Misuse objects for pedestrian protecting sensing development

Markus Härder
Fabian Ård

Technical Faculty LTH, Lund University
Department of Mechanical Engineering
Division of Mechanics
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Abstract

In the European Union around 8,000 pedestrians and pedal cyclists are killed each year in road accidents, and several hundred thousands are injured. Many of these accidents occur in areas where the speed limit is below 40km/h. Traditional pedestrian protection systems are passive and the extent of the injuries is a consequence of the stiffness of the surface and underlying structures and of how the front of the vehicle is designed. A new concept with an active bonnet, which rises when a car collides with a pedestrian, is under development. This will create a larger deformation zone between the bonnet and the hard underlying structures, and will increase the energy absorption in the bonnet and decrease pedestrian injuries.

The aim of this Master Thesis was to develop three different FE-models of misuse objects with properties similar to reality. This was done in order for Saab Automobile AB to be able to set their sensor setting to distinguish the misuse objects from pedestrians. The sensor setting will thereby prevent misuse objects from activating the protection system.

Also, the FE-models were compared with three different pedestrian impactors to evaluate the difference of the impact energy when colliding with a car. The calculations were solved with the three-dimensional explicate finite element (FE) solver LS-Dyna.

The FE-models created in this Thesis can be used for further development of protection systems.
Acknowledgements

We would like to thank Saab Automobile AB and all their employees who we got in contact with, for giving us the opportunity to perform our Master Thesis.

A special thanks to Niclas Dagson, our supervisor at Saab Automobile AB, and Solveig Melin, professor at The Division of Mechanics at Lund University, who provided us guidance and motivation during our Thesis.

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1 Introduction
To create a safer traffic environment for pedestrians, Saab Automobile has developed an active bonnet that will activate when a pedestrian is hit by a car. The active bonnet should not deploy when the car collides with misuse objects such as guiding posts or animals. This Master Thesis is about developing misuse objects.

To distinguish pedestrians from misuse objects, FE-models have been created and developed in computer simulations and then compared to real tests and known data. Improvements of the models have been made during the work and constantly compared with real misuse objects. A basketball, a guiding post and a small animal have been set as misuse objects.

All studies and writing of the Thesis have been performed in Trollhättan at Saab Automobile AB.

1.1 Background
In the European Union around 8 000 pedestrians and pedal cyclists are killed every year in road accidents, and several hundred thousands are injured. Many of these accidents occur in areas where there are many pedestrians and cars keep speeds below 40 km/h, c.f. (1), (2).

Pedestrian safety is an ever growing concern for the car industry, and has been especially during the last decade. The struggle towards better pedestrian safety can, hopefully, save the lives of many pedestrians and negate the emotional trauma many drivers encounter from the consequences of injuring, or fatally wounding, a pedestrian.

The extent of the injuries is a consequence of how the front of the vehicle hits the pedestrian, and how hard the surface and underlying structures are. Traditional pedestrian protection systems are passive but Saab Automobile is now investigating a new concept, where the bonnet is active so that it rises when a car collides with a pedestrian. This will create a larger deformation zone between the bonnet and the hard underlying structures, e.g. the engine, so that the bonnet can accommodate an increased amount of energy during the impact. This will decrease the extent of injuries in this type of collisions.

All new car models must pass certain safety tests before they are allowed on the market. This is regulated by law, but it provides only a minimum of statutory standard of safety for all new car models.

European New Car Assessment Programme (Euro NCAP) performs tests on all new car models and rates the cars’ safety after a five-star scale, with 5 stars being the best rating. Euro NCAP was established in 1997 by seven European governments together with consumers and motoring organizations and is today active in every country in Europe.

“Euro NCAP provides motoring consumers - both drivers and the automotive industry - with a realistic and independent assessment of the safety performance of some of the most popular cars sold in Europe.” (3)

The aim of Euro NCAP is to encourage manufacturers to exceed these minimum requirements, so that the safety for drivers and pedestrians can develop and improve.
In order to measure pedestrian injuries various tests are performed, where different impactors are launched against the front of the car. In this way it is possible to measure how the different areas on the front of the car affect the impactor. Impact areas are then assessed as good, adequate or marginal. Different impactors and graded areas can be seen in figure 1.

Figure 1 - Pedestrian protection tests method proposal (3)

1.2 Objective
The aim of this Master Thesis was to develop misuse object models and validate them in experimental tests. Our goal was to develop three different FE-models of misuse objects: a basketball, a guiding post and a small animal. Furthermore, we wanted to optimize and obtain as similar properties of the real misuse objects as possible. The FE-models should be compared to various tests of real misuse objects. This was done in order for Saab Automobile AB to be able to set their sensor setting to distinguish the misuse objects from pedestrians. The sensor setting will thereby prevent misuse objects from activating the protection system.
1.3 Problem description
Saab Automobile uses a simulation based vehicle development process, which means that they can perform extensive tests on virtual models instead of doing prototype experimental tests on real vehicles. This development process provides great economic benefits due to shorter testing time and fewer cars being sent to the tests. The virtual development process is depending on correct models in order to get the same results in the simulations as in real life.

Our objective was to develop three different misuse objects; a basketball, a guiding post and a small animal. The models are based upon specifications made by a working group called Arbeitskreis (AK), consisting of Audi AG, Bayerische Motorenwerke AG, Daimler AG, Porsche AG and Volkswagen AG.

These models will be used in an effort to distinguish these objects from a pedestrian in the sensing system and, later on, validate the results by experiments.

The objective of this Thesis is divided into four parts:

1. Basketball – Set up a valid FE representation of a basketball.
2. Guiding post – Set up a valid FE representation of a road pole.
3. Small animal – Build a real model according to Arbeitskreis and set up a valid FE representation.
4. See if it is possible to distinguish the misuse objects above from a pedestrian, both adult and child, with a provided mule.
2 Theoretical background
The relevant Euro NCAP tests are explained in this chapter.

This chapter also contains brief descriptions of how the pedestrian protection is used and how LS-Dyna is employed in the simulations.

2.1 Collision with a pedestrian
When a car collides with an adult pedestrian he or she is most likely to get hit occurs on the lower leg, whereas a child is more likely to get hit on the hip. The rotation of the body, due to the impact force, leads to the pedestrian’s head hitting the bonnet.

The bonnet is quite soft in comparison to the underlying structure, e.g. the engine. This is the property of which Saab Automobile wants to take more advantage. A larger deformation zone is created by raising the bonnet, making it more energy absorbent, thereby providing a much smoother impact. Figure 2 shows the head and body impact against the bonnet.

Figure 2 - Collision with pedestrian (4)

In order to properly deploy the bonnet, Saab Automobile uses a sensor that reacts on the impact of the front of the car. With the data from the sensor it is possible to determine both the point of impact and the magnitude of the energy. The latter is of great importance in the future when developing the sensor.
2.1.1 Colliding test with pedestrian impactors
When testing collisions between a car and different pedestrian impactors, some standards are used. Saab Automobile AB conducted these tests during our Thesis and gave us knowledge of the methodology.

Three different pedestrian impactors were tested. One of them is the representation of an adult’s lower leg. When performing this colliding test, the leg is simply standing on the ground, and gets hit by the car.

The other two are the representations of a child hip and a leg of a small woman. These tests are conducted by launching the impactors towards the front of the car. The firing angle of the release point was calculated so that the pedestrian impactor hits the front of the car with no vertical velocity. This can be seen in figure 3.

![Figure 3 - Colliding test with leg (4)](image)

The goal of Saab Automobile AB is to be able to differentiate between these impactors and our misuse objects, and they are performing similar tests.

These tests will not be shown in this Master Thesis, instead simulations of pedestrian impactors (PI’s) compared to misuse objects will be compared and evaluated.
2.2 LS-Dyna
To analyze the problems in this Master Thesis, the processor LS-Dyna was used. This is a three
dimensional explicit Finite Element (FE) solver for analyzing large deformations and dynamic responses
of structures.

