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Airbag triggering in a numerical vehicle fleet

development of an airbag algorithm

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Samenvatting

In de huidige numerieke voertuigmodellen wordt gebruikt gemaakt van airbags met een vaste triggertijd onafhankelijk van het soort botsing waar de auto in terechtkomt. In de praktijk hangt een juiste airbagtriggering echter af van het botsscenario (bijvoorbeeld auto tegen auto, auto tegen boom). De timing is van essentieel belang voor het correct werken van een airbag.
Het doel van deze studie is om een realistisch besluitvormingsalgoritme op te stellen voor airbagtriggering in numerieke (Multi-Body of generiek) automodellen waarin variaties van botsparameters en frontale stijfheden zijn opgenomen.
Aan de hand van een literatuurstudie is een algoritme dat gebaseerd is op een massa-demper model (Watanabe [10]) gekozen. In dit algoritme wordt aan de hand van de verplaatsing van de dummy de timing van de airbag bepaald. Dit algoritme is in Matlab/Simulink gemodelleerd en vervolgens aan de hand van USNCAP en EuroNCAP crash test data geëvalueerd.
De gevoeligheid van het algoritme is met behulp van een parameterstudie onderzocht. Uit deze analyse is gebleken dat de airbagtriggering zo goed als onafhankelijk is van de frontale voertuigstijfheid, maar dat de initiële snelheid grote invloed heeft. Verder is gebleken dat het van essentieel belang is om de verplaatsing van de dummy totdat deze in contact komt met een volledig opgeblazen airbag te bepalen. Om dit vraagstuk op te lossen is een stochastische studie uitgevoerd zodat voor elk voertuigmodel en dummygrootte de verplaatsing van de dummy tot aan de volledig opgeblazen airbag te bepalen. De resultaten van deze studie tonen aan dat voor elk voertuigmodel en dummygrootte het letsel op een gelijk niveau blijft in een bepaald tijdsbereik van airbagtriggering. Aan de hand van deze resultaten is het is nu mogelijk om de juiste dummyverplaatsing te bepalen. Aan de hand van deze waarde is het nu mogelijk om voor een willekeurig botsscenario de airbagtriggering te bepalen.
Na implementatie van het algoritme is gebleken dat voor elk scenario de airbag nu op het juiste moment opgeblazen wordt. Het variëren van de frontale stijfheid heeft bij auto tegen auto botsingen meer invloed op de airbag triggertijd, afhankelijk van het scenario, dan bij auto tegen barrière botsingen. Bij verschillende initiële snelheden is het nut van het algoritme ook zichtbaar: bij hogere snelheden moet de airbag eerder opgeblazen worden.
Het in deze studie geanalyseerde algoritme is in staat voor de hele range aan scenario's de meest optimale airbagtriggering te bepalen.

Summary

In current numerical (Multi-Body or generic) vehicle models a fixed airbag firing time is used, independent of the collision type. However, the timing depends on the crash scenario (e.g. different front-end stiffness or impact speeds) in real-life.

The objective of this study is to develop an airbag triggering algorithm with a crash (primary focus) and occupant (secondary focus) dependent airbag firing time in a numerical vehicle fleet (Multi-Body or generic). To solve this problem a number of tools are needed. The literature survey provided an algorithm concept based on a simple mass-damper model, and together with a Simulink scheme and a numerical vehicle fleet a judgement (based on vehicle acceleration and dummy movement) for determining the airbag firing time is developed. USNCAP and EuroNCAP data are used to evaluate the judgement. The USNCAP data is used for validating the b-pillar and head linear acceleration signal of the numerical vehicle model with the acceleration signal from the full-scale test. The EuroNCAP data is used as a check of the deployment phase of the airbag in the numerical vehicle models and the dummy movement until it touches the airbag.

To investigate the sensitivity and the influence of a number of parameters (dummy size, front-end stiffness, initial velocity and boundary conditions judgement) of the algorithm a parametric and stochastic study is performed.

The results of the parametric study indicate that a change in front-end stiffness does not have a major influence on the airbag firing time. However, a change in the initial velocity results in no required airbag use at low speeds to a very early firing of the airbag for high speeds. The most important and crucial parameter in the algorithm judgement for determining the airbag firing time is the dummy movement. A further investigation is required to determine the correct value for the dummy movement. Therefore a stochastic study is performed to determine the correct value for the dummy movement for every vehicle model and dummy size. This study pointed out that in a certain airbag firing time range the injuries remain at the same level for *the VC-COMPAT* vehicle models with different occupant sizes. As a result the allowable dummy movement (boundary condition in the judgement) is determined for every vehicle model and dummy size.

Implementation of the algorithm in car to car scenarios lead to an increase of airbag firing times in all configurations. In most cases the level of injuries did not dramatically change. The influence of a variation in front-end stiffness on the airbag firing time depends on the type of car-to-car configuration. Another major influence of the airbag firing time is the initial velocity in car-to-car scenarios.

As a result the airbag algorithm developed in this study is able to predict the airbag firing time for different crash scenarios.

Contents

1 Introduction

The evidence of studies conducted over the last 20 years clearly indicate that solving the problems of incompatibility between vehicles is one of the most efficient ways to reduce the number of road accident victims. New regulations that came into force at the end of 1998, as well as various ratings and customer tests, lead to a similar level of safety for all vehicles in a frontal impact. Even so, this performance in no way guarantees compatibility in the case of collision between vehicles [1].
In past TNO research programmes (e.g. EC framework 4) elaborate modelling work was done to gain insight in the problem of car-to-car compatibility. One of the main findings was that the problem of compatibility is very complex, because many factors are interrelated and are sometimes difficult to distinguish from each other. However, the research programme did highlight that in order to achieve compatibility in frontal impact, good structural interaction (geometrical compatibility) is an essential prerequisite followed by some form of stiffness matching to ensure that the impact energy is absorbed without exceeding the strength of the occupant compartment. For side impact, again it was found that good structural interaction was necessary. However, this should be achieved without compromising the intrusion profile or causing any unnecessary delay in the occupant’s acceleration. Therefore, it is still necessary to gain better insight in the problem of compatibility.
In March 2003 a new European project called *VC-COMPAT* (Vehicle Crash COMPATibility) started. The aim of this project is to develop a suite of crash test procedures, which once implemented in legislative and/or consumer testing will lead to an improvement in vehicle crash compatibility. In essence, compatibility will ensure that the smaller vehicle is not overwhelmed by the larger vehicle in typical crashes resulting in enhanced safety for all vehicles on our roads. The main aim for TNO in this project is to investigate possible methodologies how the Multi-Body vehicle models developed in earlier projects can be applied for improving car-to-car compatibility for the whole vehicle fleet. Methods that will be used are straightforward parameter studies, the more sophisticated Design of Experiments methodology (DOE) and numerical optimisations [2].

1.1 Definition of the problem

In current numerical vehicle models a fixed time for airbag triggering is used, independent of collision type. However, in real-life the airbag firing time depends on the crash scenario (e.g. car to a rigid object or car to car, or different impact speeds). In order to have full benefit of an airbag, the correct deployment time of the airbag is crucial for the level of injuries of the occupant. Other parameters such as mass flow and sheet thickness of the airbag also influence the characteristics of the airbag deployment. However, in this study the main focus is on the airbag firing time.

1.2 Objective

Development of a realistic algorithm for triggering airbags in numerical (Multi-Body or generic) vehicle models, depending on collision parameters and front-end stiffness.

1.3 Approach

The Multi-Body vehicle models that are used in the *VC-COMPAT* project have a fixed airbag deployment time. In a previous study (Bronckers [3]) it could be seen that in a number of scenarios the airbag is not deployed at the correct time. In order to gain more information about the triggering of airbags, the problem is splits up in several steps. First of all a literature survey is performed in order to gather information of existing airbag algorithm concepts and the main aspects of airbag systems. The results of the literature study are used in order to develop and algorithm concept. This concept will be validated using crash test data from EuroNCAP and USNCAP. Before implementing the algorithm in a numerical vehicle model, different numerical vehicle models (e.g. Multi-Body) are analysed for using the algorithm. The next step is implementing the algorithm and performing a large number of simulations to investigate the capabilities of the algorithm. The results of this study will be presented in this report.

2 Literature survey

A seatbelt is not capable to prevent an occupant hitting the steering wheel or the instrument panel with head and body in collisions with solid objects at speeds of over 40 km/h due to belt slack, belt stretch and the delayed effect of the belt retractor ("film-reel effect"). This results in high injury levels. To avoid hitting the steering wheel and instrument panel and reducing the level of injuries, airbag systems are developed. In order to deploy the airbag or not, the system must have the ability to detect the severity of an impact in a timely manner [4]. Keywords for this system are crash sensing, crash severity, impact speed and airbag triggering.

2.1 Airbag systems

The function of an airbag is to protect the driver against head and chest injuries in a vehicle impact with a solid obstacle at speeds up to 60 *km/h.* In a frontal impact between two vehicles, the front airbags afford protection at relative speeds (= closing speeds) of up to 100 *km/h*. In order to fulfil this function, depending on the installation location, vehicle type and structural deformation response, airbags have different filling capacities and pressure build-up sequences adapted to the specific vehicle condition [5].

2.1.1 Operating concept

To protect an occupant, a gas inflator inflates an airbag in a pyrotechnical, highly dynamic fashion after a vehicle impact is detected by sensors. In order to have maximum protection, the airbag must be fully inflated before the occupant has contact with it. The airbag then responds to upper-body contact with partial deflation in a response pattern calculated to combine "gentle" impact-energy absorption with non-critical (in terms of injury) surface pressures and deceleration forces for the occupant. This concept significantly reduces or even prevents head and chest injuries.

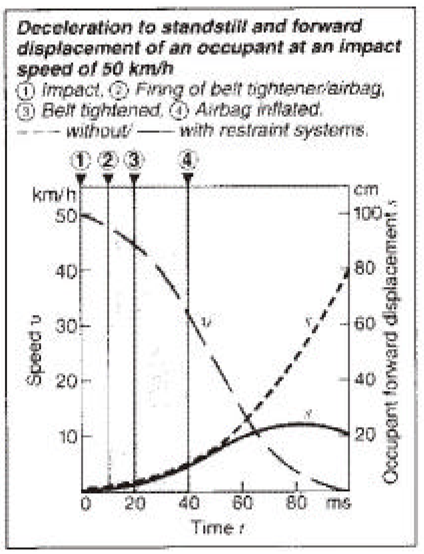


Figure 2.1 – Movement occupant [5]

There are some guidelines that can be used for determining the amount of maximum permissible forward displacement of a driver before the driver's airbag is fully inflated. One of the guidelines that can be used is that a dummy can move 0.125 *m* before the airbag is fully expanded, this corresponds to a period of approximately 0.010 + 0.030 *s* = 0.040 *s* after the initial contact (at 50 *km/h* with a solid obstacle), see figure 2.1. It needs 0.010 *s* for electronic firing to take place and 0.030 *s* for the airbag to inflate. In a 50 *km/h* crash, it takes approximately 0.040 *s* to inflate an airbag and a further 0.080 to 0.100 *s* to deflate through the deflation holes. This will change for every type of impact [5].

2.1.2 Components airbag system

An airbag system contains several components and can be divided into four main components (figure 2.2). Every component and its function will be discussed, in operation order, briefly [5].

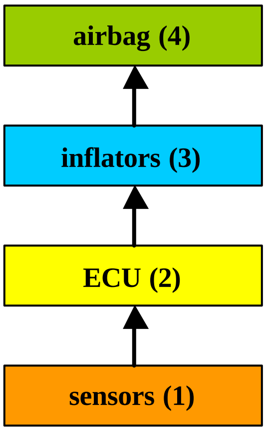


Figure 2.2 – Main components airbag system

(1) Sensors: the sensors detect the type of impact (frontal, offset oblique or pole) and send their signal to the electronic control unit (ECU). They are placed on several locations in the vehicle, because there is no known theory that allows an engineer to develop an algorithm for sensing crashes and selectively deploying the airbag except when the sensor is located in the crush zone of the vehicle. There is also insufficient information within the acceleration signal measured in the passenger compartment to sense all crashes [5],[6],[7].

(2) ECU: the electronic control unit (ECU) uses several triggering thresholds (depending on crash scenario, impact, belt usage and seat occupation) to analyse the data from the sensors to judge whether or not the airbag should be deployed. The ECU must also detect false-negative effects, e.g. driving over a kerbstone must not trigger an airbag [5].

(3) Inflators: one or more pyrotechnical inflators are used to inflate the airbag with (mainly) nitrogen. Using multiple inflators will improve the effectiveness of the airbag for out-of-position (OOP) occupants and large and heavy occupants [5].

(4) Airbag: the airbag is inflated to a certain volume (35 to 70 *l* for a driver's airbag, 70 to 150 *l* for a passenger airbag) and deflates through several vent holes. It is inflated in approximately 0.030 *s* (depending on size of airbag) after firing.

Using "intelligent airbag systems" improves the sensing functions and control options for the airbag inflation process. Such improvement functions are [5]:

- Impact severity detection through improvement of triggering algorithm
- Seat belt usage detection
- Occupant presence, position and weight
- Seat position and back rest inclination detection
- Introduction of up to ten and more different triggering thresholds
- "Depowered" airbag: it uses reduced gas inflator power, which leads to a reduced inflation speed, inflation severity and risk to OOP occupants

2.2 Airbag algorithms

One can think of two extreme scenarios to deploy an airbag. One scenario is that at the end of a crash all the information from the sensor(s) is collected and then it is possible to determine if the impact was severe enough to require deployment of the airbag. However, such a strategy is far from optimal since the airbag is deployed when the impact is over. The opposite extreme is to deploy right at the beginning of the impact. In this case the airbag will be effective in protecting the occupant, if the crash was severe, but since no information on the severity of the impact is available, the airbag will deploy in all crashes even when it is not needed. This suggests that the airbag should not be deployed too early in order to collect enough information from the sensors to establish, with some level of accuracy, if it is needed or not. And at the same time the deployment should not occur too late in the crash event in order to make the airbag system to perform effectively. One of the factors involved in tuning of an airbag system is the determination of an optimal time of deployment that balances the two requirements outlined above [4],[8].

2.2.1 Characteristics of algorithms

There are some difficulties involved in developing a straightforward triggering algorithm:

- The fact that an airbag system must be set for a variety of vehicles and the existence of the delay time of the airbag operation, i.e. the time between the firing time and the time to finish full expansion of the airbag.
- The driver's body must arrive at the surface of the airbag at the time when the expansion is completed otherwise the airbag cannot exhibit the effect. Thus it must be triggered by predicting when the driver's body arrives at the position of the surface of the expanded airbag [9],[10].

