

The Crash Pulse in Rear-End Car Accidents

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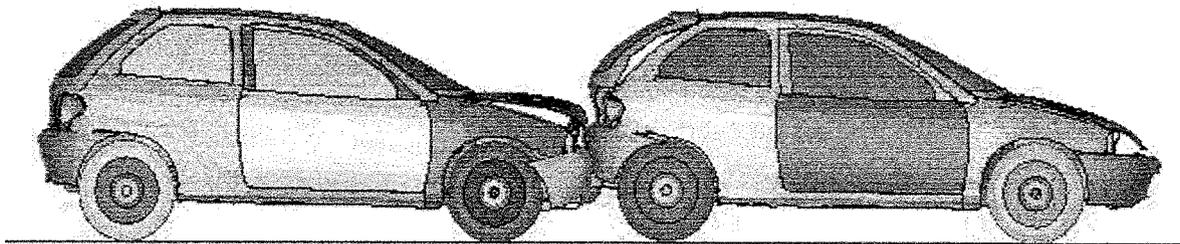
The Influence of:
Under-ride, Over-ride, Offset and a Tow-bar

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DCT 2002.68



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Gothenburg, 6 December 2002



Preface

In the last decade a lot of research is done regarding frontal collisions, especially at frontal offset crashes. This has led to a better front structure for offset crashes. However, not much attention yet has been paid to rear-end collisions, because according to statistics rear-end crashes are only a small part of all crashes.

However, the database from the Swedish insurance company Folksam and research show that rear-end collisions have twice a higher risk for whiplash injuries than frontal ones. Looking at the costs of injuries, the costs from whiplash injuries are taking a large part of the total costs and are growing steadily, and therefore research has to be done for diminishing those costs.

Nowadays lots of cars have tow-bars for e.g. towing their caravan or putting their bike on bicycle racks. But most of the times it is not used at all. So why not take it off when not using it. There are already detachable tow-bars. The main reason for developing it was from the design point of view.

If you look at the material properties of a tow-bar, it can be considered as a rigid element compared to the other components at the back of the car (e.g. plastic bumper). Therefore this change in rear-end structure can have influence on the crash pulse in a rear-end crash. Folksam and Autoliv already investigated the effect of a tow-bar in rear-end collisions by doing some full-scale crash tests, but these were single test conditions. The aim of this study is see what the effect is in multiple test conditions.

Abstract

The aim of this study is to see what the influence of tow-bars is in rear-end collisions, hereby looking at the crash pulse. The database from the Swedish insurance company Folksam and some full-scale tests performed by Autoliv [1, 24] give an indication that the tow-bar increases the injury risk. The increased average acceleration correlates to the increased injury risk.

First of all a literature survey is done to see what is already known about rear-end crashes. The survey show that there is a twice a higher risk for whiplash injuries in rear-end collisions than frontal ones, but there are more frontal collisions than rear-end collision. Therefore there are more people with whiplash injuries from frontal collisions.

For further investigation of rear-end collisions it is good to know what the distribution of this type of collision is. This distribution was found in the Whiplash II report [8]. Apparently 56% of all rear-end crashes are full overlap and 28% of rear-end collisions have $\frac{1}{3}$ to $\frac{2}{3}$ overlap. It is not interesting to investigate the 0 to $\frac{1}{3}$ overlap situation (14,2% of all rear-end collisions) in this study, because it is a small part of all rear-end crashes and the striking car is not going to hit the tow-bar of the struck car in this configuration.

In a report from Krafft et al [18] and from a report from Autoliv [1] some research has been done to see what the influence of a tow-bar is. The results show that there is an increase of 22% in risk of getting a CSD when a car has a tow-bar. The crash pulse is also different. However, only one full-scale test was done, so no conclusions could be made in other test configurations, which is shown in a report from Meyer et al [12].

The latest database from Folksam and full-scale test performed by Autoliv [24] show that 2 other parameters are influencing the crash pulse. They found that an under and over ride situation have also influence on the crash pulse.

Now all the relevant data is known, a test set up for simulation is made. Looking at the data gained from the literature survey the next 3 strategies are formulated:

1. Influence of under/over ride on the crash pulse
2. Influence of the amount of overlap on the crash pulse
3. Influence of a tow-bar on the crash pulse at different amounts of overlap and under/over ride

For strategy 1 the configuration is altered to create the under/over ride situation and for strategy 3 the tow-bar is modeled and then added to the struck car.

The results show that is not good having a rear-end collision with over ride with or without a tow-bar. The under ride configuration will give lower acceleration in the first 75 ms of the crash, thus it is better having under ride. Adding the tow-bar gave a stiffer pulse, but it is still safer to have an under ride situation with a tow-bar than the standard configuration.

In the partial overlap configuration can also be concluded there is less risk of getting a WAD than in the standard configuration. A tow-bar on the struck car in offset crashes led to higher accelerations. This proofs that the results of the single test conditions from Autoliv are also applicable to other conditions.



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Symbols & Terms

| Variable | Meaning | Unity | Unity EASi-CRASH |
|-------------------|--|----------------------|-----------------------|
| a | acceleration | [m/s ²] | [mm/s ²] |
| v | velocity | [m/s] | [mm/s] |
| Δv | change in velocity | [m/s] | [mm/s] |
| Δv_{85ms} | Δv during the first 85 ms of the crash pulse | [m/s] | [mm/s] |
| E | Young's modulus | [N/m ²] | [N/mm ²] |
| g | gravity | [m/s ²] | [mm/s ²] |
| ρ | density | [kg/m ³] | [kg/mm ³] |
| ν | Poisson's ratio | [-] | [-] |

| TERM | MEANING |
|------------|--|
| CDC | Collision Deformation Classification |
| CPR | crash pulse recorder |
| CSD | Cervical Spine Disorder |
| EBS | equivalent barrier speed |
| EES | equivalent energy speed |
| ESV | Enhanced Safety of Vehicles |
| FEM | finite element method |
| IRCOBI | International Research Council On the Biomechanics of Impact |
| LDN | long term disabling neck injury |
| NCAC | National Crash Analysis Center |
| NIC | Neck Injury Criterion |
| over ride | the striking car will <u>go up</u> because of the construction of both cars |
| QTF | Quebec Task Force |
| under ride | the striking car is going <u>under</u> the struck car because of the forward pitch when hitting the brakes hard in pre-crash |
| WAD | Whiplash Associated Disorder |

Chapter 1 Literature survey

The survey was done following the next questions:

1. What type of rear-end accidents should be studied? Full overlap or offset?
2. What factors influence the risk of getting a WAD?
3. What factors influence the crash pulse?
4. What is the change in velocity (Δv) in rear-end collisions and its relationship with the level of injury?
5. What is the duration of rear-end collisions?
6. Is there a difference in crash pulse for full overlap and offset collisions?
7. What is the influence of a tow-bar in rear-end collisions and is there a relation with overlap?

1.1 Results literature survey

The results of the literature survey are presented in the same order as the formulated questions.

1.1.1 Type of rear-end collision

Not all rear-end collisions are the same. They differ how the cars strike each other. Therefore it is helpful to know what the distribution of the collisions is. The German insurance company HUK Coburg [8] has a database concerning rear-end collisions, but no specification of the percentage of overlap is given (see table A.1 and A.2 in appendix 2). The distribution used in this database is according to the CDC index (Collision Deformation Classification, SAE J224 MAR80, SAE 1981). Every type of collision has an index 'x.y'. The first index 'x' is for the type of accident (frontal '1', right '2', rear-end '3' or left '4'), the second 'y' is for the region (see figure 1.1). For rear-end collisions the second index means:

1. 0 to $\frac{1}{3}$ overlap left
2. center (e.g. hitting a pole)
3. 0 to $\frac{2}{3}$ overlap on the right
4. $\frac{1}{3}$ to $\frac{2}{3}$ overlap on the left
5. $\frac{1}{3}$ to $\frac{2}{3}$ overlap on the right

The contents of this database gives enough data to get an idea what the distribution of rear-end collisions is. No other databases were found containing more detailed data than the database from HUK Coburg.

1.1.2 Influences for WAD

There are a lot of factors influencing the risk of getting a WAD (Whiplash Associated Disorder). The following factors were found:

- Construction of the struck/striking car [4]
- Short terms symptoms are strongly related to Δv [5]
- Long term symptoms seem to be more related to the acceleration [5]

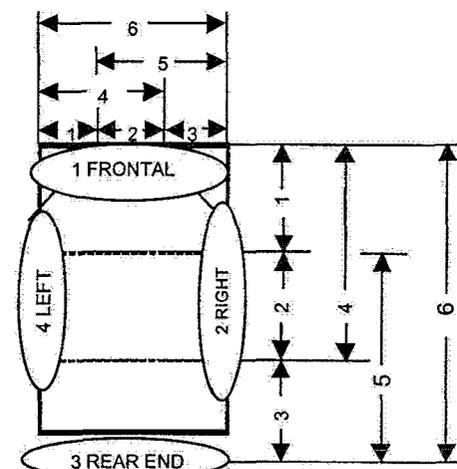


Figure 1.1: CDC index; adopted from Whiplash II report [8]

- Gender (male/female); a female has a twice higher risk of getting a WAD than a male [8]
- Height of the body; there is a higher risk for higher bodies and the influence is bigger for female occupants [8]
- Mass ratio between struck and striking car; the heavier the striking car, the higher the risk for WAD for the driver of the struck car [8]
- Shape of the crash pulse; it is reasonable to believe that during the first part of the acceleration a "stiff" impact pulse will cause greater movement than a "soft" impact pulse; a "stiff" pulse will cause a high neck movement [6]
- Seat design; a bad seat design raises the risk of getting a WAD [7]
- Frontal or rear-end crash; the risk to suffer a CSD is twice as high for rear-end collisions than for frontal crashes [8]
- The use of airbags; cars with airbags can take a higher acceleration level for the same neck injuries than cars without airbags [8]
- The use of a tow-bar; the NIC-value is higher when a tow-bar is mounted, see figure 1.2 [1, 6]

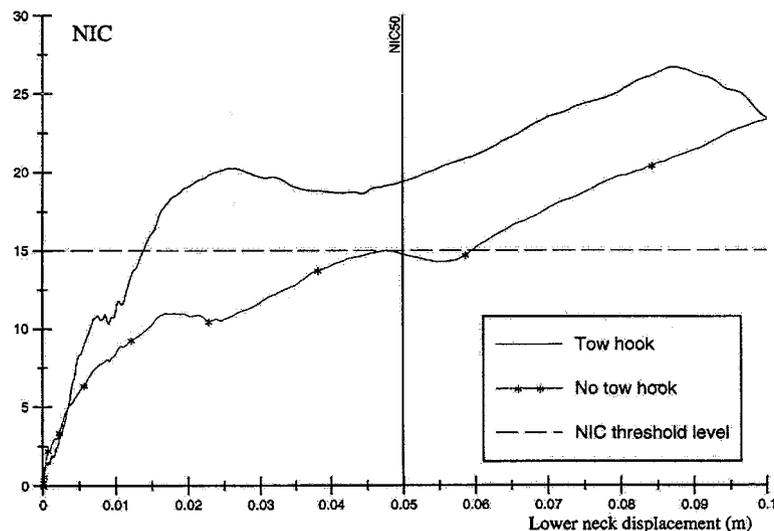


Figure 1.2: NIC values with or without tow-bar; adopted from Autoliv report [1]

1.1.3 Parameters for crash pulse

In this study there was much interest in the parameters that influence the crash pulse. The following parameters were found in the literature:

- Construction of the struck/striking car; it is reasonable to believe that during the first part of the acceleration a "stiff" impact pulse will cause greater movement than a "soft" impact pulse [2, 4]
- Under ride or over ride: this means of the striking car is going under the struck car because of the forward pitch when hitting the brakes hard in pre-crash or will the striking car go up because of the construction of both cars [24]
- The latest results from full-scale rear-end crashes from Autoliv [24] give the same indication and also that under and over ride has a major influence on the crash pulse. In one of the tests the front suspension was lowered to simulate pre-crash hard braking. This will influence the amount of under ride
 - The amount of nose-diving (forward pitch) depends on the vehicle model and make
 - Nose-dive tests at the Jiken Center, Japan [17] with a Toyota Corolla NZE120 showed that the car dived 15 to 45 mm depending on the amount of braking



- Tests at Thatcham with a Ford Mondeo (year model 1993) resulted in 120 mm nose-dive [25]
- Use of a tow-bar [1], but this was a single test condition, the influence of the tow-bar is not automatically applicable to the other test conditions, see [12]
- Full overlap or offset; the car will absorb less energy in an offset collision than in a full overlap, this will influence the crash pulse [9]

1.1.4 Value of Δv and relation with injury

The value of the change in velocity can be important for the amount of whiplash injuries and the NIC (Neck Injury Criterion) value. The following Δv -regions and relations were found:

- According to [2, 20] neck injuries in rear impacts mostly occur at low impact velocities, typically less than 20 km/h
- According to [7] the majority of the crashes have a Δv between 10 and 40 km/h
- According to a report from Folksam [8]:
 - $\Delta v_{\text{average}} = 20$ km/h for injuries during more than 1 month
 - $\Delta v_{\text{average}} = 10,3$ km/h for injuries recovering within 1 month
- Data from GDV, German insurance company [8]: $\Delta v_{\text{average}} = 17,4$ km/h
- According to various studies [3, 4, 21] rear-end collisions resulting in Δv 's below 20 km/h constitute the major part of crashes resulting into neck injuries. Eichberger et al estimated Δv to be lower than 25 km/h for 94% of the struck cars involved in rear-end impacts with insurance claims for injuries
- The mean crash pulse for occupants with symptoms more than 6 months is found to be in the order of a Δv of 25 km/h, a mean acceleration of 6 g with a peak acceleration of approximately 12 g. In addition to a test that represent the severity level where most injuries occur, it would be desirable to have a test at higher severity, $\Delta v > 20$ km/h and $a_{\text{mean}} > 5$ g, to present the more long term WAD risk [7]
- Regression analyses showed that the commonly used change in velocity, Δv is not a good predictor of NIC_{max} , nor was the crash pulse peak acceleration. However, the change in velocity during the first 85 ms of the crash pulse, $\Delta v_{85\text{ms}}$, correlated with the NIC_{max} . Therefore the $\Delta v_{85\text{ms}}$ can potentially quantify impact severity [16]
- Crashes with low acceleration and high intrusion cause higher risk than other combination for Δv between 36 and 65 km/h [22]. Tarrier and Foret-Bruno et al [22] found that the upper body injury is associated with deceleration.
- Insurance statistics indicate that the most significant frequency of injury occurs in low speed impact with Δv calculated in the 10 to 25 km/h ranges [23]. Using these results a Δv of 16 km/h was calculated as representing the most at risk collision speed.

1.1.5 Duration of collision

For the simulation part the duration of a rear-end crash is important. The duration is one of the key factors for the total calculation time.

Kullgren et al [7] did some research concerning 40% overlap and full overlap. The results the following length of crash pulse were:

- 40% overlap: length crash pulse varied from 41 to 123 ms
- Full overlap: length crash pulse varied between 65 and 95 ms

To be on the safe side that all deformation has taken place it is better to set the length of the simulation at 150 ms. But this can only be determined for certain after some test simulations.

1.1.6 Difference crash pulse between full overlap and offset

Kullgren et al [7] have done some research to see what the difference is between collisions with 40% offset and full overlap. The results were:

40% overlap: a_{peak} varies from 2,8 to 7,0 g

a_{mean} is between 1,3 and 3,7 g (same car as 100% overlap)

Δv is between 4,3 and 11,0 km/h (same car as 100% overlap)

100% overlap: a_{peak} varies between 11,0 and 30,6 g

a_{mean} is between 3,5 and 7,0 g (same car as 40% overlap)

Δv is between 11,0 and 18,8 km/h (same car as 40% overlap)

In this report from Kullgren nothing was said about the difference of the shape of the crash pulse.

1.1.7 Influence of a tow-bar

Insurance statistics from Folksam indicate that cars with and without tow-bars differ in terms of neck injury risk. In order to study the influence of a tow bar Krafft et al [18] did two full-scale car-to-car rear-impact tests. The result was that the risk for LDN (Long term Disabling

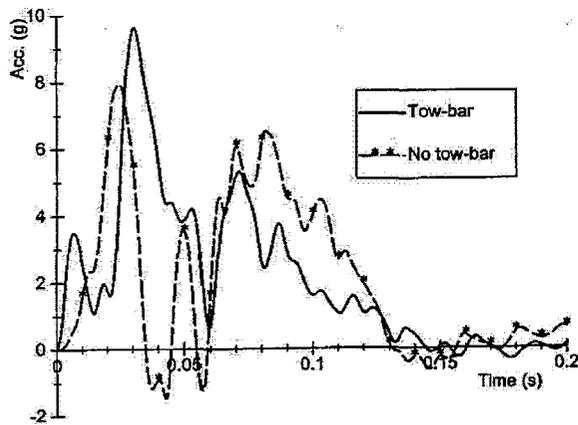


Fig. 1. Target car acceleration.

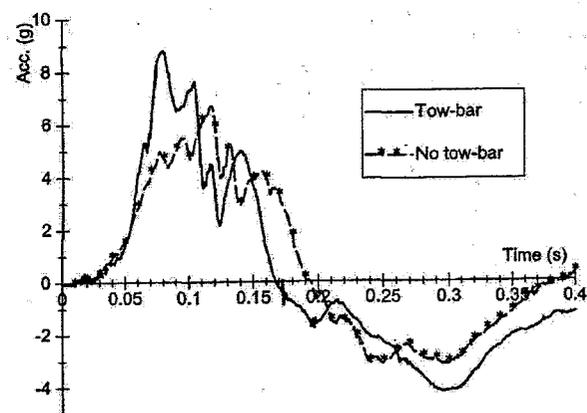


Fig. 2. Lower neck x acceleration.

Figure 1.3: Influence tow-bar on crash pulse; adopted from Krafft [18]

Neck injury) is about 22% higher for cars with a tow-bar than without one. The shape of the crash pulse is also different (see figure 1.3). However, considering this was a single test condition the influence of the tow-bar is not automatically applicable to other test conditions, see Meyer [12].

Krafft did not do any research in this report to see what the difference in crash pulse will be for offset collisions.

The full-scale tests performed by Autoliv in May 2002 [24] gave the same indication that it is not good having a tow-bar.

1.2 Aim of the present study

The aim of the present study was to investigate the influence of a tow-bar on the crash pulse in rear-end collisions. The literature survey gave more parameters that are interesting to investigate their influence on the crash pulse. Therefore the following parameters were also taken into account in this study: the influence of under/over ride and the amount of overlap.

Chapter 2 Simulation set up

To simulate the effect of some parameters on the crash pulse the simulation 3 strategies were formulated:

1. Influence of under/over ride on the crash pulse
2. Influence of the amount of overlap on the crash pulse
3. Influence of a tow-bar on the crash pulse at different amounts of overlap, under ride and over ride

2.1 Strategy 1: under ride and over ride

The latest database from Folksam and the full-scale rear-end crashes performed in May 2002 [24] by Autoliv shows that under ride and over ride influence the crash pulse. Therefore these parameters were taken into account in this study.

The standard rear-end crash configuration was altered to create an over/under ride effect. Creating an under ride situation will also simulate the same effect as pre-crash hard braking. Braking very hard will produce a forward pitch of the car. However, the amount of pitch varies from vehicle model and make [17]. This made it very difficult to simulate the correct amount of pre-crash hard braking. Therefore different amounts of over ride and under ride were simulated.

2.2 Strategy 2: amount of overlap

The Whiplash II report [8] provides a database concerning the distribution of rear-end collisions. According to this database (HUK Coburg) 56% of all rear-end crashes have full overlap and 28% have an overlap between $\frac{1}{3}$ to $\frac{2}{3}$. It was not interesting to look at collisions with less than $\frac{1}{3}$ overlap, because the number of collisions having that amount of overlap is minor. The main focus was on full overlap, but it was still interesting to see how much the crash pulse will change for offset situations, especially in the $\frac{1}{3}$ to $\frac{2}{3}$ overlap situation. In this configuration the longitudinal member of the striking car is probably going to hit the tow-bar of the struck car, resulting in a “stiff” crash pulse in the first phase of the collision. Therefore 3 offset configurations were simulated: $\frac{1}{3}$, $\frac{1}{2}$ and $\frac{2}{3}$.

2.2.1 Energy distribution

To get an indication how the crash pulse will change in offset situations it can be useful to look at the energy distribution. According to Witteman [9] and De Santis [19] a longitudinal member will absorb about 25% of the impact energy in frontal crashes (see figure 2.1). In this case the crash was divided into 2 parts. In an offset crash of $\frac{1}{3}$ overlap the structure will absorb about 25% of the energy during the first half. During the second part about 35% will be absorbed. Altogether, only 40% of the total energy will be absorbed. This will result in a different crash pulse in a full overlap collision compared with an offset one.

A crash with less than $\frac{1}{3}$ overlap only leads to a higher intrusion level in the side structure (sill and door) and not in front of the occupant [9]. This influences the crash pulse, but this type of overlap was not taken into account in this report.

The energy distribution shown in figure 2.1 is for frontal collisions, but it was assumed that the striking car will have the same energy distribution when the car crashes into the back of another car.

