

PARAMETER STUDY ON DIFFERENT FACTORS INFLUENCING LOWER EXTREMITY INJURIES

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ABSTRACT

Accident statistics show that injuries to the lower extremities are quite frequent in accidents. In most cases these injuries are not life-threatening, but the related treatment & convalescence costs are quite high. In this study different factors influencing lower extremity injuries were investigated. To define the relevant parameters, a baseline crash test under Euro NCAP conditions with instrumented hybrid III legs was performed. Using these test results, a simulation model and a sled test model were set up in parallel and validated with respect to the baseline crash test. The main areas for improvement to the lower extremities were defined and from these, six different protection concepts were investigated:

- 1.) Foot airbag
- 2.) Foam padding (toeboard)
- 3.) Active unlocking of brake pedal
- 4.) Reduction of translational toeboard intrusion
- 5.) Reduction of rotational toeboard intrusion
- 6.) Pop-up kneebolster

In order to investigate different combinations of these six protection concepts, a Design of Experiments (DoE) matrix was created and 108 simulation runs were performed. Based on the simulation results, six different combinations of these protection concepts were tested on the sled. Finally, the performance of the best protection system combination was verified in a full scale crash test.

INTRODUCTION

Injuries to the lower extremities are quite frequent in automotive crashes. Examining UK crash data (CCIS database) Pattimore (1) found, that after injuries to the head and face, injuries of the lower extremities is the second most often injury. These injuries are less severe than injuries to head or chest, but can be responsible for high injury costs. It was noted, that 50 % of the examined lower extremity injuries were

below the knee. Especially injuries to the foot and ankle were identified as the most frequent injury. These injuries often result in long term and permanent impairment.

Parenteau (2) found, that 48 % of the AIS 2+ injuries were estimated to have residual impairment and Crandall (3) reported by examining the US 1990-1992 NASS data, that injuries to the upper and lower extremities are still frequent for occupants restrained by an airbag compared to cases without an airbag.

If there are pedals concerned, Morgan (4) reported, that 57 % of the foot ankles were injured when the foot was on the brake pedal by analyzing the NASS data from 1979-1986.

Regarding the influence of the brake pedal, OPEL started to introduce their mechanical self-decoupling pedal release system in the vehicles, beginning with the OPEL Vectra in 1995.

Zuby (5) reported by a series of 17 midsize sedan car crashes, that there was a significant correlation between intrusion and the lower tibia index of the left leg.

Other investigations performed by Kuppa (6) in 1995 and Forssell (7) in 1996 showed by mathematical simulation and tests that padding is an efficient way to reduce the axial tibia load in the dummy's lower leg.

The presented study investigates the effect of different protection systems on injuries to the lower extremities in addition to the installed OPEL pedal release system. The injury reduction of each protection system or protection system combination was compared to a 64 kph 40 % ODB baseline crash test. The car basis for the presented study was a standard OPEL Astra.

METHODOLOGY

According to a baseline crash test, a sled test mock-up with corresponding intrusion was built-up.

To investigate all different parameters of each protection concept, a numerical simulation model was developed. Based on this simulation model and with the Design of Experiments (DoE) method the influence of every protection system on the loads to the dummy's lower legs were determined.

Typically, the simulation model is correlated to the sled test setup, which is correlated to the baseline crash. This means the 2nd derivation of the baseline crash. Here, because of the complexity of the footwell intrusion, another method was chosen. As the sled and the simulation model can only reflect an approximation of the original intrusion behavior, the simulation model and the sled were both validated on the baseline crash test (Figure 1) and compared with each other only referring to plausibility.

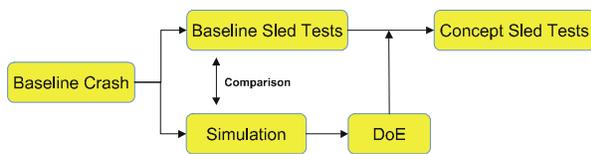


Figure 1. Methodology of Sled and Simulation Validation

The recommended protection systems out of the DoE matrix were afterwards evaluated on the sled.