Most frontal airbag systems are deployed when a sensor detects a change in velocity (16 *km/h*) within a certain time interval. However, to the diversity of crash conditions in the real world and the manufacturing tolerances of sensors, the deployment threshold will not be precisely fixed at 16 *km/h* or any other designated value. Other criteria for deploying airbags:

- Rule of 5" minus 30 *ms* (5" (= 0.127 *m*): distance between driver & steering wheel; 30 *ms*: time to inflate airbag) $\rightarrow$ 1st order approximation: x inches – y *ms* [11].
- OPC (Occupant Performance Criterion): one can use the values of FMVSS regulation 208 as a preliminary guideline in the design process: the proper timing is

determined by comparing the maximum occupant movement to the total occupant travel. If the maximum movement exceeds the total occupant travel, it implies that the movement is excessive and the restraint timing is not proper. To avoid such an unsatisfactory condition, the force exerted by the airbag must be higher or the bag will need to deploy earlier [11].

A crash can be sensed by looking at the change of speed or the amount of deformation, in other words [11],[12]:

- Speed dependent sensing: the speed measured is depending from the sensor location. Most of the time multiple sensor locations are needed.
- Crush dependent sensing: it assumes that the measurements of crush or damage can be predictive of collision severity for restraint deployment purposes. In order to recognise the pattern of deformation in time to activate the airbag or restraint system, one or more sensors are mounted in the crush zone.

2.2.2 *Algorithms concepts*

Most car manufacturers and OEM suppliers keep their airbag algorithms strictly confidential. Only a main theme or feature is provided with an approach (see appendix A). As a result the literature survey lead to only three algorithm concepts.

2.2.2.1 *Optimal timing to trigger an airbag*

In the algorithm for optimal timing of airbag triggering [10] the driver's body is watched upon collision rather than the crashing car. The driver's body upon collision is modelled as one mass and so far as the acceleration is observed, the amount of mass can be cancelled by using the equation of motion. This fact means that the algorithm can be independent to the weight of the driver, which can provide a general algorithm. Figure 2.3 and 2.4 give a physical model of the driver's motion. A one-mass model is used to indicate the mass of the upper part of the driver's body, which moves upon collision. The spring indicates the stiffness of the seatbelt when belted or the stiffness due to driver's reaction force and the damper indicates the damping characteristics of the motion.

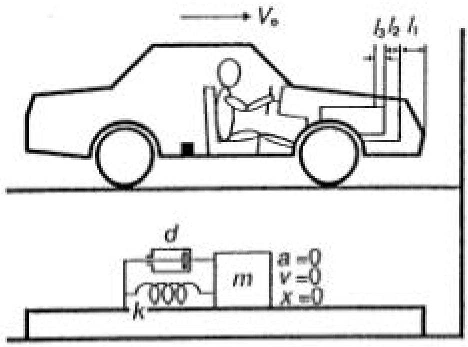


Figure 2.3 - Before collision [10]

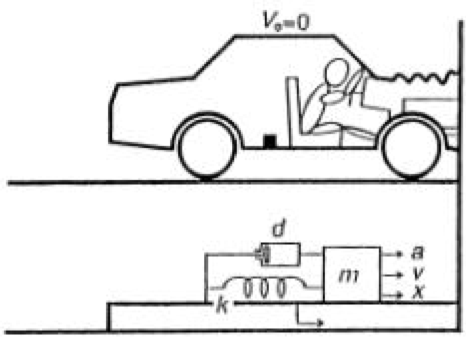


Figure 2.4 – After collision [10]

The general equation of motion for the driver's body is:

$$\frac{d\mathbf{x}_x(t)}{dt} = \mathbf{A}_x\mathbf{x}_x(t) + \mathbf{b}_x a(t) \tag{2.1}$$

Table 2.1 Variables for algorithm

Variables and constants for the system shown in figure 2.3 and 2.4	
t	time
t_t	delay time of airbag
a(t)	absolute acceleration of driver's motion
$\dot{a}(t)$	time derivative of a(t)
$a_m(t)$	measured acceleration (car)
v(t)	relative velocity of driver's motion from the seat
V_0	absolute velocity of the car just before collision
x(t)	relative displacement of driver's motion from the seat
$n_a(t)$	measurement of the noise of acceleration
R_a	variance of the noise $n_a(t)$
q_a	acceleration of vehicle
$q_{\dot{a}}$	derivative of acceleration (=jerk) of vehicle
q_V	velocity of driver's body
q_X	displacement of driver's body
$w_1(t)$	random noise (system noise) to drive the time derivative of a(t)
$w_2(t)$	random noise (system noise) to drive a(t)
Q_1	variance of the system noise $w_1(t)$
Q_2	variance of the system noise $w_2(t)$
m	mass of the part of driver's body that moves upon collision
d	damping coefficient of motion of the driver's body
k	stiffness constant of seat belt when belted or characteristic of the driver's reaction
l_1	distance from bumper to front frame
l_2	distance from front frame to engine
l_3	possible engine displacement due to collision

Figure 2.5 represents the basic scheme for the algorithm

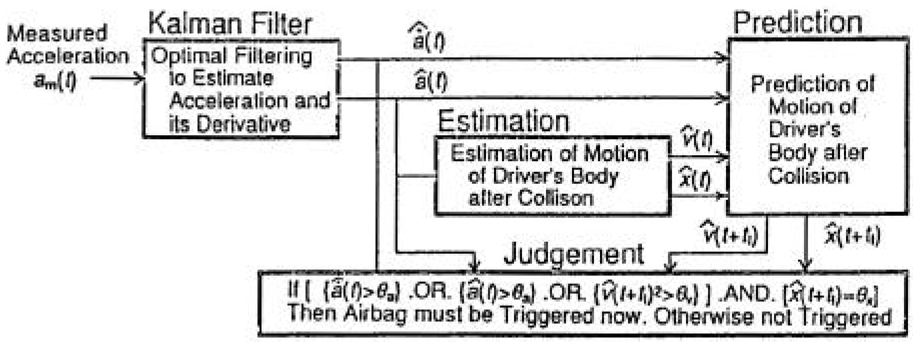


Figure 2.5 – Basic scheme for algorithm

Using the equations for a simple mass-damper model (see appendix B), the following judgement to trigger the airbag can be found:

$$\begin{aligned}&\text{If (a) } |\dot{a}(t)| > q_{\dot{a}} \quad \text{OR} \quad \text{(b) } |a(t)| > q_a \quad \text{OR} \quad \text{(c) } v(t+t_f)^2 > q_V\\ &\qquad\qquad\qquad \textit{is}\text{ true}\\ &\text{AND (d) } x(t+t_f) = q_X \quad \text{Then the airbag must me triggered}\\ &\text{Otherwise the airbag must not be triggered}\end{aligned} \tag{2.2}$$

The rule (d) is the most important. It is prepared to check if or not the driver's body touches to the surface of the expanded airbag after t_f. This means that $?_X$ is the amount of space the driver's body can move until it touches the fully expanded airbag. The optimal timing of airbag operation is determined by rule (d).

2.2.2.2 *Hidden Markov Model*

Hidden Markov Models (HMM) are statistical models of sequential data. They have been used successfully in many machine-learning applications, especially for speech recognition. One of the key advantages using HMM-based learning paradigm is that the model gets better as the training set becomes larger [13].
The Hidden Markov Models from Singh [14] are trained using a library of crash pulses. A separate HMM is constructed and trained for each of these collision types and categorised, based on the types of crash, such as driver-side head-on, passenger-side head-on side collision, angular-frontal impact etc. The crash pulse must be recognised correctly and thus avoid the "false-negative" errors where an airbag is not deployed at the appropriate time with in the crash situation. On the other hand, the airbag deployment algorithm must also reduce the rate of "false-positives".
However, the HMM from Singh cannot predict the trigger time, only classify the sort of crash. If the sort of class is known, one has to know the correct time to deploy the airbag in this situation. A database, which contains the firing time for each sort of class, is not available, and as result this type of algorithm is not useful for this study at this time.

2.2.2.3 *Pre-crash algorithm*

This concept uses the standard algorithm from Watanabe [10] with addition of a proximity sensor. The algorithm can now be considered as a pre-crash sensing algorithm [9]. The algorithm uses the following steps (see also figure 2.6):

- Estimation of the acceleration and jerk of driver's body by Kalman filtering
- Estimation of the velocity and displacement of driver's motion
- Estimation of the acceleration from running velocity
- Prediction of collision time by using proximity sensor
- Airbag trigger judgement

The assumptions are the same as the standard algorithm, but now two sensors are used. This lead to the following airbag triggering judgements:

1. Reset the output of the acceleration sensor immediately after the proximity sensor catches the object to eliminate an excessive acceleration.
2. If {(the proximity sensor catches the object) or (accreditation level) is higher than a certain level)} and $x(t+T) = 0.15[m]$ then the airbag should be triggered otherwise keep airbag trigger = OFF

If the proximity sensor fails to catch the object, the algorithm proceeds to the conventional prediction procedure.

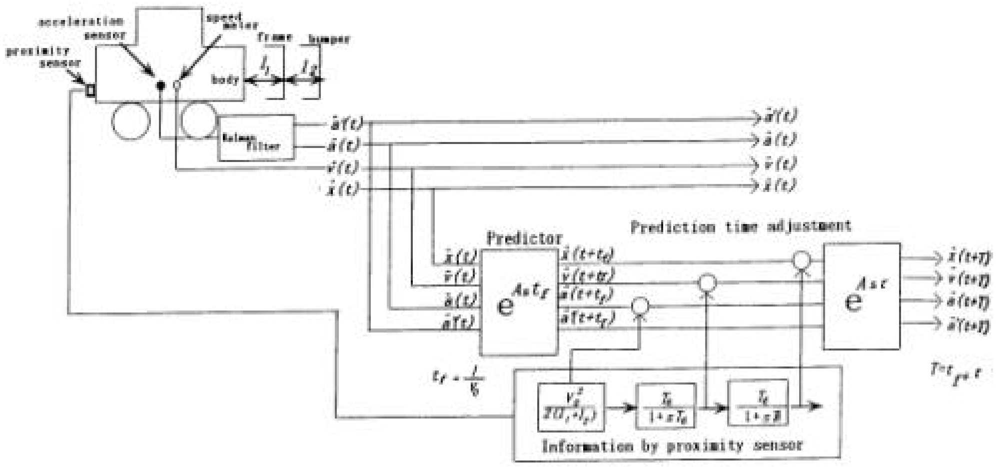


Figure 2.6 - Basic scheme of pre-crash algorithm [9]

The algorithm concept discussed in paragraph 2.2.2.1 can only predict the driver's motion after collision, what can work as a disadvantage. The assist of the proximity sensor to the conventional predictive algorithm provides the prediction before and after collision. To use this algorithm a direct real-time link between MADYMO and Matlab is necessary in order to use the proximity sensor.

2.3 Injury criteria

Besides watching the interaction between airbag and dummy, injury criteria can be used in order to judge if the interaction is good. Most common injury criteria are related to deceleration and intrusion. During a car to car or car to barrier test the acceleration, deflection and several forces are monitored by interpreting the signals of the sensors, which are placed in the car and as well as in the dummy.

2.3.1 Dummy signals

The head and thorax of a dummy are equipped with accelerometers. The femurs and tibia contain force measurements. By interpreting the signals of these sensors and combining them with accident analyses, it is possible to obtain certain injury criteria (table 2.2). These injury criteria are measured in real crash tests. However, it is also possible to calculate them by MADYMO. For a detailed description of the most relevant injury criteria see appendix C [15].

Table 2.2 Dummy Injury Criteria

Description	Abbreviations	Rec. max. value	Critical Value
Head Injury Criterion $_{\text{Time interval}}$	HIC_{36}	800	1000
Neck injury predictor	Nij	0.8	1.0
3 milliseconds Upper Torso	3MS	60 [g]	60 [g]
Combined Thorax Index	CTI	-	1
Viscous injury response Criterion	VC	1 [m/s^2]	1 [m/s^2]
Femur Force Criterion	FFC	7.8 [kN]	10 [kN]
Tibia Index	TI	0.8	1
Tibia Compressive Force Criterion	TCFC	8 [kN]	10 [kN]

Critical value equals the Injury Assessment Reference Value (IARV)
The critical values are for a 50th percentile dummy

2.3.2 *Injury levels*

There are several ways to create an index to obtain the overall severity of a crash. This is a study by itself. In this paragraph several injury criteria are discussed in order to select an appropriate one that can be used in this study. Most of these indices are based on the dummy injury criteria. The Abbreviated Injury Scale (AIS) [16] is a so-called ‘threat to life’ ranking. It distinguishes the following levels of injury:

Table 2.3 AIS - level of injury

AIS	Injury Severity
0	No
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6 +	Lethal

The AIS is a combination of the injury parameters as mentioned in the previous paragraph and the probability. The probability of a certain AIS level increases with higher values for the injury criteria or with the number of types of injury.

The Severe Injury Ratio (SIR) embraces also a statistical element. It relates the probability of injury computed by weighting the probability of injury at each impact by the likelihood of that speed occurring. These weighted probabilities are summed for each vehicle to obtain the total probability of injury given that a particular crash pairing had occurred. The SIR is computed by dividing the two total probabilities of a particular vehicle driver injury by the total probability of the collision partner injury. In contrast to the AIS scale the SIR scale is developed to indicate the safety of a car-to-car collision based on both dummy signals and accident statistics.

To be able to compare injury risk in scenarios with different airbag firing times an overall injury risk is used. Injury criteria levels are converted into a measure that gives an indication of the overall injury risk. In previous car-to-car optimisation studies this was achieved by summing weighted squared normalised injury values for head, chest and upper leg [18], the AIR method.

$$AIR = \sum_i \left(a \left(\frac{HIC(i)}{HIC_{crit}} \right)^2 + b \left(\frac{3MS(i)}{3MS_{crit}} \right)^2 + g \left(\frac{FFC(i)}{FFC_{crit}} \right)^2 \right) \qquad (2.3)$$

The injury criteria used in equation (2.3) are based on results of parametric studies [18]. This function was found to be quite effective as it is very discriminative for critical or near critical injuries. The weighing factors *a*, *ß* and *?* are for the respective injury types. Estimates for the weight factors are provided in table 2.4. These numbers, based on field studies, were derived in the early 1990s to evaluate the performance of restraint systems [19].