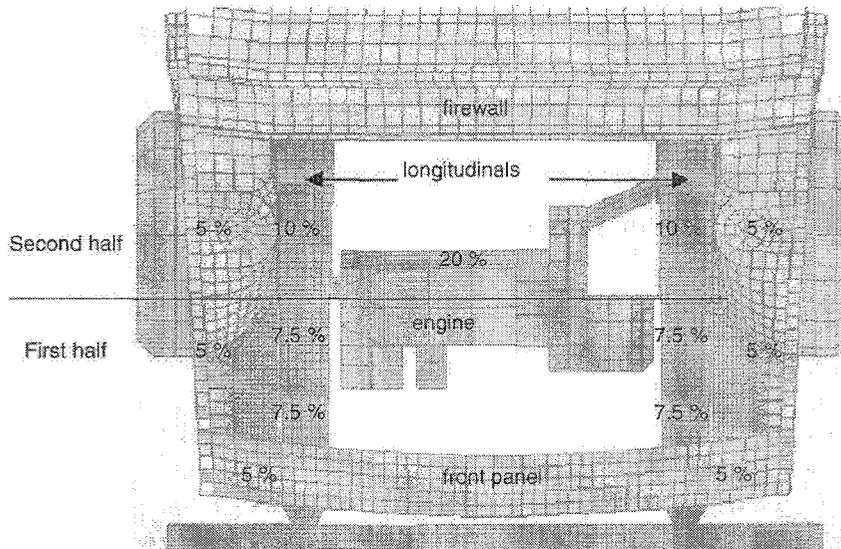


Figure 2.1: Energy absorption of front side; adopted from Witteman [9]

No energy distribution was found for the rear of a car. However, there are also 2 longitudinal members mounted on the rear of the car like the front. Therefore the energy absorption of the rear-end will also be different (like frontal impacts) in full overlap rear-end collisions or offset crashes. The difference in energy absorption will lead to difference crash pulses for full overlap and offset rear-end collisions.

2.3 Strategy 3: tow-bar

The database from the Swedish insurance company Folksam [24] shows that a tow-bar increases the risk of getting a WAD. Since there was no database found in the literature survey containing data from other countries on the effect of a tow-bar, the focus of this study was be on Sweden. To get results that can be compared to the database from Folksam, the same sort of tow-bar that is mounted on Swedish cars (e.g. a Volvo or Saab) was modeled. Autoliv did some full-scale tests in 1998 [1] and in May 2002 [24] to see what the effect of a tow-bar is. Since they were single test conditions, the results only give an indication what the influence of the tow-bar is. By running computer simulations with and without a tow-bar in different test set ups this study can give a more clear indication of the effect of a tow-bar.

2.4 Initial velocity of the striking vehicle

To simulate a rear-end collision the striking car was given an initial velocity. After colliding with the struck car there will be a change in velocity (Δv). Several databases have a different point of view concerning the change in velocity (see §1.1.4).

As mentioned before, the focus of this study is on the Swedish market, therefore the same Δv as in the report of Folksam [1] was used. This means $\Delta v = 15$ km/h. This change in velocity is high enough to get a good idea of the influence on the crash pulse of several parameters. The correct initial velocity was determined after running some simulations.



Chapter 3 Simulation

For simulation the preprocessor EASi-CRASH 1.6 and the simulation program LS-DYNA was used. First was decided which car model will be used. Then the car model was altered for each parameter (e.g. adding a tow-bar). In appendix 13 some more details can be read concerning problems encountered during the simulation.

3.1 Car used for simulation

The intention of this study was not to model a car for rear-end collisions. Therefore an existing FEM car model was used. The following car models can be used:

- Geo Metro: small car, detailed (193.200 elements) or reduced (15.670 elements) version; this is the US-version of the Suzuki Swift
- Ford Taurus: luxury car, modified, 28.400 elements
- Dodge/Chrysler Neon: midsize car, 272.200 elements
- Ford Festiva: small car, 9107 elements

These models were already available at the Machine and Vehicle Systems Department of Chalmers. They were downloaded from the web site of NCAC [13]. There are more cars available, but they are not representative for the European market.

A simple or reduced version of a car saves calculation time, but it is not sure if it can be used. Looking at the limited time of this study a model with reasonable computing time was needed. This led to a comparison between the following two car models: the reduced version of the Geo Metro and the Ford Festiva.

There are some differences on how the two cars are modeled (see table 3). The main problem of the models is that they are mainly developed for frontal crashes. Therefore the rear-end of the model probably has to be remeshed for more realistic behavior. For this study the tow-bar was the only part that had to be modeled.

| | Geo Metro (1998 2-door hatchback) | Ford Festiva (1989) |
|-----------------------|--|---|
| Method of development | vehicle geometry was collected from disassembled vehicles that were scanned and digitized. Material data and sheet thickness were gained through material laboratory testing | design was loosely based on a 1989 Ford Festiva weighting 820 kg. Only structural and critical components were considered. Efforts were made to ensure that the location of the center of mass was correct. However, there were no efforts made to match the moments of inertia |
| Intended usage | this vehicle was intended for use in front, corner and rear impact tests of rigid barriers | intended for use in full frontal and offset impact situations of roadside hardware |
| Verification | simulation of and verification against physical NCAP test results was planned but not yet performed in the studied reference literature | the results from the full frontal simulation were compared with physical crash test data |
| Modeling | symmetrical; geometry and mass density of the left-hand side are equal to the right-hand side | asymmetrical; left-hand side is modeled with a finer element net than right-hand. Entire body modeled as one component → more stiffer than reality |
| no of elements | 15670 | 9107 |
| General | not adapted for any particular impact load | rigid rear suspension |

Table 3: Difference between Geo Metro and Ford Festiva; adopted from ERAB report [14]

After considering the level of detail, computing time and differences between the cars the Geo Metro was chosen. The division of the elements for the Geo Metro is pretty good. The elements at the back of the car are a lot smaller than the elements from the Festiva. The Geo Metro has 2 longitudinal beams at the back to mount the tow-bar and the suspension is quite



realistic. It is not so easy to mount a tow-bar on the Ford Festiva. The Festiva has only 2 very simple straight beams to which the rear bumper is attached and this will need a lot of alterations when a tow-bar has to be added. The rest of the back of the Festiva has not that amount of detail to expect a good behavior in rear-end collision simulations. The computation time of the Geo Metro will be higher, but it is reasonable, especially if the computation can take place on 2 nodes on the LINUX-cluster[†]

3.2 Boundary conditions

3.2.1 Simulation length & time steps

The length of the simulation was determined by looking at the length of a normal rear-end collision. In §1.1.5 was decided to use 150 ms for the duration of the collision. To see if that assumption was right, first a length of 100 ms was used. If this length proves to be long enough, this will save calculation time. However the results showed that there was still too much acceleration and an increase of velocity for both cars. Therefore the simulation length was set at 150 ms. In EASi-CRASH a value of 0,15 s is set for the end time.

There are a couple of time steps that had to be set. The first time step is when the program should create an image of the collision. These images can be used later on to view the results and make an AVI-file. The step size is set to 5 ms. The second time step is the time step for the output file to create time history. This step size was set at $1 \cdot 10^{-5}$ s.

3.2.2 Initial velocity

To simulate a rear-end collision the striking car was given an initial velocity. The struck car is standing still, simulating it is waiting at a stoplight. The initial velocity simulates that the striking car is driving with a certain velocity before hitting the struck car. The correct value was not known, because the only known value is the Δv of the struck car, which is 15 km/h. Using some trial & error simulations the correct initial velocity is decided. It turned out to be that an initial velocity of 32 km/h gave the correct Δv . EASi-CRASH however uses millimeters instead of meters, so this means an initial velocity of 8888,88 mm/s was used.

3.2.3 Geometric contact

The contact between both cars had to be defined to let the program know which parts are going to hit each other. A sliding contact was defined between the rear-end of the struck car and the front of the striking car. The reason for not selecting both complete cars was to save calculation time and the speed is too low to deform both cars completely. For the striking car the front up to the B-sill was selected. The struck car was selected from the rear to the B-sill. In this study surface type number 13 was used. For the over ride situation the soft constraint formulation was used in stead of the penalty formulation.

The contact between the wheels and the surface also had to be defined. These contacts were defined after the surfaces were modeled. For each surface contact a node set was created with the wheels that are going to make contact with the selected surface.

[†] Computer system with multiple nodes (processors) that will speed up the calculation time varying from selecting 1 to 4 nodes

3.2.4 Surface

To simulate that both cars are driving on a ground a rigid wall was defined. In EASi-CRASH an infinite plane with a local axis was selected to use as the road surface. The friction coefficient of the plane was set to 0,9 [-] to simulate a very dry surface. This means there will not be any slipping of the wheels respect to the surface.

For simulating under ride 3 surfaces were needed. The size of the surfaces was calculated by measuring the distance between the front and rear wheels of the striking car. The size of the surface under the front wheels of the striking car was calculated using the displacement of the striking car in a standard rear-end collision. Finally the surface under the struck car was given a length that will be long enough for the displacement of the struck car.

The width for the surfaces was set at 3 times the width of the car. This gives enough room for the cars in a crash if the cars are going to jaw.

3.2.5 Gravity

The gravity also had to be added. This is done by assigning a body load with a load curve for a certain length of time. The length was set at 0,3 s with a scaling factor of 1 (the normal gravitation constant). The body load works in the z-direction and has a value of 9810 [mm/s²].

3.3 Alterations on the car model

For all the simulations it is necessary to put the cars as close as possible to each other. This will save calculation time moving the striking car to the struck car. Further several nodes were selected on parts of the car (see appendix 3) to gain data such as velocity, acceleration and change in energy. The node on the small beam under the driver (node ID 762027) was used for plotting the results.

3.3.1 Over and under ride

To simulate the influence of under ride on the crash pulse the front wheels of the striking car were placed on a higher surface. This is schematically shown in figure 3.1. By placing the front wheels on a different surface the car had to be rotated in order to get contact between the

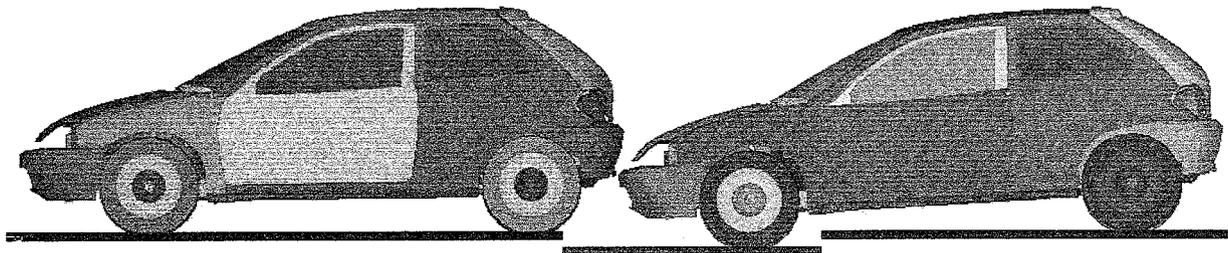


Figure 3.1: Representation of simulating under ride

wheels and the surface. The surface was placed 25, 50, 75 and 100 mm lower than the other 2 surfaces. The steps were used to see the change in crash pulse step by step. The amount of lowering to simulate pre-crash hard braking (thus creating under ride) was found to be realistic from results from different nose-dive tests [17].

To simulate the effect of over ride the complete striking car was placed on a higher surface (see figure 3.2). The same steps of 25 to 100 mm were used as in the under ride situation.

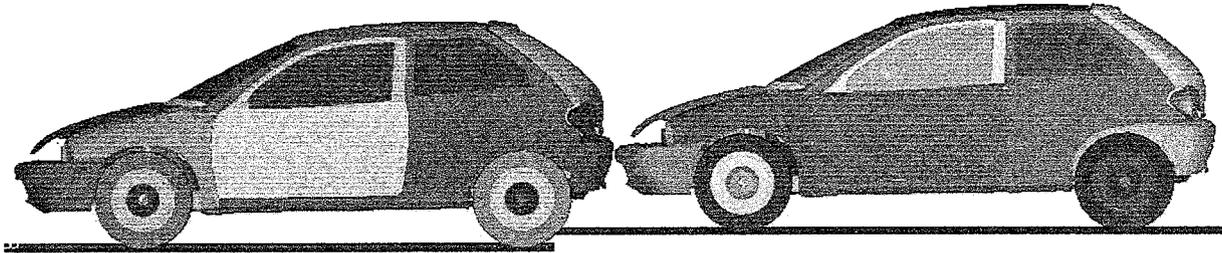


Figure 3.2: Representation of simulating override

3.3.2 Tow-bar

This study was focused on the Swedish market and therefore the same type of tow-bar that is mounted under a Volvo V70 P26 (model 2000) was modeled for simulation use. In appendix 4 is a picture of this tow-bar [15].

For modeling the tow-bar the material properties of the plates and beam were needed. The material properties for the tow-bar are given in table 4 [15]. The part numbers are shown in appendix 4.

| part | E-modulus [GPa] | density [kg/m ³] | ν [-] | size [mm] |
|--------|-----------------|------------------------------|-----------|----------------|
| A1, A2 | 205 | 7860 | 0,3 | thickness 10 |
| B | 205 | 7860 | 0,3 | 60 x 60 x 8 |
| C | 205 | 7860 | 0,3 | thickness 10 |
| D | 205 | 7860 | 0,3 | radius ball 36 |

Table 4: Material properties tow-bar

The tow-bar was modeled as simple as possible. All the parts were modeled using the shell element type. For part C and D the mesh is finer, because they will immediately have contact with the striking car. Part D was not modeled as a round ball, but a bit square-shaped. This is shown in appendix 5.

The tow-bar was mounted on the rear longitudinal members of the struck car by using the nodal rigid body constraint. This means that the nodes from the longitudinal members and tow-bar are connected to each other.

Figure 3.3 gives the setup for the rear-end collision with a tow-bar.

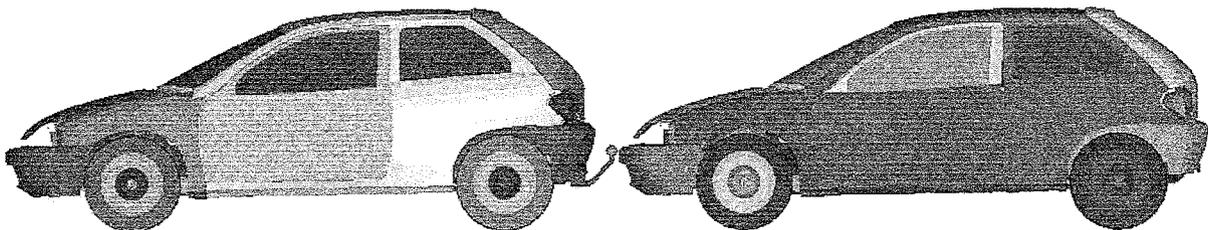


Figure 3.3: Representation of the rear-end crash with a tow-bar

The sliding contact between the struck and striking car was modified in such a way that the tow-bar is also part of the contact.

3.3.3 Amount of overlap

The amount of overlap can be set by simply translating the striking car to the right or left. To set a specific percentage of overlap, the width of the car was measured and then the amount of translation was calculated. The following offsets were modeled: $\frac{1}{3}$, $\frac{1}{2}$ and $\frac{2}{3}$ overlap. Only the effect of overlap on the left side of the struck car was simulated, assuming symmetry.

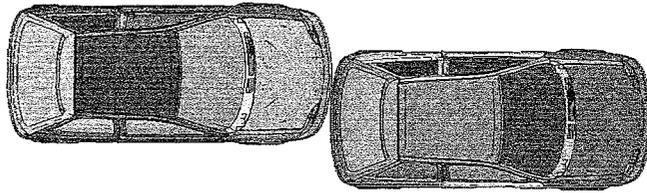


Figure 3.4: Top view 33% offset set up

For $\frac{1}{2}$ and $\frac{2}{3}$ overlap the translation was respectively 784 and 522,67 mm (see respectively figure 3.5 and 3.6).

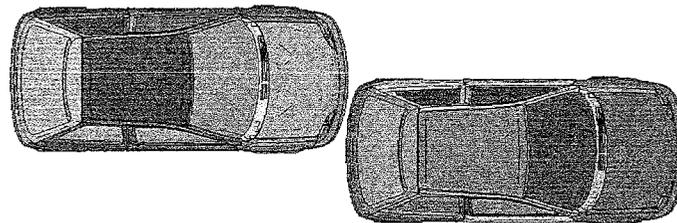


Figure 3.5: Top view 50% offset set up

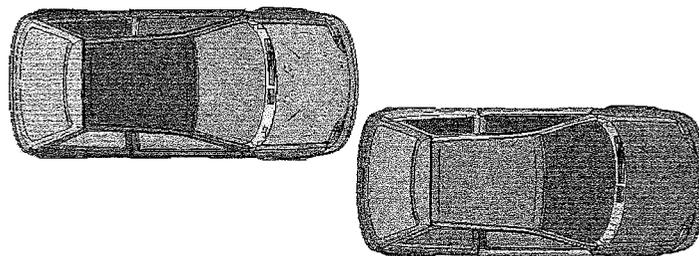


Figure 3.6: Top view 66% offset set up

Chapter 4 Simulation results

After running some simulations it was possible to say something about the influence of the parameters on the crash pulse. For easy use an extra line was added to the plots in the appendices 6 to 8 for $t = 85$ ms. There is a CD-ROM included with this report which contains all the data gained during this project. From every simulation 3 AVI-files were made: side, bottom and top-view of the collisions. These files can help explaining the acceleration and velocity curves.

First of all must be said that there was still some acceleration left at the end of the simulation in some cases, but the first part (until $t = 85$ ms) of the crash is the most critical for whiplash injuries [16].

4.1 Change in neck injury risk

The results of the simulations can not give a clear answer of the change in neck injury risk in the different crash conditions. However, according to Krafft [6] a “stiff” impact pulse during the first part of the acceleration will cause high neck movement than a “soft” pulse. Eriksson [16] found that the change in velocity during the first 85 ms correlates with the NIC_{max} . Therefore the Δv_{85ms} can potentially quantify impact severity.

Looking at the results of the simulation these studies can help to give an indication in change in neck injury risk.

4.2 Under ride results

The results of simulating an under ride situation are shown in figure 4.1. The main focus was on the x-acceleration and the change in velocity (Δv). Figure 4.1 displays the acceleration and change in velocity in x-direction of the struck car. The x-axis is defined along the longitudinal

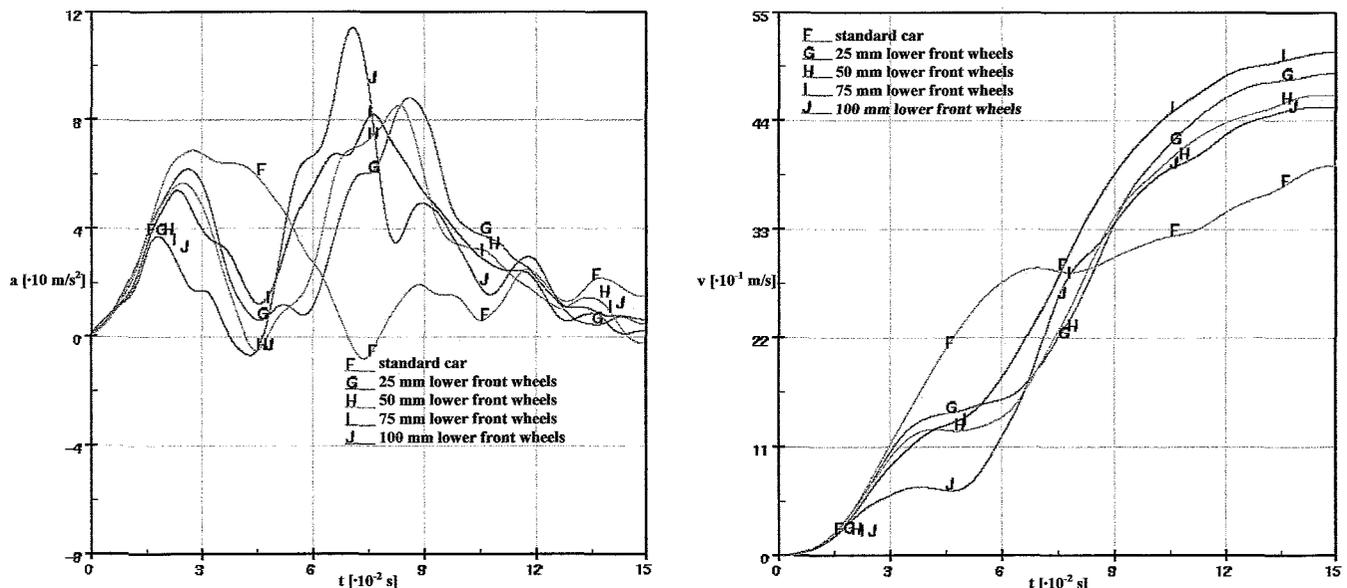


Figure 4.1: Acceleration and change in velocity of the struck car for under ride

axis of the car. The index of curves (letters F to J) is explained in table 6. Appendix 6 contains all the results for the acceleration and change in velocity. In the appendix curve G to J are compared separately with curve F.

| curve | under ride situation | over ride situation |
|-------|------------------------------------|----------------------------|
| F | standard car (no adjustments made) | |
| G | 25 mm lower front wheels | 25 mm higher striking car |
| H | 50 mm lower front wheels | 50 mm higher striking car |
| I | 75 mm lower front wheels | 75 mm higher striking car |
| J | 100 mm lower front wheels | 100 mm higher striking car |

Table 5: Explanation of the index of curves

It can be seen that the first peak is lower (from 7 to 4 g) in the under ride configurations. The area under the peak is also smaller. The negative peak (for the standard configuration round 75 ms) maintains its value, but it is shifted forward. The second peak (for the standard collision just before 90 ms) is increasing in duration and height. The reason for the change in the first peak is that the striking car is sliding more and more under the struck car (see also the bottom-view AVI-files on the CD-ROM). This results in folding of the hood and bumpers and not hitting the longitudinal members or other stiff parts. This can also be seen on the AVI-files. With more under ride the striking car is sliding more under the struck car and lifting it more. This results that the longitudinal members are hit later when stiff parts (e.g. the engine) of the striking car hits the struck car. This results in the second acceleration peak.