BASELINE CRASH TEST

A special baseline crash test had been carried out to get detailed data of the vehicle's footwell intrusion. This was important to get an understanding of the injury mechanisms of the footwell and the pedal acting to the dummy's lower legs.

As high footwell intrusions are often related to injuries to the lower leg, a crash test under Euro NCAP condition was performed. The base car was OPEL Astra, which is the latest engineered vehicle with an OPEL pedal release system.

In order to get higher intrusions and higher loads to the lower legs the mass on the rear axle needed to be increased, which resulted in an increased footwell intrusion compared to a "regular" Euro NCAP crash test.

A hybrid III dummy typically used in frontal crashes was fitted with instrumented lower legs to measure forces, moments and accelerations caused by the interaction of the dummy's legs with the intruding vehicle structure.

The left foot of the dummy was placed on the footrest. Different to the regulation of Euro NCAP where the right foot should be placed on the accelerator pedal, the right foot was placed on the brake pedal which is equipped with the OPEL pedal release system.

Besides the vehicle data recorded generally during a crash, extended data of the intruding footwell and brake pedal were recorded: the brake pedal, footrest, firewall, toeboard, tunnel and side sill were fitted with nine 3-axis accelerometers. To evaluate the magnitude of the footwell intrusion, the deformations of the firewall and toeboard under both feet were additionally measured by potentiometers in the x-axis plane.

Three stationary and three onboard cameras were installed. One camera in the left car door, one in the passenger footwell parallel to the firewall and one on the right car side beneath the dummy's shoulder enabled the exact analysis of the dummy's instrumented legs interacting with the intruding footwell. Despite aggravated test conditions the car showed good crash behavior. All dummy loads were within the norm range, apart from, as expected, the tibia indices (Figure 2).

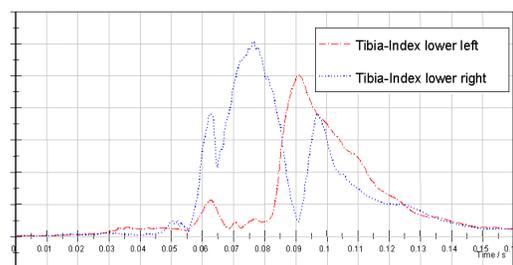


Figure 2. Lower Left and Right Tibia Indices

Motion analysis of dummy and footwell high speed films together with the measured dummy loads were used to evaluate injury mechanisms and the source for these mechanisms. An overview of the intrusion phases is shown in Table 1.

Table 1.
Intrusion Phases

Phases (right foot):	
0 – 45 ms	Foot movement
55 ms	Heel on firewall (dummy moves forward)
55 – 75 ms	Rotational intrusion of firewall and brake pedal
75 ms	Unlocking of brake pedal
75 – 90 ms	Brake pedal hits the firewall
90 ms	Common intrusion of brake pedal and firewall

Phases (left foot):	
0 – 55 ms	Dummy moves forward
80 ms	Intrusion of the footrest
80 – 90 ms	Overlap of footrest intrusion and dummy movement

Analysis of the footwell deformation characteristics showed a combination of translational and rotational intrusion. The right foot obtained high tibia loads on account of the overlap of rotational firewall intrusion, brake pedal and dummy movement. This resulted in a high dorsiflexion of the right foot.

The left foot was pushed backwards by the intruding footrest which caused high foot acceleration and high tibia moment.

SLED MODEL DESCRIPTION

Analysis of static and dynamic footwell deformation showed mainly the following two intrusion mechanisms: a rotation of the firewall around vehicle transverse (y) axis and a translation of the footwell in vehicle longitudinal (x) direction.

The two mechanisms were not proceeding one after the other but combined. To realize this combination of translational and rotational footwell intrusion, the hydraulic footwell intrusion system from Siemens Restraint Systems was used.

The principle assembly of the footwell intrusion system with its major parts is shown in Figure 3.