The theory behind LS-Dyna is described in this chapter, c.f. (5). Material models are presented and
explained in LS-Dyna® Keyword User’s Manual Version 971 and will not be elaborated further in this
Master Thesis.

2.2.1 Governing equations

Figure 4 - Notation of time-dependent deformation (5)

Figure 4 shows a time-dependent deformation, in which a point in b, initially at \( X_{\alpha} \) \( (\alpha = 1, 2, 3) \), moves
to a point \( x_i \) \( (i = 1, 2, 3) \). This deformation is stated through the initial coordinates \( X_{\alpha} \) and the time \( t \) in
equation (2.1) so that the new position is

\[
x_i = x_i(X_{\alpha}, t) \tag{2.1}
\]

The initial conditions are given by (2.2) and (2.3), where \( V_i \) defines the initial velocities

\[
x_i(X_{\alpha}, 0) = X_{\alpha} \tag{2.2}
\]

\[
\dot{x}_i(X_{\alpha}, 0) = V_i(X_{\alpha}) \tag{2.3}
\]
The momentum equation is defined as (2.4), where $\rho$ is the current density, $f_i$ is the body force density, and $\sigma_{ij}$ is the Cauchy stress. The comma denotes covariant differentiation.

\[ \sigma_{ij,j} + \rho f_i = \rho \ddot{x}_i \]  

(2.4)

The solution to equation 2.4 should satisfy the boundary conditions below, c.f. Figure 4. $\partial b = \partial b_1 \cup \partial b_2$

- The traction boundary conditions on boundary $\partial b_1$, defined in (2.5)
  \[ \sigma_{ij,n_i} = t_i(t) \]  

(2.5)

- The displacement boundary conditions on boundary $\partial b_2$, defined in (2.6)
  \[ x_i(X, t) = D_i(t) \]  

(2.6)

- The contact discontinuity along an interior boundary $\partial b_3$ when $x_i^+ = x_i^-$, defined in (2.7). The superscripts + and - denotes positive and negative side, respectively.
  \[ (\sigma_{ij}^+ - \sigma_{ij}^-) n_i = 0 \]  

(2.7)

Mass conservation is stated as (2.8), where $V$ is the relative volume and $\rho_0$ is the reference density.

\[ \rho V = \rho_0 \]  

(2.8)

The relative volume is defined as the determinant of the deformation gradient matrix; $F_{ij}$. This matrix is given in (2.9)

\[ F_{ij} = \frac{\partial x_i}{\partial X_j} \Rightarrow V = \det \left( \frac{\partial x_i}{\partial X_j} \right) \]  

(2.9)

The energy equation is integrated in time and defined in (2.10). $\dot{\varepsilon}_{ij}$ is the strain rate tensor, $q$ is the bulk viscosity, and $\delta_{ij}$ is the Kronecker delta.

\[ \dot{E} = Vs_{ij}\dot{\varepsilon}_{ij} - (p + q)V \]  

(2.10)

$s_{ij}$ defines the stress (2.11)

\[ s_{ij} = \sigma_{ij} + (p + q)\delta_{ij} \]  

(2.11)

$p$ defines the pressure (2.12)

\[ p = -\frac{1}{3}\sigma_{ij}\delta_{ij} - q = -\frac{1}{3}\sigma_{kk} - q \]  

(2.12)
2.2.2 Weak form
Let \( \partial \delta x_i \) be a function, that satisfies all boundary conditions of \( \partial b_2 \). This, together with equations (2.4), (2.5) and (2.7), integrated over the current geometry, gives equation (2.13)

\[
\int_v (\rho \ddot{x}_i - \sigma_{ij,j} - \rho f) \delta x_i dv + \int_{\partial b_1} (\sigma_{ij} n_j - t_i) \delta x_i ds + \int_{\partial b_3} (\sigma_{ij}^+ - \sigma_{ij}^-) n_j \delta x_i ds
\]

(2.13)

Applying the divergence theorem provides equation (2.14)

\[
\int_v (\sigma_{ij} \delta x_i)_{i,j} \, dv = \int_{\partial b_1} \sigma_{ij} n_j \delta x_i ds + \int_{\partial b_3} (\sigma_{ij}^+ - \sigma_{ij}^-) n_j \delta x_i ds
\]

(2.14)

Noting that \((\sigma_{ij} \delta x_i)_{i,j} \sigma_{ij,j} \delta x_i = \sigma_{ij} \delta x_{i,j} \) leads to the weak form of the equilibrium equation (2.15), which is a statement of the principle of virtual work.

\[
\delta \pi = \int_v \rho \ddot{x}_i \delta x_i dv + \int_v \sigma_{ij} \delta x_{i,j} dv - \int_v \rho f_i \delta x_i dv - \int_{\partial b_1} t_i \delta x_i ds = 0
\]

(2.15)

2.2.3 FE description
A FE mesh, interconnected at nodal points, is introduced. It describes the current position of a particle at a given time (2.16). \( \phi_j \) are shape functions of the parametric coordinates \((\xi, \eta, \zeta)\), \( k \) is the number of nodal points defining the element. \( x_i^j \) is the nodal coordinate of the \( j \)-th node in the \( i \)-th direction.

\[
x_i(X_{\alpha}, t) = x_i(X_{\alpha}(\xi, \eta, \zeta), t) = \sum_{j=1}^{k} \phi_j(\xi, \eta, \zeta) x_i^j (t)
\]

(2.16)

Equation (2.16) can be approximated as (2.17). This leads to equation (2.18), where \( \Phi_i^m = (\phi_1, \phi_2, ..., \phi_k)^i_m \).

\[
\delta \pi = \sum_{m=1}^{n} \delta \pi_m = 0
\]

(2.17)

\[
\sum_{m=1}^{n} \left\{ \int_v \rho \ddot{x}_i \Phi_i^m dv + \int_v \sigma_{ij} \Phi_i^m dv - \int_v \rho f_i \Phi_i^m dv - \int_{\partial b_1} t_i \Phi_i^m ds \right\} = 0
\]

(2.18)

Written in matrix form, equation (2.18) can be written as (2.19).

\[
\sum_{m=1}^{n} \left\{ \int_v \rho N^t N \dot{a} dv + \int_v B^t \sigma dv - \int_v \rho N^t b dv - \int_{\partial b_1} N^t t ds \right\}^m = 0
\]

(2.19)

\( N \) is an interpolation matrix, \( B \) is the strain-displacement matrix, \( \sigma \) is the stress vector, \( a \) is the nodal acceleration vector, \( b \) is the body force vector, and \( t \) are the applied traction loads, see equations (2.20)- (2.23).

\[
\sigma^t = (\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \sigma_{xy}, \sigma_{xz}, \sigma_{yz})
\]

(2.20)

\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3
\end{bmatrix} = N \begin{bmatrix}
a_{x_1} \\
a_{y_1} \\
\vdots \\
a_{y_k} \\
a_{z_k}
\end{bmatrix} = Na
\]

(2.21)
\[ b = \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} \quad (2.22) \]

\[ t = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} \quad (2.23) \]

2.2.4 Time integration

LS-Dyna uses a modification of the central difference time integration scheme, through a central difference method. In equation (2.24) the central difference method is stated. \( x \) is the nodal coordinate vector, \( x^0 \) is the nodal coordinate vector at time zero seconds, and \( u \) is the nodal coordinate displacement vector.

\[ x^{n+1} = x^0 + u^{n+1} \quad (2.25) \]

The nodal coordinate displacement vector is given in equation (2.26).

\[ u^{n+1} = u^n + v^{n+1/2} \Delta t^{n+1/2} \quad (2.26) \]

where \( v \) is the nodal coordinate velocity vector and can be seen in equation (2.27).

\[ v^{n+1/2} = v^{n-1/2} + a^n \Delta t^n \quad (2.27) \]

\( a^n \) is the nodal acceleration vector and \( \Delta t^n \) is the time step at time \( n \). The time step equation is shown in (2.28).

\[ \Delta t^{n+1/2} = \frac{(\Delta t^n + \Delta t^{n+1})}{2} \quad (2.28) \]
3 Methodology
The Thesis work began with literature studies, mostly directed towards the sensing system and solutions found by different manufacturers. Moreover, a theoretical study was made through the FEM used in the simulations.