Comparing the Δv -curves of the standard situation with the curves for the under ride configuration, the standard configuration has a faster increase of speed in the first 85 ms. This indicates that there will probably result in a higher NIC value [6, 16].

Therefore an under ride situation is probably safer in rear-end collision. These results are in line what Autoliv found in the full-scale tests that they performed in May 2002 [24].

Hereby must be said that the cars are already shaped at the front and back that a small amount of under ride will automatically happen in the standard rear-end collision.

4.3 Over ride results

For the over ride situation the G to J curve now represents the striking car on a higher surface. It was put higher on a higher surface with the same amount the front wheels were put lower (see table 5). The results for the acceleration and change in velocity are shown in figure 4.2.

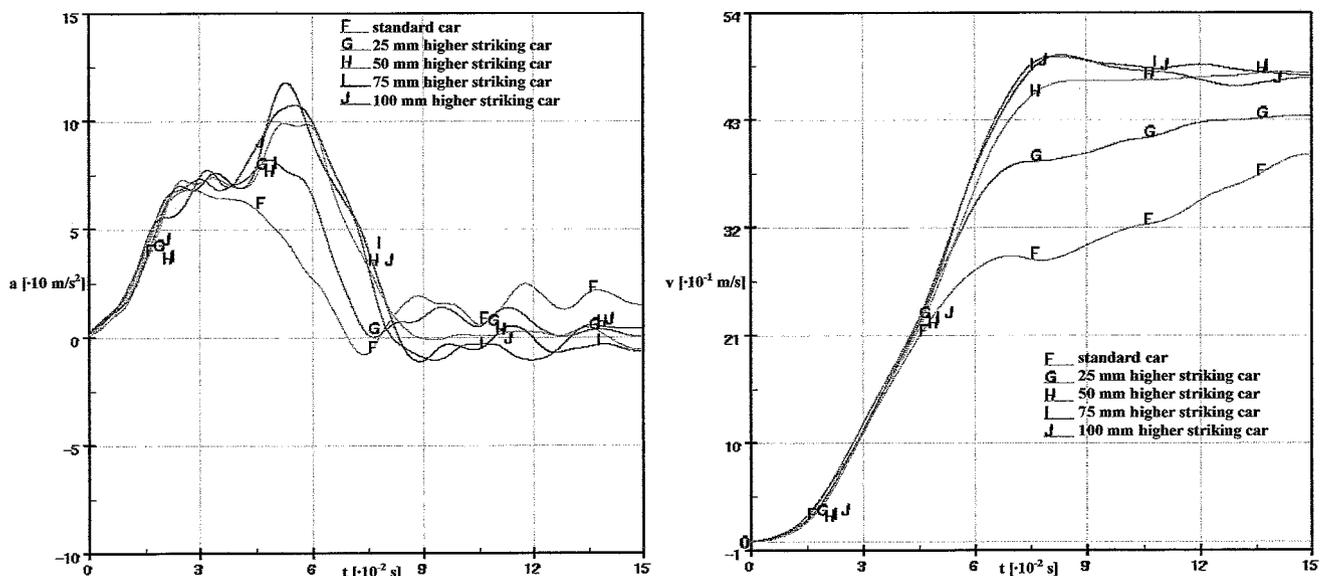


Figure 4.2: Acceleration and change in velocity of the struck car for over ride



In appendix 7 the curves are plotted again, but the G to J curve are compared separately with the standard configuration.

The acceleration peak beginning at $t = 0$ ms is getting higher and the duration increases. In the standard configuration the peak acceleration is 7 g at 30 ms, whereas the 100 mm higher striking car gives the struck car a peak acceleration of 11 g at 50 ms, resulting in a higher change in velocity. There is no second peak in the acceleration as in the under ride situation, but just one big peak. This could also be seen on the AVI-files. In the first phase there is a stiff pulse and after that the struck car is going to move, what finally results in a higher Δv . The stiff parts (e.g. the longitudinal members) are now directly hit without first a lot of folding of softer parts as in the under ride configuration. The Δv_{85ms} is also a higher for the over ride situations and this can result in a higher NIC_{max} [16]. This means it is not good having over ride in rear-end collisions. These results are also in line what Autoliv concluded from their tests.

4.4 Offset situations results

After translating the striking car to create overlaps of $\frac{1}{3}$, $\frac{1}{2}$ and $\frac{2}{3}$ it shows that the first acceleration peak in the first 60 ms is lower for less overlap (see figure 4.3 and appendix 8). But at $t = 85$ ms there is not much difference in velocity. In the first part the striking car is deforming a lot. When the stiffer parts of the striking car are hit (a “stiff” pulse), the struck car is going to have a higher acceleration. This results in the higher acceleration after 60 ms and a higher Δv at the end.

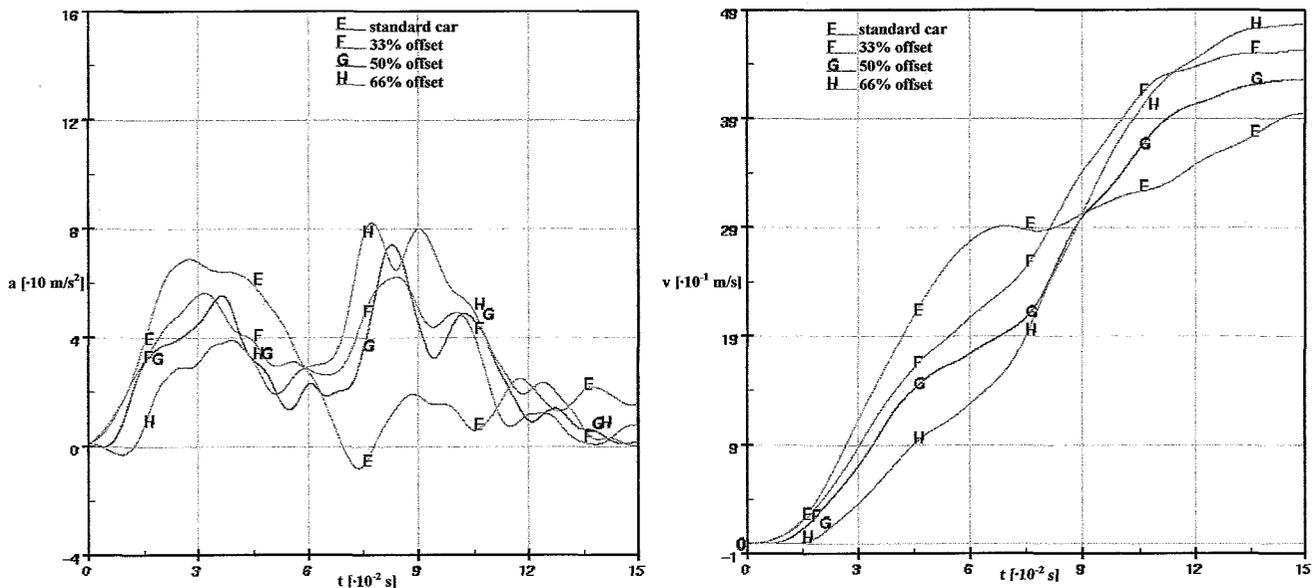


Figure 4.3: Acceleration and change in velocity of the struck car for offset

| curve | amount of offset |
|-------|------------------------|
| E | standard configuration |
| F | 33% offset |
| G | 50% offset |
| H | 66% offset |

Table 6: Explanation of the index of curves

Since the acceleration level is higher during the first 75 ms (a somewhat “stiff” pulse at the beginning, [6]) in the standard configuration, the offset collision will probably have a lower neck injury risk.

4.5 Tow-bar results

After modeling the tow-bar and attaching it to the struck car simulations with full overlap, partial overlap and 100 mm under ride and over ride were done. The results for these configurations are shown in appendix 9 to 12 and discussed in the following paragraphs.

The tow-bar was modeled as an elastic part and not as a rigid one. Modeling the tow-bar as a rigid part gave a lot of errors that could not be solved during this study (see appendix 13).

In every simulation the striking car is hitting the struck car about 2 ms later compared to the simulation without tow-bar. This means that when comparing the results the curves with tow-bar have to be shifted to the left along the time axis.

4.5.1 Full overlap

The results (see figure 4.4 and appendix 9) show that it is not good having a tow-bar mounted on the car. The acceleration is starting at a lower level at the beginning, but when the striking car is really hitting the struck car the acceleration increases rapidly. This results in a higher peak acceleration (10 g in stead of 7 g) and the Δv_{85ms} has a higher value.

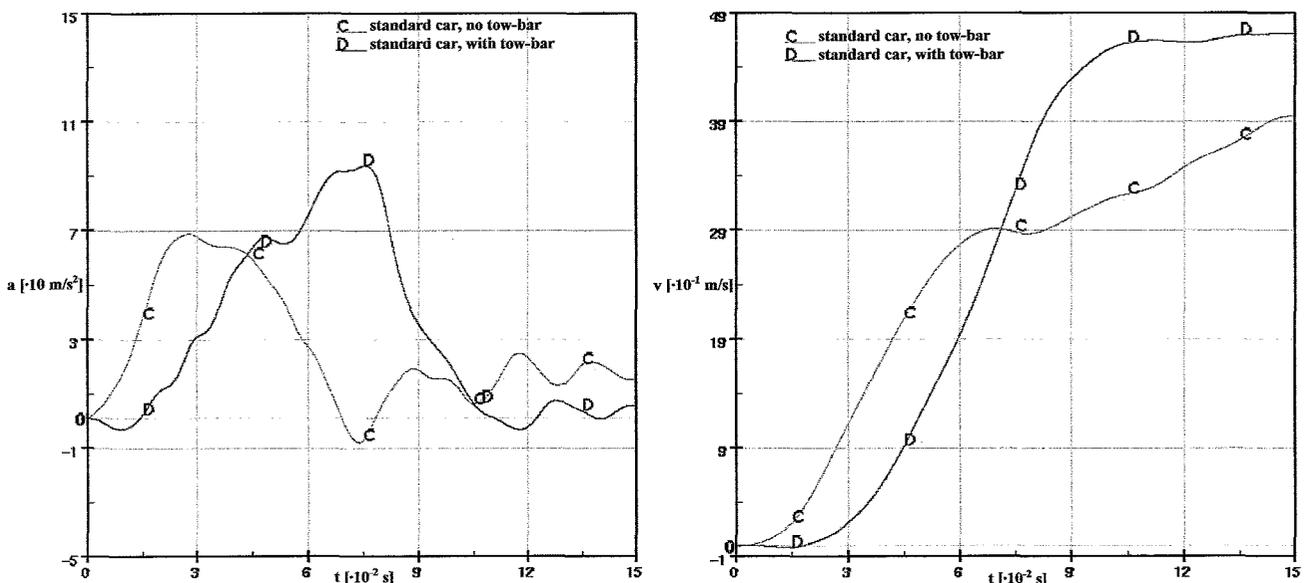


Figure 4.4: Acceleration and change in velocity with and without tow-bar

| Curve | Configuration |
|-------|---------------|
| C | no tow-bar |
| D | tow-bar |

Table 7: Explanation labels figure 4.4

On the AVI-files can be seen that there is almost no under ride anymore after mounting the tow-bar. This can be explained that part B (see appendix 3) of the tow-bar is preventing the striking car to slide under the struck car. This results that more stiff parts are hit which leads to a stiffer crash pulse. This means the risk of getting a WAD is probably higher [6].

4.5.2 Over and under ride

For the over ride and under ride configuration only the most lower and higher positions (100 mm) were chosen. In §4.2 and §4.3 is already concluded what the main effect of under and over ride is on the crash pulse. The results of the under/over ride simulations with a tow-bar



mounted on the struck car are presented in appendix 10 and 11. Table 8 gives the explanation of the labels used in the curves.

In the over ride simulation the shape of the crash pulse is almost the same as in the configuration without a tow-bar. But now the acceleration peak is higher, because of the stiffer structure at the back of the struck car. The Δv_{85ms} is now higher compared to the standard configuration. This indicates in a higher NIC_{max} [16]. This indicates that also in the over ride situation it is not good having a tow-bar.

| curve | configuration | |
|-------|--|-----------------------------------|
| | under ride | over ride |
| D | standard configuration with no tow-bar | |
| E | lower front wheels, no tow-bar | higher striking car, no tow-bar |
| F | lower front wheels with tow-bar | higher striking car, with tow-bar |

Table 8: Explanation labels from curves in appendix 10 and 11

For the under ride situation can be seen on the AVI-files that there is less pitch of the striking car when a tow-bar is mounted. The tow-bar is preventing the struck car to slide more under the struck car and therefore lifting it less. In the acceleration curve can be seen that this leads to a bigger and higher first acceleration peak. However, this peak is still smaller than the first peak of the standard configuration. This means that the risk of getting a whiplash injury is probably higher in an under ride situation when a tow-bar is mounted than without one, but it is probably still safer having under ride with or without a tow-bar than no under ride at all.

4.5.3 Offset

For the offset collision only the $2/3$ configuration was simulated. For this amount of offset the tow-bar is going to hit the longitudinal member of the striking car. The results for this simulation are presented in appendix 12. Table 9 gives the explanation of the curves in appendix 12.

| curve | configuration |
|-------|--|
| D | standard configuration with no tow-bar |
| E | offset configuration with no tow-bar |
| F | offset configuration with tow-bar |

Table 9: Explanation labels from curves in appendix 12

The results show that the acceleration has one big pulse with 2 local maximums. This is somewhat different than the offset collision without tow-bar. The second maximum is a lot higher for the struck car with tow-bar. This is when the longitudinal member and its surrounding stiff structure of the striking car are hitting the tow-bar. This is also the reason why Δv_{85ms} is a lot higher. After that time the acceleration decreases more in the case with tow-bar. This leads to almost the same Δv at $t = 150$ ms for the offset collision with and without tow-bar. The higher Δv_{85ms} is an indication that it is not good having a tow-bar in this offset type of rear-end collision.



Chapter 5 Conclusion

The aim of this study was to see what the influence of a tow-bar is on the crash pulse in rear-end collisions. After a literature survey data was found indicating that additional parameters influence the crash pulse in rear-end collisions: an under/over ride situation or the amount of offset. With the results of the survey 3 strategies were formulated.

1. Influence of under/over ride on the crash pulse
2. Influence of the amount of overlap on the crash pulse
3. Influence of a tow-bar on the crash pulse at different amounts of overlap and under/over ride

The results of strategy 1 showed that it is not good having an over ride situation, because of the more stiff impact pulse during the first 85 ms. On the other hand an under ride situation results in a “softer” impact pulse.

Results of strategy 2 led to the answer that an offset collision lead to a “softer” impact pulse in the beginning and a second acceleration peak after 75 ms. Although there is not much difference in change of velocity at $t = 85$ ms, it is reasonable to believe that the faster increase of velocity in the first part for the standard configuration will lead to higher neck injuries.

The simulations of strategy 3 led to the conclusion that by adding a tow-bar there is probably a higher risk of getting neck injuries. By mounting a tow-bar on a car a stiffer rear structure is created and there was a decrease in under ride due to the tow-bar interaction. This causes a stiffer impact pulse in every case that is simulated in this report. The decrease in under ride can also be seen on the AVI-files on the included CD-ROM.

Looking back at the results that were found during the literature survey, the results from the full-scale test from Autoliv already indicated that it was not good having a tow-bar. The results of this study prove that the results of their tests are true for more test conditions.



Chapter 6 Discussion & Recommendations

The results showed that it is not good having a tow-bar on a car when someone is involved in a rear-end crash. Therefore it is better considering mounting a removable one on the car and remove it when it is not in use. But after “removing the tow-bar” part A and B are still mounted on the car. These parts are a lot stiffer than the rest of the rear structure of the car. The increased neck injury risk is still there. To reduce the risk of higher neck injuries the structure of the tow-bar should be better integrated in the rear of the car. This is possible when a car manufacturer is taking the tow-bar already into consideration during the early development of a new car model. In this way the construction of the tow-bar will be different and then if you remove it there will be no difference in neck injuries for cars with or without tow-bar.

The tests from Autoliv [1, 24] already showed that it was not good having a tow-bar, but the full-scale tests were single test conditions. The simulations in this project prove that it is true additional crash conditions. However, the results from the computer simulations are not validated in real life. The results from the simulation can therefore only be used to see a trend of what the effect of a tow-bar on the crash pulse is.

The results can also vary on how part D is shaped. Some car models have the tow-bar ball placed on a longitudinal straight beam (see the AVI-files from Autoliv on CD-ROM). This design will be significantly stiffer than the “C”-shaped part D of the present model. This makes it very hard to make the model generally applicable: every tow-bar is designed specifically for a car model.

The tow-bar in this study was not modeled as a rigid part, which led to bending of part D of the tow-bar instead of denting the front bumper of the striking car as expected.

The conclusions of this study are only based on the acceleration and velocity curves. To get a better idea what the increase in neck injury is, the data of the acceleration curves should be implemented into a dummy model to calculate the NIC-values. These values will give a better indication what the influence of the tow-bar is on the injury risk in a rear-end collision. The acceleration pulse gained from the simulation can be used in e.g. MADYMO to see how the difference will be in the dummy behavior.

There is still room for improvement after this study. The tow-bar can be modeled with varying stiffness (one of the first things is to get a more realistic behavior the tow-bar, especially part D). Modeling the tow-bar with varying stiffness would give a better understanding of the influence of the tow-bar stiffness. A stiffer tow-bar is expected to penetrate into the bumper foam of the striking vehicle. In case the tow-bar is aligned with the longitudinal beams and bumper attachments (figure 2.1) a very stiff contact could be expected.

An attempt to model a stiffer tow-bar was made in the present study. Due to calculation problems the model failed to execute when the tow-bar stiffness was increased. This problem could probably be overcome if the contact conditions between tow-bar and front bumper were re-modeled.



Acknowledgements

First I want to thank all the people at the Machine and Vehicle Systems Department at Chalmers. It was very nice to work there and the lunches were splendid.

I want thank the following persons personally who helped me throughout my project:

- Mats Y Svensson, associate professor at the Crash Safety Division, Department of Machine and Vehicle Systems, Chalmers University of Technology, my supervisor
- Robert Thomson, assistant professor at the Crash Safety Division, Department of Machine and Vehicle Systems, Chalmers University of Technology, for helping me with the computer problems and EASi-CRASH
- Weijia Wu, Ph.D. student at the Crash Safety Division, Department of Machine and Vehicle Design, Chalmers University of Technology, for helping me with EASi-CRASH
- Dr. Ola Boström, Autoliv Research, for providing me with their latest results and his ideas
- Jonas Sjoberg, professor at the Mechatronics Division, Department of Machine and Vehicle Systems, Chalmers University of Technology, who brought me in contact with Mats Svensson
- Bengt Pipkorn, Ph.D., Graduate Studies Director, for valuable advice and guidance in the choice of the mathematical car model
- Astrid Linder, Ph.D., Thatcham, UK, for the valuable meeting and the nose-dive test data



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Appendix 2 Distribution rear-end collisions

| Main Impact | Impact Area (IA) | | | | | | | Total |
|-------------|------------------|-----|-----|-----|------|------|------|-------|
| | IA | 3.1 | 3.2 | 3.3 | 3.4 | 3.5 | 3.6 | |
| Rear-end | No. | 18 | 4 | 17 | 36 | 33 | 138 | 246 |
| | total % | 2,4 | 0,5 | 2,3 | 4,8 | 4,4 | 18,3 | 32,6 |
| | rel % | 7,3 | 1,3 | 6,9 | 14,6 | 13,4 | 56,1 | 100 |

Table A.1: Number of rear-end collisions; adopted from Whiplash II report [8]

| Main Impact Claimant- Causator | Overlap | Impact Conf. | Impact Area Claimant | Impact Area Causator | Direction of Impact | No. | Total | Percentage |
|--------------------------------|----------------------------------|--------------|----------------------|----------------------|---------------------|-----|-------|------------|
| Rear-end-Frontal | Full | 1 | 36 | 16 | 06 | 140 | 140 | 59,6 |
| | Offset | 2.1 | 31 / 34 | 13 / 15 | 06 | 43 | 82 | 33,4 |
| | | 2.2 | 33 / 35 | 11 / 14 | 06 | 39 | | |
| | Angled | 3.1 | 3 | 1 | 07 | 12 | 24 | 9,8 |
| | | 3.2 | 3 | 1 | 05 | 12 | | |
| | Rear-end-Frontal (total): | | | | | | | 246 |

Table A.2: Division of rear-end collisions; adopted from Whiplash II report [8]



Appendix 3 Selected nodes for data

This table gives the selected nodes that can be used for plotting the acceleration, velocity and pitch in that node. The plots in this report are all from node ID 762027.

| car | part | set ID | node ID |
|---------------------|----------------------------|---------------|----------------|
| struck car | left beam | 865 | 747320 |
| | right beam | 863 | 748321 |
| | engine | 864 | 913362 |
| | rear axle | 866 | 742549 |
| | small beam under passenger | 872 | 763044 |
| | small beam under driver | 874 | 762027 |
| | central tunnel beam | 873 | 741395 |
| striking car | left beam | 869 | 47315 |
| | right beam | 867 | 48313 |
| | engine | 868 | 213344 |
| | rear axle | 870 | 71053 |