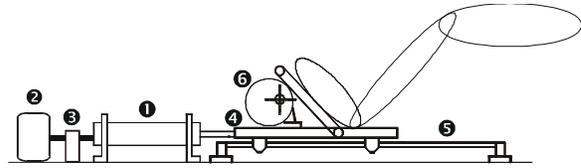


Figure 3. Principle assembly of the footwell intrusion system (8)

The system is activated by a hydraulic cylinder ① which is charged by a hydraulic unit consisting of a pressure reservoir ② and a control valve ③. The load of the cylinder is applied by a piston rod to the sled ④. The sled is mounted on a shaft ⑤ so that it is able to perform a linear movement in direction of the x-axis. The rotation of the firewall is realized by a curve disc ⑥, which is assembled on a spline shaft. A gear drive is the connection between the linear movement and the rotation. At the end of the linear movement a deformation tube absorbs the remaining kinetic energy of the sled and fixes the system in the end position to avoid a shifting of the intrusion by the HYGESled acceleration pulse. To realize the pedal release system a blow-up screw was used to release the brake pedal at a defined time during the test.

The sled test was validated on the results of the baseline crash test. The left foot was placed on the footrest, the right foot was placed on the brake pedal according to the dummy position in the baseline crash test.

The main focus was on the loads measured at the lower extremities, but also the global kinematics of the occupant was considered. Figure 4 and 5 show the correlation of the lower right and left tibia index.

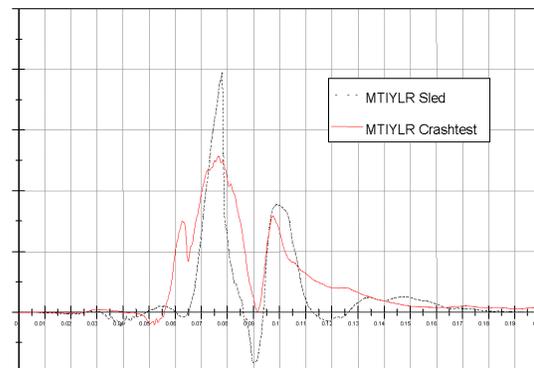


Figure 4. Correlation of Lower Right Tibia Moment

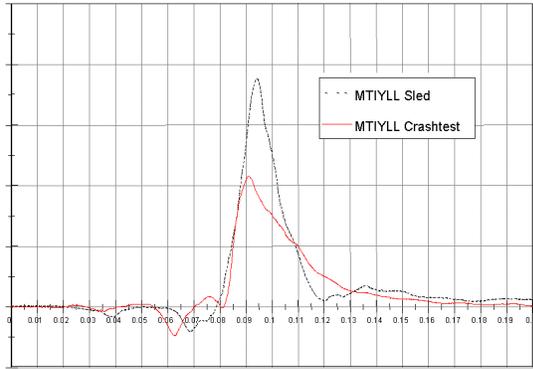


Figure 5. Correlation of Lower Left Tibia Moment

The peak values for the right and left foot were higher than the values for the baseline crash test, but the timing and curve characteristics matched quite well. The higher absolute values were acceptable, as the protection systems were only compared to the baseline sled test.

SIMULATION MODEL DESCRIPTION

An occupant simulation model of the OPEL Astra was set up for the simulation code MADYMO 5.3 (Figure 6). The interior of the vehicle and the dummy was modeled as a multibody system. The airbags (driver airbag and foot airbag) were modeled with finite elements. A 50 %-tile hybrid III dummy with instrumented lower legs was used to get accurate information about the loads acting on the lower extremities. The left foot was placed on the footrest, the right foot was placed on the brake pedal according to the dummy position in the baseline crash test. The motion of the toeboard, firewall and the mounting point of the brake pedal was included in the model according to the static measurements before and after the baseline crash test, and the motion of the toeboard/firewall and the brake pedal visible in the crash film. Therefore the toeboard was divided in four parts.

The lower left and right part simulated a rotational and translational intrusion according to the crash film. The rotation axis was the intersection of toeboard and floor.

The upper right and left part of the toeboard (firewall) had only one translational degree of freedom to simulate the translational intrusion, because only insignificant rotational motion in this

part of the firewall occurred during the baseline crash test.