The computer simulations were made by using the software below:

- Altair’s HyperMesh v10 as pre-processor
- LSTC’s LS-Dyna as processor
- Altair’s HyperView and GNS’ Animator 4 as post-processors.

Knowledge of the software above was gained through a course provided by Altair and tutorial studies.

At the beginning of the Thesis work, a time-plan was discussed and created together with our supervisor Niclas Dagson. The time-plan is shown in table 1.

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</table>

Table 1 – Preliminary time plan

The objective was, as previously mentioned, divided into four sub-objectives, specified in their own respective section. Note that sub-objective 4 is not mentioned in the table. This objective was a supplement to the Thesis, due to problems with the small animal impactor.
3.1 Sub-objective 1: Basketball impactor

Modeling a basketball in FE provided a series of difficulties, and experimental tests had to be performed in order to get a good representation. The pressure was measured and material studies, e.g. tensile tests, were performed to acquire material data.

The ball consists of an airtight black bladder made of butyl rubber and a protecting carcass made of blue natural rubber. There is also a reinforcement made of grey polyester between the two materials. The layers can be seen in figure 5.

![Figure 5 – Close up picture of material](image)

A FE model of the basketball was created according to the known material data and dimensions of the different layers, as well as the measured pressure. The pressure inside the ball was represented by an airbag entity, AIRBAG_SIMPLE_PRESSURE_VOLUME. The layers were modeled by shell elements with their respective material properties and dimensions. The mesh is shown in figure 6, and 4015 elements were used in each layer, adds up to a total of 12045 elements. The total amount of nodes was 3908.

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Nodes</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bladder</td>
<td>3 908</td>
<td>4 015</td>
</tr>
<tr>
<td>Reinforcement</td>
<td>3 908</td>
<td>4 015</td>
</tr>
<tr>
<td>Carcass</td>
<td>3 908</td>
<td>4 015</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3 908</td>
<td><strong>12 045</strong></td>
</tr>
</tbody>
</table>

Table 2 – Data of the simulation impactors

The material model MAT_MOONEY_RIVLIN_RUBBER was used for modeling the bladder and carcass. MAT_FABRIC was used for the reinforcement.
Figure 6 shows the mesh used for the basketball.

Numerous models were tested until a stable ball was successfully created. Some errors which encountered with the early versions were such as the ball exploding, pulsating, extending its volume by 50% under applied pressure as well as layers not finding contact definitions due to the high speed. After some trial and error simulations all the errors mentioned above were solved by:

- Using a ramped curve for applying pressure to the ball.
- Applying the pressure in a dynamic relaxation phase before going into the transient phase.
- Modeling the ball with three layers of identical elements but with different material properties, and shared nodes between the layers.
- Using a mass damping factor on the airbag.
### 3.1.1 Validating test

The FE model was validated through a drop test of the real ball. The test was conducted by releasing the ball from a height of 1.8 m and measuring the rebound height. This was accomplished by means of a checkered wall and a high-speed camera.

The pressure inside the ball has a great impact on the results and had to be monitored. A newly calibrated pump was used to keep the pressure at 0.8 bar before each test.

To neglect any influence from the floor, the test was performed by letting the ball bounce against concrete. Figure 7 shows how the drop test was performed.
The floor was modeled as a rigid wall, which is an entity in LS-Dyna that is non-deformable and locked in every degree of freedom.

The energy loss due to the hysteresis work of the ball in impact with a solid surface was compared to the energy loss in the FE simulation of the same test. Since an explicit solver was used in the simulation, the duration was supposed to be as short as possible, preferably less than 200 ms. Since the drop and the rebound required a lot longer time, the problem was simplified accordingly:

- Instead of letting the ball fall from 1.8 m it was placed just above the rigid wall with an initial velocity, \( v_{ini} \), according to the height of the fall. \( v_{ini} = 5.94 \) m/s. See eq. (3.1)-(3.3).
- The rebound velocity, \( v_{rebound} \), was measured instead of the rebound height.
- The loss in energy was calculated by comparing \( E_{ini} \) and \( E_{rebound} \), according to (3.4).

\[
\ddot{z} = -g
\]  
\[
\dot{z} = -gt + C
\]  
\[
z = -\frac{gt^2}{2} + Ct + D
\]

C and D are denoting initial velocity and initial height respectively. By setting the constants to their respective values, the time \( t \) for impact (\( z=0 \)) can be calculated.

\[
\begin{align*}
C &= 0 \\
D &= 1.8 \Rightarrow t = 0.6058 \text{ s}
\end{align*}
\]

Using \( t \) in eq. (3.2) provides the velocity just prior to impact. \( v_{ini} = 5.94 \) m/s.

\[
\text{Energy loss} = 1 - \frac{E_{ini}}{E_{rebound}} = 1 - \frac{E_{kin,ini}}{E_{kin,rebound}}
\]

The damping factor of the airbag entity was found to have the most impact on the results. It was the only variable which had been changed until satisfactory results were achieved, i.e. until the same energy loss as for the real ball was finally reached.

Figure 8 shows the real ball relative the FE model in bounce.
3.2 Sub-objective 2: Guiding post

To model the guiding post in FE, dimensions, material and mounting had to be investigated. A road pole was bought and used for both measuring and material testing.

The black part of the pole had a PE-stamp which means that the material is polyethylene. Material tests were needed to be performed on the white part.

To describe the plastic material in LS-Dyna, the material model MAT_PIECEWISE_LINEAR_PLASTICITY was used. The input variables for the material card were Young’s modulus, density and Poisson’s ratio. In addition, a true stress versus true plastic strain curve was demanded. The curves were also supposed to be connected to their respective strain rate.

Six tensile tests with two different strain rates were performed. Three tests at a slow strain rate of 2 mm/minute, and three tests at a faster strain rate of 50 mm/minute were performed. Samples from the two types of strain rates can be seen in figure 9, where the upper sample is from the slower strain rate.

![Figure 9 - Samples of tensile tests](image)

The data acquired from the tensile test is engineering stress vs. engineering strain. In order to obtain the true stress and strain from the engineering data, as required by the material card, equation (3.5) was used. (6)

\[
\sigma_{\text{true}} = \sigma_{\text{engineering}} (1 + \varepsilon_{\text{engineering}})
\]  

(3.5)

The relationship between engineering strain and true strain can be seen in equation (3.6).

\[
\varepsilon_{\text{true}} = \ln(1 + \varepsilon_{\text{engineering}})
\]  

(3.6)

The true stress versus true plastic strain curve could be obtained by neglecting the elastic strain, according to equation (3.7).

\[
\varepsilon_{\text{true,pl}} = \varepsilon_{\text{true}} - \frac{\sigma_{\text{true}}}{E}
\]  

(3.7)

In order to obtain Young’s modulus, a bending test was performed.
The FE model of the guiding post was modeled according to the dimensions of the guiding post. Some of the details, such as the reflex, are not included in the model since their influence to the end result can be neglected. The guiding post and the cross section are shown in figure 10 and figure 11 respectively.

![Figure 10 - Guiding post and FE-model](image)

![Figure 11 - Cross section](image)

The outer diameter of the white part is 105 mm and the diameter of the black is 112 mm. The length of the guiding post is 1.6 m and thickness is 4 mm. The weight is 2.0 kg.
The geometry was modeled from the mid surface and meshed with shell elements. Due to the geometry, 7 mm quad elements with a thickness of 4 mm were used for the mesh. The mesh consisted of 13,251 nodes and 13,159 elements.