Table A.3: Selected parts for data



Appendix 4 Tow-bar model Volvo S/V70

The tow-bar model shown below mounted on the latest Volvo V70 models (model year 2000). This tow-bar is used for modeling an FEM tow-bar. It is mounted on the rear longitudinal members of the car model using parts A1 and A2

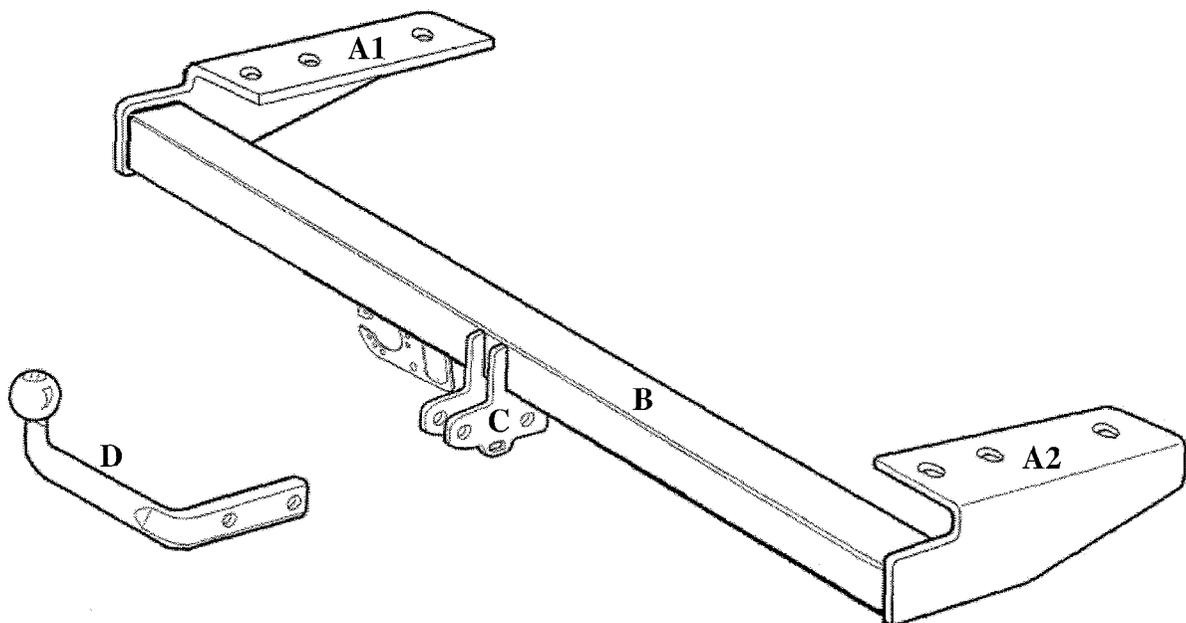
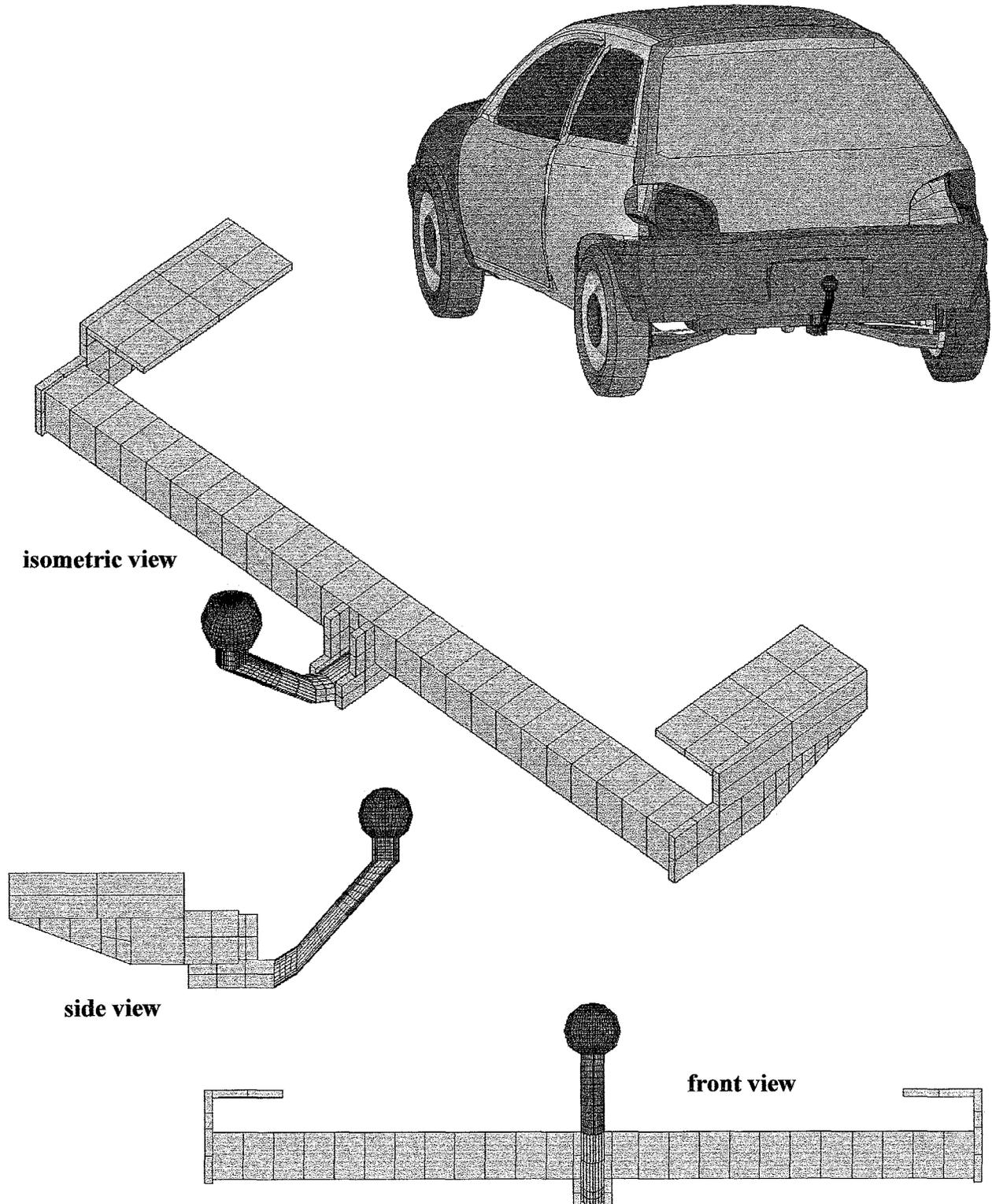


Figure A.1: Tow-bar of the Volvo S/V70 type 3530; adopted from the Brink web site [15]



Appendix 5 View of the tow-bar on the struck car

View of the FEM tow-bar, mounted on the struck car

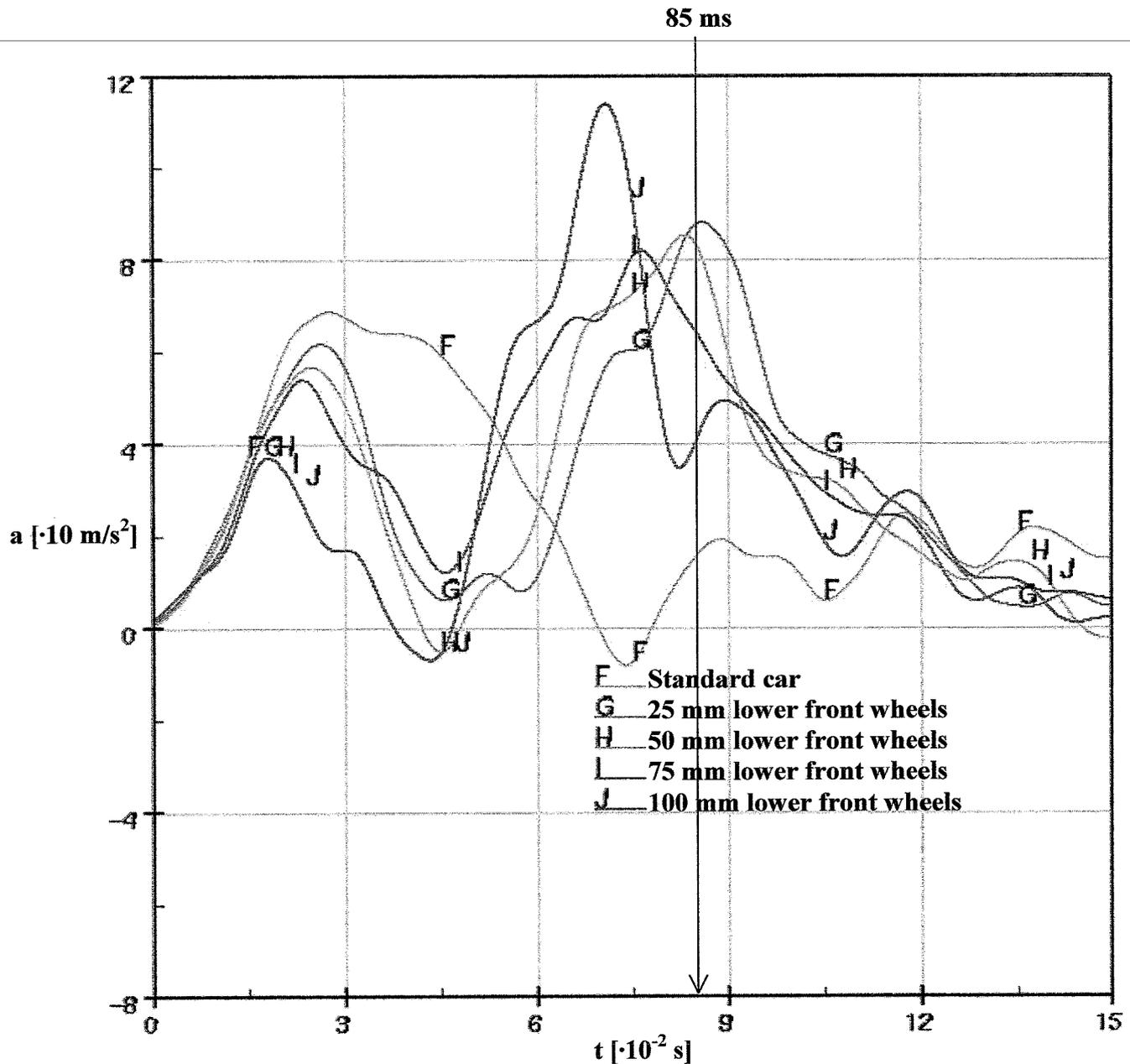


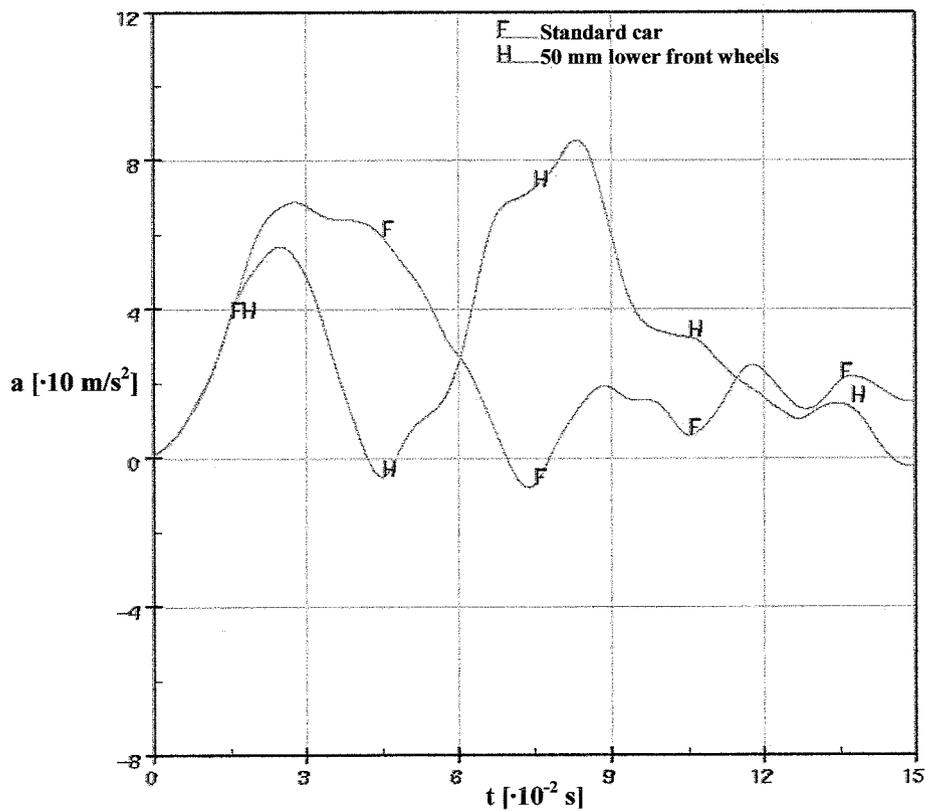
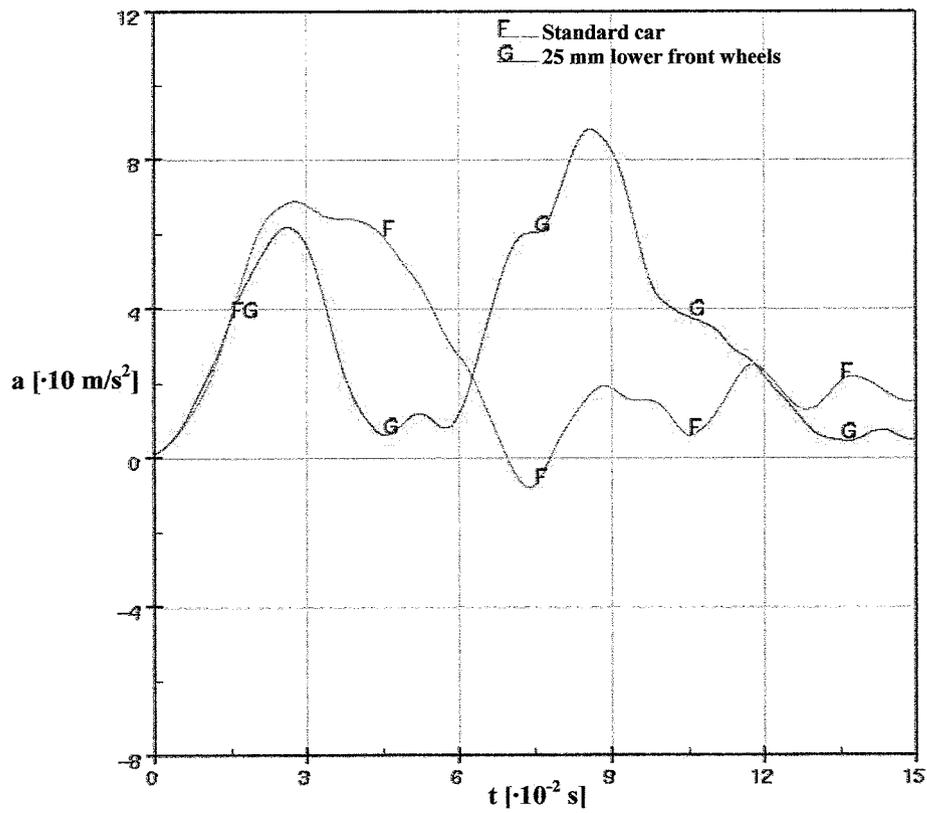


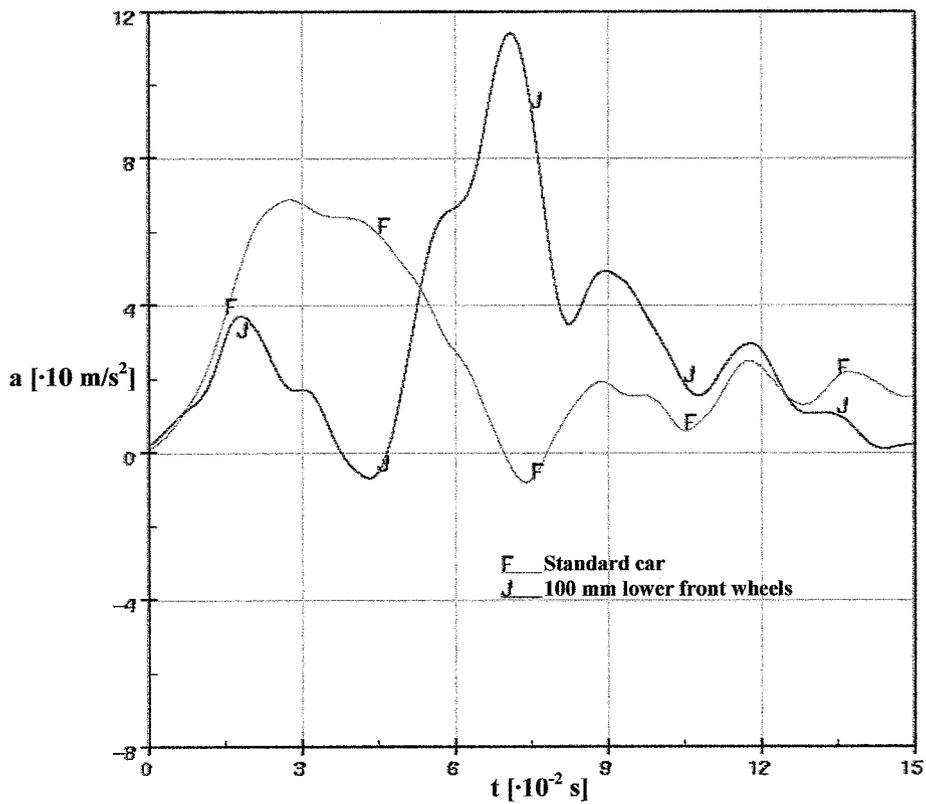
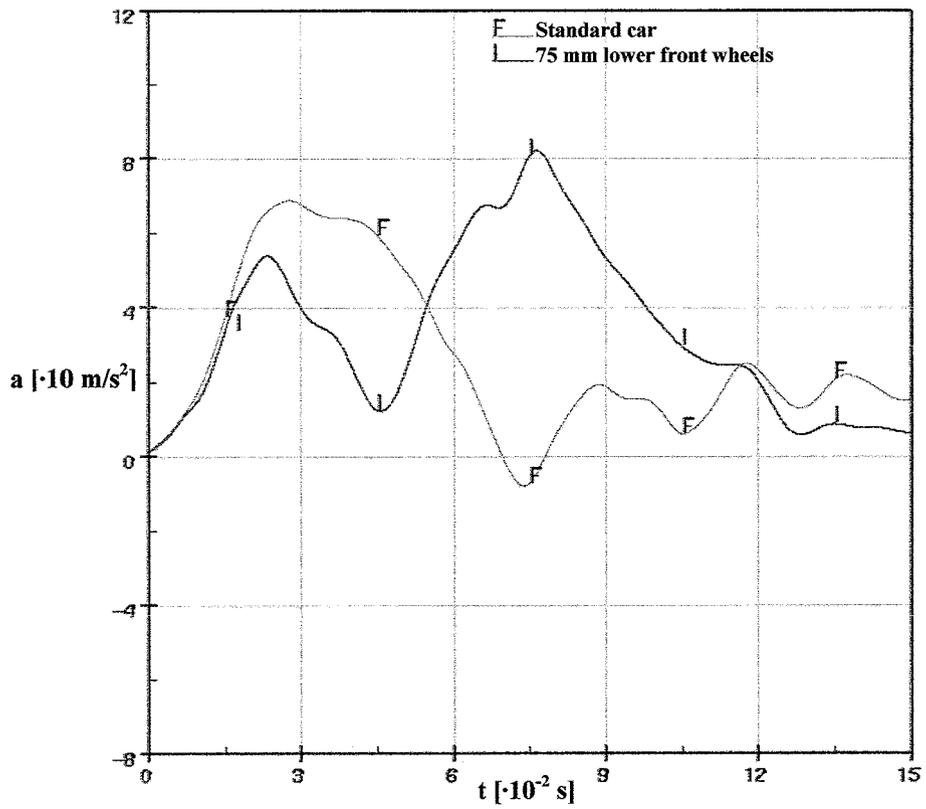
Appendix 6 Results under ride

In this appendix are the plots are shown for the under ride situation. The front wheels were placed on respectively 25, 50, 75 and 100 mm lower surface. The results are compared to a standard car. To see the change acceleration and speed first all the curves are put into 1 figure, then every step is put into another figure to compare the result with a standard car.

First the results of the acceleration are given then the change in velocity. All the results are from the struck car.