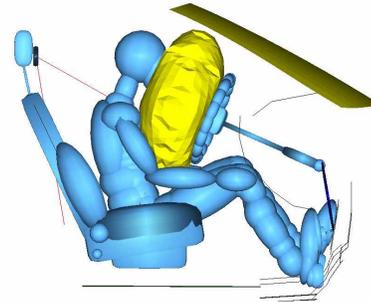


Figure 6. Baseline Simulation Model (9)

The simulation model was validated with the results of the baseline crash test. Focal point of the validation was to achieve optimum correlation of simulation and test for the loads measured at the lower extremities (Figure 7, Figure 8), but also considering the overall occupant kinematics.

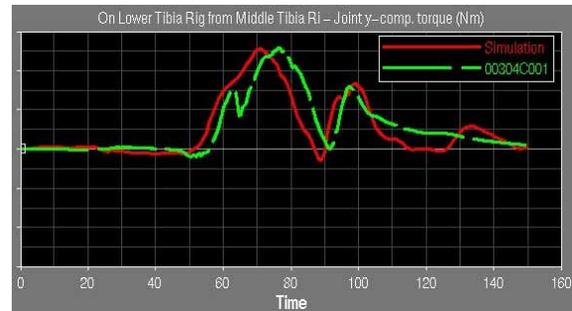


Figure 7. Correlation of Lower Right Tibia Moment



Figure 8. Correlation of Lower Left Tibia Moment

The results of the validation showed, that the important simulation curves, lower tibia moments, and the corresponding test curves matched quite well.

PROTECTION CONCEPTS

The injury of the lower extremities is evaluated by use of the upper and lower tibia index. The tibia index is defined as:

$$\text{Tibia Index} = \left| \frac{\text{Moment}}{225Nm} \right| + \left| \frac{\text{AxialForce}}{35,9kN} \right|$$

where "Moment" is the resultant tibia moment for either the upper or lower tibia moments:

$$M_{res} = \sqrt{(M_x)^2 + (M_y)^2}$$

The performed baseline crash test showed, that the lower tibia index in the OPEL Astra environment was mainly driven by the tibia moments but nevertheless, axial force was also considered in the study. Several investigations showed, that axial load can be reduced by foam padding.

Pre studies at Siemens Restraint Systems showed, that the lower tibia moments caused by the intruding footwell can be significantly reduced by a foot airbag.

Regarding the two influencing factors on the lower tibia index, tibia axial force and lower tibia moment, two parameter studies were defined out of six different basic protection concepts:

- 1.) Foot airbag
- 2.) Foam padding
- 3.) Active pedal release system
- 4.) Reduction of translational footwell intrusion
- 5.) Reduction of rotational footwell intrusion
- 6.) Pop-up kneebolster

The parameter study foot airbag shown in table 2 consists of all combinations of protection system 1.) and 3.) through 6.). The parameter study foam padding consists of all combinations 2.) through 6.) and is shown in table 3.

Table 2.
Parameter Study Foot Airbag

Parameter	Level 1	Level 2	Level 3
Foot airbag	No	-	Yes
Translational intrusion	None	Baseline/2	Baseline
Rotational intrusion	None	Baseline/2	Baseline
Brake pedal	Active release	-	Baseline
Pop-up kneebolster	Yes	-	No

Table 3.
Parameter Study Foam Padding

Parameter	Level 1	Level 2	Level 3
Foam padding	No	-	Yes
Translational intrusion	None	Baseline/2	Baseline
Rotational intrusion	None	Baseline/2	Baseline
Brake pedal	Active release	-	Baseline
Pop-up kneebolster	Yes	-	No

The combination of either foot airbag or foam padding with each parameter resulted in 108 different combinations, which were evaluated in simulations with the DoE method. The main focus was on the reduction of the lower tibia indices, as the lower tibia indices were identified as the most critical values in the baseline crash test. The upper tibia indices were also monitored, but identified as non critical.