Table 2.4 Injury significance factors and critical values

Body region	Significance	Weight	Critical value
Head	60%	α = 0.60	1000
Chest	35%	β = 0.35	600
Extremities	5%	γ = 0.05	10000

None of the above ratios describes the total amount of injury done to an occupant. The lack of a worldwide overall injury criterion makes it hard to assess crash safety. Tests of USNCAP and EuroNCAP already use a five star rating scale. The EuroNCAP rewards also points for non-related issues. The overall rating is based on a frontal, side and pole impact together. Separate points are also available for each test type. However, the scale is very rough and therefore not appropriate for simulations or optimisation.

2.4 Results literature survey

The literature survey resulted in three airbag algorithm concepts. The concept algorithm from Singh [14] only distinguishes crashes into categories of severity and needs a database, which is not available, with pre-calculated airbag trigger times. As a result it does not provide the actual airbag firing time, which is needed in this study. Therefore the concept from Watanabe [10] is used for further modelling. EuroNCAP and USNCAP data are used to validate this concept.

An airbag prevents the occupant hitting the steering wheel and dashboard with its head and body. The head and body have their own injury criterion (HIC and 3MS). However, an overall injury criterion is useful to determine whether there is an overall reduction in the level of injuries. Therefore the AIR method and its injury criteria (HIC, 3MS and FFC) are used to judge whether the airbag firing time calculated by the algorithm is correct.

3 Implementation in Simulink

The algorithm concept discussed in paragraph 2.2.2.1 is implemented in Matlab/Simulink 6.5 [35] and adjusted for optimal triggering of the airbag. The main scheme is depicted in figure 3.1.

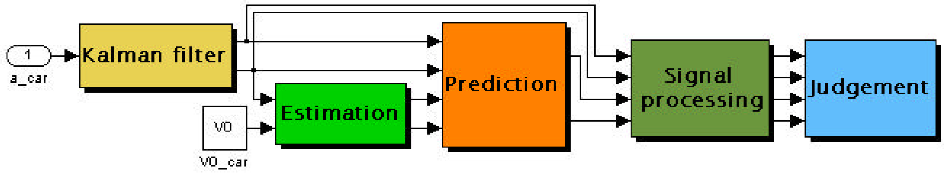


Figure 3.1 – Standard algorithm

The *Kalman filter*, *Estimation* and *Prediction* are modelled according to the scheme depicted in figure B.1 in appendix B. An extra block called *Signal Processing* is added. In this block the signals are transformed in the right order for the *Judgement*. The most important part of the Simulink algorithm is the *Judgement* block (see figure 3.2). In this block is decided if the airbag should be triggered or not. The other coloured blocks are given in more detail in appendix D.

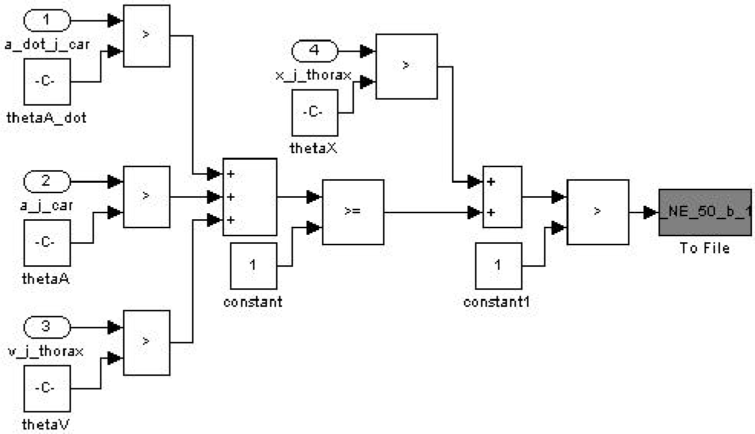


Figure 3.2 – Judgement block

For a correct input of the model the linear acceleration file (*.LAC) from MADYMO is converted in such a way that it has the correct format for Matlab. The b-pillar linear acceleration in x-direction is used as input for the acceleration of the car. After loading the constants, the Simulink model is started (see appendix E for Matlab script).

3.1 Modifications algorithm

The algorithm is modified for several reasons. In the original algorithm the measured acceleration signal is an unfiltered signal. It is filtered using a Kalman filter. Instead of using this filter an acceleration signal with a SAE CFC60 filter is used. As a result the *Kalman* filter block is redundant.

The *Estimation* and *Prediction* block are removed after implementing the linear acceleration signal in x-direction from the thorax. A new block called *Derivative & Integration* is modelled to integrate the acceleration signal of the thorax in order to obtain the velocity and displacement of the driver's body. It also determines the derivative of the car acceleration to obtain $\dot{a}(t)$. Figure 3.3 gives the modified Simulink scheme.

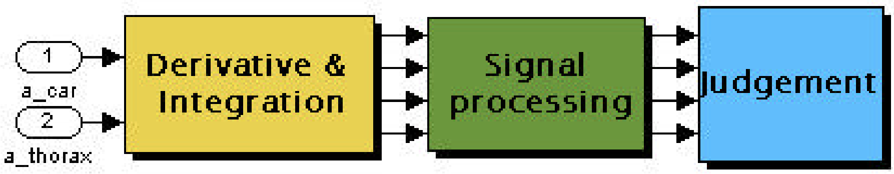


Figure 3.3 – Modified algorithm

The statements of the judgement in equation 2.2 are adjusted for Simulink use. It is almost impossible that the displacement of the dummy *x_j_thorax* = $?_X$, therefore this statement is changed in *x_j_thorax* > $?_X$.
In order to obtain the airbag firing time, the time to fully deploy the airbag is subtracted from the calculated time when all judgements are overruled in Simulink.

3.2 Fine tuning algorithm

The boundary conditions (acceleration q_A and jerk $\dot{q}_A$ car, velocity q_V and displacement q_X of dummy) have to be checked for the *VC-COMPAT* vehicle fleet. In paragraph 2.2.2.1 is stated that rule (d) - displacement of the dummy – is the most important rule. According to Watanabe [10] the distance between the dummy and a fully inflated airbag ($?_X$) is 0.10 *m*. However, in the literature was stated that it is approximately 0.125 *m* [5]. A small change in $?_X$ can have big influences on the firing time, thus how the dummy will make contact with the airbag and as a result the level of injuries will increase or decrease.
The size of the occupant can also influence the amount of allowable dummy movement. A 5th percentile occupant for instance is sitting closer to the steering wheel in order to reach the pedals than a 95th percentile occupant. Therefore an optimisation process is needed to determine the correct value for the dummy movement ($?_X$) for every vehicle model and occupant size.
Another value that has to be determined correctly is the time to inflate the airbag. According to Breed [20] airbags have traditionally been designed on the assumption that 0.030 *s* of deployment time is available before the occupant, as represented by a dummy corresponding to the average male, has moved 0.127 *m* (= 5 inches). Bloch [21] and Kramer [22] state that a driver airbag inflates fully in 0.030 to 0.040 *s*. Therefore the airbag models in the numerical vehicle models have to be studied in detail.

4 Vehicle models

The objective of this study is to develop a realistic algorithm that is general applicable in numerical vehicle models, and in particular Multi-Body, for predicting airbag triggering. First the differences in modelling techniques of the numerical vehicle models will be discussed briefly. Secondly the crash test data (USNCAP and EuroNCAP) will be discussed. These data are used in order to validate numerical vehicle models and provide validation of the algorithm.

4.1 Numerical vehicle models

There are several techniques to develop numerical vehicle models to describe the crash behaviour in frontal collisions, e.g.:

- (Reduced) finite element models (FEM), centre vehicle model in figure 4.1
- Multi-Body models, right vehicle model in figure 4.1
- Beam structure method (Bronckers [3], Relou [23]), left side figure 4.2
- Generic model (Bronckers [3]), right side figure 4.2
- PRISM models (see next page for explanation)

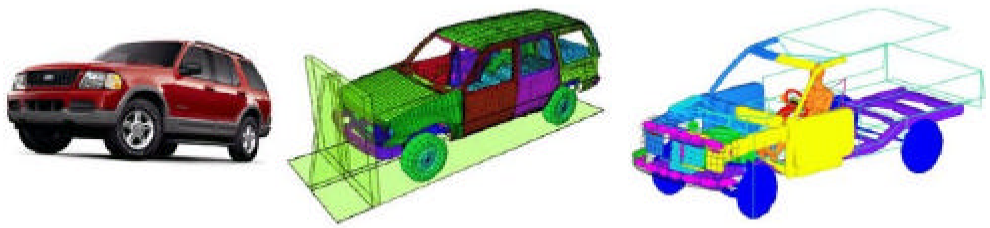


Figure 4.1 - From real car model to Finite Element to Multi-Body [24]

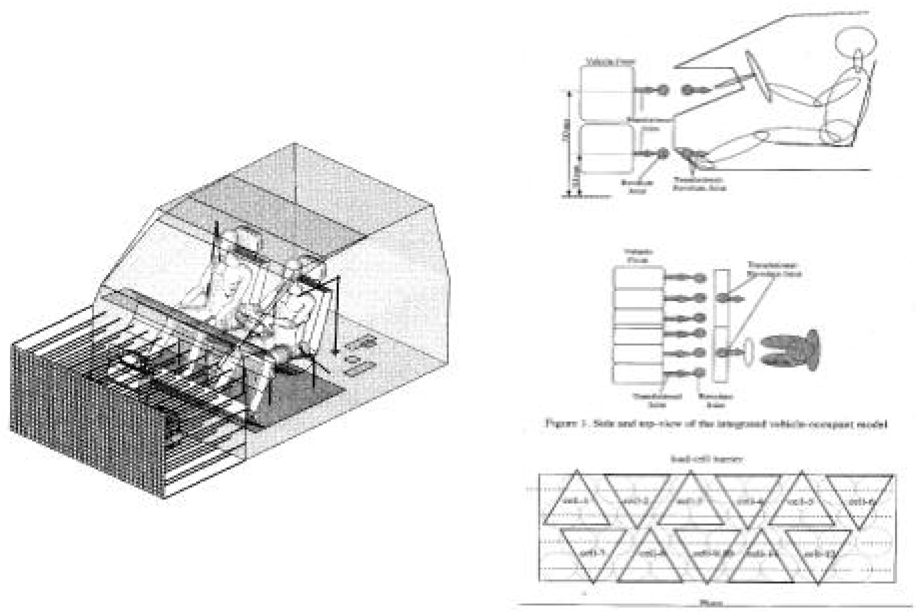


*Figure 4.2 - **Left**: Beam structure method; **Right**: Generic model [3]*

At TNO, several numerical vehicle models are available from different projects*: VC-COMPAT* models, a generic Geo Metro model and PRISM models. Each type of vehicle model will be discussed shortly:

- *VC-COMPAT* models: a Multi-Body vehicle fleet varying from small to large (Geo Metro to Ford Explorer, see figure 4.3). These models are developed over the past years by TNO. This report will not go into detail about the modelling technique of the vehicle models. Further details about the vehicle models are placed in appendix F and Van der Zweep [24].

Figure 4.3 – From top left to bottom right: Geo Metro, Chrysler Neon, Ford Crown Victoria, Ford Taurus and Ford Explorer

- Generic Geo Metro model (left side figure 4.3, Chalmers, [25]): For a generic model the front-end of a vehicle is described by 12 bodies (right side figure 4.2). Each body has a certain characteristic, previously determined by real crash test results with a load-cell barrier. The difference compared to the Beam Element method (Bronckers [3], Relou [23]) is that intrusion is also simulated. The characteristics of the bodies representing the interior are also pre-determined. Multi-Body dummies represent the occupants. This model provides a good representation of the reality. A major disadvantage is the need for input from an actual crash test in order to determine the characteristics of every separate body. However, once the characteristics have been determined for several vehicles it is relative easy to simulate car-to-car crash tests and study compatibility. The parameters of the front-end are easily altered.
- PRISM models: in the PRISM vehicle models only the interior of the vehicle is modelled by measuring the interior of a real vehicle at a large number of points. After gathering all the co-ordinates, it is possible to create a generic passenger cell of a vehicle model (see right side figure 4.4).

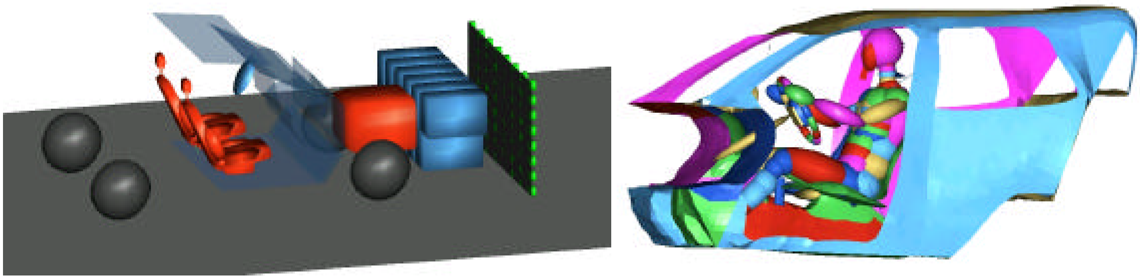


*Figure 4.4 – **Left:** Generic Geo Metro model [25]; **Right:** PRISM model*

The input for the algorithm (see figure 3.3) requires the acceleration signal of the b-pillar and thorax. The *VC-COMPAT* models, generic Geo Metro model and PRISM models all have a linear acceleration file as output file after simulation. As a result the airbag algorithm developed in this study is usable for all vehicle models.
The major disadvantage of Finite Element models is the large calculation time of the simulations. In vehicle fleet studies over 2000 simulations are performed and as a result Finite Element models are not useful in fleet studies. As a result, the *VC-COMPAT* Multi-Body vehicle models are used, because of relatively short calculations times per simulation.
The *VC-COMPAT* vehicle models are modelled and modified by several people in a couple of years. In a previous study (Bronckers [3]) is stated that in car-to-car scenarios the airbag firing time is not correct. The firing time (see table 4.1 for the default firing times) is not changed for different crash scenarios and as a result the timing of the deployment of the airbag is incorrect.

Table 4.1 Original airbag firing time of vehicle model (taken from USNCAP data) [24]

	Geo Metro	Chrysler Neon	Ford Taurus	Ford Crown Victoria	Ford Explorer
time [s]	0.017	0.0225	0.0225	0.022	0.015

Before implementing the algorithm in the numerical vehicle fleet, the airbag models of the vehicle models and integration method during calculation are studied in order to improve the airbag deployment and to determine the correct airbag firing time.