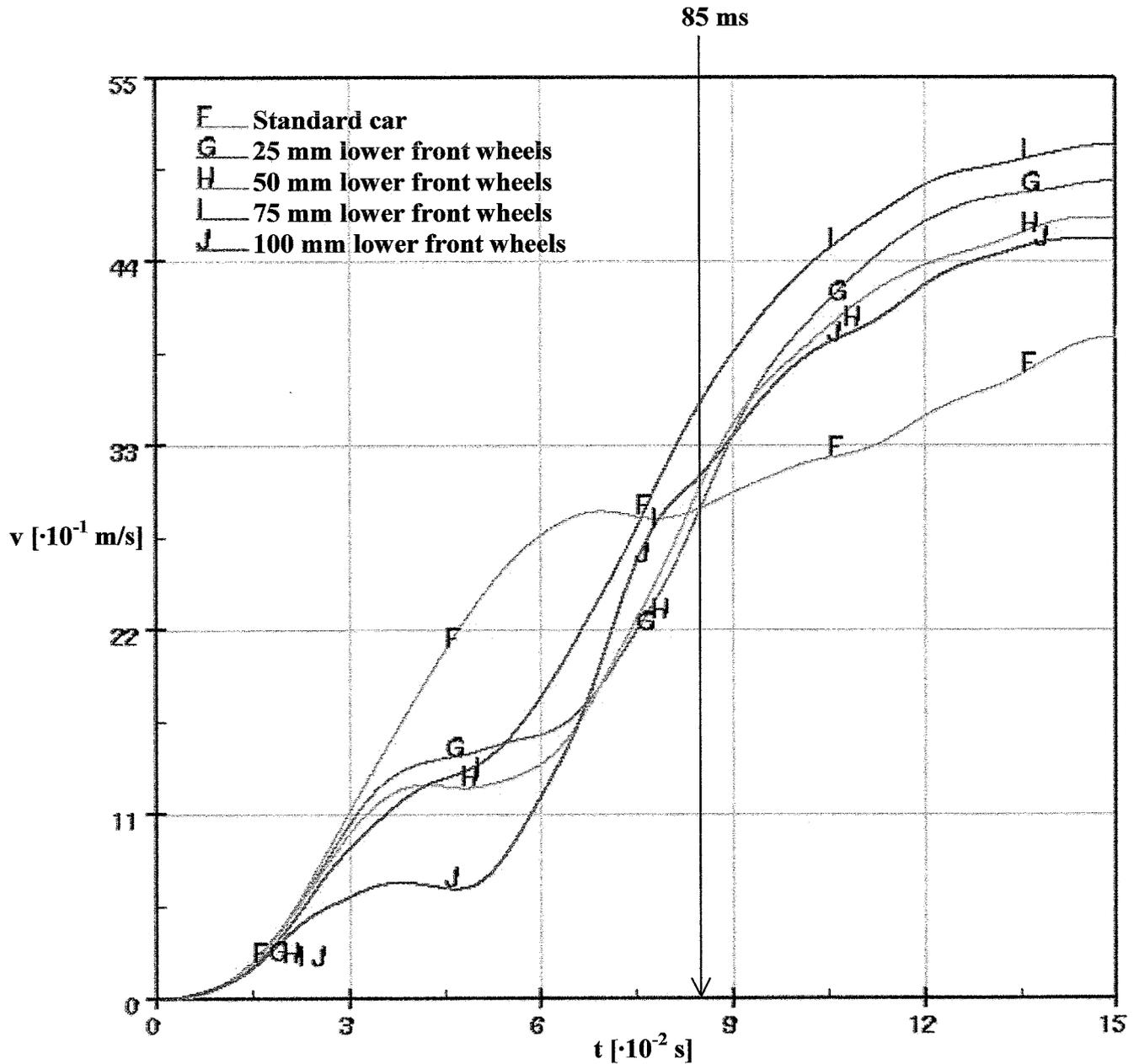


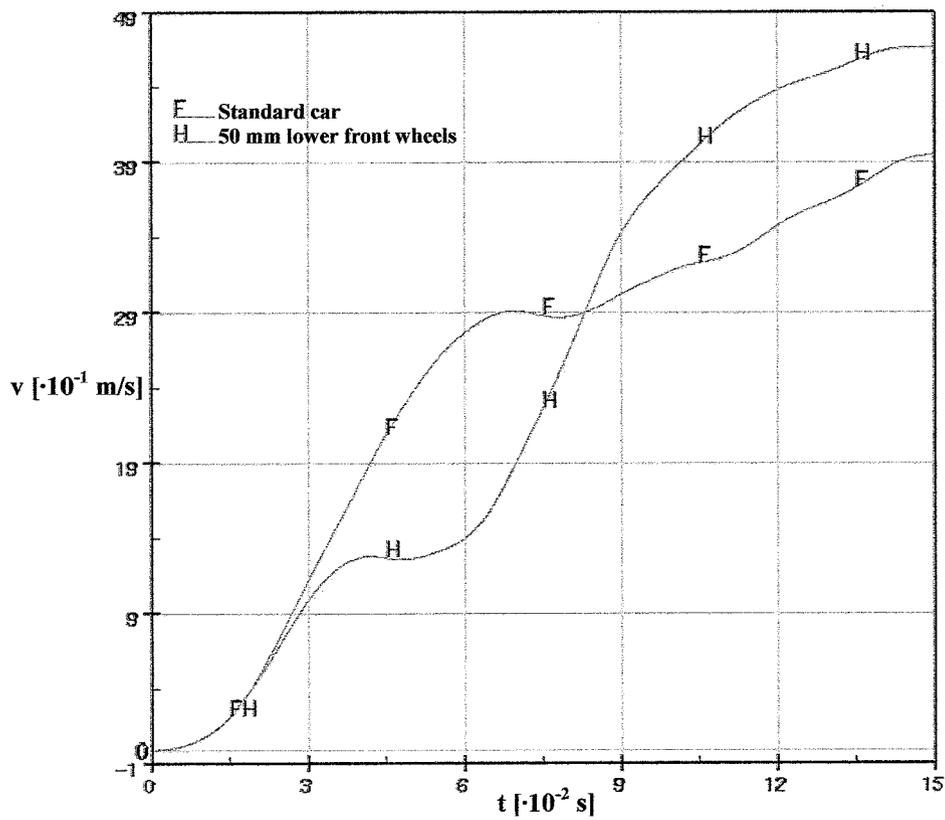
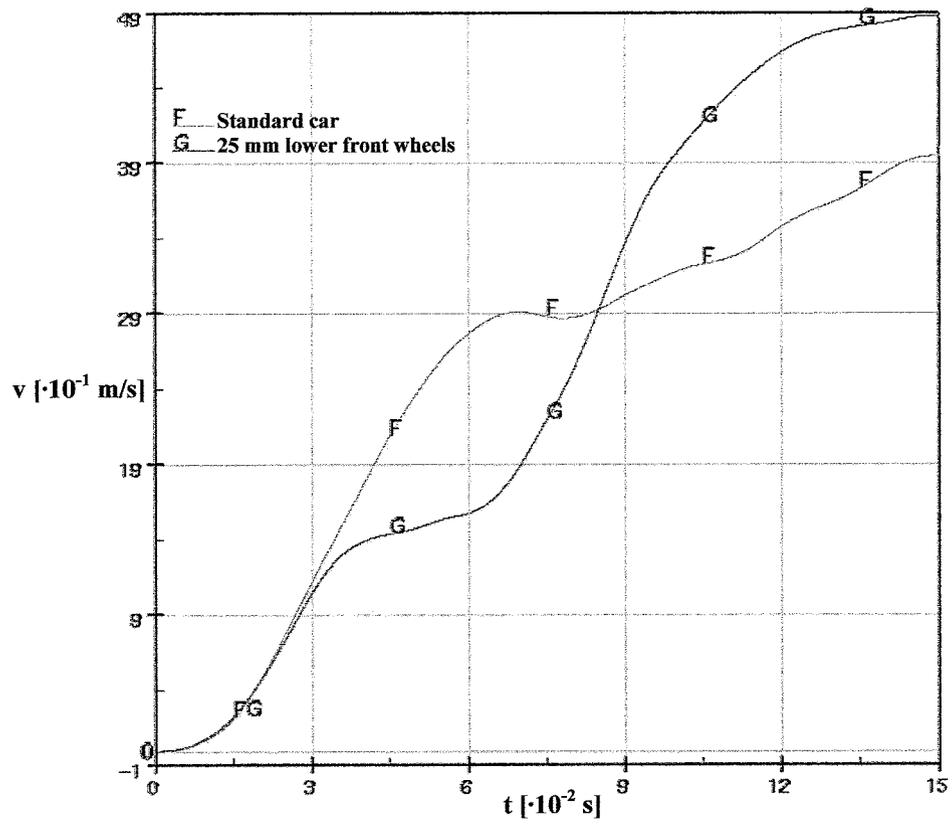


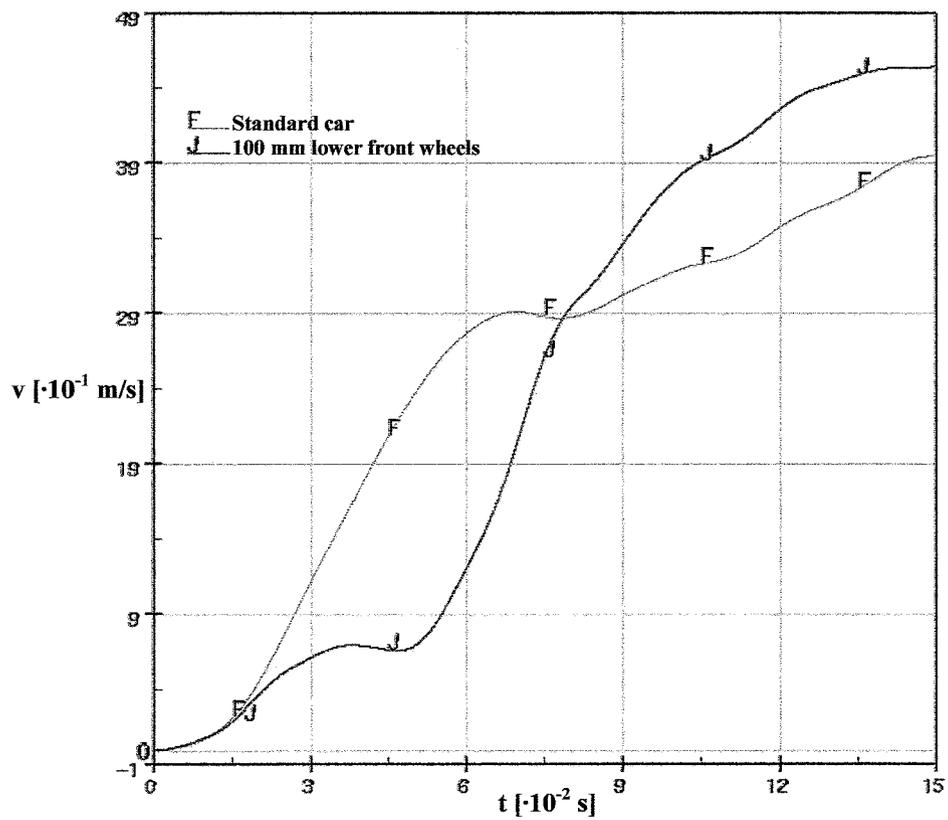
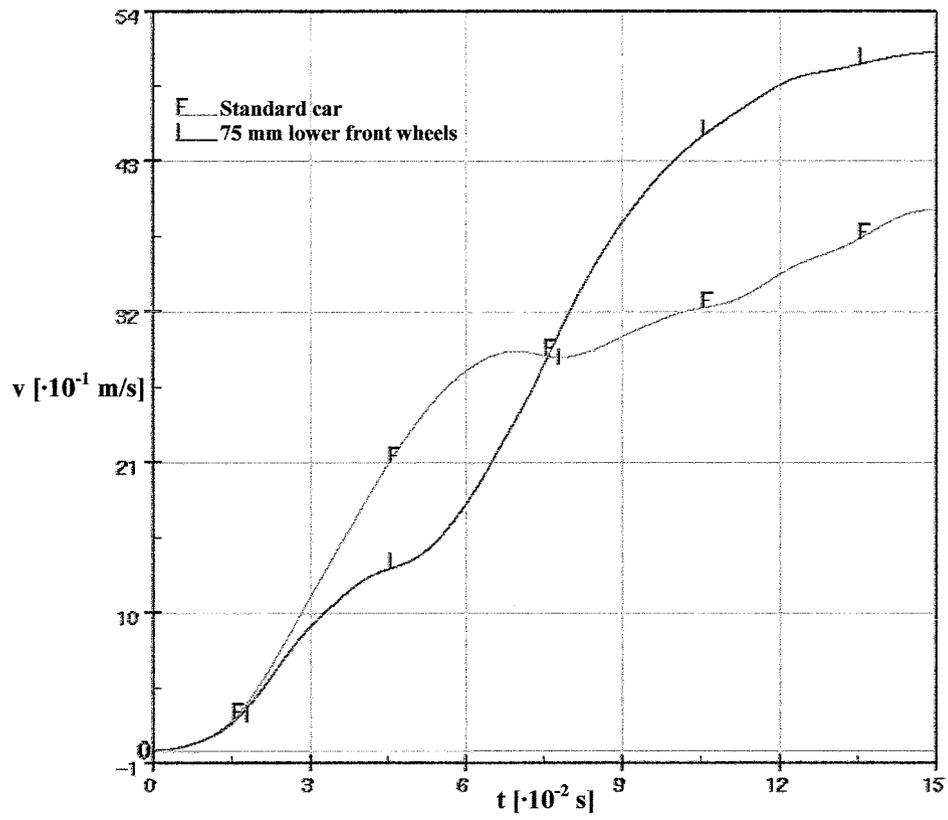




Now the results of the change in velocity of the struck car are given





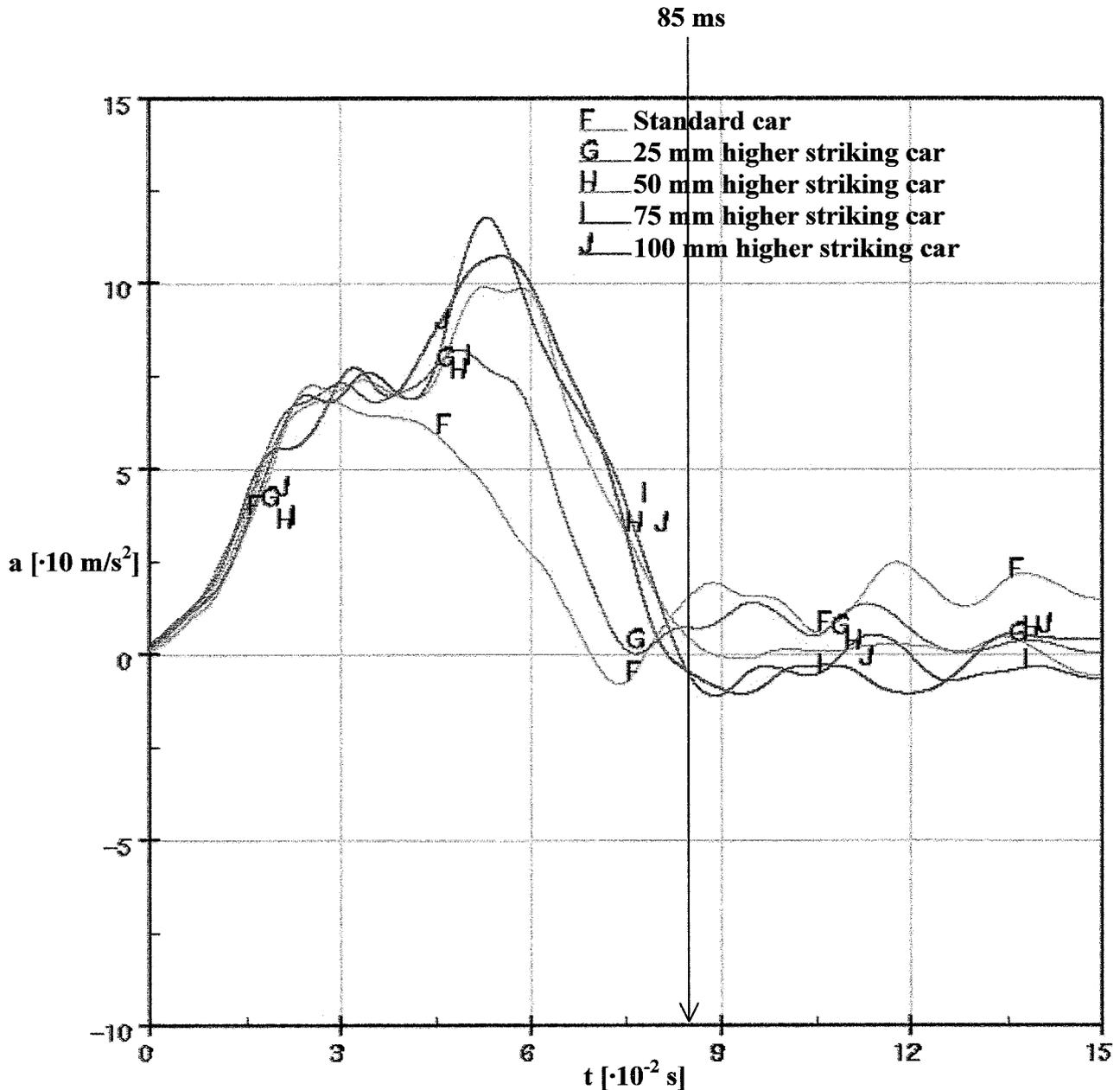


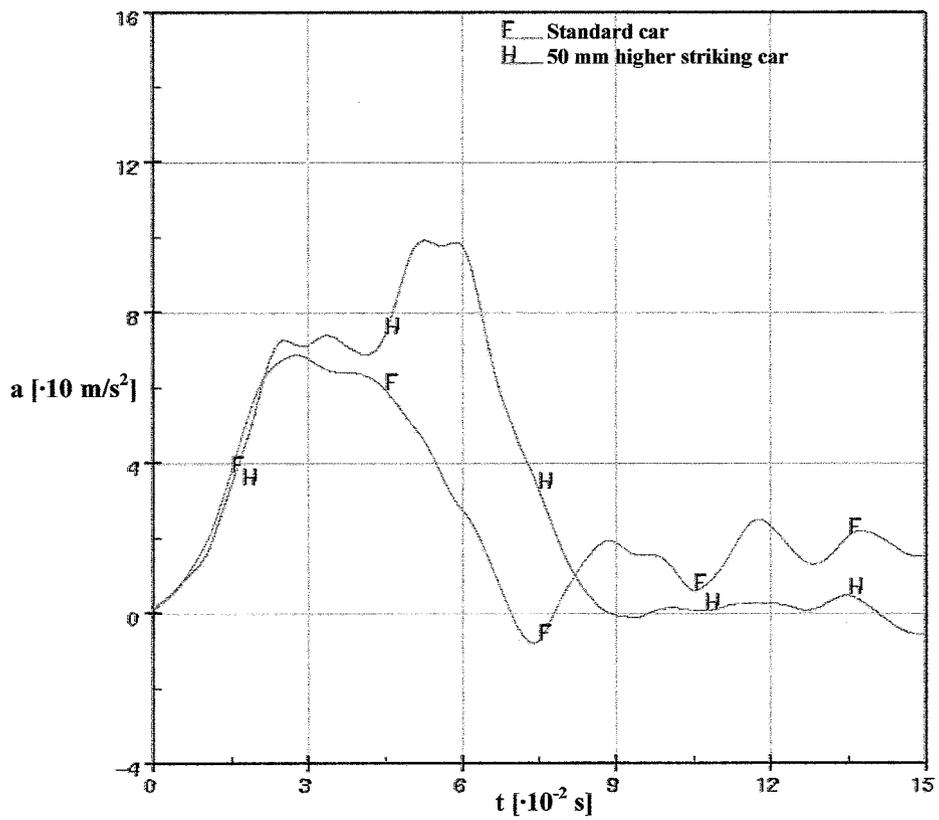
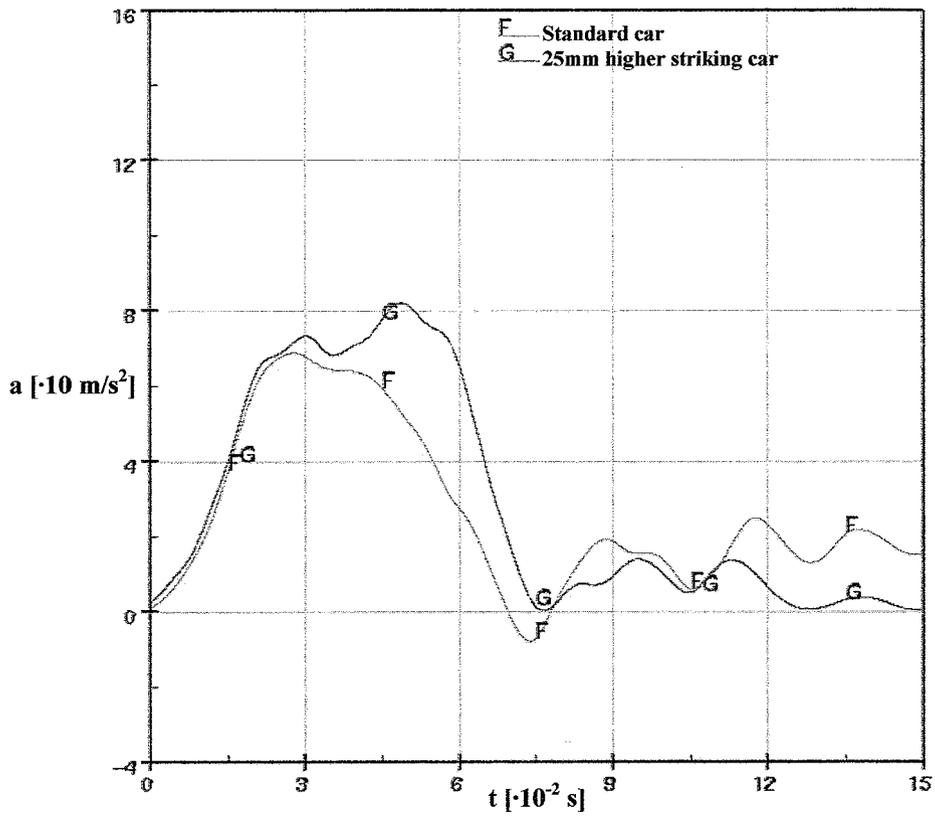