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Nodes</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>White part</td>
<td>11,475</td>
<td>11,430</td>
</tr>
<tr>
<td>Black part</td>
<td>1,776</td>
<td>1,728</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>13,251</strong></td>
<td><strong>13,159</strong></td>
</tr>
</tbody>
</table>

Table 3 – Data of the simulation impactors

A frictional contact was defined between the white and black part of the post, as well as a rigid body element to symbolize the screw between the two parts.

To describe the material properties of the guiding post in LS-Dyna, a few variables in the material card were investigated and changed until satisfaction was reached.
3.2.1 Validating test

In order to validate the FE model of the guiding post, a test with few sources of errors, thereby allowing repeatable tests with matching results, was sought. The idea was to strike the post with some sort of entity and monitor the reaction forces. This chapter describes the work towards such a test.

In order to validate the FE model, a machine performing linear impacts, was used. The post was in a fixed mounted position and struck by the impactor of the machine. The machine builds up an internal pressure in order to shoot a bar forward along a rail. An impactor can be placed at the end of the bar, thereby making the machine pretty versatile. Usually the machine is used for testing head impacts, but an impactor with simpler geometry and material properties was sought for this test.

The impactor used was sketched up and manufactured out of polyurethane in order to get a, by comparison to the post, non-deformable body. To eliminate local stress concentrations, the impactor was made with rounded corners and a large surface area. The impactor can be seen in figure 12. The non-deformable material as well as the simple geometry is easy to represent in FE.

To measure the accelerations and displacements of the impactor two accelerometers were placed on the back of the impactor. These provided important data of the impact and the reactions of the guiding post. Displacement-, acceleration- and velocity graphs were created from these data. This was used to validate and configure the FE model of the guiding post.

![Figure 12 - Impactor for guiding post made in polyurethane and as FE-model](image)

The impactor was modeled with solid elements and with rigid material to describe the non-deformable body. The mesh consists of 27 270 nodes and 24 552 hex elements. The mass had to be increased in order to represent both the mass of the impactor and the bar it was mounted upon in the test. Since the bar and the impactor had a total weight of 17.4 kg, the FE-model was designed to have the same weight.

The dimensions were modeled after the real impactor and are set to 220x165x80 (x,y,z) mm, according to the coordinate system in figure 18. The rounded corners have a radius of 20 mm.
In order to be able to strike the post, a carrier for mounting the post was manufactured. Along roads the posts are stuck in the ground, which makes the mounting very dependent to weather, location and temperature. To properly validate the post and allow repeatable results, a rigid carrier was preferred.

The outer skeleton of the carrier was made of steel and the fixating parts of the guiding post were made of polyurethane. The height of the carrier is 520 mm. The hole of the upper fixating part has a smooth edge with a radius of 20 mm to eliminate high local stress concentrations. The carrier is shown in figure 13. The carrier was mounted on the workshop floor thereby denying any kind of movement.

![Figure 13 - Carrier for guiding post](image)

To prevent displacement in upward direction the post was locked with a screw. This can be seen in figure 14.

![Figure 14 – Lock to prevent displacement in upward direction](image)
The carrier was modeled in another shape than the carrier used in the real tests. This was done to save time in simulations and should have no effect on the result. However, the important geometric properties are the same, i.e. height, radius and smooth edge.

The mesh consists of 3900 nodes and 3848 shell elements, and can be seen in figure 15. The nodes of the carrier were locked in every degree of freedom since it was considered to be rigid, which neglected any influence due to the low modeled mass.

Figure 15 - FE-modeled carrier
The test was, as previously mentioned, performed by striking the guiding post with the impactor. The bar and the impactor used provided a total mass of 17.4 kg. The test was performed at three different velocities: 10.6, 13.4 and 15.8 km/h.

To examine the reactions of the guiding post during the collision, the test was filmed with a high speed camera. The film collected was compared with the FE-simulation and can be seen in appendix, figure 73. The camera has a speed of 1000 frames/second.

The setup of the linear impactor test can be seen in figure 16 and figure 17. The markings in the figures are presented below.

S1 – Impactor
S2 – Guiding post
S3 – Carrier
S4 – Light sources
S5 – High speed camera
S6 – Monitor and data collector

Figure 16 - Set-up of guiding post of linear impactor test

Figure 17 - Monitoring of linear impactor test
The simulated test was set up according to the validating test.

A global contact definition was used in the simulation to define the contacts post-carrier and post-impactor.

The nodes of the impactor were locked in every degree of freedom except for translation in the y-direction, to represent the properties of the linear impactor. The nodes in the lower end of the post were locked in z-direction to represent the screws in the mounting.

The distance between the bottom of the post and the bottom of the impactor, marked as B in figure 17, was set to 900 mm.

An initial velocity, \(v_{ini}\), was defined on the impactor in negative y-direction. The acceleration, velocity and displacement of a specific node on the impactor, were plotted and compared to the experimental tests.

Simulations were run until satisfactory results were achieved. The material properties of the post were the only variables changed when iterating.
3.3 Sub-objective 3: Small animal impactor

The small animal impactor was described by the coalition as a leather bag filled with shredded tires and a small bag of steel grit in the middle of the bag. Saab Automobile had already performed some tests of colliding with such an impactor, thus a similar small animal impactor had already been made. The impactor was made of a core of sand and surrounding walls of foam and then coated with a bag of leather. The small animal impactor can be seen in Figure 19.

![Figure 19 – Small animal impactor seen with leather bag](image1)

The foam inside the leather bag is made of memory foam (Confor foam), which is a foam that returns to its original shape once pressure is removed. Memory foam is made of polyurethane with additional chemicals increasing its density and viscosity, c.f. (6). The total mass of the animal is 2.52 kg. Figure 20 shows the memory foam that encloses the core of sand.

![Figure 20 - Small animal impactor seen without the leather bag](image2)
Figure 21 shows the behavior of the memory foam when pressure is applied.

![Figure 21 - Memory foam](image)

The core of sand and the memory foam are modeled with solid elements and the enclosing leather bag is modeled with shell elements. To the left in figure 22 the small animal is shown and the leather surface can be seen. To the right a transparent picture of the impactor and the core of sand can be seen.

![Figure 22 - FE-model of small animal](image)

The material models used for the different parts are MAT_SOIL_AND_FOAM for the sand core, MAT_VISCOUS FOAM for the memory foam, and MAT_FABRIC for the leather bag.
3.3.1 Validating test
The machine performing linear impacts and being used to validate the guiding post, was supposed to validate the small animal. This should have been done with the same impactor used in the tests of the guiding post.

The small animal was supposed to hang free in the air by means of wires, and get struck by the impactor, with accelerometers providing data for comparison.

Depending on the results another test was discussed, where the hanging animal is struck by an impactor in a pendulum. The mass of the impactor in the pendulum is much lower than in the linear impactor, allowing hits with higher velocity and perhaps better values from the accelerometers.

Since no tests have been accomplished, there are no results from this section. A simulation was however set up to represent both tests, due to the similarity at the point of impact.

An initial velocity, in negative y-direction, is set on the impactor. The nodes of the impactor were locked in every degree of freedom, except for translation in the y-direction, to represent the properties of the linear impactor or pendulum. The animal can move freely and is not locked in any degree of freedom.

![Figure 23 - Setup of the FE-simulation](image-url)
3.4 Sub-objective 4: Pedestrian sensing
This chapter is about evaluating whether the misuse impactors can be distinguished from a pedestrian. Simulations were performed using a model of the front of a car with the sensor in place. The FE models of the car front and different pedestrian impactors (PI's) have already been constructed, or bought, by Saab Automobile AB and will not be explained. They can however be seen in figure 24-27.

![Figure 24 - Pedestrian impactors (not in scale)](image)

The first PI from the left in figure 24 is a FE representation of a lower body of a child (PI 1). The second is a representation of a leg belonging to a small woman or child (PI 2). The last PI is a representation of an adult lower leg (PI 3). Note that they are not shown in correct scale in figure 24.

The PIs are supposed to affect the sensor to deploy the hood, whereas the misuse objects should not.

The method was to launch the different impactors against the front of the car which can be seen in figure 25-29. This was modeled by defining an initial velocity towards the car, \( v_{ini} \), on the impactor.