4.1.1 Airbag models

Lack of data and other airbag models resulted in using a generic airbag model in the *VC-COMPAT* vehicle fleet. Some airbag parameters are altered slightly to make the airbag suitable for the vehicle model. As a result the Ford Taurus, Chrysler Neon and Ford Explorer have the same airbag. The other vehicles (Geo Metro and Ford Crown Victoria) have a different airbag. This can effect the allowable dummy movement (different $?_X$).
A mass flow function is defined to deploy the airbag. For each vehicle model a different mass flow is used. However, some can be grouped, e.g. Chrysler Neon, Ford Taurus and Ford Explorer (appendix G). All airbags have a mass flow function from 0 to 0.040 *s*. The airbag in the Chrysler Neon (and also Ford Taurus and Ford Explorer) deploys different compared to the airbag in the Ford Crown Victoria (and Geo Metro). The airbag in the Ford Crown Victoria is already operational after 0.030 *s* in contrast with

the airbag in the Chrysler Neon: 0.040 s. Comparing the input file (XML format) and using the MADYMO manual [26] the differences in airbag are depicted in table 4.2.

Table 4.2 Differences in airbags in Chrysler Neon and Ford Crown Victoria

parameter	**Chrysler Neon**	**Ford Crown Victoria**	**default MADYMO**
thickness	$5 \cdot 10^{-3}$ [m]	$5 \cdot 10^{-4}$ [m]	
friction coefficient[@]	0.2	0.1	0 – 0.1
THERMC	-	3	1
IMM damping	-	$3 \cdot 10^{-4}$ [-]	0

[@] friction between airbag and driver

For the Chrysler Neon the parameters THERMC and IMM_DAMP are not specified in the XML-file and as a result MADYMO uses the default values.
The term *IMM* (Initial Metric Method) damping allows the airbag to begin inflating in a more realistic start. This is advised for out-of-position (OOP) simulations [26],[27], see appendix H for more information about IMM. The damping should not be chosen too large, $10^{-5} – 10^{-4}$.
The term *THERMC* defines the number of sub cycles of thermodynamical calculations in one Finite Element time step. According to the MADYMO manual the number of subcycles may vary from 0 to infinite [26].
Adjusting the airbag characteristics of the Chrysler Neon with the specifications of the other airbag model and setting THERMC at 25, a more stable airbag deployment process is created. The airbag is inflated faster and is operational after 0.030 *s* instead of 0.040 *s*.

4.1.2 *Integration method*

There are two integration methods with a fixed time step in MADYMO: Euler and Runge-Kutta4. To point out which method should be used for simulation purposes, the theory behind the two methods is discussed briefly.
Simulating the behaviour of the system governed by the ODE generates a numerical solution of an ordinary differential equation (ODE). Starting at t_0 with the given initial value, the trajectory dictated by the ODE is tracked. By evaluating $f(t_0, y_0)$, the slope of the trajectory is known at that point. This information is used to predict the value t_1 of the solution at some future time $t_1 = t_0 + h$ for some suitably chosen increment h. The simplest example of this approach is Euler's method. Consider the Taylor series [28]:

$$y(t+h) = y(t) + y'(t)h + \frac{y''(t)}{2}h^2 + \ldots = y(t) + f(t, y(t))h + \frac{y''(t)}{2}h^2 \quad (4.1)$$

Dropping terms of second and higher order to obtain the approximate solution value derives Euler's method

$$y_{k+1} = y_k + f(t_k, y_k)\, h_k \quad (4.2)$$

in order to get from time t_k to time $t_{k+1} = t_k + h_k$. Equivalently, if the derivative in the differential equation $y' = f(t, y)$ is replaced with a finite difference quotient, an approximating algebraic equation is obtained

$$\frac{y_{k+1} - y_k}{h_k} = f(t_k, y_k) \tag{4.3}$$

which provides the Euler's method when solved for y_{k+1}. Thus, Euler's method advances the solution by extrapolating along a straight line whose slope is given by $f(t_k, y_k)$. Euler's method is called a *single-step* method because it depends on information at only one point in time (t_k in figure 4.4) to advance to the next point (t_{k+1} in figure 4.4).

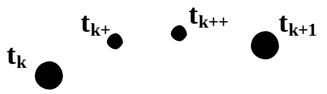


Figure 4.5 – Schematic representation of integration method

Runge-Kutta methods are single-step methods that are similar in motivation to Taylor series. However, they do not require the computation of higher order derivatives. Instead, Runge-Kutta methods simulate the effect by evaluating *f* several times between t_k and t_{k+1} (points t_{k+} and t_{k++} in figure 4.4). The best-known Runge-Kutta method is the classical fourth-order scheme, as used in MADYMO:

$$y_{k+1} = y_k + \tfrac{1}{6}\left(k_1 + 2k_2 + 2k_3 + k_4\right) \tag{4.4}$$

where:

$$\begin{aligned} k_1 &= f(t_k, y_k)\,h_k \\ k_2 &= f\left(t_k + h_k/2, y_k + k_1/2\right)h_k \\ k_3 &= f\left(t_k + h_k/2, y_k + k_2/2\right)h_k \\ k_4 &= f\left(t_k + h_k/2, y_k + k_3/2\right)h_k \end{aligned} \tag{4.5}$$

When *f* is evaluated several times between t_k and t_{k+1}, the reaction forces (equal to the reaction forces at t_{k+1}) of a Finite Element model on a rigid body in the sub time steps are kept constant using Runge-Kutta4 in MADYMO. This can cause instability. The Euler method does not evaluate *f* several times between t_k and t_{k+1} and therefore does not have this problem. As a result it is better the use the Euler method when using FEM on a rigid body [27],[28].

4.2 Test data

Crash test data from real cars are used to validate numerical vehicle models. It is also used for validation of the algorithm. Two test databases are used for validation. The USNCAP data is used for the validation of the numerical vehicle models and the EuroNCAP data is used for validation of the algorithm.

4.2.1 USNCAP

In 1978 the U.S. National Highway Traffic Safety Administration (NHTSA) began crash-testing popular vehicle models in the United States. Their protocol (FMVSS 208) involved running vehicles head-on into a fixed barrier at 35 *mph*. Results were published for the information of consumers, as the US arm of the international New Car Assessment Program (NCAP) [29].
The USNCAP data is used for validating the numerical vehicle models (see table 4.3 for injury criteria of USNCAP test data). In a previous study (Van der Zweep, [24]) the *VC-COMPAT* vehicle models are validated comparing the b-pillar and head linear acceleration signal of the numerical vehicle model with the acceleration signal from the full-scale test. The algorithm is validated using the same acceleration signals.

Table 4.3 USNCAP validation data [30]

car	test no	barrier	HIC		3MS [m/s^2]
			value	time window	
Geo Metro (1995)	2239	rigid load cell	467	[64.92 - 97.2]	510
Chrysler Neon (1996)	2320	rigid load cell	610	[51.36 - 84.96]	549
Ford Taurus (1991)	1600	rigid flat barrier	480	[58.68 - 92.88]	433
Ford Crown Victoria (1998)	2764	rigid flat barrier	602	[73.2 - 109.2]	383
Ford Explorer (1998)	2749	rigid flat barrier	567	[44.6 - 80.6]	546

4.2.2 EuroNCAP

The purpose of the European New Car Assessment Program (EuroNCAP) is to provide motoring consumers with a realistic and independent assessment of the safety performance of some of the most popular cars sold in Europe. Established in 1997 and now backed by five European Governments, the European Commission and motoring and consumer organisations in every EU country, EuroNCAP has rapidly become a catalyst for encouraging significant safety improvements to new car design [31].
The EuroNCAP data is used as a check of the deployment phase of the airbag in the numerical vehicle models. Another parameter that is checked is the dummy movement until it touches the airbag. Since this parameter is the most important rule for triggering the airbag in the algorithm concept that will be used (see equation 2.2), the test data provide a validation of the dummy movement. Further it is determined if the dummy movement ($?_X$) is depending on the size and/or type of vehicle. The longitudinal chest displacement, determined by integrating the longitudinal chest acceleration, provide the displacement of the chest ($?_X$) until it has contact with the airbag. The results of the analysis are given in table 4.4. The specifications of the vehicles are in appendix F.
The analysis is done using the program DIAdem (National Instruments, [32]). This program offers the possibilities to view multiple crash movies at the same time and to evaluate the measured signals.

Table 4.4 EuroNCAP data [31]

car	EuroNCAP rating	firing time [s]	$?_X$ [m]
BMW 3-series (2000)	****	0.021	0.036
Nissan Primera (2003)	****	0.066	0.098
Nissan X-Trail (2003)	****	0.037	0.062
Renault Megane (2003)	*****	0.025	0.072
Suzuki Grand Vitara XL-7 (2002)	***	0.035	0.048

After analysing several EuroNCAP crashes for different vehicle models with the same size or vehicle type as the *VC-COMPAT* vehicle fleet, it was almost impossible to determine the exact firing time due to delay times (actuation and distribution, see figure 2.1) in the sensors. It is also difficult to determine the time it takes to fully inflate the airbag, because in most cases the dummy is already in contact with the airbag before it is noticeable that the airbag is completely full.
The airbag firing range is between 0.021 and 0.037 *s* except for the Nissan Primera. During the analysis the kinematics point out that the airbag is triggered much too late and as a result the dummy has a large forward displacement until it has contact with the airbag.
The Suzuki Grand Vitara and Nissan X-Trail are both Sport Utility Vehicles (SUV). However, the seating position in the X-Trail is more like in passenger cars. The Suzuki is a larger SUV and the seating position corresponds with the Ford Explorer (used in the VC-COMPAT vehicle fleet). The dummy is sitting closer to the steering wheel compared to the other cars and as a result the dummy movement is smaller than the other cars. The BMW is an exception. The forward displacement of the dummy in the BMW is very little before it has contact with the airbag, thus $?_X$ is also small.

5 Parameter study

The previous chapters provided a number of tools in order to determine an airbag firing time in a crash scenario. The tools are used as schematically shown in figure 5.1.

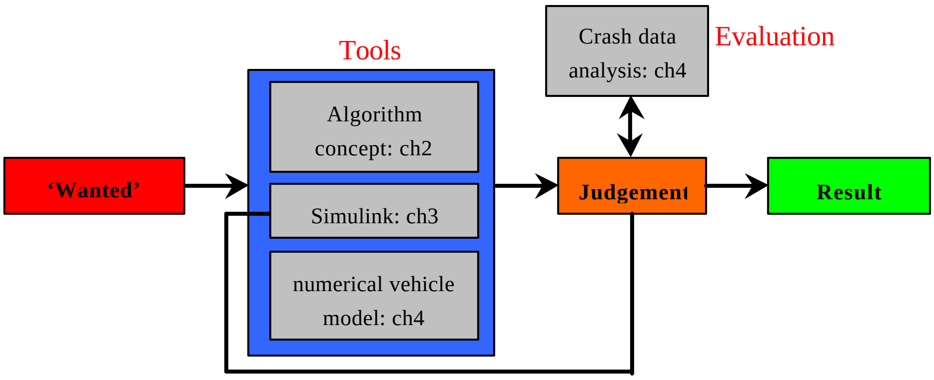


Figure 5.1 - Schematic representation of the problem

The objective (depicted as 'wanted' in figure 5.1) is to develop an airbag triggering algorithm with a crash (primary focus) and occupant (secondary focus) dependent airbag firing time in a numerical vehicle fleet (Multi-Body or generic). To solve this problem a number of tools are needed. The literature survey provided an algorithm concept and together with a Simulink scheme and a numerical vehicle fleet a judgement (based on car acceleration and dummy movement) for determining the airbag firing time is developed. USNCAP and EuroNCAP data are used to evaluate the judgement and, if needed, the car fleet and/or Simulink scheme is adopted for better results. And as a result the 'wanted' is solved.

5.1 Parameter selection

Before implementing the airbag algorithm in the vehicle fleet it must be evaluated in several ways. As stated in chapter 4, the numerical vehicle models are validated using USNCAP and EuroNCAP data. The USNCAP test consists of a car to Full-width barrier crash test. In order to compare the results of the algorithm, the same scenario is used. The judgement is adjusted to match the results of the simulation data with test data. The regulations for EuroNCAP data are different compared to the USNCAP data. The EuroNCAP test consists of a car to Offset Deformable Barrier (ODB) tests. However, the amount of forward displacement of the dummy until it touches the airbag will be the same as for a car to Full-width scenario. Therefore the EuroNCAP provide validation of the boundary condition q_X (dummy movement).
The sensitivity of the algorithm is investigated by setting up variations in certain parameters. The variations in parameters exist of:

- Different boundary conditions in judgement: $\dot{q}_A$, q_A, q_V and q_X
- Changing the front-end stiffness: varying from 75 to 150% of the original stiffness
- Initial velocity; below which velocity is no airbag deployment needed?
- Dummy size: 5th, 50th or 95th percentile dummy

5.2 Parametric study

In the parametric study the influence of variations of parameters mentioned in the previous paragraph is investigated. In order to compare the results for changing parameters, the test set-up is kept the same in every scenario: a Chrysler Neon against a Full-width barrier (FWB). In every scenario, except when investigating the influence of different dummy sizes, the occupant is a 50th percentile dummy.
In order to determine the actual movement of the dummy with the belt as the only restraint system, the airbag is switched off by setting the firing time at the end of the simulation time. This results in a new airbag firing time.

5.2.1 Boundary conditions

The judgement (see equation 2.2) consists of four rules concerning jerk ($\dot{q}_A$) and acceleration (q_A) of the vehicle and speed (q_V) and displacement (q_X) of the occupant. A couple of simulations indicated that changing the first three boundary conditions does not have influence on the trigger time since these conditions are already exceeded in an early stage of the crash (left side figure 5.2). The airbag is only fired if the rule for q_X is also broken. This supports the statement that rule (d) in the judgement (equation 2.2) is the most important one.
According to the literature survey the distance between the driver and a fully inflated airbag is approximately 0.125 *m* [5]. Watanabe [10] set this distance for his algorithm at 0.10 *m*. The value of $?_X$ depends on the type of vehicle or size of the driver. Therefore it is interesting to investigate the correct value for the modified Watanabe algorithm and the Multi-Body vehicle models in the fleet. Therefore simulations are performed with $?_X$ varying from 0.0508 to 0.1778 *m* (2 to 7 inches) with increments of 0.0254 *m* (1 inch). The algorithm calculates for every $?_X$ the corresponding firing time. A simulation is performed with the calculated firing time to investigate the effect of the firing time on the injuries. The results are depicted on the right side of figure 5.2.

