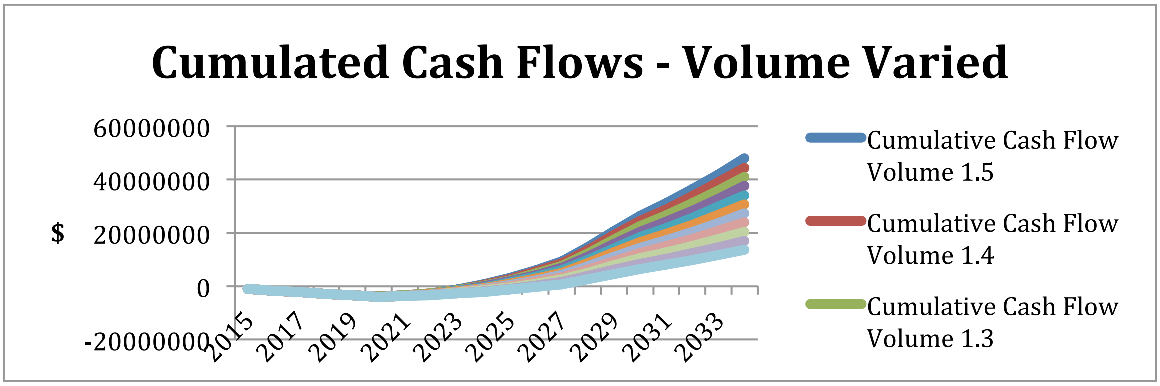

Figure 75 – Undiscounted cumulated cash flows when Volume is varied

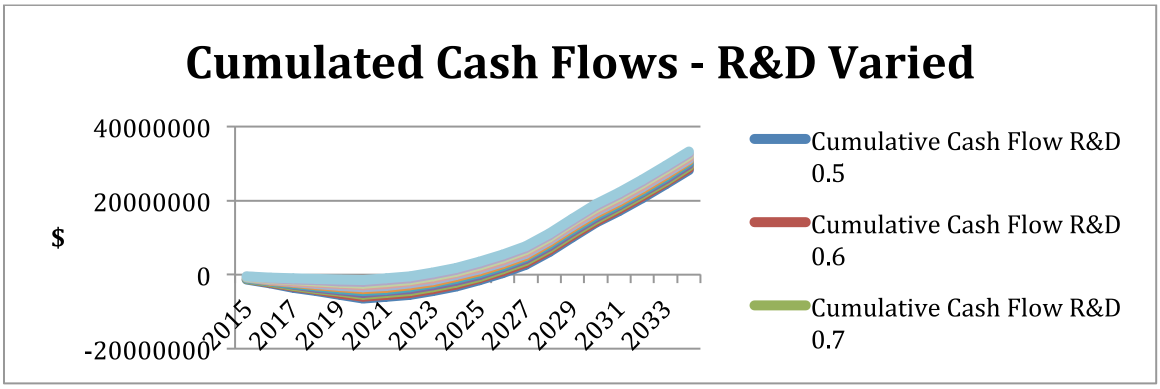

Figure 76 – Undiscounted cumulated cash flows when R&D is varied

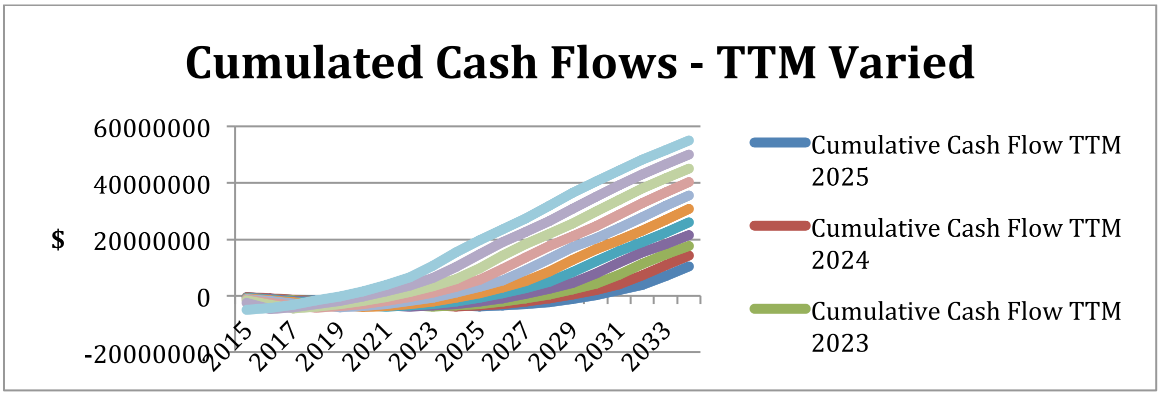

Figure 77 – Undiscounted cumulated cash flows when TTM is varied

Appendix VIII – Sustainability

Pedestrian safety calculations

$$P(v) = \frac{1}{1 + exp(6.9 - 0.090v)}$$

Equation 36 – Fatality risk

Determine the fatality risk at impact speed v without VEB and impact speed 0.7*v with a VEB. This gives a risk improvement as:

$$P_{Improved}(v) = \frac{P(v_{NO\ VEB})}{P(v_{VEB})}$$

Equation 37 – Risk improvement

Calculate how many cases there would be if a VEB would have been used;

$$Cases_{VEB} = \frac{Cases_{NO\ VEB}}{P_{Improved}}$$

Equation 38 – Fatalities with VEB

Compensate for the spillover effect when the impact speed is lower. (An accident previously occurring at one impact speed is now assumed to take place at a lower impact speed) This is illustrated in the figure below.

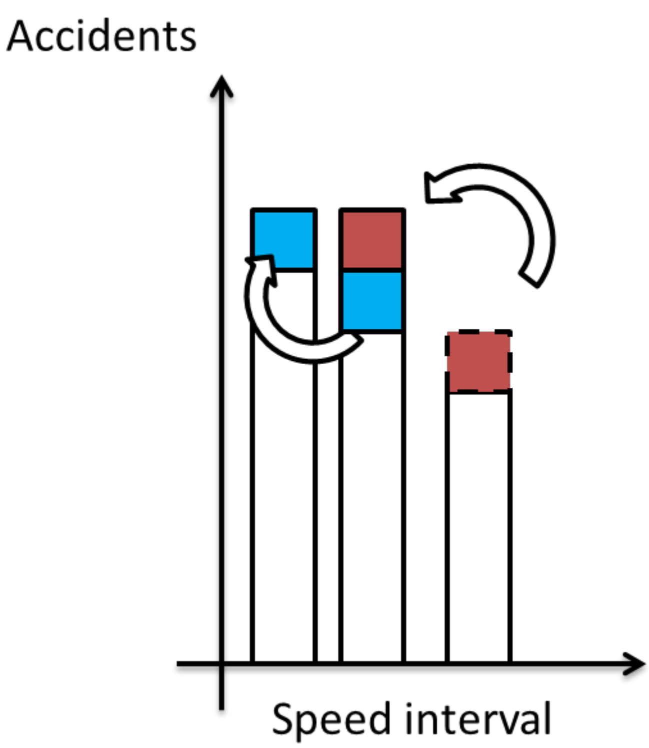

Figure 78 – Illustration of spillover effect compensation

For each interval the number of accidents that will be calculated and put into the correct interval.

The cost is then calculated using

$$Total\ cost, All\ cars\ with\ VEB = \frac{Fatalities_{VEB}}{Fatalities_{NO\ VEB}} * Total\ Cost_{NO\ VEB}$$

Equation 39 – Cost of accident

The cost for Fatal, Severe; Minor and Property is den determined with the fractions from the statics for 2005

$$Cost_{Fatal} = 0.15 * \ Total\ cost, All\ cars\ with\ VEB$$
$$Cost_{Severe} = 0.40 * \ Total\ cost, All\ cars\ with\ VEB$$
$$Cost_{Minor} = 0.12 * \ Total\ cost, All\ cars\ with\ VEB$$
$$Cost_{Property} = 0.33 * \ Total\ cost, All\ cars\ with\ VEB$$

Including a scaling factor for the fraction of vehicles with VEB gives a rough estimation of the cost for society.

Appendix IX – List Of Variables

General

$m = Mass$

$F_f = Friction\ force$

Brake system

$T_e = Requires\ braking\ torque$

$r_e = Wheel\ radius$

$\mu_{road} = Friction\ of\ the\ road\ surface$

$F_z = Normal\ Load$

$t_b = Time\ to\ stop$

$\omega_0 = Initial\ angular\ velocity$

$c = Heat\ capacivity$

$T = Brake\ torque$

$A = Brake\ disc\ area$

$H = Brake\ disc\ thickness$

$\rho = Density$

Lateral dynamics

$R = Turning\ radius$

$\dot{v} = Lateral\ acceleration$

$r = Yaw\ velocity$

$I_z = Yaw\ intertia\ of\ the\ vehicle$