The basketball was set up so that the center of mass of the impactor was in line with the sensor. The impact points, i.e. height, of PI 1-3 were provided by Saab Automobile AB, and are used both in these simulations as well as in the real tests. Gravity was not used in these simulations and thereby no firing angle of the release point was needed.

When setting up the simulation of the guiding post, an initial velocity of the guiding post was set. A constant velocity of the carrier was set by means of boundary conditions. The carrier was also locked in every degree of freedom, except translation towards the car.

No tests of the small animal were performed since no complete model had been created.
Figure 25 – PDI-Leg (Pl 1) launched against the front of the car

Figure 26 – IEE-Leg (Pl 2) launched against the front of the car
Figure 27 – Lower-Leg (PI 3) launched against the front of the car

Figure 28 - Basketball launched against the front of the car
Figure 29 – Guiding post launched against the front of the car

The impact caused deformation of the front and thereby affected the sensor. The energy of the impact could be measured and plotted.

Validation tests of these impacts were made during this thesis by Saab Automobile AB. No data from these tests were used for comparison, but presence at the tests provided knowledge about the methodology.

Table 4 shows the different impactors with their respective velocities and properties. The simulations of all impactors were performed at 20 and 55 km/h, except for the basketball which was also analyzed at 80 km/h. This is due to the probability of the ball having a velocity towards the car before impact.

The velocities are set according to the range in which the sensor is active. It activates at 20 km/h and deactivates when reaching 55 km/h.

<table>
<thead>
<tr>
<th>Impactor</th>
<th>$v_{init}$ [km/h]</th>
<th>Mass [kg]</th>
<th>Deploy hood [yes/no]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basketball</td>
<td>20, 55, 80</td>
<td>0.6</td>
<td>No</td>
</tr>
<tr>
<td>Guiding post</td>
<td>20, 55</td>
<td>2.0</td>
<td>No</td>
</tr>
<tr>
<td>PDI-leg</td>
<td>Pl 1</td>
<td>20, 55</td>
<td>9.9</td>
</tr>
<tr>
<td>IEE-Leg</td>
<td>Pl 2</td>
<td>20, 55</td>
<td>6.0</td>
</tr>
<tr>
<td>Lower-Leg</td>
<td>Pl 3</td>
<td>20, 55</td>
<td>13.9</td>
</tr>
</tbody>
</table>

Table 4 – Data of the simulation impactors
4 Results

4.1 Sub-objective 1: Basketball impactor
Results from the drop test of the basketball are presented in table 5 below.

<table>
<thead>
<tr>
<th>#</th>
<th>Rebound height [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>1.380</td>
</tr>
<tr>
<td>Test 2</td>
<td>1.350</td>
</tr>
<tr>
<td>Test 3</td>
<td>1.350</td>
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<tr>
<td>Test 4</td>
<td>1.345</td>
</tr>
<tr>
<td>Test 5</td>
<td>1.345</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td><strong>1.354</strong></td>
</tr>
</tbody>
</table>

Table 5 – Rebound height of the basketball

A mean rebound height of 1.345 m gives 24.8 % energy loss in the bounce.

Different level of damping of the airbag was investigated to find a value equivalent to the energy loss in bounce for the real basketball. An energy loss in bounce of 24.8 % was desired in the simulations. The damping factor also affected the pressure in the airbag and was investigated and presented below.

Note that the scales are flawed for some reason. Picking points on the lines gives exact values.
Graphs over $P$ and $E_{\text{kin}}$ are shown in figure 30 and 31 respectively, with the mass damping factor set to 0.

**Figure 30 - Pressure in the basketball**

Note that the pressure oscillates and is not stable with 0 damping.

**Figure 31 - Kinetic Energy for the basketball**

The kinetic energy loss was about 0% after bounce, with 0 damping in the airbag.
Graphs over $P$ and $E_{\text{kin}}$ are shown in figure 32 and 33 respectively, with the mass damping factor set to 0.5.

**Figure 32 - Pressure in the basketball**

Airbag pressure was affected and became more stable when damping factor was increased. The pressure can be considered completely stable with a damping factor over 0.5.

**Figure 33 - Kinetic Energy for the basketball**

An energy loss of 12.9% was received with a damping factor of 0.5.
Graphs over $P$ and $E_{kin}$ are shown in figure 34 and 35 respectively, with the mass damping factor set to 1.0.

![Figure 34 - Pressure in the basketball](image1)

Pressure in the airbag is considered stable.

![Figure 35 - Kinetic Energy for the basketball](image2)

An energy loss of 29.0% was received with a damping factor of 1 and considered too high.
Graphs over $P$ and $E_{\text{kin}}$ are shown in figure 36 and 37 respectively, with the mass damping factor set to 0.8.

![Figure 36 - Pressure in the basketball](image)

Pressure in the airbag considered stable.

![Figure 37 - Kinetic Energy for the basketball](image)

An energy loss of 25.7% was received with a damping factor of 0.8 and considered too high.
Graphs over $P$ and $E_{kin}$ are shown in figure 38 and 39 respectively, with the mass damping factor set to 0.7.

The pressure in the airbag remained stable with a damping factor of 0.7.

An energy loss of 23.3% was received and was considered a little too low.
Graphs over $P$ and $E_{\text{kin}}$ are shown in figure 40 and 41 respectively, with the mass damping factor set to 0.725.

The sought energy loss of 24.8% was received.
The reaction force of the rigid wall was simulated in LS-Dyna and can be seen in figure 42.

![Figure 42 - Reaction force of the rigid wall](image)

The damping factor was changed to achieve an energy loss in bounce that resembled the real test result in energy loss. This can be seen in table 6.

<table>
<thead>
<tr>
<th>Damping factor</th>
<th>Kinetic Energy after bounce [J]</th>
<th>Energy loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>~10.58</td>
<td>0 %</td>
</tr>
<tr>
<td>0.5</td>
<td>9.22</td>
<td>12.9 %</td>
</tr>
<tr>
<td>1.0</td>
<td>7.51</td>
<td>29.0 %</td>
</tr>
<tr>
<td>0.8</td>
<td>7.86</td>
<td>25.7 %</td>
</tr>
<tr>
<td>0.7</td>
<td>8.11</td>
<td>23.3 %</td>
</tr>
<tr>
<td>0.725</td>
<td>7.96</td>
<td>24.8 %</td>
</tr>
</tbody>
</table>

Table 6 - Kinetic energy and energy loss for the basketball
The FE-models data compared to the real basketball can be seen in table 7.

<table>
<thead>
<tr>
<th></th>
<th>Basketball</th>
<th>FE model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>0.6 [kg]</td>
<td>0.6 [kg]</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.241 [m]</td>
<td>~0.240 [m]</td>
</tr>
<tr>
<td>Pressure</td>
<td>0.8 [bar]</td>
<td>~0.8 [bar]</td>
</tr>
<tr>
<td>Drop height</td>
<td>1.8 [m]</td>
<td>Not measured</td>
</tr>
<tr>
<td>Rebound height</td>
<td>1.354 [m]</td>
<td>Not measured</td>
</tr>
<tr>
<td>Kinetic energy prior to bounce</td>
<td>Not measured</td>
<td>10.58 [J]</td>
</tr>
<tr>
<td>Kinetic energy after bounce</td>
<td>Not measured</td>
<td>7.96 [J]</td>
</tr>
<tr>
<td>Energy loss</td>
<td>24.8 [%]</td>
<td>24.8 [%]</td>
</tr>
</tbody>
</table>

Table 7 – Data for basketball and FE-model

Energy loss in bounce for the FE-model is consistent with the real basketball.

Note the ~-signs on the diameter and pressure of the ball. The values are not constant and therefore the mean value is presented.
4.2 Sub-objective 2: Guiding post impactor

4.2.1 Material data
Material data captured from the tensile tests is presented below.

Bending tests and tensile tests of the white part of the pole provided a Young’s modulus of 700 MPa. This confirmed that the white part also was made of polyethylene. The data from the tensile test with slow strain rate could be plotted as a tensile curve, shown in figure 43.