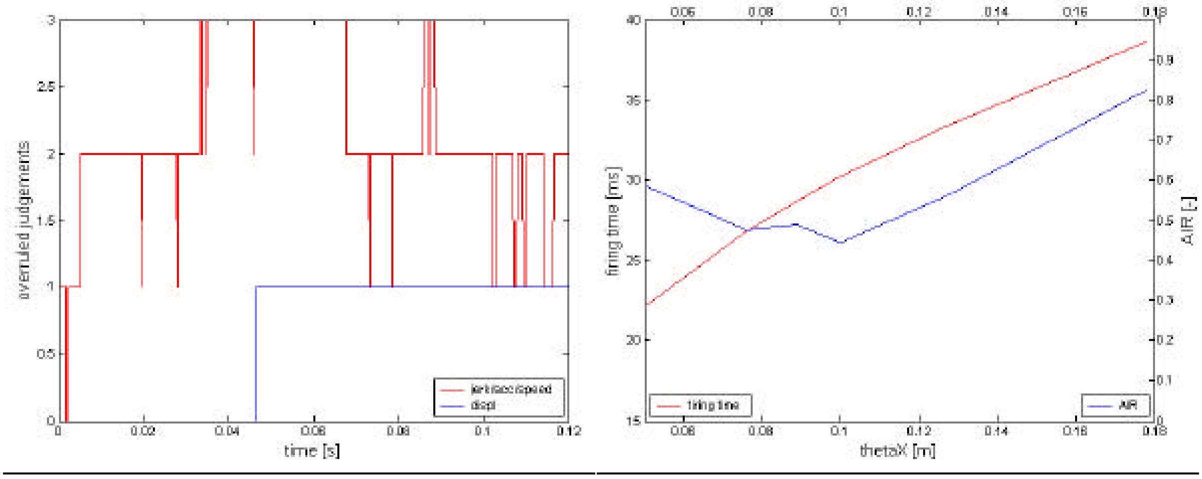


*Figure 5.2 - **Left**: Plot of overruled judgements; **Right**: Influence of $?_X$ on firing time*

There is a strong linear relation between $?_X$ and the firing time and above $?_X$ = 0.10 *m* also a linear relation between firing time and injury level. By looking at the AIR, there is a clear indication that $?_X$ = 0.10 *m* provides the smallest injuries for the Chrysler

Neon with a 50th percentile occupant. For other occupant sizes the dummy movement (?$_X$) has still to be determined. A closer look at the Multi-Body vehicle models indicate that the dummy in the Ford Explorer is sitting closer to the steering wheel compared to the Chrysler Neon (see figure 5.3 and 5.4), thus ?$_X$ will be different for these vehicles. To find the correct ?$_X$ for every vehicle model, an optimisation process is needed to find that typical value with its corresponding airbag firing time.

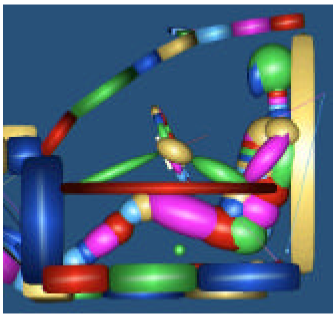


Figure 5.3 - Seating position Chrysler Neon

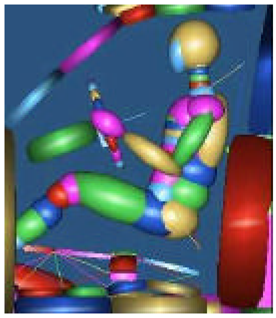


Figure 5.4 - Seating position Ford Explorer

5.2.2 *Influence of different front-end stiffness*

In order to investigate the influence of a different front-end stiffness on the airbag firing time, the stiffness of only the longitudinal load members is varied from 75 to 150% of the original stiffness. In order to compare the results of different front-end stiffness, the boundary condition ?$_X$ is kept at 0.10 *m*.
Changing the front-end stiffness results in an increase of firing time in every scenario. However, the variation in firing time for different front-end stiffness (left side figure 5.5) is small. For a two times higher front-end stiffness, the firing time decreases with only 0.001 *s*. In the scenario builder only the stiffness of the longitudinal load members is changed and therefore not the complete front-end stiffness. As a result only changing the stiffness load members has little influence on the airbag firing time. However, a different front-end stiffness has more effect on the injuries (right side figure 5.5). The head injury criterion (HIC) decreases for a lower front-end stiffness.

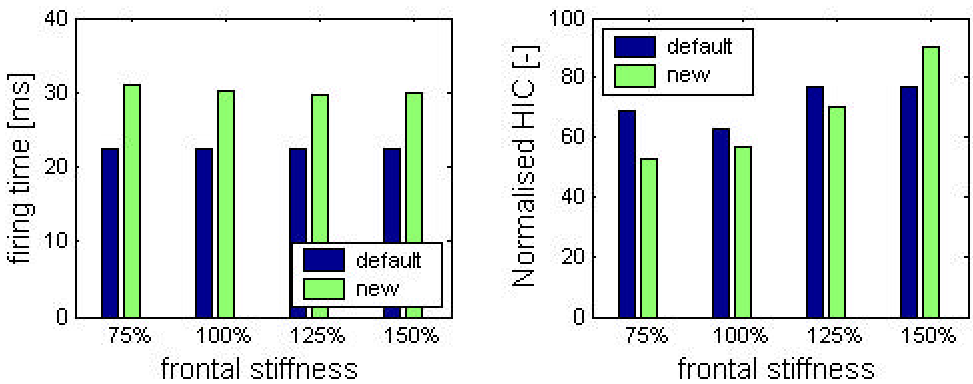


Figure 5.5 - Influence of front-end stiffness on firing time; new = firing time calculated by algorithm

5.2.3 *Influence of different initial velocity*

The standard initial velocity for Full-width barrier simulations is 56.34 *km/h* (˜ 35 mph; default speed for USNCAP barrier tests). To investigate the effect of the initial velocity on the trigger time 25 simulations with an initial velocity stochastically chosen between 2 and 20 *m/s* (7.2 to 72 *km/h*) are performed. The linear acceleration file is put into Matlab to calculate the corresponding airbag firing times (red line figure 5.6) and performing new simulations the corresponding HIC (black and blue line figure 5.6) is calculated. The results (depicted in figure 5.6) indicate that the firing time is changing for different velocities. For the lowest speed the airbag does not have a big influence on the protection of the occupant. As stated in the beginning of chapter 2, the belt is not capable to prevent the occupant hitting the steering wheel at speeds of over 40 *km/h* [5]. For the Chrysler Neon an airbag is not necessary for reducing injuries at speeds below 33 *km/h* (black vs. blue line figure 5.6). For higher speeds, above 65 *km/h*, large deformations of the vehicle will lead to other type of injuries than acceleration or head contact related injuries. Due to the large deformations of the vehicle the compartment collapses, and intrusion will occur. The restraint systems are not capable to avoid the occurring injuries. Therefore, the algorithm will be effective up to a certain initial velocity, depending on the vehicle type and size.

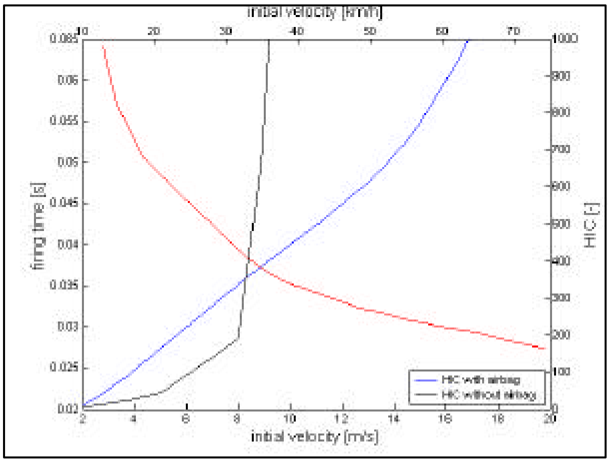


Figure 5.6 - Influence of initial velocity on firing time

5.2.4 *Influence of dummy size*

The crash tests from EuroNCAP and USNCAP are frontal crash tests with a 50th percentile dummy. To gather the results for the 5th and 95th percentile dummies, the vehicle acceleration signals measured during the test with the 50th percentile dummy is used as an input for sled tests with a passenger cell with airbag and the 5th or 95th percentile dummy. Therefore the primary focus in this study is on a crash depending firing time. However, it is interesting to investigate if the firing time is occupant dependent. The 5th percentile dummy is the smallest dummy (see table 5.1) and as a result this dummy is sitting closer to the steering wheel to reach the pedals compared to the 95th percentile dummy (appendix I for seating position dummies [24]).

Table 5.1 Dummy specifications [24]

Hybrid III	mass [kg]	length [m]
5^{th} percentile	48	1.52
50^{th} percentile	77	1.72
95^{th} percentile	101	1.85

This is especially the case for the 5^{th} percentile dummy seated in the Ford Explorer. This driver is almost seated out-of-position (OOP). Studies (Rekveldt [33]) showed that there are two main out-of-position: chin on rim steering wheel and chin on airbag. In the first case the chest compression exceeded the critical value and there are also high neck tension forces. In the second case the neck extension is the most crucial criterion. In other words: the maximum allowable dummy movement ($?_X$) must be changed in the algorithm in order to get the proper airbag firing time for the 5^{th} percentile dummy.
The kinematics points out that the 5^{th} percentile dummy has normal contact with the airbag in the initial phase. Due to the fact that the dummy is sitting closer to the steering wheel, the contact between the airbag and dummy is becoming incorrect due to the further inflation process of the airbag and further forward movement of the dummy (see appendix J). In this case the dummy does not have the full benefit of the airbag and therefore higher injuries occur when using the default value of $?_X$. Changing $?_X$ from 0.10 *m* to 0.05 *m* (˜ 2”) for the 5^{th} percentile dummy leads to an earlier airbag firing time. This results in a better contact with the airbag, providing less injury (figure 5.7).
The 95^{th} percentile dummy is taller compared to the 50^{th} percentile dummy. This causes a high contact with the airbag and leading to high injuries. In order to provide a good airbag contact the correct $?_X$ must be determined.

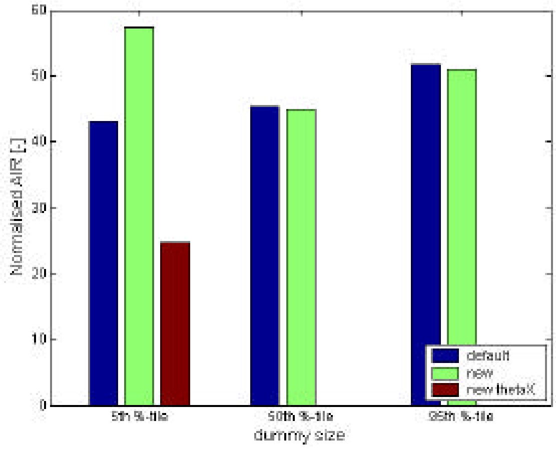


Figure 5.7 - Influence of dummy size; new thetaX only for 5^{th} %-tile

5.3 Stochastic study

The results of the parametric study in the previous paragraph pointed out that it is necessary to determine the correct dummy movement ($?_X$) in order to find the correct airbag firing time in every vehicle model with different occupant sizes and other variables (e.g. initial velocity and front-end stiffness). The right side of figure 5.2 indicates that there are two local minima and therefore a optimisation process is not usable. Therefore a stochastic study is performed using MC-ADVISE. MC-ADVISE is part of the program ADVISER and contains a model quality-rating module. It provides:

- Useful for trend analysis
- Useful for starting a large number of simulations on multiple computers with one or parameters varying randomly
- Influence of firing time on injury criteria within a large time window
- Indicates robustness of the used model

In this study the function of starting a large number of simulations with a stochastically varying parameter (airbag firing time) is used. For every vehicle model and dummy (5^{th}, 50^{th} and 95^{th} %-tile) 150 simulations with a stochastically varying firing time are performed. The goal of this study is to investigate the influence of the airbag firing time on a number of injury criterions and for which firing time the injury is minimal.
As mentioned before (paragraph 4.2.1) the numerical vehicle models are validated with USNCAP data (table 4.3, [24],[30]). The USNCAP data consists of car to Full-width barrier test. In order to validate the results of the stochastic study the same scenario is used. The results are put into Matlab to create scatter plots of an injury criterion versus firing time.
During the stochastic study it appears that the influence of a changing airbag firing time is the most for the head injury criterion (HIC) and less for the 3MS torso and FFC (see figure 5.8). The contact between head and airbag is the most crucial contact and therefore changes the most with varying firing times. Besides, the HIC has a weighing factor of 60% in the AIR method (see equation 2.3). Therefore only the HIC is used and eventually a check on AIR.

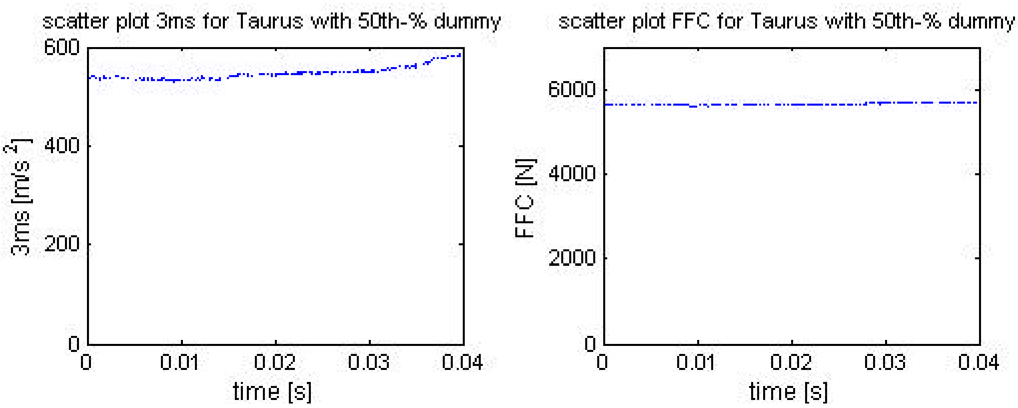


Figure 5.8 - Example of scatter plots 3MS and FFC: Ford Taurus with 50^{th} %-tile dummy

Due to translations (old to new MADYMO versions) and other modifications an unrealistic airbag fabric thickness was used (5 *mm* in stead of 0.5 *mm*). In paragraph 4.1.1 other differences between the two airbag models are given. The scatter plot for the Chrysler Neon with the default airbag indicates that the airbag deployment causes unstable results (upper side of figure 5.10). A small change in firing time (0.5 *ms*) results in a change in HIC of almost 200. The kinematics of the unfolding process of the airbag model in the Chrysler Neon showed an unrealistic deployment process. This causes the large spreading in HIC for a small change in airbag firing time. Modifying the airbag (fabric thickness = 0.5 *mm*, THERMC = 25, IMM = $3*10^{-4}$), the airbag deployment process is more stable and the spreading in HIC is smaller. The Ford Taurus also has better results with the modified airbag model. However, after modifying the airbag model in the Ford Explorer, the results (see bottom figure 5.10) did not correspond with the USNCAP data, which is used for validation. The head injury criterion (HIC) is too high. Therefore the default airbag is used in further simulations.