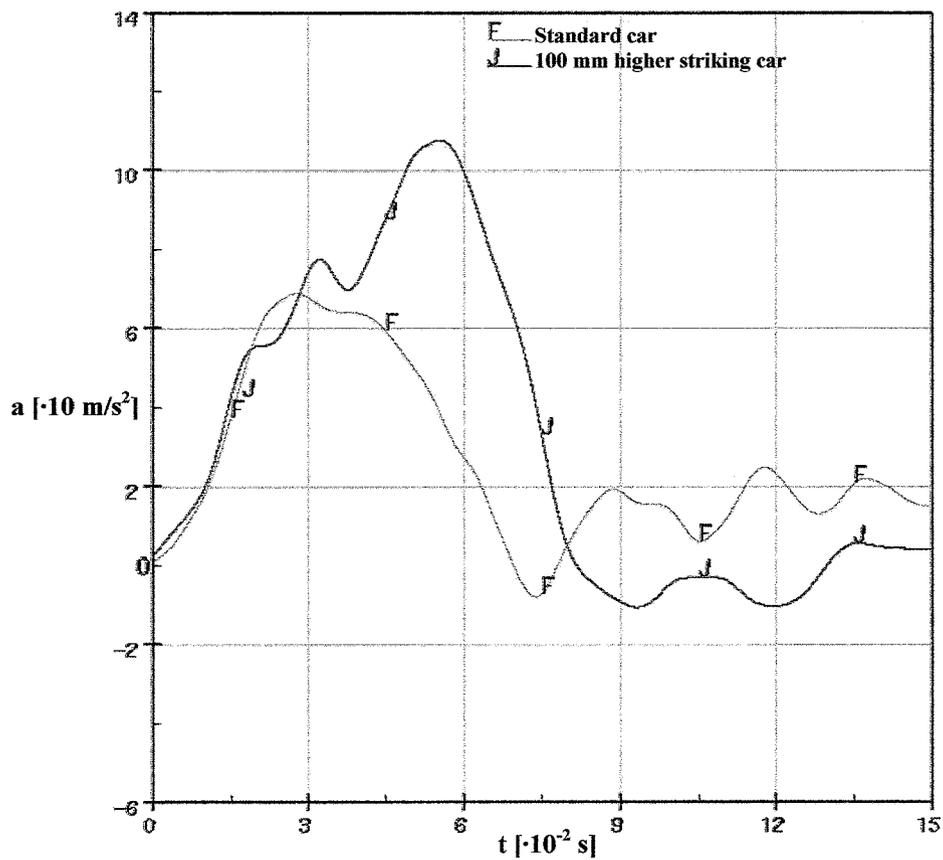
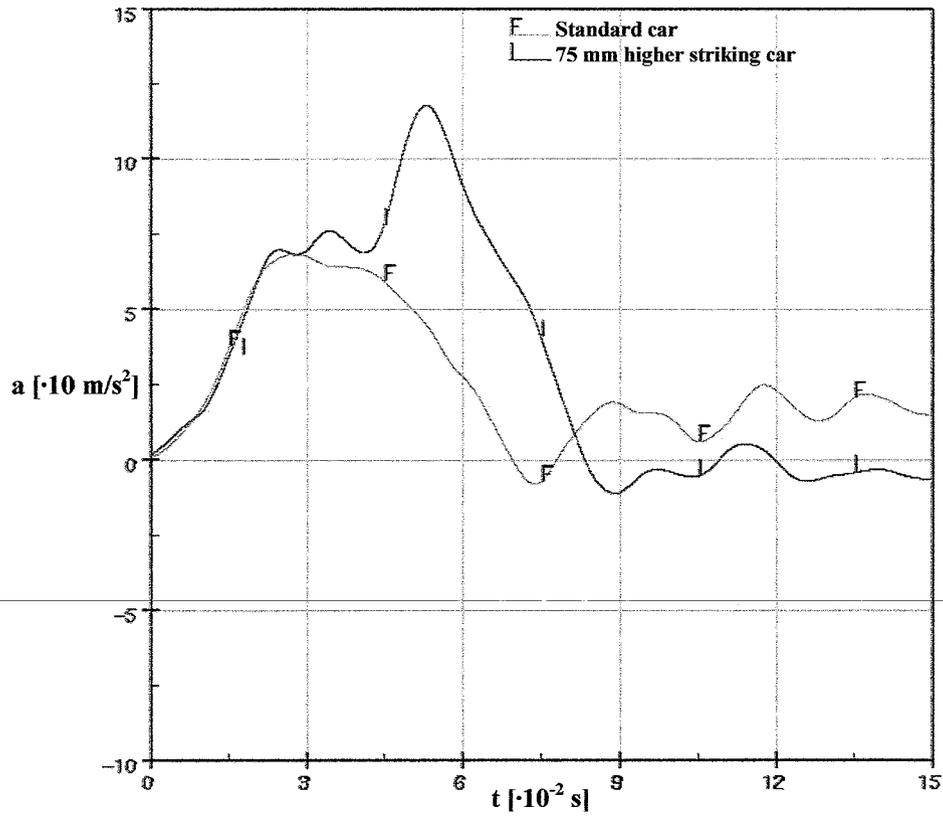
Appendix 7 Results over ride

In this appendix are the plots are shown for the over ride situation. The striking car is placed on respectively 25, 50, 75 and 100 mm higher surface. The results are compared to a standard car. To see the change acceleration and speed first all the curves are put into 1 figure, then every step is put into another figure to compare the result with a standard car.

First the results of the acceleration are given then the change in velocity. All the results are from the struck car.

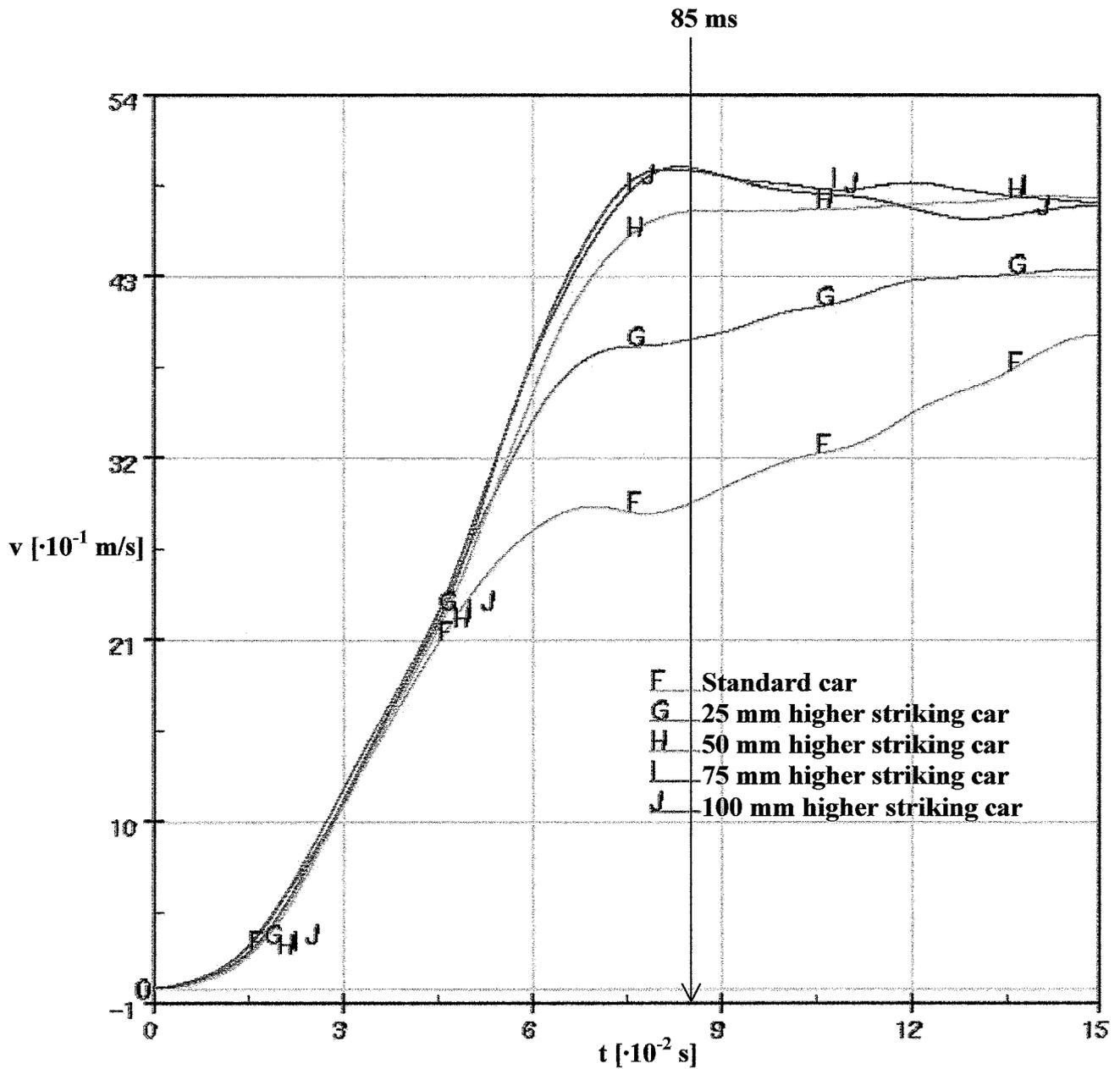


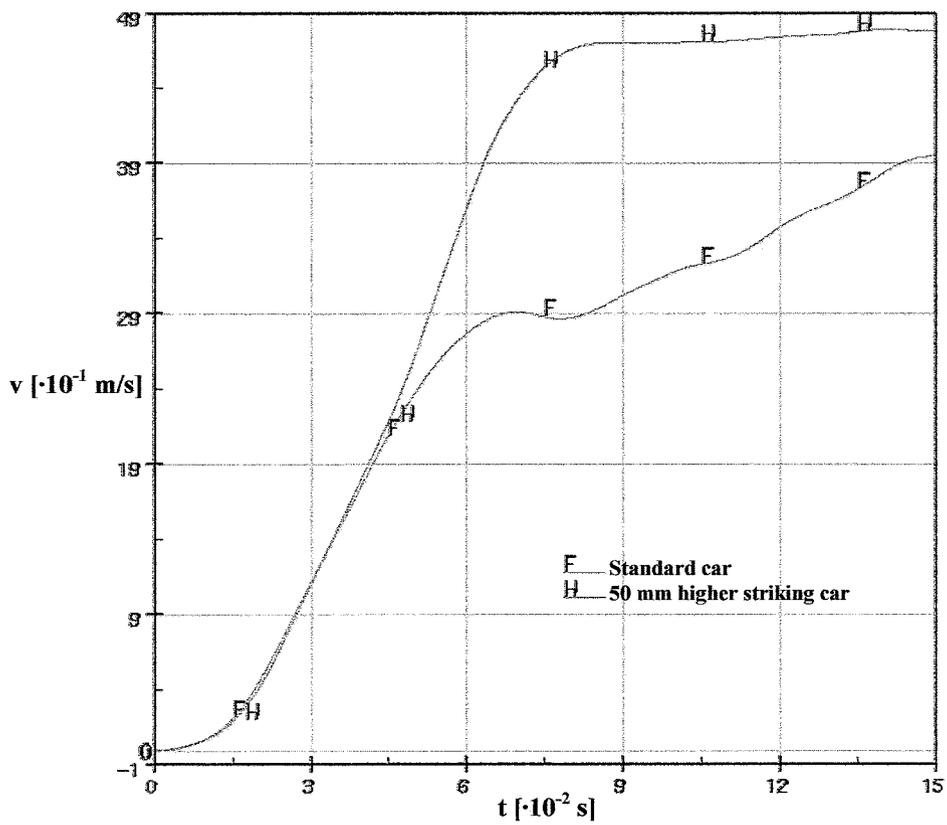
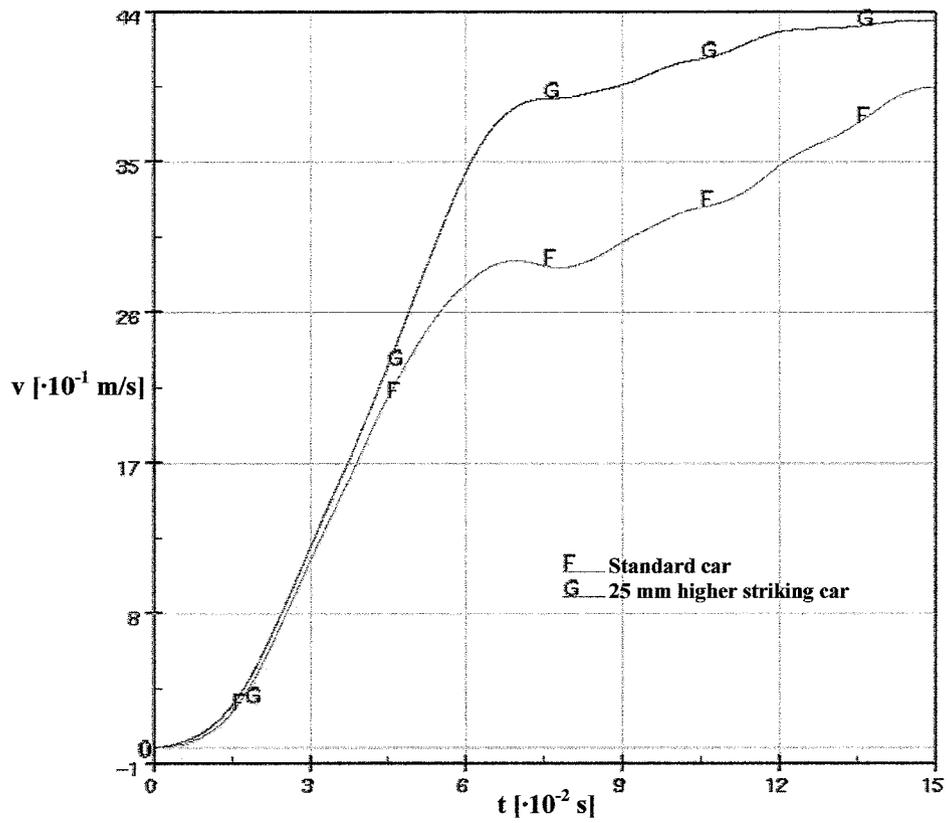


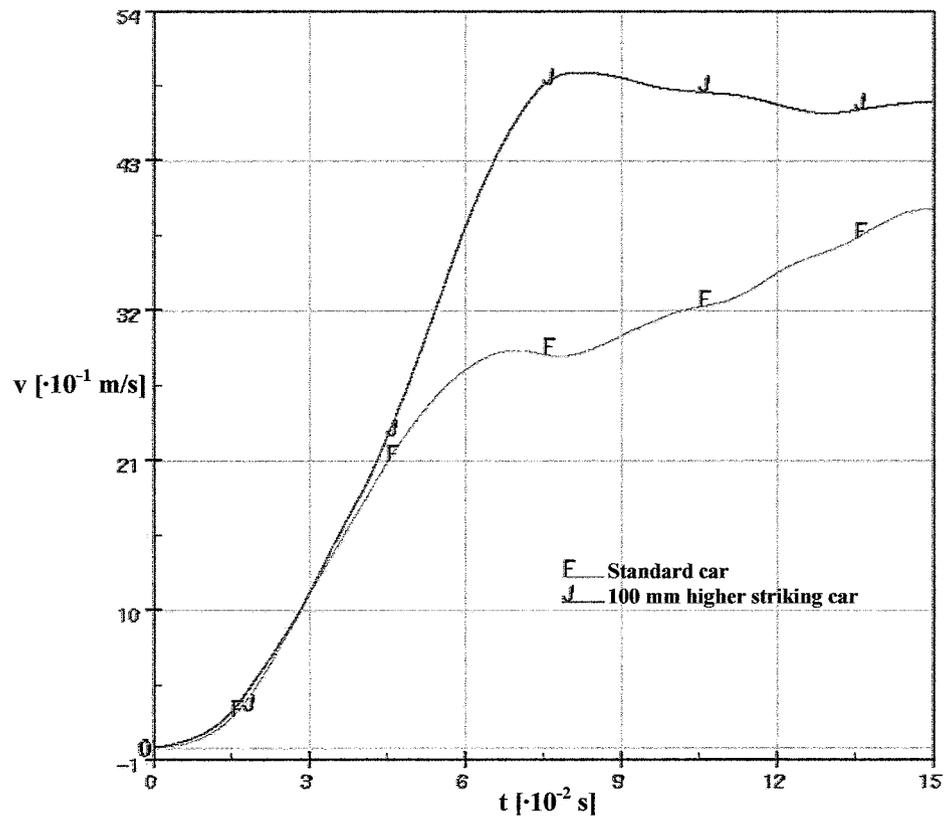
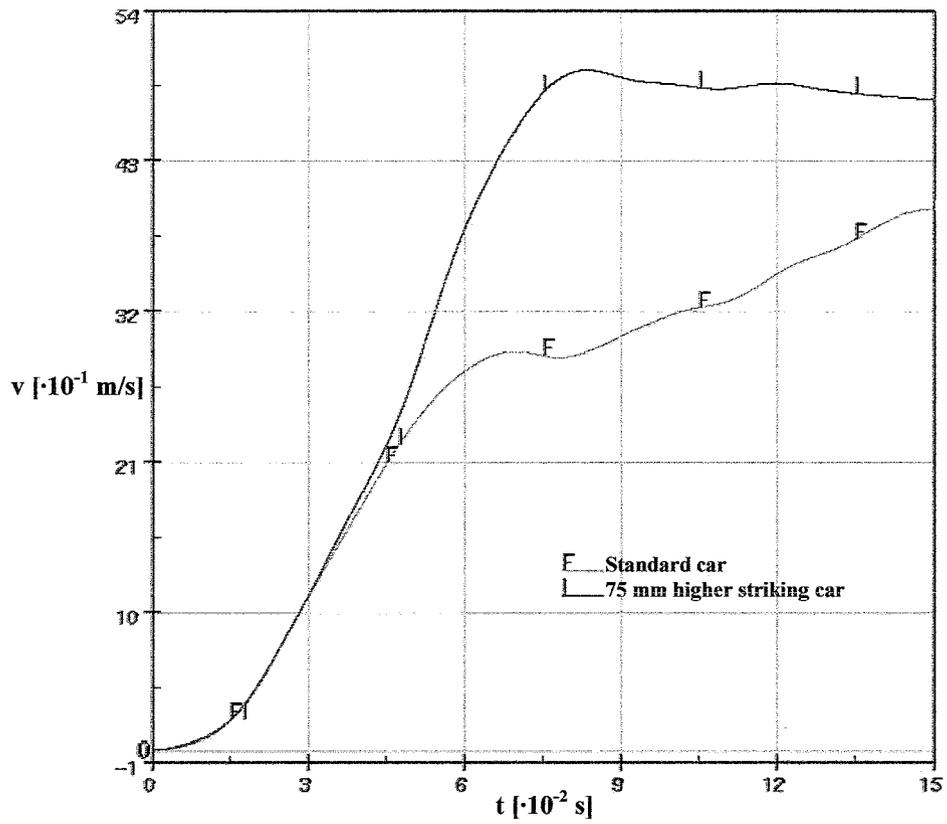