![Figure 43](image1.png)

**Figure 43 - Engineering stress vs Engineering strain - Strain rate 2 mm/minute**

The tensile test with faster strain rate was plotted as a tensile curve in figure 44.

![Figure 44](image2.png)

**Figure 44 - Engineering stress vs Engineering strain - Strain rate 50 mm/minute**
To obtain the true stress and strain from the engineering data, equation (3.5) was used. To retrieve true strain equation (3.6) was used. The curves were plotted in figure 45 and 46, for the slow and fast strain rate respectively.

Figure 45 - True stress vs True strain - Strain rate 2 mm/minute

Figure 46 - True stress vs True strain - Strain rate 50 mm/minute
To obtain the true plastic strain equation (3.7) was used and plotted as a True stress versus True plastic strain curve in figure 47 at the strain rate of 2 mm/minute.

![Figure 47 - True stress vs True plastic strain - Strain rate 2 mm/minute](image)

The curve for the True stress versus True plastic strain at the strain rate of 50 mm/minute is plotted in figure 48.

![Figure 48 - True stress vs True plastic strain - Strain rate 50 mm/minute](image)
4.2.2 Validation
The results of the different simulation runs and the corresponding real tests are presented below. The red curve represents the data from the accelerometers, whereas the blue curve represents the simulated values. Table 8 describes the different runs. Of the different in-parameters for the material card, only Young’s modulus, $E$, and yield stress, $\sigma_y$, were changed.

<table>
<thead>
<tr>
<th>Run [#]</th>
<th>E [MPa]</th>
<th>$\sigma_y$ offset [MPa]</th>
<th>$v_{ini}$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>700</td>
<td>0</td>
<td>3.82</td>
</tr>
<tr>
<td>2</td>
<td>900</td>
<td>0</td>
<td>3.82</td>
</tr>
<tr>
<td>3</td>
<td>1000</td>
<td>20</td>
<td>3.82</td>
</tr>
<tr>
<td>4</td>
<td>1000</td>
<td>0</td>
<td>3.82</td>
</tr>
<tr>
<td>5</td>
<td>1100</td>
<td>0</td>
<td>3.82</td>
</tr>
<tr>
<td>6</td>
<td>1200</td>
<td>0</td>
<td>3.82</td>
</tr>
</tbody>
</table>

Table 8 – Validation tests for guiding post

All simulations were compared with the data from the accelerometers.
Acceleration, velocity and displacement for run 1 are shown in figure 49.

Figure 49 - Curves obtained from Run 1
Acceleration, velocity and displacement for run 2 are shown in figure 50.
Acceleration, velocity and displacement for run 3 are shown in figure 51.

Figure 51 - Curves obtained from Run 3
Acceleration, velocity and displacement for run 4 are shown in figure 52.

Figure 52 - Curves obtained from Run 4
Acceleration, velocity and displacement for run 5 are shown in figure 53.

Figure S3 - Curves obtained from Run 5
Acceleration, velocity and displacement for run 6 are shown in figure 54.

![Curves obtained from Run 6](image)
The six different runs were compared to each other and to the curves from the real tests.

<table>
<thead>
<tr>
<th>Run [#]</th>
<th>E [MPa]</th>
<th>σ_y offset [MPa]</th>
<th>v_{ini} [m/s]</th>
<th>α_{max} [m/s^2]</th>
<th>u_{max} [mm]</th>
<th>Corresponds to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>4.56</td>
<td>151.0</td>
<td>125.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R2</td>
<td>3.82</td>
<td>138.4</td>
<td>96.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R3</td>
<td>3.06</td>
<td>107.9</td>
<td>79.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>700</td>
<td>0</td>
<td>3.82</td>
<td>107.7</td>
<td>119.1</td>
<td>R2</td>
</tr>
<tr>
<td>2</td>
<td>900</td>
<td>0</td>
<td>3.82</td>
<td>127.6</td>
<td>97.8</td>
<td>R2</td>
</tr>
<tr>
<td>3</td>
<td>1 000</td>
<td>20</td>
<td>3.82</td>
<td>129.8</td>
<td>91.9</td>
<td>R2</td>
</tr>
<tr>
<td>4</td>
<td>1 000</td>
<td>0</td>
<td>3.82</td>
<td>118.8</td>
<td>92.3</td>
<td>R2</td>
</tr>
<tr>
<td>5</td>
<td>1 100</td>
<td>0</td>
<td>3.82</td>
<td>132.6</td>
<td>88.4</td>
<td>R2</td>
</tr>
<tr>
<td>6</td>
<td>1 200</td>
<td>0</td>
<td>3.82</td>
<td>138.3</td>
<td>84.5</td>
<td>R2</td>
</tr>
</tbody>
</table>

Table 9 – Data from the test of the guiding post and from the simulation of the FE-model

Table 9 shows that the different values of the Young’s modulus give different values in the $\alpha_{max}$ (max acceleration) and $u_{max}$ (max displacement). High values of Young’s modulus, set higher values of max acceleration and lower values of max displacement.

Young’s modulus of 1 200 MPa for the FE-model presents a value for $\alpha_{max}$ that is very close to the value given from the tests but also presents a low value for the $u_{max}$. 
In order to change $\sigma_y$ for the plastic material, the true stress vs. true strain has to be modified. Changes of the ordinate and abscissa values can be seen in figure 55. The load curve of values from the tensile test are scaled and offset by:

- Abscissa value = Factor X * (Defined value + Offset X)
- Ordinate value = Factor Y * (Defined value + Offset Y)

![Figure 55 - Changes of the abscissa and ordinate values](image)

The red solid line describes the displacement of the impactor colliding with the post. The blue line is the FE-model with no change in the abscissa or ordinate values. The Factor X is increased in the drawn green curve and the Factor Y is increased in the pink curve.

From here onwards, no changes have been made in the abscissa or ordinate values.

Run 4, 5 and 6 provided best results and will be further evaluated.
Filtered data from the accelerometers as well as the simulated results from run 4, 5 and 6, can be seen in figure 56. The filter used is a standard filter (SAE 180).

The acceleration curves of the simulations with three different Young's modulus are very close to the real test. To evaluate the results further the simulations were compared with the real test with greater accuracy.
The most interesting part of the graph is from where the impact occurs until the highest acceleration value is reached. This area is marked with a red box in figure 57 and will be examined more in the next three graphs. The initial velocity in test R2 was set to 3.82 m/s.

Figure 57 - Overview of the whole acceleration curves corresponding to test R2

The acceleration curve in the red box from figure 57 can be seen in figure 58 in a more detailed view.

Figure 58 - Acceleration curves corresponding to test R2
Figure 59 shows the velocity curves for Run 4, 5 and 6 compared to test R2. The curve from Run 6 follows the accelerometer values very well.

![Figure 59 - Velocity curves corresponding to test R2](image)

The displacement curves at the highest acceleration for test R2 are shown in figure 60.

![Figure 60 - Displacement curves at highest acceleration values corresponding to R2](image)
Run 7, 8 and 9 are compared to the impact test with the velocity of 4.56 m/s, called test R1. The acceleration curves for the impact test and the simulations can be seen in figure 61.

![Figure 61 - Overview of the whole acceleration curves corresponding to test R1](image1)

A view with a more detailed plot of acceleration from the red box in figure 61 is shown in figure 62.

![Figure 62 - Acceleration curves corresponding to test R1](image2)
The velocity curves for Run 7, 8 and 9 compared to test R1 are shown in figure 63.

![Figure 63 - Velocity curves corresponding to test R1](image)

The displacement curves at the highest acceleration values from figure 63 are show in figure 64.

![Figure 64 - Displacement curves at highest acceleration values corresponding to R1](image)
Run 10, 11 and 12 are compared to the impact test with the velocity of 3.06 m/s, called test R3. The acceleration curves for the impact test and the simulations can be seen in figure 65.