PARAMETER STUDY FOOT AIRBAG

In this parameter study an airbag, which was placed underneath the heels of the driver was used. The simulation model with foot airbag is shown in Figure 9. The foot airbag supported the heels and therefore reduced the y-component of the lower tibia moments (dorsiflexion).

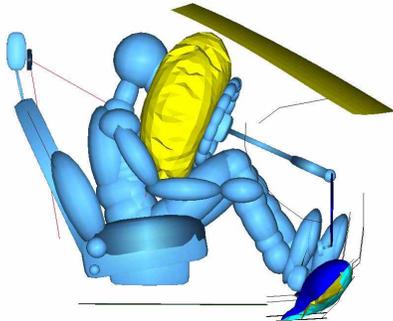


Figure 9. Simulation model with foot airbag

The parameter study foot airbag consisted of 72 simulation runs with different combinations of protection systems for the lower extremities. The results give an overview of all simulation runs, but it was very difficult to determine the best protection system and the effects of the different protection concepts. Therefore, a systematic evaluation tool (DoE method) was used. The most critical values in the baseline crash test were the lower tibia indices. Another index to rate the quality of the protection system was the upper tibia index. Consequently, the evaluation of the parameter study was focussed on the lower and upper tibia index of the left and right leg.

Results of the DoE Analysis Foot Airbag

Results for the Lower Left Tibia Index - The results for the lower left tibia index are shown in Figure 10. It shows the effects and interactions of the different protection concepts on the lower left tibia index.

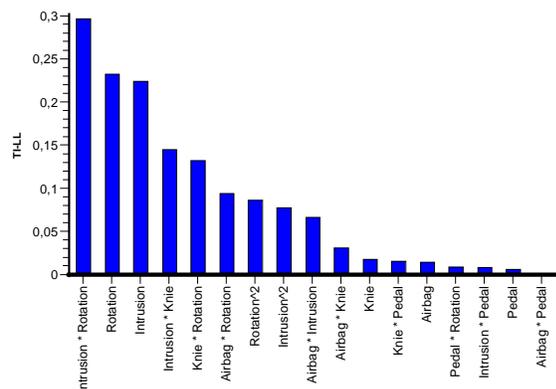


Figure 10. Effects graph for the lower left tibia index

The effects of the rotational (marked as ,rotation') and translational intrusion (marked as ,intrusion') and their interaction were much higher than the effects and interactions of any other parameter. The

effect of the pedal (unlocking or not) and any interaction of the pedal with other parameters were negligible as the load of the left leg is not influenced by the motion of the brake pedal. The effects of airbag and kneebolster were minor compared to the effect of the rotational and translational intrusion.

Another important result was, that the airbag or the pop-up kneebolster can only improve the lower left tibia index, if full translational and rotational intrusion occurs.

Results for the Lower Right Tibia Index - The effects graph for the lower right tibia index is shown in Figure 11.

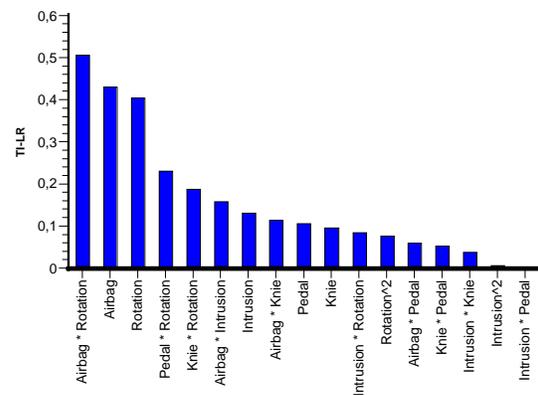


Figure 11. Effects for the lower right tibia index

The effects graph shows that the foot airbag and the rotational intrusion have the biggest effect on the lower right tibia index. Intrusion, pedal and kneebolster have also an effect, but small compared to the effect of foot airbag and rotational intrusion.

Results for the Upper Left Tibia Index - The pop-up kneebolster had the most significant effect on the upper left tibia index, followed by the effects of the airbag and the rotational intrusion. The pop-up kneebolster increased the upper left tibia index compared to the normal IP and should, therefore, not be used. A reduction of the toeboard rotation and the use of an airbag in the footwell also increased the values of the upper left tibia index slightly.