Now the results of the change in velocity of the struck car are given





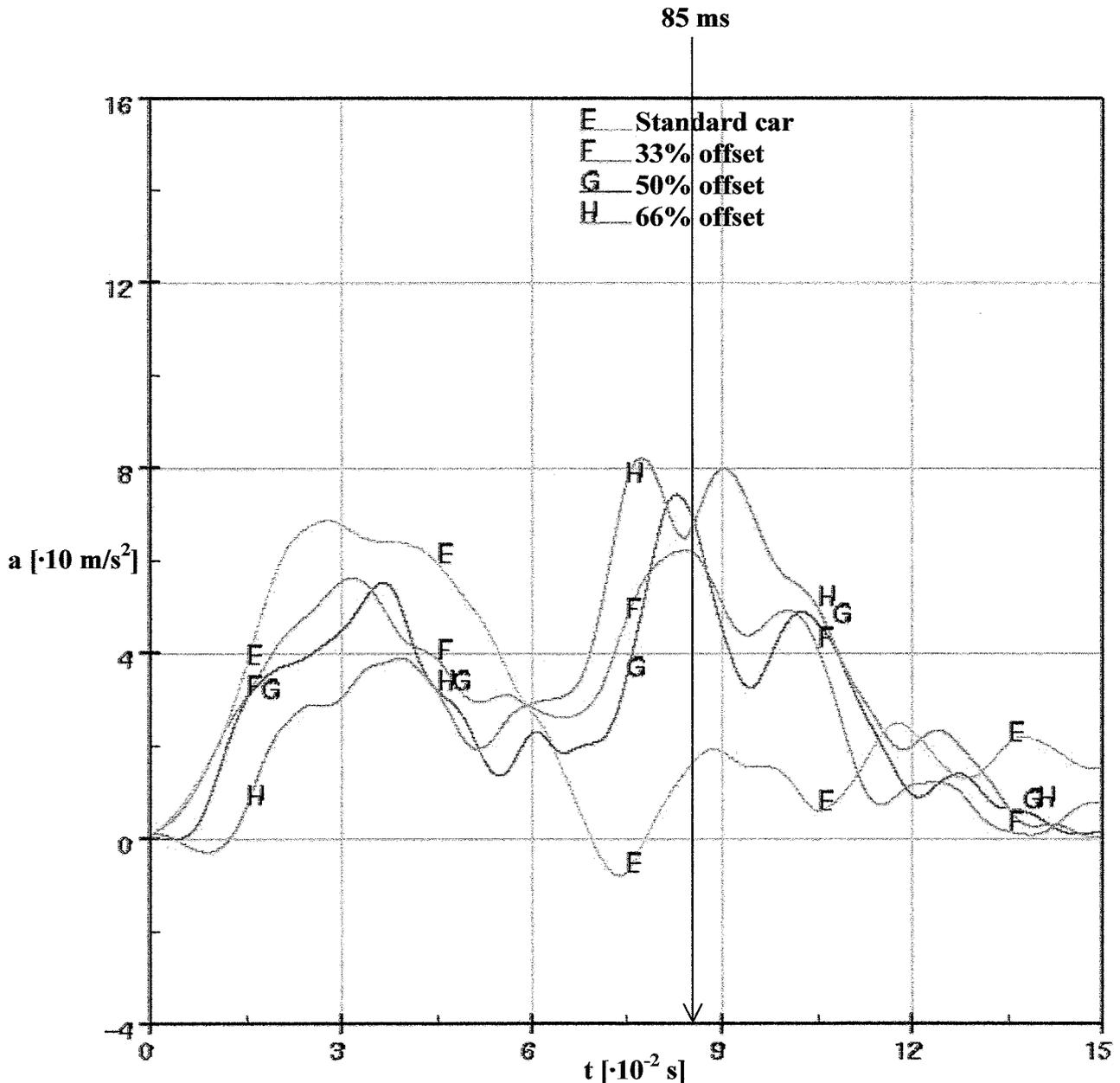


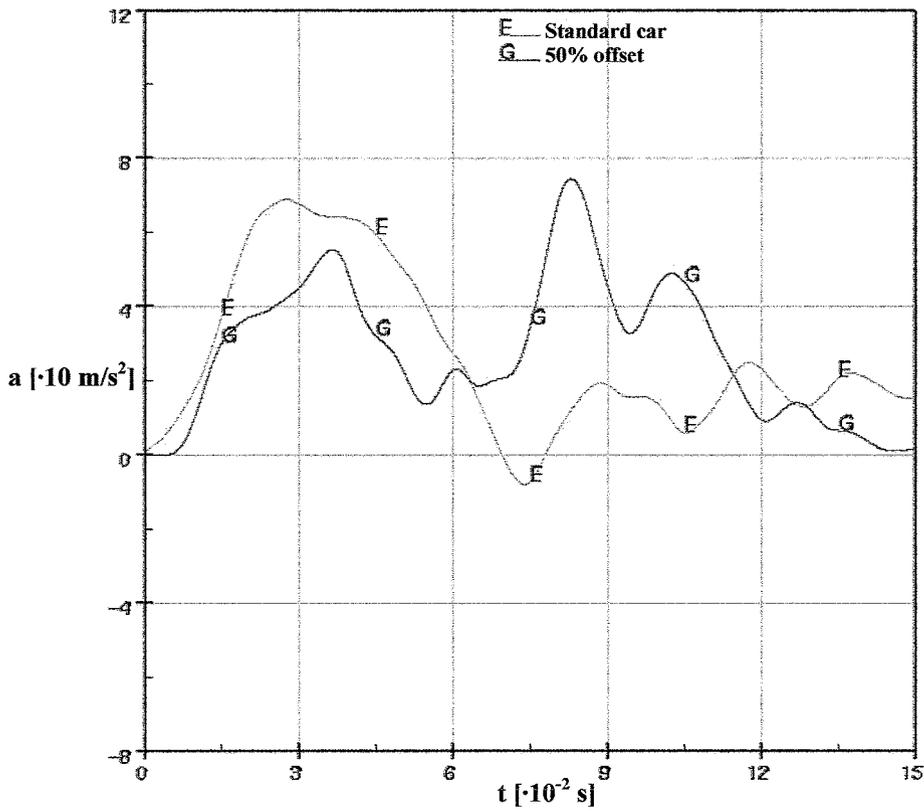
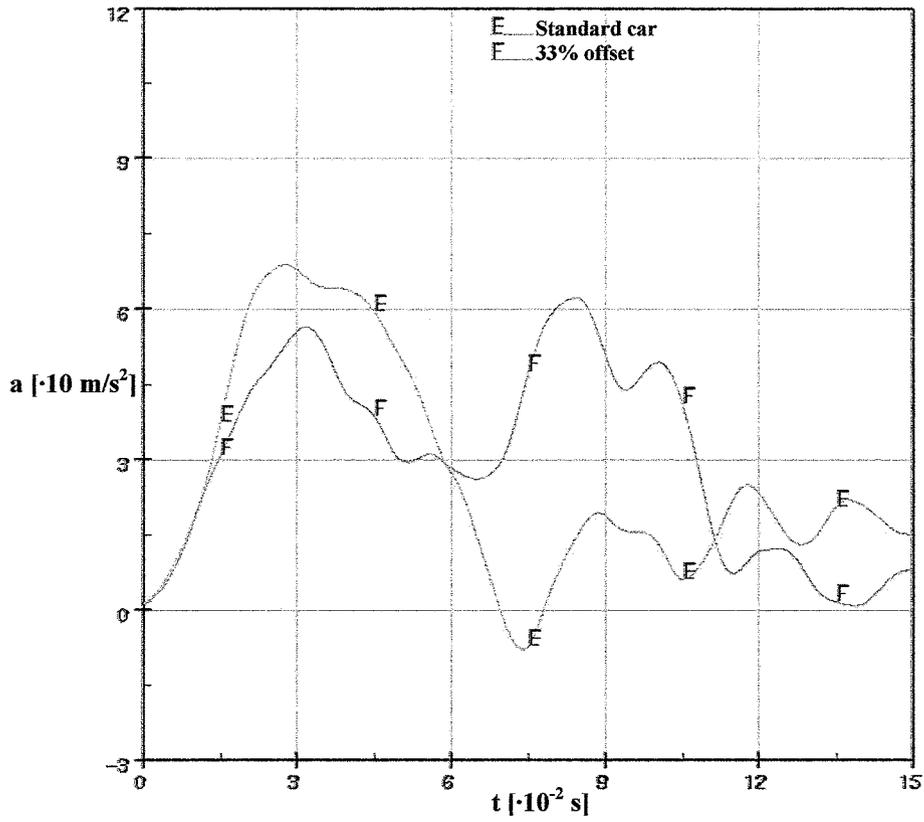


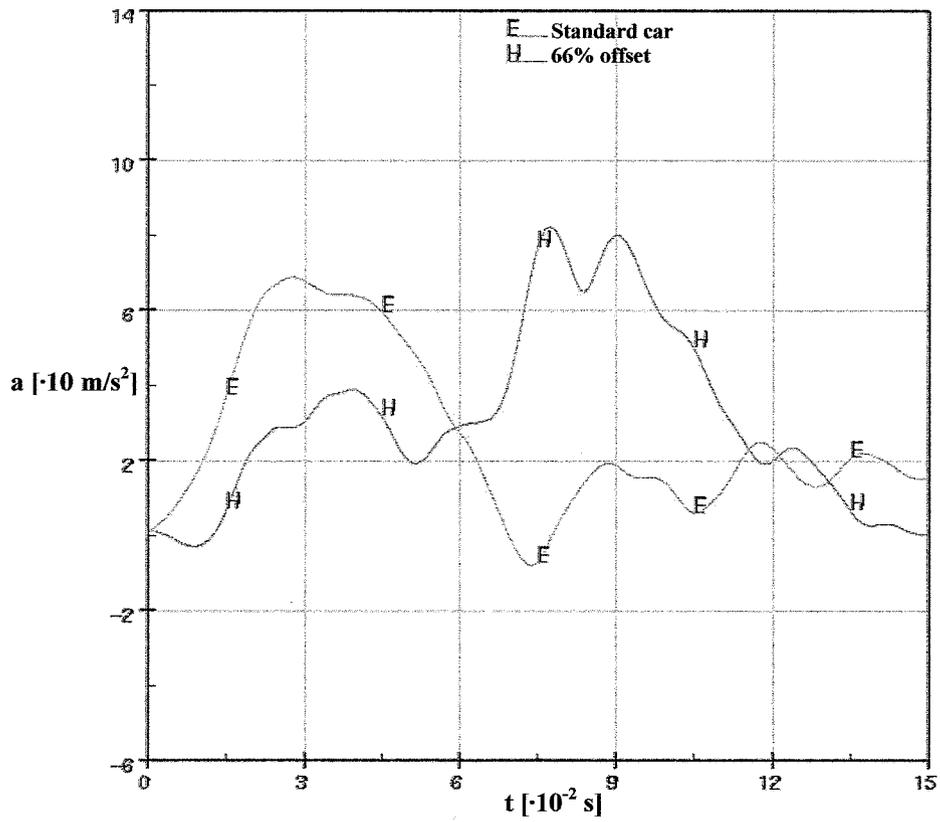
Appendix 8 Results offset situations

In this appendix are the plots are shown for the offset situation. The striking car is translated in such a way to create an offset of respectively $\frac{1}{3}$, $\frac{1}{2}$ and $\frac{2}{3}$ overlap (or respectively 66%, 50% and 33% offset) on the left side of the struck car. The results are compared to a standard car. To see the change acceleration and speed first all the curves are put into 1 figure, then every step is put into another figure to compare the result with a standard car.

First the results of the acceleration are given then the change in velocity. All the results are from the struck car.

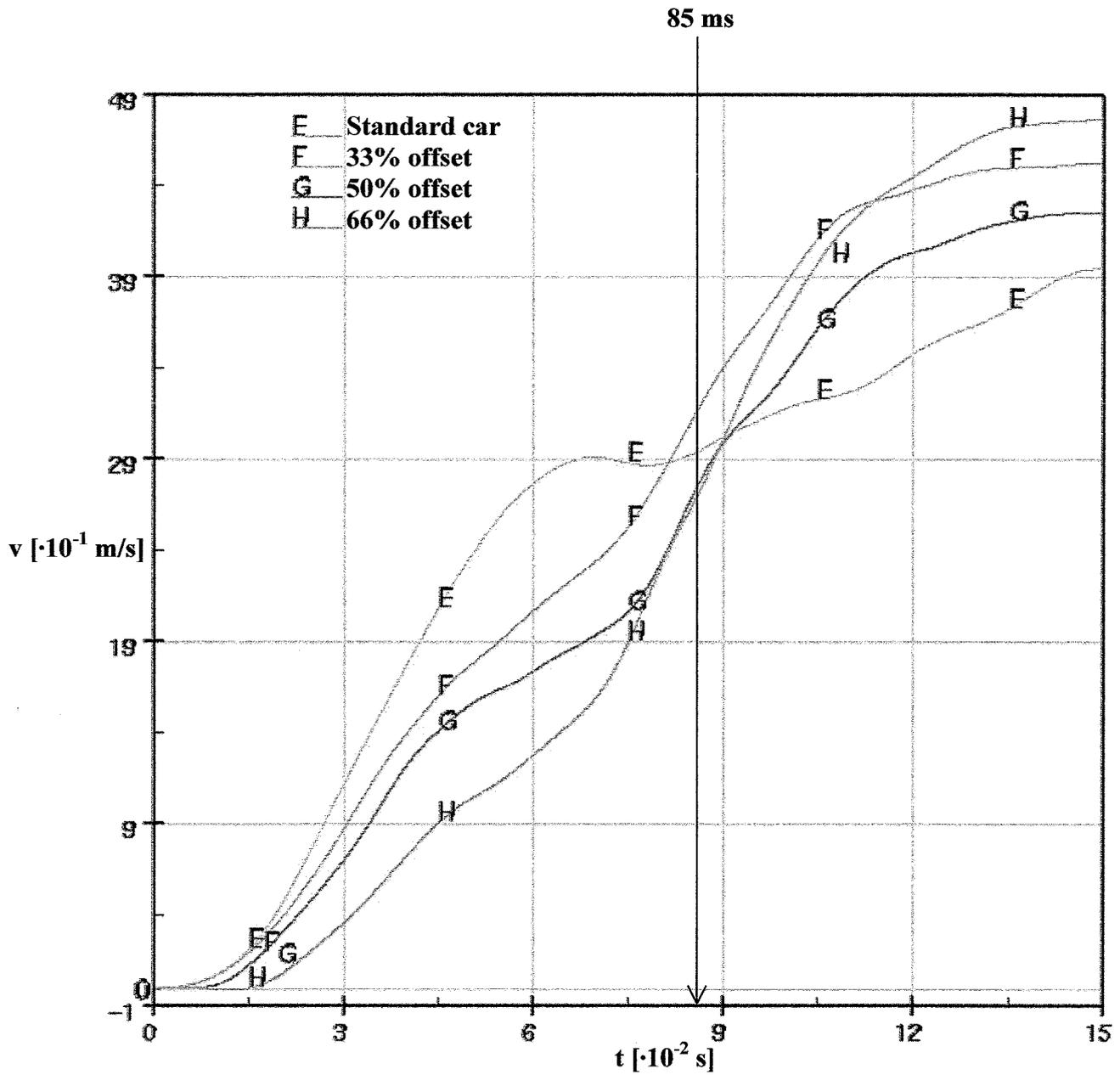


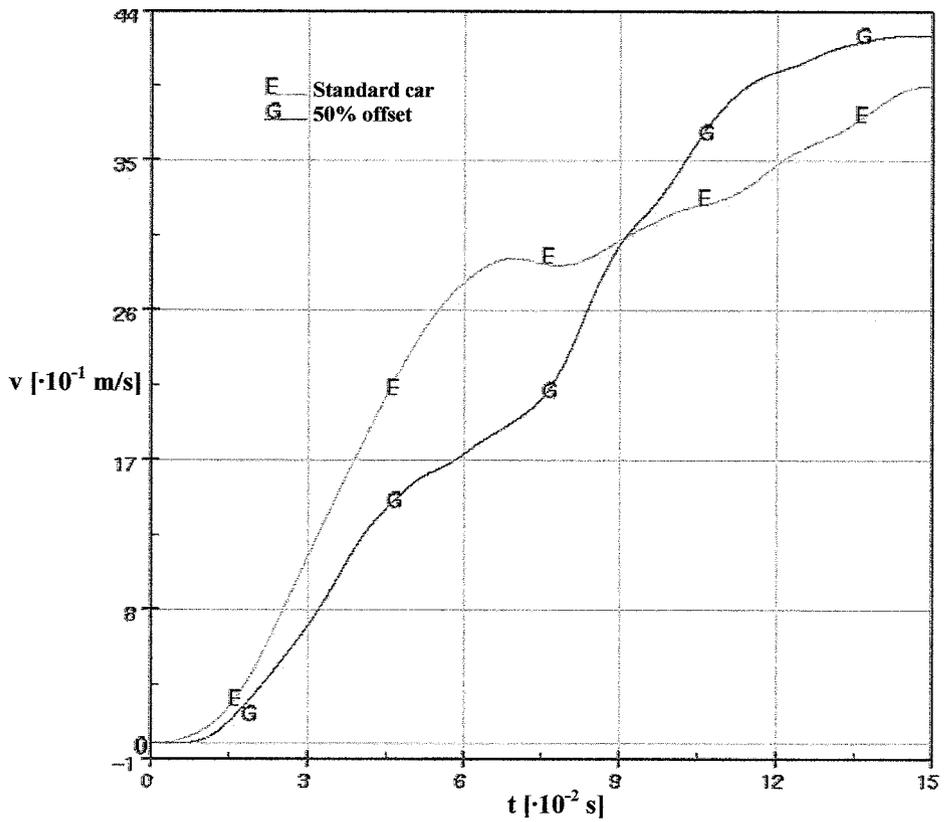
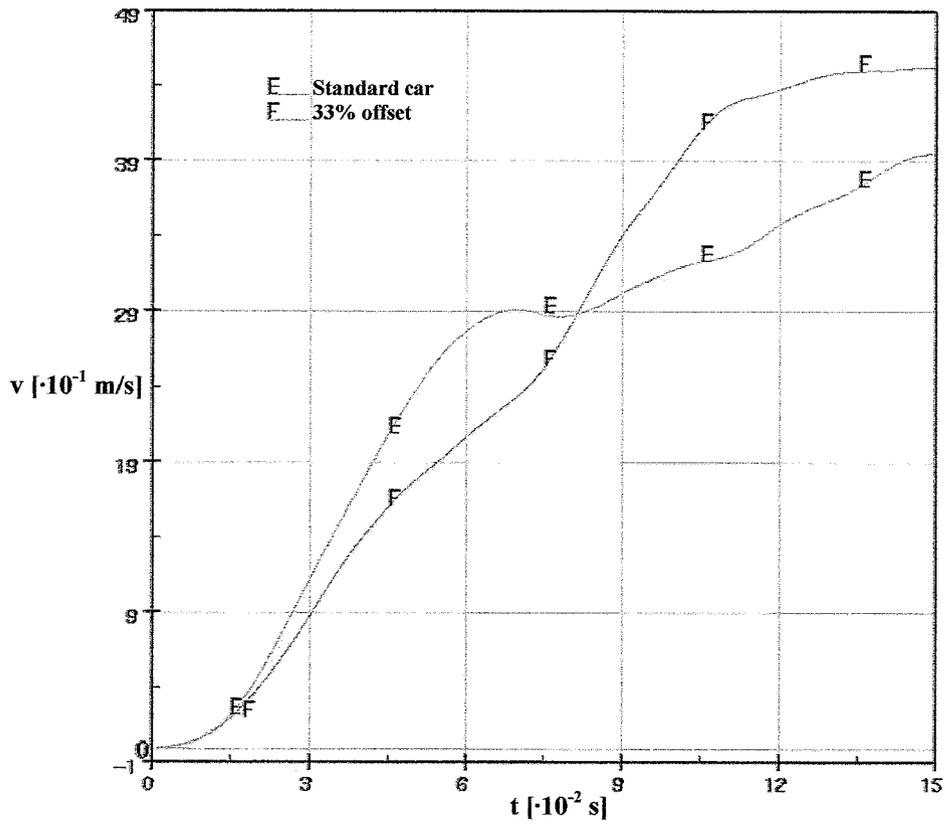