Figure 65 - Overview of the whole acceleration curves corresponding to test R1

Figure 66 shows a more detailed plot of the acceleration from the view of red box in figure 65.

Figure 66 - Acceleration curves corresponding to test R3
The velocity curves for Run 10, 11 and 12 compared to test R3 and are shown in figure 67.

![Figure 67 - Velocity curves corresponding to test R3](image)

The displacement curves at the highest accelerometer value from figure 67 are shown in figure 68.

![Figure 68 - Displacement curves at highest acceleration values corresponding to R3](image)
A summary of the graphs is presented in Table 10.

| Run [#] | E  [MPa] | $\nu_{ini}$ [m/s] | $|a_{real} - a_{run}|$ [m/s²] | $|v_{real} - v_{run}|$ [m/s] | $|u_{real} - u_{run}|$ [mm] | Corresponds to test |
|---------|----------|-------------------|-------------------------------|-------------------------------|-----------------------------|------------------|
| 4       | 1 000    | 3.82              | 19.6                          | 0.12                          | 0.32                        | R2               |
| 5       | 1 100    | 3.82              | 5.8                           | 0.06                          | 0.12                        | R2               |
| 6       | 1 200    | 3.82              | 0.1                           | 0                             | 0.1                         | R2               |
| 7       | 1 000    | 4.56              | 3.5                           | 0.04                          | 0.05                        | R1               |
| 8       | 1 100    | 4.56              | 5                             | 0.04                          | 0.2                         | R1               |
| 9       | 1 200    | 4.56              | 11.2                          | 0.11                          | 0.9                         | R1               |
| 10      | 1 000    | 3.06              | 1.18                          | 0.03                          | 0.1                         | R3               |
| 11      | 1 100    | 3.06              | 4.25                          | 0.05                          | 0.31                        | R3               |
| 12      | 1 200    | 3.06              | 8.33                          | 0.1                           | 0.51                        | R3               |

Table 10 – Comparisons between test runs and simulations

The runs with a Young’s modulus of 1 000 MPa, run 7 and 10, are most similar to the real tests R1 and R3 respectively. In the simulations corresponding to R2, run 6 with a Young’s modulus of 1 200 MPa resembles the real test the most.

The final FE-model data compared to the guiding post can be seen in table 11.

<table>
<thead>
<tr>
<th></th>
<th>Guiding post</th>
<th>FE model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>2.0 [kg]</td>
<td>2.0 [kg]</td>
</tr>
<tr>
<td>Outer diameter - white part</td>
<td>0.105 [m]</td>
<td>0.105 [m]</td>
</tr>
<tr>
<td>Outer diameter - black part</td>
<td>0.112 [m]</td>
<td>0.112 [m]</td>
</tr>
<tr>
<td>Length</td>
<td>1.6 [m]</td>
<td>1.6 [m]</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>~0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>700 [MPa]</td>
<td>1200 [MPa]</td>
</tr>
<tr>
<td>Density</td>
<td>0.917-0.965 [g/cm³]</td>
<td>0.858 [g/cm³]</td>
</tr>
</tbody>
</table>

Table 11 – Data for guiding post and FE-model
4.3 Sub-objective 3: Small animal impactor

No results were acquired, neither from material tests nor correlation tests.
4.4 Sub-objective 4: Pedestrian sensing

The results from the different impactors can be seen in figure 69-71 below. Figure 69 shows the pedestrian impactors at 20 km/h and the misuse objects at all speeds. Note that the reaction from the guiding post at 55 km/h exceeds the reactions from the pedestrian impactors.

Figure 69 – The effect on the sensor from the different impactors

Figure 70 shows the reactions from the pedestrian impactors and misuse impactors, all at 20 km/h. The reaction from the basketball is however also shown at 55 and 80 km/h. Note that all reactions from the misuse impactors are lower than the ones from the pedestrian impactors.

Figure 70 – The effect on the sensor from the different impactors at 20 km/h
Figure 71 shows the reactions from the pedestrian impactors and misuse impactors, all at 55 km/h. The reaction from the basketball is also shown at 80 km/h. Note that all reactions from the misuse impactors are lower than the ones from pedestrian impactors. Moreover, the reactions from the basketball at 55 km/h are very low and could be neglected.
5 Discussion and conclusion

5.1 Sub-objective 1: Basketball
Complications started when obtaining material properties for the different materials used in the ball. The idea was to perform a tensile test on each of the different layers. This was, however, not possible since the materials were glued and compressed together. A tensile test was still performed, but it was for all three layers simultaneously and the data could hopefully be used to model the three layers as one.

As the modeling work progressed it was concluded that it was not possible to use one layer to represent all. Two different material models were used in the struggle towards a stable model, MAT_MOONEY-RIVLIN_RUBBER and MAT_FABRIC. The pressure was represented by an AIRBAG_SIMPLE_PRESSURE_VOLUME which basically created a pressure inside a defined part or part set.

The rubber model was used in the first revisions of the basketball, but was found to stretch due to the pressure, before exploding. No stable model could be found using this material model.

Thus, the trial with the fabric material model began which uses membrane elements and does not take compressive stresses in consideration. This material model was found to have great properties in terms of stretch. However, it pulsates heavily which no damping seemed to be able to compensate for.

The conclusion was to combine the two material models. A new material study was performed in order to obtain the material used, and material specialists were asked for properties which eventually led to getting Shore values on the two rubber layers. Shore is a measurement of hardness for rubber and plastic materials, performed in a durometer. The measurement method is to push a cone or sphere onto the material surface, with a specific force, and measure the deformation.

The material properties of the reinforcement, and the modeling of the same, did not have any reference to reality, other than the estimated thickness of the layer. The reinforcement had one purpose, which was to prevent stretching.

A new revision of the ball was modeled. The new ball had three layers: Rubber-Fabric-Rubber. All layers with their specific material properties and dimensions. Pressure was applied to the rubber bladder which was supposed to stretch and create a pressure onto the reinforcement layer.

However, this was not the outcome of the simulations. The bladder grew through the other layers and exploded within the first iteration. The velocity of the elements in the normal direction was probably too high, making the contact definition obsolete. The time steps were significantly lowered, the diameter of the bladder was both in- and decreased, but the contact definition would still not work.
A lot of work was put into solving this problem, but with no success. The conclusion was to model the three layers with shared nodes, in order to make it impossible for one layer to move unless the others do as well. The first stable revision of the ball was modeled.

The ball was still pulsating and a lot of time, more than 300 ms, was needed until it was in equilibrium. In an effort to decrease the time a ramped curve defining pressure over time, was used to slowly increase the pressure up to 0.8 bar. This provided a significant improvement, but not fully satisfying.

An initial dynamic relaxation phase was introduced in which the pressure was applied with a ramped curve. The dynamic relaxation phase did not take displacements, velocities or boundary conditions in concern. This phase focused on body applied loads, in this case: pressure. It allowed LS-Dyna to obtain the initial stress and displacements before the first iteration.

The ball was now behaving as wanted, although some pulsating was still present as can be seen in figure 30. This was, however, nothing compared to the prior models and was neglected. Increasing the pressure with a slower rate could perhaps have provided an even more stable model. At the same time, it would have been more time consuming to analyze and therefore not worth pursuing.

The work with validating our model, and brainstorming how to validate it began. The simplest thinkable way was a drop test, where the ball is dropped from a certain height and the rebound height is measured. This was performed, as can be read in 3.1.1. The measuring equipment available was a high speed camera and a checkered wall. The height of the camera was set to the estimated rebound height, to neglect the influence of the angle, see appendix, figure 72.

Other sources of error are the hand dropping the ball, and the fact that the ball is not homogeneous. Setting up the camera and checking pressure before each test was time-consuming. This, together with some tests with faulty bounces, provided five test results remaining for comparison. Five are too few to provide statistically significant results, but enough to provide some understanding of the rebound height.