Results for the Upper Right Tibia Index - The unlocking of the brake pedal and the pop-up kneebolster had the most effect on the upper right tibia index. They increased the upper tibia index compared to the baseline crash. A foot airbag lead to a minor reduction of the upper right tibia index.

Results for the Tibia Compression Forces - The tibia compression force measured at the left leg was generally small. The most efficient protection concept was the reduction of the translational intrusion. The effect itself was minor and can be hardly proven by a real crash. The other effects were even smaller, so the influence of these protection systems on the left tibia force was negligible.

A significant effect of the foot airbag, brake pedal characteristics and translational intrusion on the right tibia index was found. A reduction of the tibia force by 30 % was possible with a foot airbag supporting the right foot. The airbag prevented the heel of the right foot from impacting the toeboard.

PARAMETER STUDY FOAM PADDING

In this parameter study a foam padding was mounted at the toeboard and firewall. The foam padding was designed as follows:

Left foot:

Thickness: 20 mm

Density: 30 g/l

Right foot:

Thickness: 30 mm

Density: 50 g/l

The simulation model is shown in Figure 12.

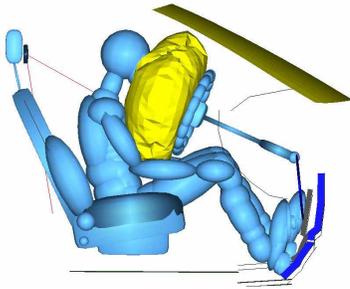


Figure 12. Simulation model with foam padding

Results of the DoE Analysis Foam Padding

The parameter study foam padding also consisted of 72 simulations. The simulation runs without foam padding were identical with the simulation runs without airbag. So only 36 additional simulation runs were carried out.

Results for the Lower Left Tibia Index - The results of the parameter study foam padding were similar to the results of the parameter study for the airbag. The most important protection concept was

the reduction of the rotation and intrusion of the toeboard and the firewall. A reduction from 100 % intrusion to 50 % intrusion was more effective, than a further reduction from 50 % intrusion to 0 % intrusion. The effect of the pedal was negligible, because the kinematics of the left foot was not influenced by the brake pedal. A reduction of the lower left tibia index by use of a foam padding was possible, if the intrusions (rotation, translation) were very small. In case of a high intrusion the foam padding increased the tibia moment, because the heel deformed the foam padding whilst the front part of the shoe did not deform the foam padding. This led to a smaller angle between the foot and the tibia and therefore increased the tibia moment. The pop-up kneebolster reduced the lower left tibia index if the intrusion was high.

Results for the Lower Right Tibia Index - The analysis showed, that reduction of the rotational intrusion had the biggest effect on the lower right tibia index. The effect of any other protection concept was smaller. The foam padding was less efficient than the foot airbag. An early decoupled brake pedal had a positive effect on the lower right tibia index, especially, if the rotational intrusion was small.

Results for the Upper Left Tibia Index - The effects of all parameters were smaller than the effects for the lower tibia indices. A high rotation (between 50 % and 100 %) of the toeboard and the foam padding slightly reduced the upper right tibia index, compared to the case without foam padding and rotation. The pop-up kneebolster could increase the upper left tibia index, but as the effects of rotation and foam padding this effect was so small, that it was not statistically significant and possibly can not be proved in a real crash.

Results for the Upper Right Tibia Index - The brake pedal was the most important factor for the upper right tibia index. It is recommended not to unlock the pedal too early, because this increases the upper right tibia index. The effect of any other protection concept was statistically insignificant and might not be detectable in real crash tests.

Results for the Tibia Compression Forces - The results for the compression forces were similar to the results of the parameter study with foot airbag. The only significant parameter was the translational intrusion. The effects of any other parameter were negligible.