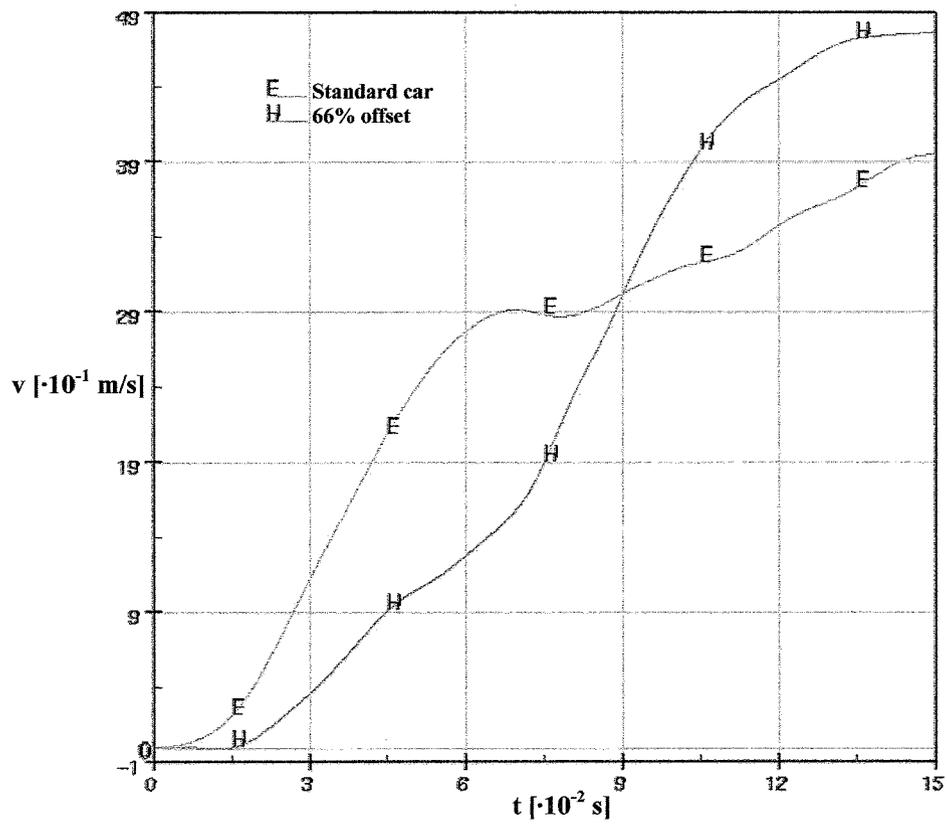




Now the results of the change in velocity of the struck car are given

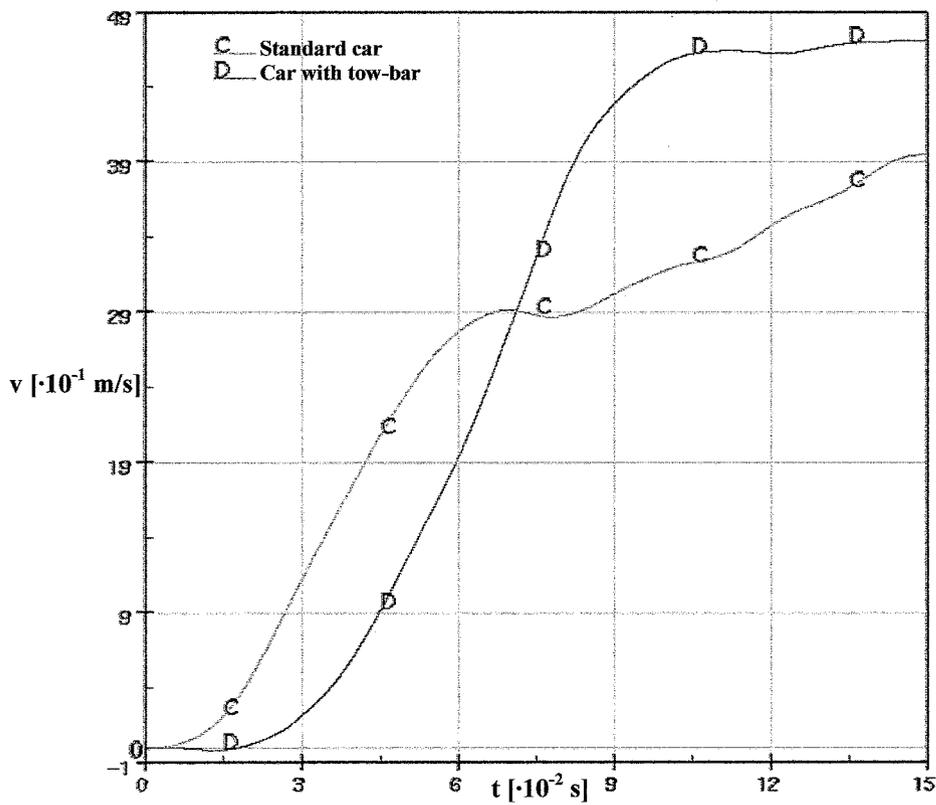
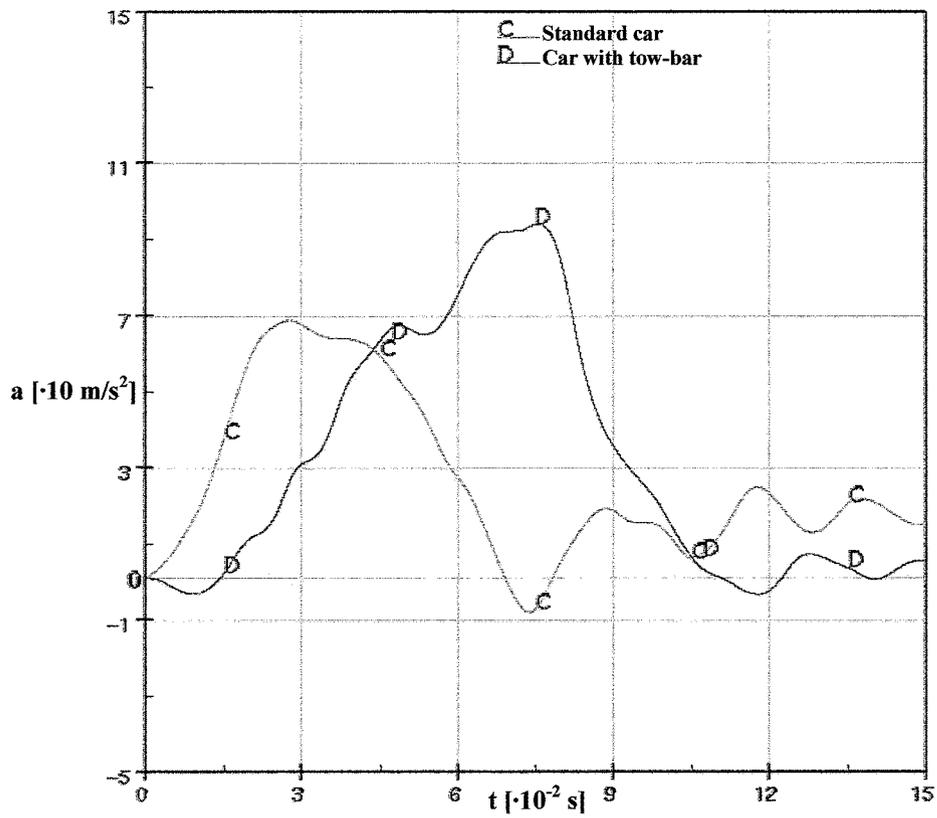






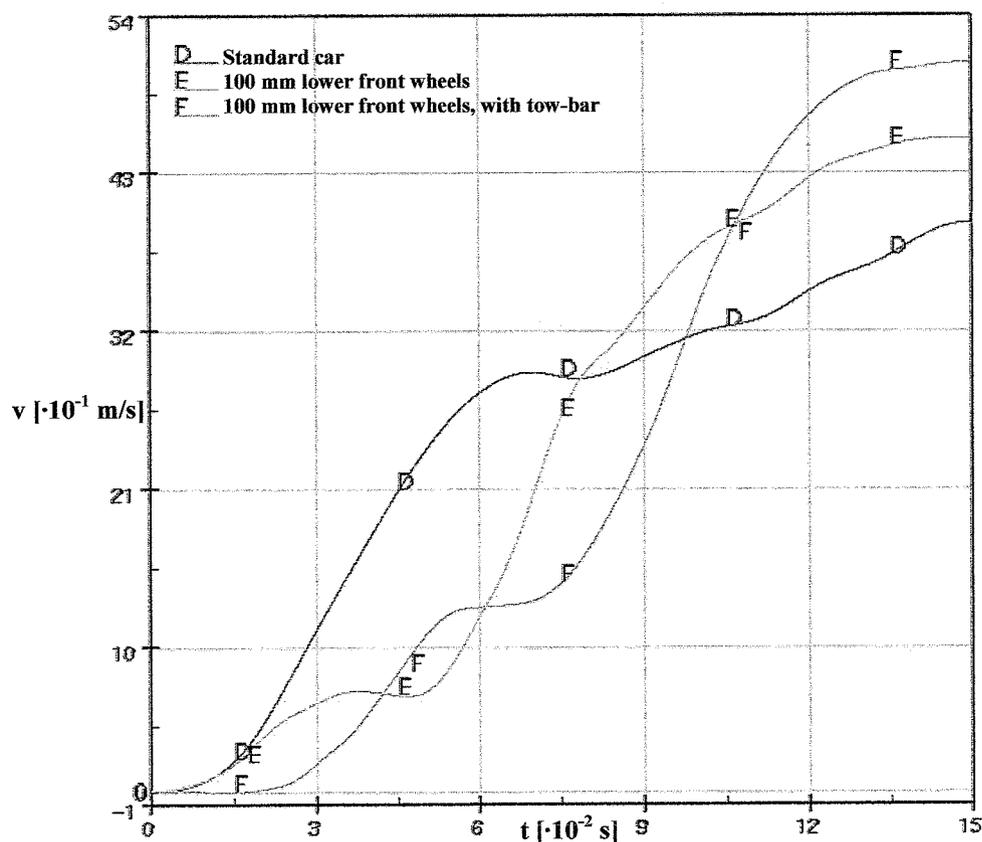
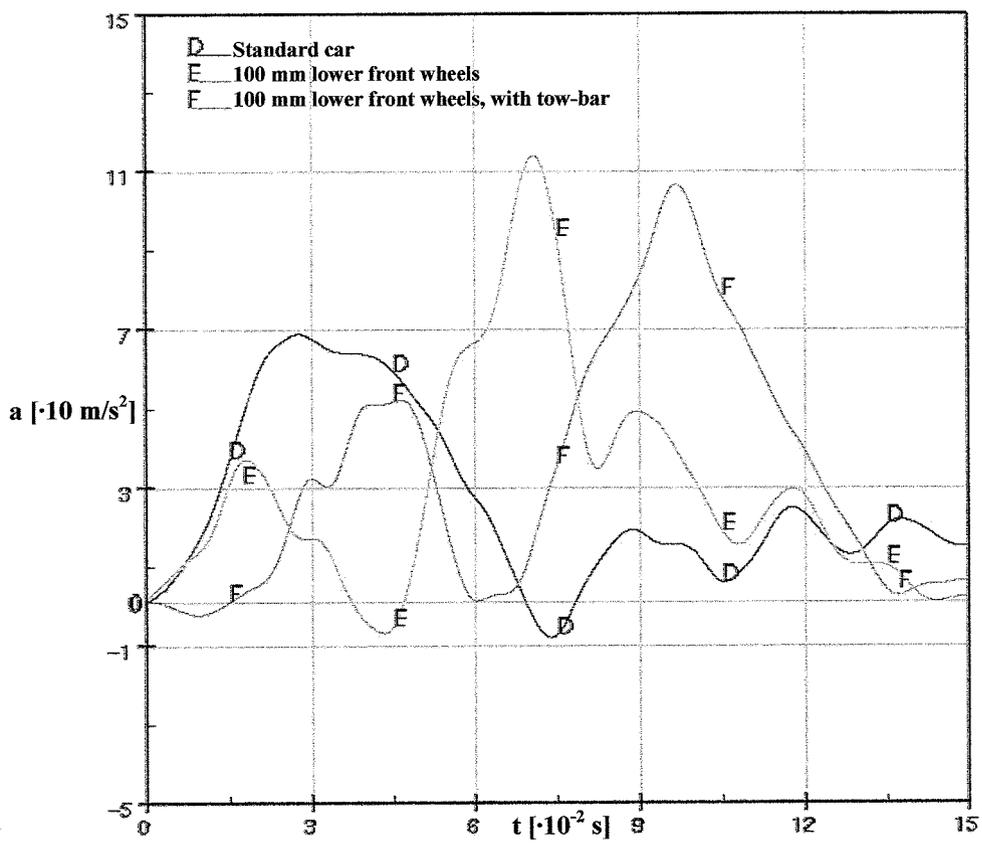


Appendix 9 Results tow-bar: full overlap



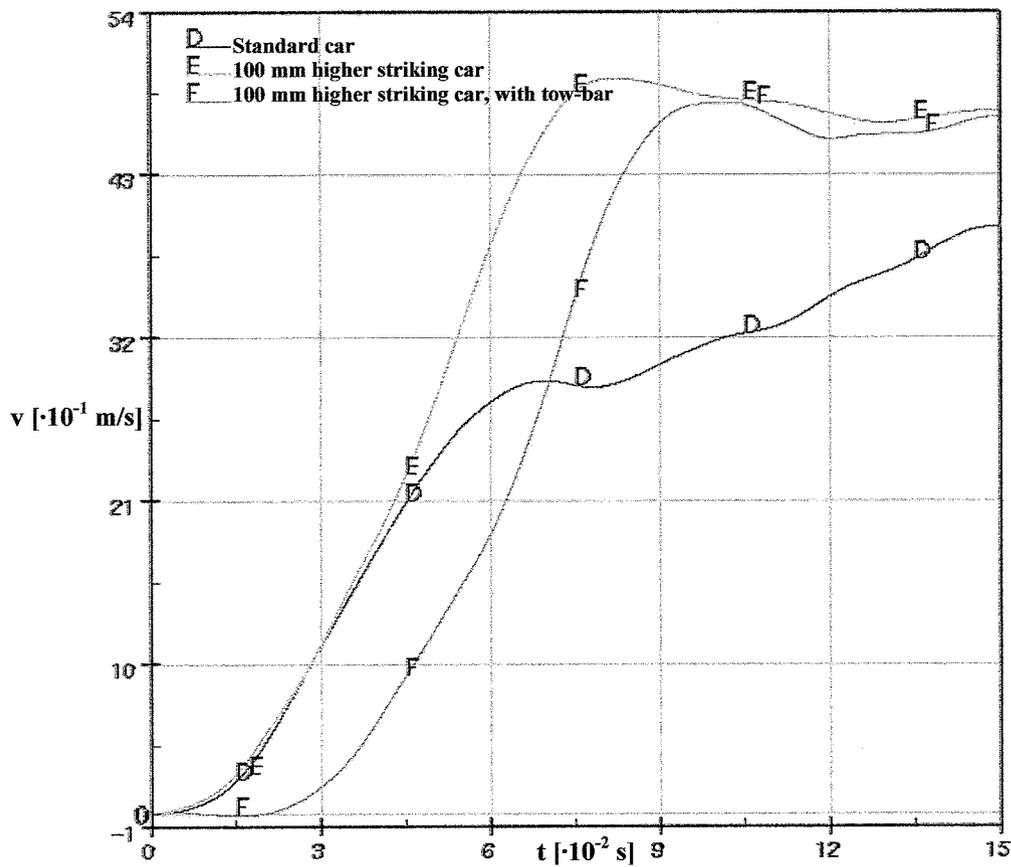
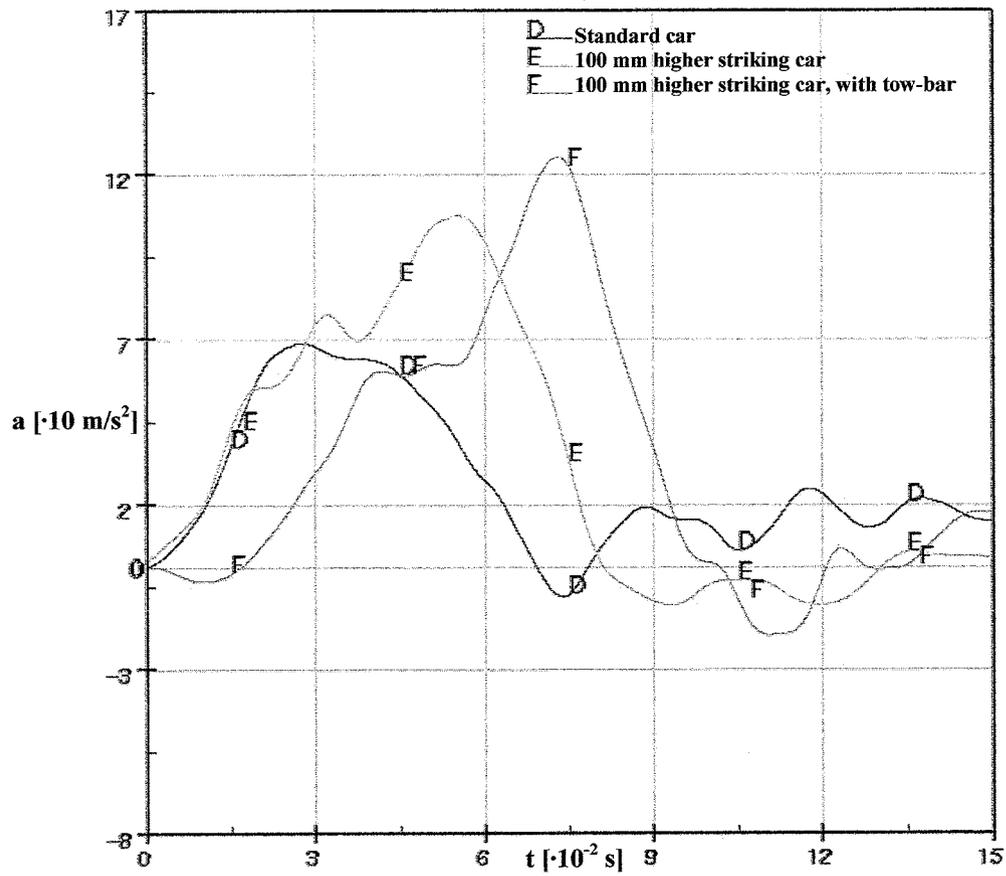


Appendix 10 Results tow-bar: under ride



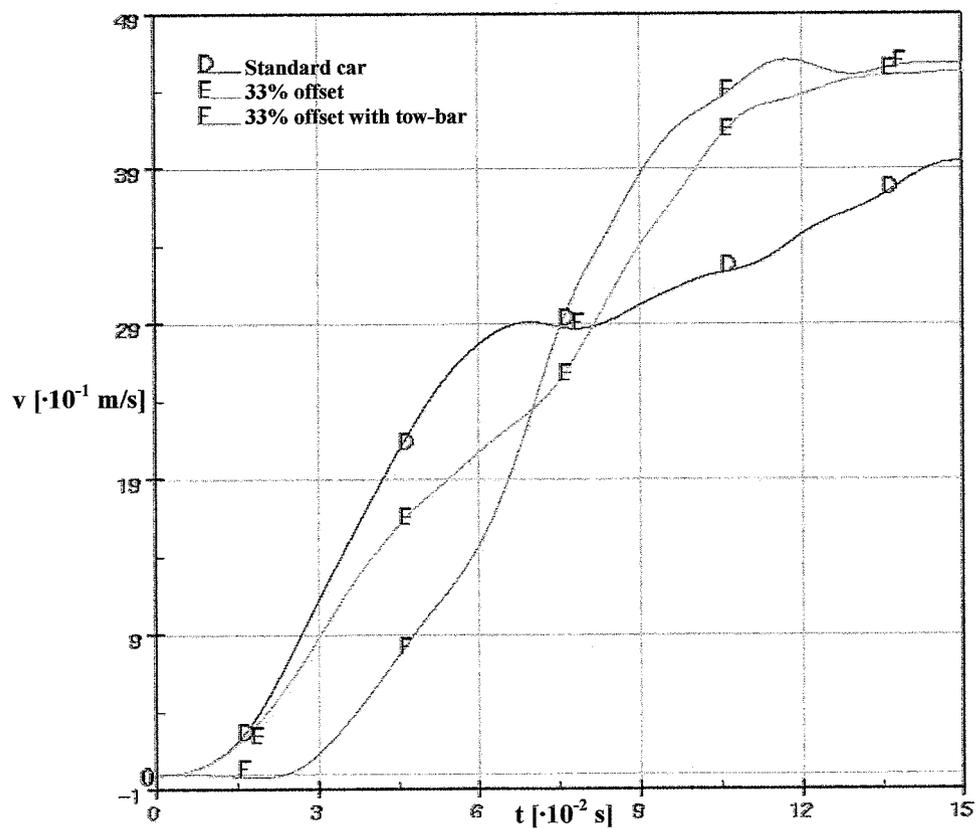
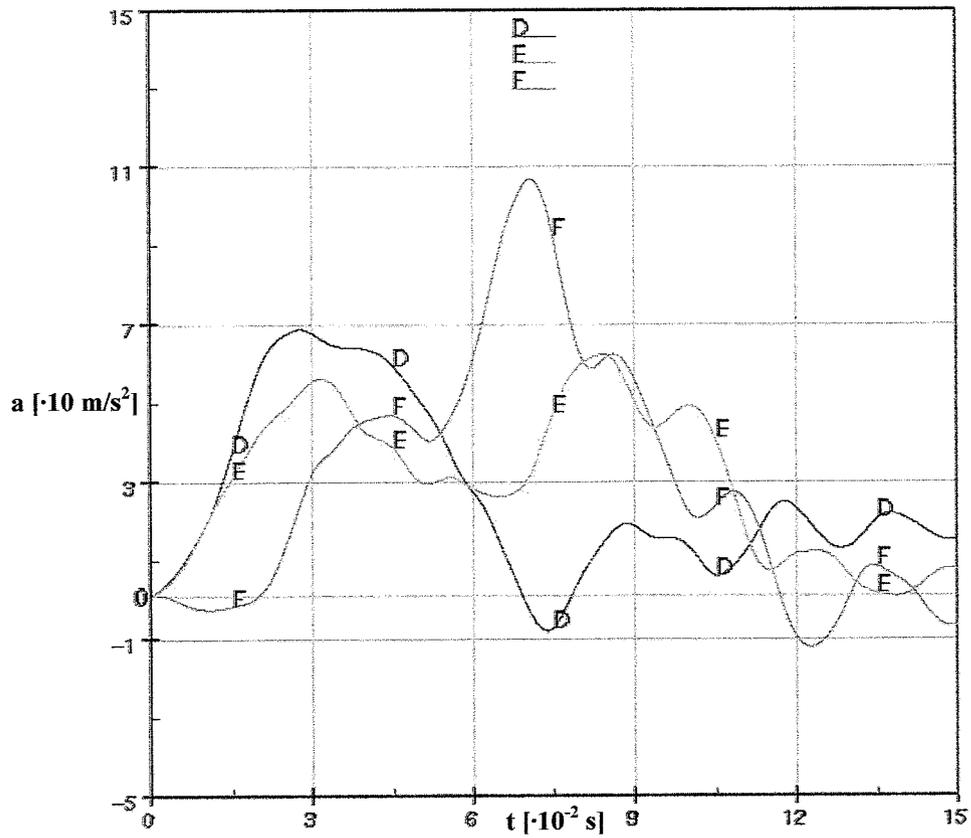


Appendix 11 Results tow-bar: over ride





Appendix 12 Results tow-bar: offset





Appendix 13 Problems encountered during simulation

Boundary conditions: time steps

For the boundary conditions several time steps had to be set. The second time step was the time step for the output file to create time history plots (e.g. velocity, acceleration). First the standard step size of $5 \cdot 10^{-5}$ s was used. But after a couple of simulations it turned out to be the step size was too large to calculate the correct velocity and acceleration. One example is that the integrated acceleration curve did not provide the same curve as the velocity curve. Changing the step size to $1 \cdot 10^{-5}$ s the problem was gone.

Creating under/over ride

The intention of this study was to lower the suspension in the same way as in the report from Autoliv [1]. This meant compressing or stretching the spring/damper combination in the FEM car with a certain amount. To simulate compression the spring/damper combination is given a negative offset. This offset means that the 2 nodes, which define the end en beginning of the spring/damper combination, are put on a negative offset to create the compression. For simulating stretching, the offset is set positive. Unfortunately, after running some simulations the compressing or stretching of the springs didn't give the suspected effect. The front wheels immediately went into the air when the spring/damper combination was given a positive offset. This resulted in a very strange collision. The opposite happened when the offset was negative: the front of the car was going back to the original height.

Sliding contact between the cars:

In some simulations another type of formulation of the sliding contact had to be used. It turned out to be that some elements were gaining a lot of mass when using the penalty formula. Some elements of the striking car were merging with elements of the struck car. Using the soft constraint formulation solved this problem.