Setting up a simulation of the same tests provided a series of difficulties, mainly of the terms of LS-Dyna. LS-Dyna is an explicit solver, which makes it very dependent on the length of the simulation time. There is no Newton-Raphson iteration to enforce equilibrium of the internal structure forces with the externally applied loads. It is therefore important that the time steps are small enough to acquire accurate results. Bearing this in mind, the simulation was set up in a fashion so that the simulation time was as short as possible. The ball was placed just above the rigid wall and the kinetic energy after impact was measured, instead of the potential energy as in the real test.

LS-Dyna does not have a general energy dissipation, which enforces the user to specify where the energy should be lost. The energy loss in the bounce is probably the heat generation, due to the hysteresis in the rubber, and thusly the point of interest when modeling. According to LS-Dyna support, the hysteresis work is best captured by setting a damping factor in the Airbag card. This factor was the only factor changed until a satisfactory result was achieved.
5.2 Sub-objective 2: Guiding post

The material model MAT_PIECEWISE_LINEAR_PLASTICITY depicts the properties of polyethylene and other plastic materials in LS-Dyna. In order to describe the material in LS-Dyna, data from the tensile test of two different strain rates was demanded, as well as Young’s modulus, Poisson’s ratio and the density of the material.

Six different tensile tests were performed to investigate the material properties. This was done to investigate if any of the tests differed from the others, and to deny eventual local properties causing misleading results.

Changing Poisson’s ratio for polyethylene did not have any major impact on the FE-model and was therefore set to 0.35 according to Per Hässelgren (Material Engineer at Saab Automobile AB).

The density of the material model was changed so that the weight of the FE-model was consistent with the weight and inertia of the guiding post. The density has no reference to polyethylene in reality.

The data collected from the tensile tests described the material properties for engineering stress versus engineering plastic strain in two different strain rates. These values had to be recalculated according to the equations in chapter 3.2.

Different types of tests to examine how the guiding post reacts to an impact were discussed. A collision between a solid, linear impactor and a fixed guiding post was assigned to be the best way to compare the FE-model to the guiding post. The values from the accelerometers on the impactor described the impact and could be contrasted with the result from the simulation.

The impact tests were compared to the simulations in order to evaluate the FE-model. Curves of acceleration, velocity and displacement were reviewed. The fluctuations of the acceleration curves for the guiding post could be filtered with SAE 180 in Hyperworks. Using higher filtration it was considered that too much information was lost and with lower filtration the curves were difficult to verify.

As previously mentioned, the properties with most effect on the results were Young’s modulus and yield stress. In- and decreasing true stress vs. true strain did however also effect the results.

The new curves could be increased or decreased by a factor or and offset value in LS-Dyna.

- Abscissa value = Factor X * (Defined value + Offset X)
- Ordinate value = Factor Y * (Defined value + Offset Y)

In order to investigate how the scale and offset of the abscissa and ordinate values affected the material properties, three different tests were performed. Two tests with increased factors X and Y, and one with increased offset Y. These tests were compared to the curves of the real guiding post and to a FE-model with no changes in the abscissa or ordinate values.
Increasing Factor X made the material softer, which made the FE-model bend more by the impact. The ordinate value was increased when the Factor Y was raised. This made the material harder and the displacement curve was lower than the displacement curve of the real guiding post. Changes of the abscissa value led to changes of the x-axis (strain rate), and modification of the ordinate value led to changes of the y-axis (stress rate).

If the acceleration, velocity and displacement curves for the FE-model were compared to the curves for the real guiding post, the best results were achieved as long as the Factors and the Offsets were not changed.

The Young’s modulus for polyethylene usually is between 700 and 1 000 MPa. These values were tried first, but the FE-model appeared a little bit too soft. Simulations of higher values for the Young’s modulus were tested, and seemed to conform better. The most conform and interesting values for Young’s modulus were between 1 000 and 1 200 MPa.

For the final revision of the guiding post, a Young’s modulus 1 200 MPa was chosen. Several tests at a constant velocity would have provided more data to support the decision. With the data in hand, the choice was to chose the hardest guiding post, as the data suggested this to be the worst case scenario in future simulations.

There was insecurity whether the results of the guiding posts were influenced of any unknown factors since we did not perform several impact tests for every velocity. Material defects such as undetected scratches and varying thickness, may have influenced the final results. This may be a reason for the value of Young’s modulus to present different results at different velocities.
5.3 Sub-objective 3: Small animal
The first idea was to manufacture our own impactor from scratch. A study was performed upon already existing variants and one was chosen to be a reference. It can be seen in appendix, figure 74, and is simply a leather bag filled with small pieces of rubber and a core of steel grit, according to the coalition. However, Saab Automobile’s current circumstances prohibited us from purchasing and acquiring the materials needed.

By the end of this thesis a new impactor was found. It was a small animal impactor already manufactured by Saab Automobile which can be seen in chapter 3.3. With the limited amount of time that was left it was modeled in FE with the appropriate material cards, which was acquired after some research.

The brainstorming began of how to validate the model. The easiest way would be to use the same impactor utilized for the guiding post, since this was already manufactured. During the thesis a test was performed where a car hit the small animal impactor. The same rig used then could be used in this test. The only problem would be the high mass of the impactor relative to the small animal.

Another way would be to apply a pendulum together with that rig. The mass of the impactor in the pendulum is much lower, and it is easier to set exact velocities for the impact.

However, there was no time to perform a correlation test since all testing equipment was occupied by other tests, and the test engineers had more pressing matters to attend to.

An FE model of the simulation that could be used for both methods was, however, set up. The only thing which differs is, as previously mentioned, the mass. The impact during the time span could in both cases be considered linear.

Due to this fact, there is neither material data nor correlating data for this impactor. The material models used for the impactor are therefore the best guess and could possibly be wrong.
5.4 Sub-objective 4: Pedestrian sensing
In consideration of the situation at Saab Automobile AB a new sub-objective was developed. The new sub-objective was to launch the different impactors against a mule and monitor the reactions of the sensor modeled.

There was no time to correlate the data from the FE simulations and the real tests, which was not one of the aims of this Master Thesis.

The different pedestrian impactors had already been modeled and the only thing that needed to be done was setting the correct height and initial velocity towards the car.

The basketball and guiding post were more difficult. First of all, everything has numbers; nodes, elements, parts, sets, contacts, materials and so on. The first thing to do was to renumber and reorder all of these numbers to prevent them from interfering with the numbers on the mule. Saab Automobile AB has general rules when numbering different objects and parts, i.e. which number range certain items should have. The impactors made in this thesis should now be “Saab-friendly” in that sense.

The basketball was easy to set up, after the renumbering. It was placed in the correct height i.e. the center of mass was placed in the same height as the sensor.

The guiding post needed further boundary conditions since it should be mounted into the ground, whereas the other impactors were in free flight. One way to perform this would have been to use the same boundary conditions as in the simulations of the validating test, giving the car an initial velocity. However, there are so many different parts on the mule, which made it easier to set a velocity on the guiding post.

A boundary condition, BOUNDARY_PRESCRIBED_MOTION, with constant velocity was set on the mounting of the guiding post. This was done to represent the bottom of the post being installed in the ground and the vehicle driving forward without losing velocity in impact.

To eliminate the effects of accelerating the post due to the boundary condition set on the mounting, an initial velocity was set on the guiding post.

According to the results of the simulations it is impossible to distinguish a pedestrian from the misuse objects without taking the current velocity in concern. If the velocity is calculated from the wheel speed sensor and used for calculating new trigger values, it should be possible to trigger only for pedestrians.
5.5 Remaining work
As previously mentioned in this thesis, validating and material tests are needed for the small animal as well as finishing the FE model with correct material data and if needed other material models.

A correlation of the mule sensor and the real one is needed; this has, however, never been intended in this thesis. FE simulations should be performed with the new revision of sensor for the misuse and pedestrian impactors.
7 References


8 Appendix

Figure 72 - Angel of spectator

Figure 73 - Picture sequence from validating test
Figure 74 - Small animal reference