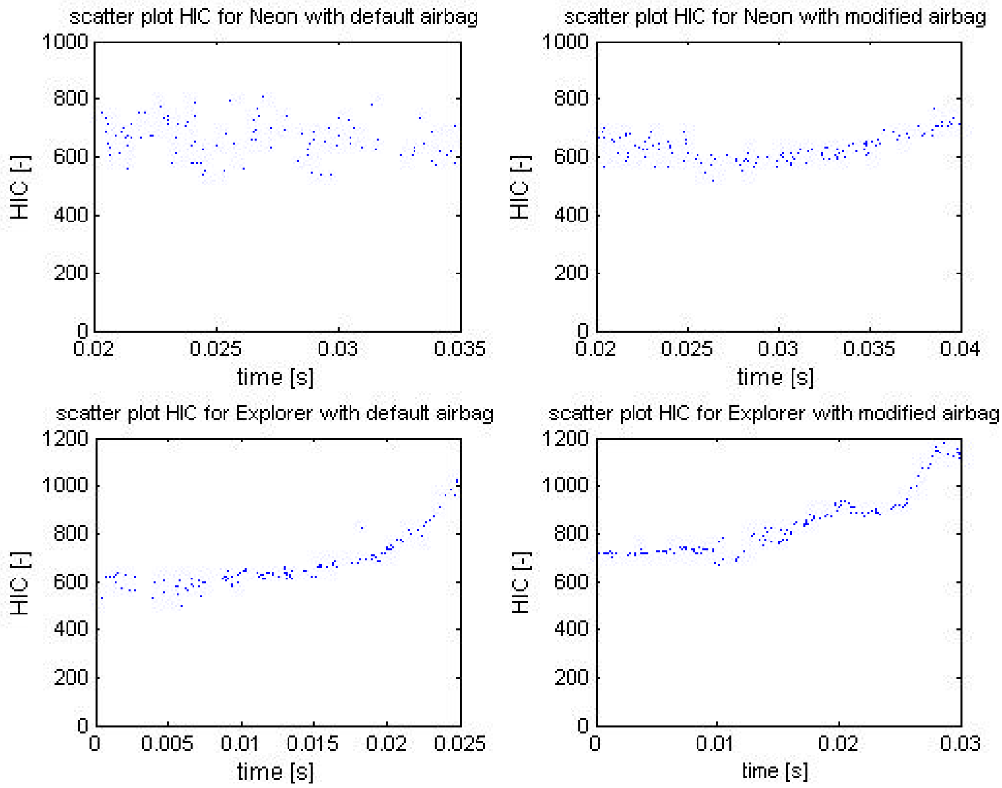


Figure 5.9 - Results stochastic study for Chrysler Neon and Ford Explorer

The combination of the Geo Metro with the 95th percentile dummy result in unstable airbag deployment (figure 5.10). Due to the fact that the Geo Metro is not as stable as the other vehicle models, the effect of using the Runge-Kutta4 integration method causes instability in the airbag deflation process (see §4.1.2) and as a result large variations in the level of injuries occur. Using the Euler method solved the problem (right side figure 5.10).

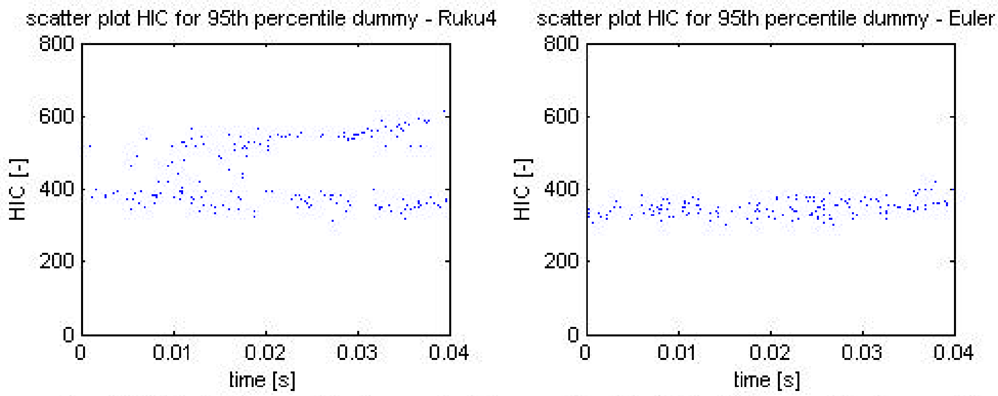


*Figure 5.10 - Results for Geo Metro with 95th %-tile dummy; **Left:** Runge-Kutta4 method; **Right:** Euler method*

5.3.1 *Results stochastic study*

The results for the stochastic study give a good idea of the effect of changing the airbag firing time. Figure 5.11 represents the HIC scatter plots for all five vehicle models with a 50th percentile dummy as occupant. Comparing the AIR plots with the HIC plots, it is justified to focus on the HIC to determine the optimal airbag firing time range.
The results for the 5th and 95th dummies do no differ a lot compared to the 50th percentile dummy results and therefore only the results of the 50th percentile dummy are discussed in detail. The results for the 5th and 95th percentile dummies, together with scatter plots of the overall criterion AIR, the thorax acceleration 3 *ms* clip and femur force criterion (FFC) are placed in appendix K.
All vehicles of the *VC-COMPAT* fleet with different occupants (5th, 50th and 95th percentile dummy) have a optimum airbag firing time within 0 to 40 *ms.* Most vehicles have a stable area with constant level of injuries. The new airbag firing time is chosen at the centre of the area in which the injuries are constant. This eliminates the effect of a small perturbation (e.g. unequal distance between car to barrier). Implementing the airbag firing time in Matlab, the airbag algorithm judgement determines the dummy movement $?_X$ for every vehicle model and dummy size. For some vehicle models the dummy movement depends on the dummy size, due to the seating position of the dummy. The results of the stochastic study indicated that the airbag has to fired earlier for those dummies, see table 5.2

Table 5.2 Airbag firing time for vehicle models and dummies in Full-width studies

	5th %-tile dummy			**50th %-tile dummy**			**95th %-tile dummy**		
	trigger time [ms]		**q_x [m]**	**trigger time [ms]**		**q_x [m]**	**trigger time [ms]**		**q_x [m]**
car	time window	centre		time window	centre		time window	centre	
Geo Metro	10 – 25	17.5	0.035	14 – 40	27	0.075	0 – 35	17.5	0.075
Chrysler Neon	0 – 18	9	0.06	25 – 34	29	0.085	23 – 31	27	0.085
Ford Taurus	0 – 25	12.5	0.01	0 – 32	16	0.02	0 – 40	20	0.02
Crown Victoria	20 – 30	25	0.07	30 – 40	35	0.08	32 – 40	36	0.08
Ford Explorer	0 – 10	5	0.045	0 – 10	5	0.045	0 – 10	5	0.045

The bandwidth in the scatter plot of the Geo Metro is quite large between 0 and 0.010 *s* compared to the bandwidth between 0.010 and 0.040 *s* as a result of unstable airbag deployment. As a result the bandwidth increases.
The Ford Crown Victoria is a large vehicle and as a result the dummy is seated further from the steering wheel. Therefore the airbag firing time range lies at the end of the time window: 0.030 to 0.040 *s.*
It is difficult to determine the dummy movement for the Ford Taurus. However, using HIC = 500 with a bandwidth of ± 50, which is acceptable, an airbag firing time window is created and the corresponding dummy movement $?_X$ is determined.
Due to the seating position in the Ford Explorer (see figure 5.4), the distance between the steering wheel is smaller compared to the other vehicle models. This results in an optimal firing time in an earlier range compared to the other vehicle models. The range is between 0 and 0.010 *s.*

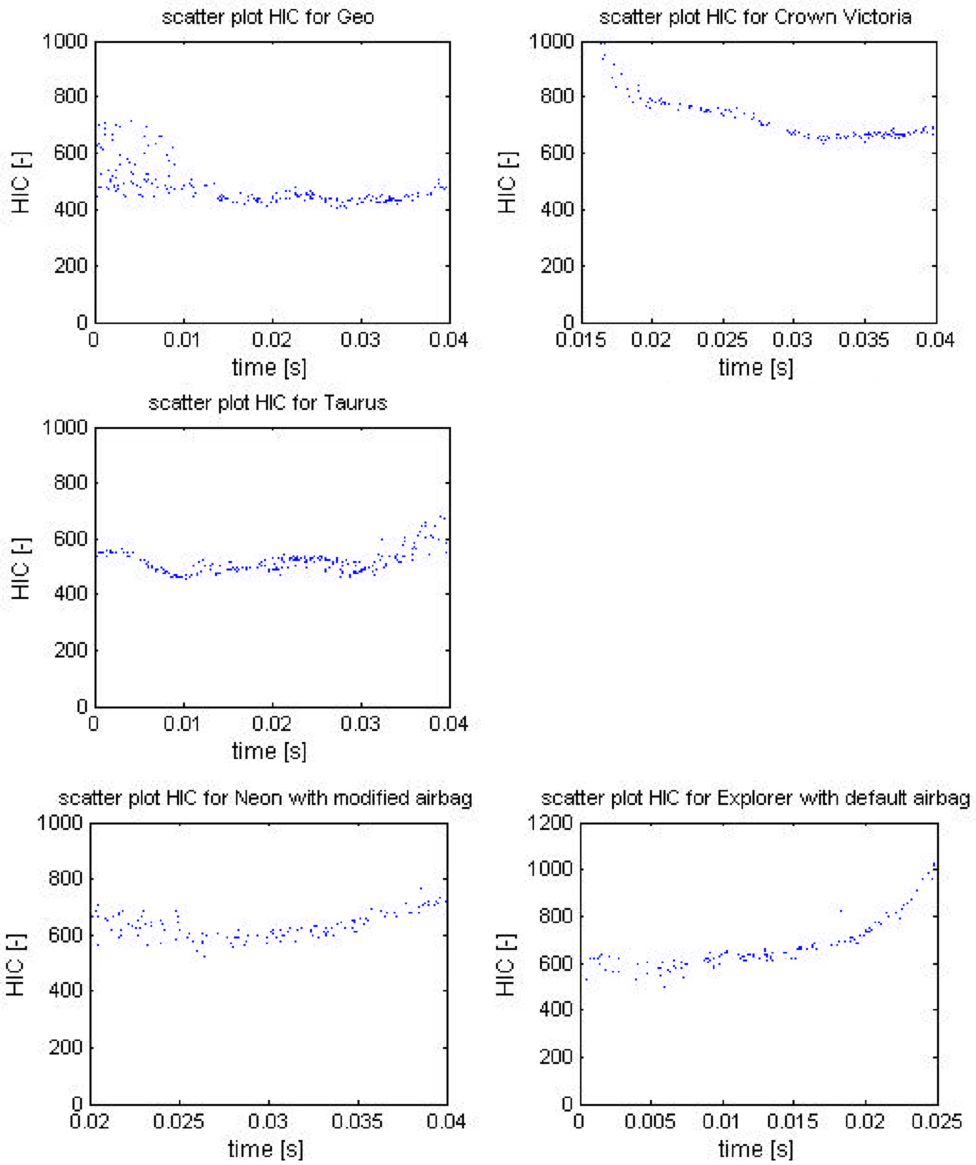


Figure 5.11 - Results stochastic study for Geo Metro, Chrysler Neon, Ford Taurus, Ford Crown Victoria and Ford Explorer

5.3.2 Validation stochastic study

Due to the small distance between the car and barrier, there is a small time delay between the head acceleration of the simulation data and the USNCAP data. Therefore the curve is translated on the time axis to remove the time delay to compare the results.
The level of injuries and the shape of the acceleration signals (see appendix L) for the Geo Metro, Chrysler Neon and Ford Taurus match the USNCAP data (table 4.3).
The airbag deployment and the values of the dummy movement ($?_X$) are validated using EuroNCAP data (table 4.4). After modifying the airbag model in the Chrysler Neon and Ford Taurus, the deployment phase of the airbag in the numerical vehicle models correspond with the airbags in real-life. The allowable dummy movement in the numerical vehicle models are in line with the EuroNCAP data (see table 4.4).

6 Implementation algorithm

In the previous chapters the algorithm concept provided in chapter 2 was modelled in Matlab and investigated in chapter 5. The results of this investigation lead to the values for the dummy movement ($?_X$) for every vehicle model in a car to Full-width barrier scenario. The goal in this chapter is an implementation of the algorithm in the *VC-COMPAT* fleet for car-to-car scenarios and the possibility of using the algorithm for other types of numerical vehicle models, such as a PRISM model.

6.1 VC-COMPAT vehicle fleet

The stochastic study lead to a value for the dummy movement ($?_X$) for every vehicle model (see table 5.2). These values are implemented in the algorithm and the airbag firing times are calculated using the algorithm and the change in injury levels is visible. The influence of dummy size was also taken into account. However, in most cases the dummy size has no major influence on $?_X$. Therefore only the 50th percentile dummy is used and as a result the following data of the stochastic study is used:

Table 6.1 Dummy movement

vehicle model	dummy movement, $?_X$ [m]
Geo Metro	0.075
Chrysler Neon	0.085
Ford Taurus	0.02
Ford Crown Victoria	0.08
Ford Explorer	0.045

Data is for 50th %-tile dummy

First, car to (Full-width and Offset Deformable) barrier scenarios are performed before starting car-to-car scenarios. In the stochastic study car to Full-width barrier scenarios are already used, however not compared to the default configurations. An Offset Deformable barrier scenario approximates the essence of a car-to-car scenario. It is a 50% offset scenario (figure 6.1), just like a car-to-car scenario. However, the interaction between the vehicles is evaded. Therefore the results of this configuration are easy to interpret.

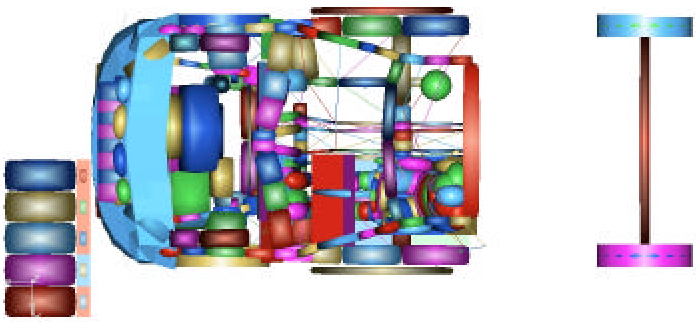


Figure 6.1 – Chrysler Neon to Offset Deformable Barrier

6.1.1 *Car to barrier scenario*

The values of table 6.1 are implemented in car to Full-width and Offset Deformable barrier configurations. First simulations are performed without using an airbag in order to determine the actual dummy movement. Implementing the acceleration signal into the algorithm, the new airbag firing times are calculated (table 6.2). The results of using the new airbag firing times are depicted in figure 6.2.