SUMMARY OF THE PARAMETER STUDIES

Both parameter studies (foot airbag and foam padding) showed similar results. The most critical tibia indices in the baseline configuration were the lower tibia indices. Therefore, the goal of this study was the reduction of the lower tibia index. The upper tibia index must not be neglected as the results of the parameter study showed that a reduction of the lower tibia index can lead to an increase of the upper tibia index. The combination of all protection concepts lead to a recommendable protection system as follows:

1. Reduced rotational and translational intrusion.
2. A foot airbag that covers the heels of both feet.
3. A completely unlocked brake pedal is not ideal. A characteristic similar to the current OPEL pedal release system is the better alternative.

Obviously the foot airbag is necessary to reduce the lower right tibia index. A reduction of the intrusion is necessary to reduce the lower left tibia index. The combination of both systems lead to low tibia indices which were even lower than the upper ones.

NUMERICAL OPTIMIZATION OF THE PROTECTION SYSTEMS

In the foregoing analysis the protection system was optimized by analytical interpretation of the results and logical evaluation of the effects of each component for each response (tibia index).

Another way to optimize the system is the numerical optimization. Here all responses can be optimized at one time under different restrictions. Weighting factors for the optimized responses can be defined. In this investigation, the weighting factor was chosen identical for all responses.

Only the results of the parameter study with foot airbag were taken into account, because a higher effect showed up by the foot airbag compared to foam padding.

The results of the numerical optimization were quite similar to the settings for the recommended system. The numerical optimization lead to a little higher rotational intrusion and a smaller translational intrusion. The values of the tibia indices were similar to the values produced by the recommended system.

It is also possible to optimize the system for specific constraints. The optimization was performed for minimum lower tibia indices (Figure 13). The upper tibia indices were not optimized in this case.

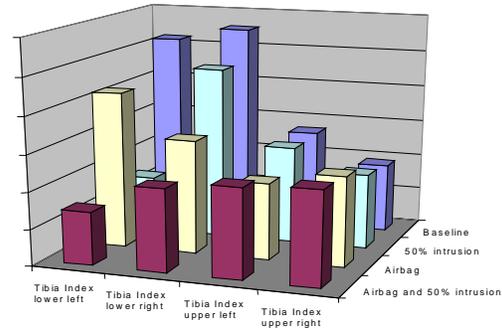


Figure 13. Optimization of the lower tibia indices

Figure 13 shows, that even in case of high intrusions an airbag mounted at the toeboard can reduce the tibia loads. A tibia index lower than 80 % compared to the baseline crash can be achieved even without reduction of the footwell intrusion.

No special optimization was performed for the protection concepts foot airbag and kneebolster. Therefore a further reduction, especially of the left tibia index might be possible by optimization of shape and characteristics of foot airbag and pop-up kneebolster.

SLED TEST

After evaluation of the DoE matrix, the following concepts were chosen to be tested on the sled:

- 1.) Foot airbag
- 2.) Foam padding
- 3.) Pop-up kneebolster
- 4.) 50 % reduction of intrusion
- 5.) 50 % reduction of intrusion & unlocking of brake pedal
- 6.) 50 % reduction of intrusion & foot airbag

Foot Airbag

The foot airbag used in this study was a pre-optimized airbag with 6 liters bag volume, filled by a standard SHI airbag inflator with diffuser. It was mounted on top of the carpet. The airbag triggering time was 24 ms after car to barrier contact.

The test showed, that the lower tibia index on the left side could be reduced by 34 % compared to the baseline sled test.

As the right foot was positioned on the brake pedal, the foot airbag supported the heel of the foot. The reduced dorsiflexion resulted in a 52 % reduced lower tibia index.

Foam Padding

To prove the effectiveness of foam padding, a sled test with pre-optimized foam padding for the left and right foot was performed. The padding for the left and right foot had different foam thickness and density as described in the parameter study foam padding. This resulted in a reduced foot acceleration of 39 % and a reduced tibia axial force of 14 % for the left foot. The lower left tibia moment was not reduced. This resulted in a minor reduction of the lower left tibia index.

The foam padding for the right foot caused no reduction of the tibia axial forces or lower tibia moments, as the loads of the right foot were dominated by the influence of the brake pedal. The lower right tibia index was not reduced by foam padding.