Table 6.2 New airbag firing times for car to barrier scenarios

car	original firing time [s]	firing time [s] for FWB	firing time [s] for ODB
Geo Metro	0.017	0.027	0.0308
Chrysler Neon	0.0225	0.029	0.0448
Ford Taurus	0.0225	0.016	0.0317
Crown Victoria	0.022	0.035	0.0522
Ford Explorer	0.015	0.005	0.0263

All firing times are calculated with the 50th percentile dummy as occupant

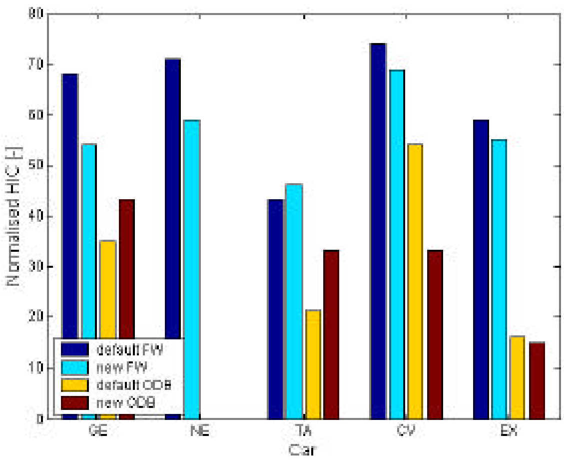


Figure 6.2 - HIC results of new airbag firing time for car to FWB and ODB for 50th %-tile dummy

The results of the car to barrier simulations indicate a reduction in injuries for the new firing times in almost every scenario. However, the injuries in the Ford Taurus are higher. The results of the stochastic study for this vehicle model pointed out that within a firing time range the HIC is 500 ± 50. As a result there is a slight change in injuries for a small change in firing time. The increase in the level of injuries is however acceptable, since they are not close to the critical values.

The injuries in the Geo Metro to Offset Deformable barrier are higher for the new firing time. The results of the stochastic study indicate a variation of injuries within the defined airbag firing time window. As a result of this variation the injuries in the ODB scenario is slightly higher.

6.1.2 Car to car scenario

There are five vehicles for the car-to-car scenarios. Previous studies (Bronckers [3], van der Zweep [24] and Kellendonk [34]) showed that not all the configurations could be run in the original configuration (e.g. Ford Explorer to Geo Metro). Improvements have been made in order to improve the compatibility of the Geo Metro (called G1) [3] and Chrysler Neon (called N1) [34]. These variants are added to the existing vehicle fleet and also investigated to determine the optimal firing time.
First the default car-to-car collisions (with default firing time) are compared to the configurations with modified airbag firing time. The next step is to investigate the influence of changing parameters in the configuration, such as front-end stiffness or is initial velocity. For the car-to-car scenarios the improved airbag will be used for the Chrysler Neon and Ford Taurus.

6.1.2.1 Standard car to car configurations

The results for the default configurations are displayed in appendix L.1. For the entire default car-to-car configurations the airbag firing time increases. In the Geo Metro to Geo Metro scenario, rule (d) in the judgement of the algorithm (see equation 2.2) is not overruled. This results in no airbag deployment. Therefore the firing time is set at 0.12 *s*, see figure 6.3). The injuries for the target vehicle without airbag are lower compared to the target vehicle with default airbag firing time. However, for the bullet (= opponent) vehicle the injuries are slightly higher. Theoretically the injuries in both cars should be the same. However, due to instabilities in the vehicle model, a difference in injuries occurs.

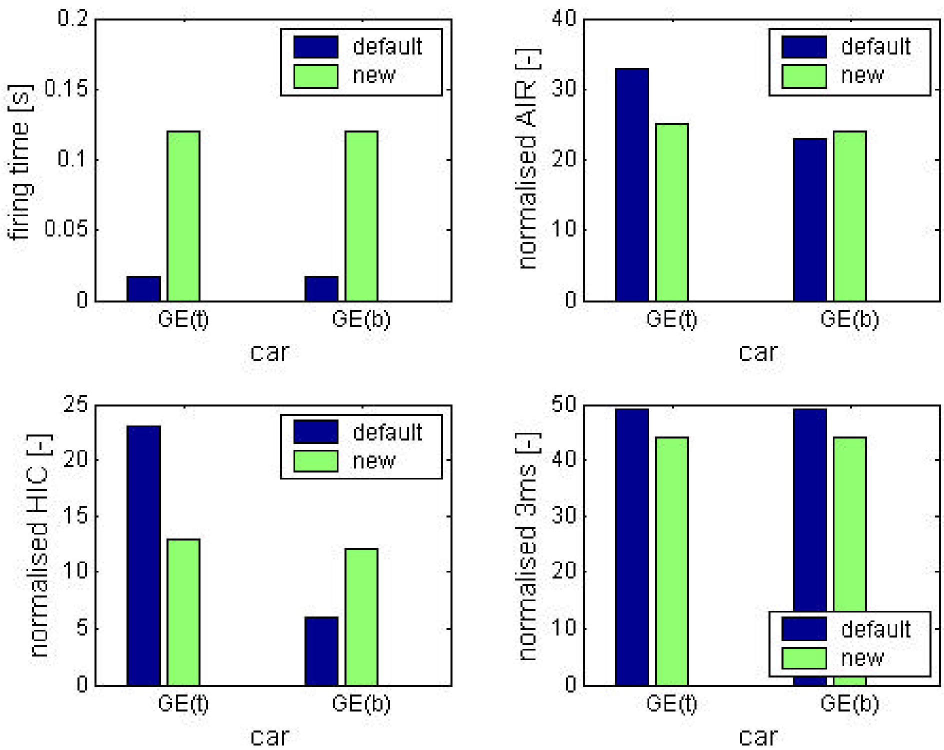
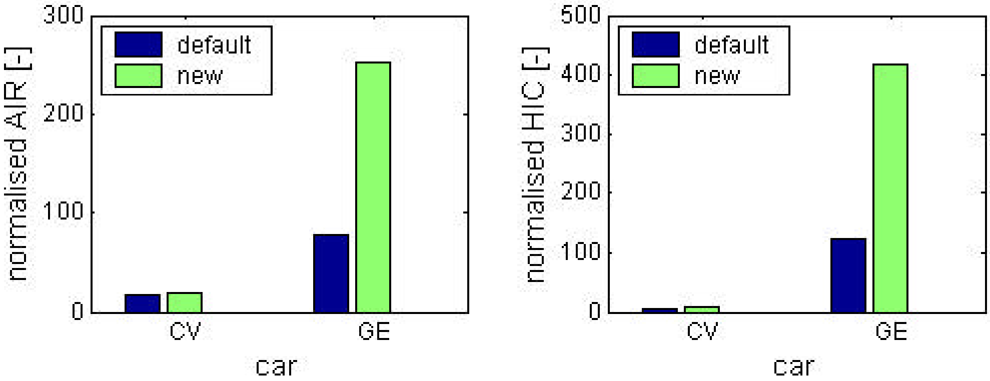


Figure 6.3 - Results of Geo Metro (target -t-) to Geo Metro (bullet (opponent) -b-)

The results in the other configurations indicate that the injuries are not changing dramatically. In some scenarios the injuries are decreasing and in other scenarios slightly increasing. The results of the stochastic study pointed out that there is a airbag firing time range with a flat area of injuries. As a result the injuries remain almost constant. However, there is one scenario with extreme differences compared to the scenario with default airbag firing times. In the Ford Crown Victoria to Geo Metro scenario the injuries in the Geo Metro with the default and new are above the critical value ($HIC_{normalised} > 100$, figure 6.3 and also appendix L.1). The kinematics points out that the Geo Metro is overrun by the Ford Crown Victoria, causing large deformations and the dummy in the Geo Metro is hit by the front bumper of the Ford Crown Victoria. This results in unacceptable high injuries. In this scenario restraint systems, such as an airbag do not prevent these injuries.



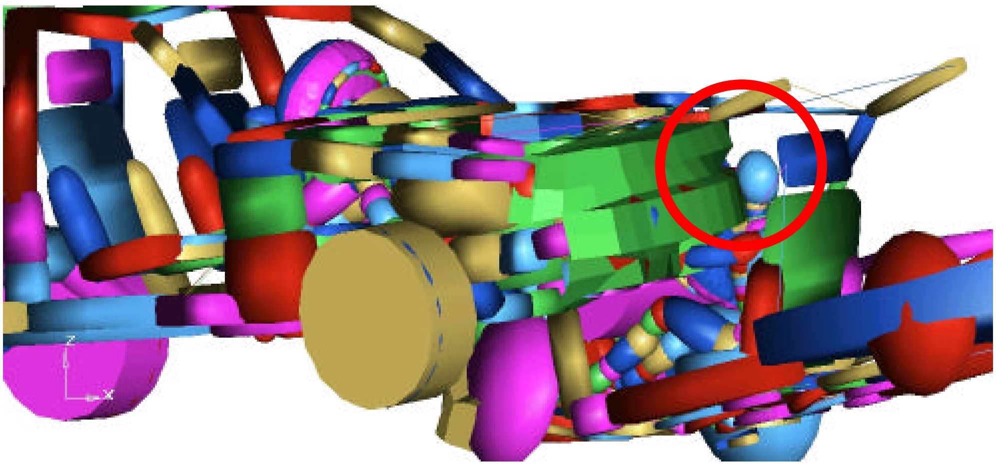


Figure 6.4 - Results of Ford Crown Victoria to Geo Metro scenario

6.1.2.2 *Influence of different front-end stiffness*

A change in front-end stiffness had a minor influence on the airbag firing time in the parametric study (see paragraph 5.3.2). Therefore the primary focus is not on varying front-end stiffness. However, to investigate the influence of front-end stiffness in car to car scenario, two car to car scenarios of different vehicle size and vehicle type are investigated with: a big car against a small vehicle (Ford Crown Victoria to Chrysler Neon) and a big car against a SUV (Ford Crown Victoria to Ford Explorer).
The results of the Ford Crown Victoria to Chrysler Neon scenario (top figure 6.4 and also appendix M.2) indicate that the airbag firing time in all scenarios increases. The firing time in the Ford Crown Victoria is changing more than for the Chrysler Neon.

For all scenarios with the new airbag firing time the level of injuries in the Chrysler Neon are higher, especially in the scenarios when the front-end stiffness of the Ford Crown Victoria is increased. This vehicle is larger and heavier than the Chrysler Neon and increasing the front-end stiffness of this vehicle result in even higher injuries for the Chrysler Neon.
The Ford Crown Victoria to Ford Explorer scenario results (bottom figure 6.4 and also appendix M.2) in lower injuries in the Ford Crown Victoria with increased front-end stiffness of the Ford Crown Victoria and decreased front-end stiffness in the Ford Explorer. The change in firing time for both vehicle models is the same.
As a result changing the front-end stiffness of a vehicle has positive and negative effects on the level of injuries, depending on the selected car-to-car scenario.

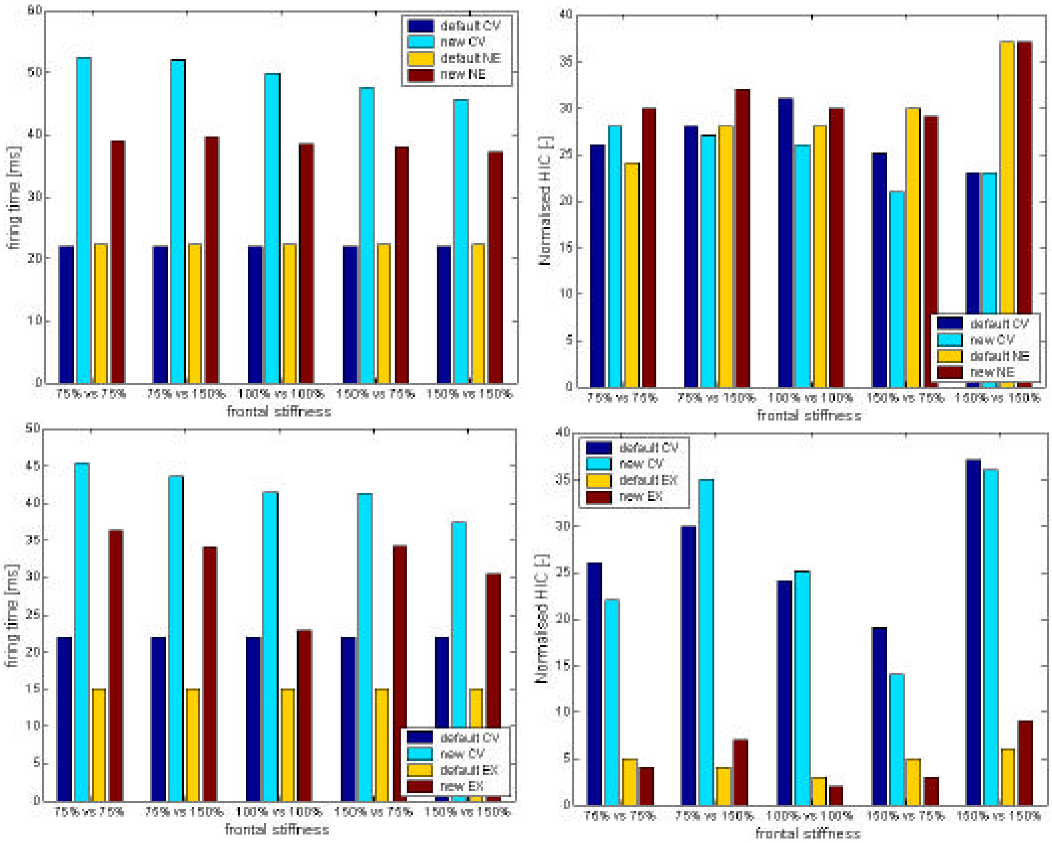


*Figure 6.5 - Results varying stiffness for Ford Crown Victoria to Chrysler Neon (**top**) and Ford Explorer (**bottom**) scenario*

6.1.2.3 Influence of different initial velocity

The results of paragraph 5.3.3 indicated that the initial velocity has a major influence on the airbag firing time and therefore the initial velocity is also varied in car-to-car scenarios.
The Ford Crown Victoria to Chrysler Neon scenario is chosen for this study. The initial velocity of each vehicle is varied between 20 to 60 *km/h* (resulting in closing speeds of 40 to 120 *km/h*) with a step size of 5 *km/h*.
Setting the closing speed at 40 *km/h*, rule (d) in the judgement of the algorithm (see equation 2.2) is not overruled for the Ford Crown Victoria. This results in no airbag deployment and therefore the firing time is set at 0.120 *s* (see figure 6.6 and also

appendix L.3). This results in a bigger firing time range for the Ford Crown Victoria compared to the Chrysler Neon.
For higher velocities the deformations are larger, resulting in higher injuries in both vehicles and the differences in injuries between the vehicles diminish (figure 6.6). As stated before in paragraph 5.3.3 for higher velocities intrusions and compartment collapse occur. As a result it is not possible to run simulations with closing speeds > 120 *km/h* in this car-to-car scenario.
During the stochastic study the initial velocity was kept constant and the results gave a flat area for injuries at a certain time range for a varying airbag firing time (see table 5.2). Setting the firing time at the value for the highest initial velocity, resulting in a correct fired airbag at high speeds, and performing simulations the results indicate that the injuries do not differ with the results of a varying airbag firing time. This means that setting the airbag firing time at the calculated time for high speeds results in a correct firing for also lower velocities.

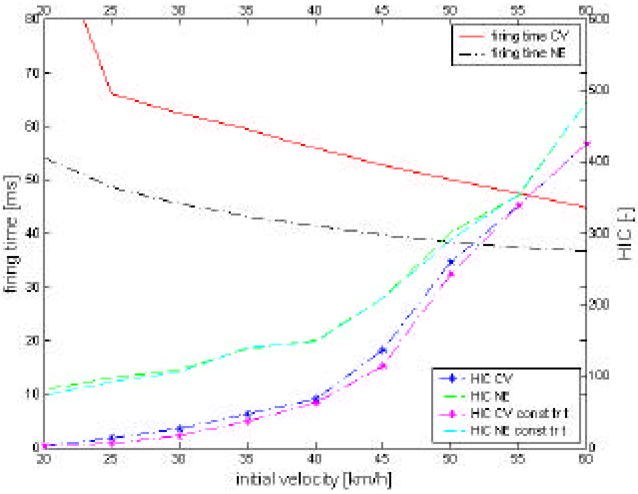


Figure 6.6 - Results Ford Crown Victoria to Chrysler Neon with varying initial velocity

6.2 Generic vehicle model

A PRISM vehicle model is used to evaluate the algorithm for generic models. The vehicle model represents the medium class vehicle models (e.g. Renault Megane). The input for the algorithm is exactly the same as for Multi-Body models: acceleration signal of the b-pillar and acceleration signal from the thorax.
The results of implementing the algorithm (table 6.2 and appendix M) in the generic vehicle point out that the algorithm is also working for generic models.

Table 6.3 Results implementation algorithm in generic model

acceleration signal		q_x [m]	firing time [ms]	HIC	AIR
Mazda6	original	-	25	416	0.400
	new	0.025	23.5	410	0.396
Megane II	original	-	25	875	0.795
	new	0.018	19.8	868	0.79

6.3 Results implementation

During the implementation of the airbag algorithm in the *VC-COMPAT* vehicle fleet several scenarios were investigated:

- Car to barrier: Full-width and Offset Deformable
- Car to car: six vehicle models with two modified COMPAT models
- Occupants: 5^{th}, 50^{th} or 95^{th} %-tile dummy
- Dummy movement: $?_X$
- Initial velocity
- Front-end stiffness
- PRISM model

The stochastic study in the previous chapter, using a car to Full-width barrier scenario, indicated that the value for the dummy movement ($?_X$) is independent for the dummy size and as a result in future studies only the dummy movement for the 50^{th} percentile has to be determined. The results also pointed out that in a certain airbag firing time range (e.g. 0.030 to 0.040 *s*) the injuries are independent of the firing time.
The car to Offset Deformable barrier scenario pointed out that for deformable objects the dummy movement is slower compared to rigid object, resulting in higher airbag firing times.
The results of the car to car scenarios, including different initial velocities and front-end stiffness' provided an increase of airbag firing times in every scenario. Implementing the results into a matrix or table, a database is created which is useful in further fleet studies. The database contains the airbag firing times for every possible scenario, see table 6.4 for an example. In this example in the COMPAT Geo Metro (G1) to Chrysler Neon scenario, the airbag firing time for G1 is 0.0248 *s* and for NE 0.031 *s*. Some scenarios cannot be run due to too large deformations.

Table 6.4 Optimal airbag firing times for different car-to-car scenarios

13.89 m/s		**firing time TARGET (t) [s]**						
		GE	**G1**	**NE**	**N1**	**TA**	**CV**	**EX**
firing time BULLET (b) [s]	**GE**	**t:** - **b:** -	**t:** 0.0274 **b:** 0.0357	#	**t:** 0.0331 **b:** 0.0336	**t:** 0.0296 **b:** 0.0363	**t:** 0.0546 **b:** 0.0393	#
	G1	**t:** 0.0357 **b:** 0.0274	@	**t:** 0.031 **b:** 0.0248	**t:** 0.00289 **b:** 0.0254	**t:** 0.0213 **b:** 0.0244	#	#
	NE	#	**t:** 0.0248 **b:** 0.031	0.0378	**t:** 0.036 **b:** 0.0376	**t:** 0.0195 **b:** 0.0311	**t:** 0.0499 **b:** 0.0384	**t:** 0.0318 **b:** 0.0327
	N1	**t:** 0.0336 **b:** 0.0331	**t:** 0.00254 **b:** 0.0289	**t:** 0.0376 **b:** 0.036	0.036	**t:** 0.0191 **b:** 0.0314	#	**t:** 0.0315 **b:** 0.0322
	TA	**t:** 0.0363 **b:** 0.0296	**t:** 0.0244 **b:** 0.0213	**t:** 0.0311 **b:** 0.0195	**t:** 0.0314 **b:** 0.0191	0.0266	**t:** 0.0499 **b:** 0.0301	**t:** 0.0278 **b:** 0.0176
	CV	**t:** 0.03936 **b:** 0.0546	#	**t:** 0.0384 **b:** 0.0499	#	**t:** 0.0499 **b:** 0.0301	0.0507	**t:** 0.023 **b:** 0.0414
	EX	#	#	**t:** 0.0327 **b:** 0.0318	**t:** 0.0322 **b:** 0.0315	**t:** 0.0176 **b:** 0.0278	**t:** 0.0414 **b:** 0.023	0.0192

- No airbag deployment required
Unable to run scenario
@ Scenario does not exist

In the first cell an initial velocity of 13.89 *m/s* (= 50 *km/h*) is given. This parameter is exchangeable with a different initial velocity, thus creating new airbag firing times, or with a different parameter, e.g. front-end stiffness. And as a result for every scenario a matrix like table 6.4 is created and in further fleet studies, the airbag firing time for the target and vehicle car is chosen from the database and simulations are performed with the correct airbag firing time.

Implementing the algorithm in a PRISM vehicle model, pointed out that the algorithm is not only capable of determining the airbag firing time in the *VC-COMPAT* Multi-Body vehicle fleet but also for generic vehicle models.

7 Conclusions & Recommendations

The objective of this study was to develop an airbag triggering algorithm with a crash (primary focus) and occupant (secondary focus) dependent airbag firing time in a numerical vehicle fleet. To solve this problem a number of tools were needed. The literature survey provided an algorithm concept based on a simple mass-damper model, and together with a Simulink scheme and a numerical vehicle fleet a judgement (based on vehicle acceleration and dummy movement) for determining the airbag firing time was developed. Out of the results of implementation of the concept airbag algorithm in a numerical vehicle fleet is concluded:

- The dummy movement is the most important rule in this algorithm judgement

  The values for the dummy movement of every vehicle model and dummy size is determined using the scatter plots of the stochastic study (§5.3.1)

- The head injury criterion (HIC) is the most sensitive injury criterion above the 3MS and FFC for variation in airbag firing times (§5.3)

- The stochastic study indicated that there is a flat area for the injuries within a certain airbag firing time window for every vehicle model in the *VC-COMPAT* fleet with different occupants (5^{th}, 50^{th} or 95^{th} percentile dummy)

- The influence of a different front-end stiffness (75 to 150% of original stiffness) on the airbag firing time has no influence in car to barrier scenarios. However, in car to car scenarios the influence of the front-end stiffness depends on the car to car crash scenario

  The airbag firing time is changing more in the Ford Explorer to Chrysler Neon scenario compared to the Ford Crown Victoria to Chrysler Neon (§6.1.2.2)

- Changing the initial velocity results in no required airbag deployment for low initial velocities to an early airbag deployment

  No airbag deployment is required for $v_{initial}$ = 15 *km/h* in the Chrysler Neon to Full-width barrier scenario, compared to an airbag firing time of 0.030 *s* for $v_{initial}$ = 60 *km/h* (§5.2.3)

- The airbag algorithm is suitable for Multi-Body and generic vehicle models. As long as the linear acceleration output file contains the acceleration signal of the vehicle and occupant, the algorithm will also be usable for Finite Element models and other types of numerical vehicle models

- The airbag algorithm is able to create a database that contains the airbag firing times for every possible scenario (see table 6.4 for an example). Combining the database with a scenario builder, the correct airbag firing time is selected

The overall conclusion is that the algorithm developed in this study is able to predict a realistic airbag firing time for different crash scenarios in the numerical Multi-Body *VC-COMPAT* vehicle fleet. In paragraph 4.1.1 other airbag parameters (e.g. sheet thickness and mass flow) are given that can influence the airbag deployment process. These parameters are kept constant during this study. However, modifying these parameters can influence the airbag deployment and as a result also the airbag firing time.

However, some recommendations can be formulated for further improvement of the airbag algorithm:

- The generic airbag models in the *VC-COMPAT* vehicle models are modified during the development and implementation of the algorithm for a more realistic airbag deployment and therefore the modifications should be used in further fleet studies.
- The Euler integration method is preferred above the Runge-Kutta4 integration to avoid instability in the airbag deployment. Therefore this integration method should be used in the rest of the vehicle fleet
- Using an intelligent algorithm based on a Hidden Markov model [14], as described in the literature survey, the crash pulses gathered through simulations can be used to train the Hidden Markov model in order to recognise the pulse and determine if the crash is severe enough for airbag deployment. Using the algorithm developed in this study, the correct airbag firing time can be selected from a database (created with the airbag algorithm) or calculated if the scenario does not exist in the database
- Another solution to avoid a pre-simulation is to create a real-time linkage between Matlab and MADYMO. To create this linkage will determine the need for airbag deployment or not and can directly deploy the airbag. As a result a pre-simulation will be unnecessary. However, to create this link will increase the simulation time dramatically

Due to the fact that car manufacturers and OEM suppliers do not publicise their airbag algorithm, it is difficult to develop an algorithm that behaves exactly as the algorithm modelled in real life. However, the algorithm developed in this study can be used as a useful guide when new numerical vehicle models are developed and there is no knowledge of the airbag firing time.

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Abbreviations

3MS	3 millisecond criterion
AC	Alternating Current
AIR	Absolute Injury Risk
AIS	Abbreviated Injury Scale
DOE	Design of Experiments
ECU	Electronic Control Unit
EC	European Community
ESV	Enhanced Safety of Vehicles
EuroNCAP	European New Car Assessment Program
FEM	Finite Element Method
FFC	Femur Force Criterion
FMVSS	Federal Motor Safety Standard
FWB	Full-width barrier
HIC	Head Injury Criterion
HMM	Hidden Markov Model
IMM	Initial Metric Method
MB	Multi-Body
MDB	Movable Deformable Barrier
NHTSA	National Highway Traffic Safety Administration
ODB	Offset Deformable Barrier
ODE	Ordinary Differential Equation
OOP	Out Of Position
OPC	Occupant Performance Criterion
SIR	Severe Injury Ratio
USNCAP	United States New Car Assessment Program
VC	Viscous Criterion
VC-COMPAT	Vehicle Crash COMPATibility

A Examples of algorithms

Individual/Organisation	Main theme or features	Approach
Diller et al / TRW	Total and partial energies	Energy in time domain
Allen / ASL	Power rate	Energy + jerk + acceleration + ?V
Gioutsos / ASL	Waveform recognition	Jerk
Watanabe, Umezawa	Optimal triggering	Predicted displacement + acceleration + jerk + energy
Mattes et al. / Robert Bosch GmbH	Adjustable velocity threshold	? V
Diller / TRW	Summation of expert circuits	?V + jerk + displacement
Eigler and Weber / Siemens	Multiple evaluation circuits and time window	Acceleration recognition + velocity + displacement
Tohbaru/Honda, Blackburn/TRW, Blackburn & Gentry/TRW	Power of acceleration signal in an frequency range	?V + energy in frequency domain
Cashler and Kelly / Delco Electronics	Occupant displacement and crash severity	Jerk + acceleration + ? V + displacement
McIver et al / TRW	Crash velocity and crash metrics	?V + acceleration + shape function
Sada and Moriyama / STC	Adjustable velocity based on physical quantities	Jerk + acceleration + ?V + displacement
Kosiak / Delco Electronics	Crash sensing using anticipatory sensor inputs	Acceleration scaling with anticipatory sensors

Signals and variables for algorithms

Signal/variable	source
Speed change	Integrated from acceleration signal. The threshold value for speed change in an electronic sensor can be adjustable. The ?V variable is often used in conjunction with other variables and is present in almost all algorithms. The speed change variable remains an essential element of crash detection
Acceleration	Raw output from the accelerometer is usually filtered before it is used in calculation. The acceleration magnitude is often compared to a threshold value before a crash condition is recognised. Most algorithms utilise the acceleration value in a manipulated manner, but not directly
Jerk	Derivative of acceleration signal. A filter is usually involved before consecutive acceleration values are used in the differentiation calculation. The jerk value is then used as an indicator of the crash severity. It may be combined with other variables to avoid direct usage, such in the power rate method. The jerk variable can also be used to modify the calculation of other variables in the algorithm
Energy	Correlates well with the severity of a collision. The physical meaning of an energy change during a collision can easily be comprehended. The energy

	variable can also be used in other forms, such as in the power rate method
Displacement	Direct measurement of occupant displacement is not a reliable index of crash severity. However, in several algorithms the predicted occupant displacement derived from the acceleration signal is proposed as a predictor. In particular, the predicted displacement at a certain time period ahead is used to determine the proper or optimal timing of restraint deployment. The robustness of these algorithms depends on the accuracy achieved in estimating the occupant displacement