Pop-up Kneebolster

If no foot airbag is used, the simulation showed an effect of a pop-up kneebolster on the lower left tibia index. For that reason, the influence of a knee protection system was studied. The kneebolster was 100 mm thick and had a foam density of 50 g/l. The bolster was installed in a position, where an inflated knee bag would be positioned. The performed test showed, that the lower tibia index for the left foot was reduced by 34 %. The lower right tibia index was reduced by 47 %. This was the effect of the early contact between the dummy knees and the pop-up kneebolster.

Reduction of Intrusion

In this sled test, the positive effect of a reduced intrusion on the left lower tibia index determined from the simulated DoE matrix was evaluated. The translational and rotational intrusion of the footwell was reduced by 50 %.

For the left foot a reduction of the lower tibia index by 86 % was seen. The lower tibia index of the right foot was only reduced by 28 % because the pedal release characteristics was not changed compared to the baseline sled test.

Reduction of Intrusion and unlocking of Brake Pedal

By additionally unlocking the brake pedal, the right lower tibia index was further reduced compared to the foregoing sled test with reduced intrusion only. By releasing the brake pedal 50 ms earlier compared to the baseline sled a 82 % reduction of the lower right tibia index was achieved, while the reduced intrusion caused a reduction of the lower left tibia index of 84 % .

Reduction of Intrusion and Foot Airbag

The other investigated combination with good results in the simulation was the combination of 50 % reduced intrusion with a foot airbag.

The performed sled tests showed, that the lower tibia index of the left foot was reduced by 77 %, the lower tibia moment of the right foot was reduced by 81 %.

RECOMMENDED PROTECTION SYSTEMS AFTER SLED TESTING

Figure 14 shows an overview of the different protection systems and their combinations after sled testing.

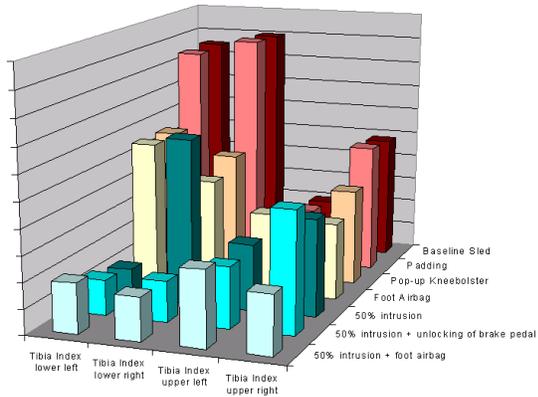


Figure 14. Recommended Systems after Sled Testing

It was found, that the reduction of the translational and rotational intrusion in combination with an improved decoupling brake pedal or a foot airbag provides the most benefit for the reduction of the lower tibia index.

The performed investigation indicates low significance of foam padding on the tibia index.

CONCLUSIONS

The foregoing results of simulation and sled testing show, that the lower left tibia index is strongly influenced by the magnitude of the footwell intrusion. A reduction of the footwell intrusion by 50 % improves the lower left tibia index by 86 %. Other additional measures like foot airbag or foot padding do not provide any additional improvements for the lower left tibia index.

The lower right tibia index is dependent on the pedal intrusion characteristics. Therefore, the reduction of the footwell intrusion by 50 % provides only minor improvements for the right lower leg.

The combination of 50 % reduced intrusion with an optimized pedal release system or a foot airbag was identified as the best protection system for the left and right lower leg.

At higher intrusions, the foot airbag or the pop-up kneebolster provide the most improvements for the lower right and left tibia indices.

Foot padding had no influence on the lower left tibia moment, but it was found, that foam padding could reduce the axial tibia loads and foot accelerations.

An influence on the lower right tibia index by foot padding was also not found, because the lower right tibia index was dominated by the brake pedal. Nevertheless a positive influence of the foot padding could have been shown up, if the foot had moved off the brake pedal during the test.

A final crash test with an installed foot airbag showed that the lower left tibia index was reduced by 69 % and the lower right tibia index by 55 %.

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