FOOT AND LEG INJURIES IN FRONTAL CAR COLLISIONS

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ABSTRACT

Attention to injuries to foot, ankle and tibia is becoming increasingly focused as safety improvements are made in other areas. As our knowledge increases, views concerning the factors that cause leg injuries, become more varied. This paper presents Volvo's view on the subject and focuses on four main factors: Geometry, Pedals, Acceleration and Intrusion. The risk of injury is believed to be an accumulation of these factors. In order to achieve significant improvements in the area of leg injuries, it is therefore necessary to address all factors.

INTRODUCTION

Overall occupant safety has improved significantly throughout the past 20 years. Leg injuries are however still frequent and when long term consequences are considered, injuries to the lower limb account for an important issue (Mc Kenzie; 1986). It is therefore important to understand the injury factors behind leg injuries, in order to know how to help reducing them.

This paper presents the main factors of foot injury in frontal impacts, namely:

- Geometry - local differences in height and width of the footwell.
- Acceleration - generation of contact forces between foot and surface through change in relative speed
- Pedals - design and behaviour
- Intrusion - in the footwell area

The factors are identified by presenting the statistic material available, discussing the results of an in-depth study of 20 injured ankles and thereafter linking this material together in a discussion, pointing out the main injury factors. Results from simulation and testing are presented, to strengthen the arguments.

Throughout this paper, the injuries are divided into foot, ankle and tibia injuries. The term leg injuries is used to, in one word, represent foot, ankle and tibia injuries.

LITERATURE SURVEY

The mechanisms of foot and ankle injuries are very complex. Several different injury factors have been identified in the literature, although there are few papers which cover more than one or two at a time. In addition, several different (and sometimes) contradictory injury mechanisms, have also been pointed out.

Mechanisms

In an extensive in-depth accident study, Fildes et al. (1995) identified the main injury mechanisms as compression of the leg, perpendicular load to the knee and crushing or twisting of the foot.

In another in-depth study, Lestina et al. (1992) found four common fracture mechanisms of the foot and ankle: inversion or eversion, direct vertical force, dorsiflexion and direct side force. The Lestina study confirmed the frequencies of the six injury mechanisms identified by Morgan et al. (1991), with the addition of identification of inversion or eversion as a prominent fracture mechanism.

In an accident study, Portier et al. (1993) identified two main mechanisms: forces acting under the metatarsal condyles, coupled with the inertial effect of a dorsiflexing foot, producing metatarsal fractures and eversion /inversion motions, caused by forces acting under the ball of the foot, producing malleolar fractures and ankle sprains.

Intrusion

The effect of intrusion has been studied by several authors. Many published studies (Gloyns et al. 1979, Portier et al. 1993, Pattimore et al. 1991, Otte et al. 1992 and more), suggest that intrusion, as well as delta-V, increase the risk of leg injuries. In a recently published study by Thomas (1995), the effect of intrusion could be separated from crash severity, stating that intrusion in the footwell increases the risk of leg injury to a greater extent than crash severity.

Pedals

Thomas (1995) also identified a higher risk of AIS2+ leg injuries to the driver than to front seat passenger. He suggests that this is mainly due to the pedals. In a computer simulation study, by Pilkey et al. (1994), a correlation was found between position of the foot on the brake pedal and the load transmitted to the heel of the braking foot, suggesting that minimised intrusion combined with a brake pedal position, which allows the heel to remain close to the toepan, would be the optimum way to limit impact on the foot.

Geometry

Otte et al. (1992) identified two characteristic mechanisms which should be regarded separately. Apart from the force mechanism, which always results from intrusion of the footwell, the study identified another mechanism, a simple supporting and slip-off mechanism of the feet, which may already occur in connection with less severe accidents, in which there is no intrusion of the footwell.

Acceleration

In a study by Crandall et al. (1995), it was found that 71% of injuries below the knee, sustained by front seat occupants in head-on collisions, occur with less than 3 cm of intrusion. The study pointed out that factors such as the vehicle's change in velocity and the rate and timing of intrusion, must be considered when examining injury mechanisms to the lower extremities.

Frampton et al. (1995) found lower limb injuries occurring under conditions of very little or no intrusion, suggesting padding in the footwell would diminish peak loads and thus, reduce injury more effectively than merely aiming to reduce intrusion.

ACCIDENT DATA

The accident data is an important source of information, for determining the injury factors. The acceleration, intrusion and geometry factors can be determined by investigating:

- Crash severity
- Exterior deformation of the car

Distribution of the impact area for driver and front seat passenger

The effect of the pedals can be determined by investigating:

- Use of brake pedal by the driver
- Distribution of injury to left and right leg
- Distribution of the impact area together with injuries to driver and front seat passenger

General Information

The following data is taken from Volvo's own data base, which contains accidents involving Volvo cars in Sweden. The present data base consists of about 25 000 accidents.

Out of the AIS2+ injuries involving belted driver in Volvo 700 and Volvo 900, about 20% are injuries to thigh and leg. The risk of sustaining long term consequences from these type of injuries, is 2.4% (Mixed model, Koch et al 1992), which indicates the significance of leg injuries.

The cases selected for the study were frontal impacts involving Volvo 200, 700 and 900 series cars, where the driver and the front seat passenger (when present) had been belted, totally 6040 accidents. From this selection, a subset of leg injuries where at least one of the occupants had sustained leg injuries of the type AIS2+, was used.

Injury Type

The database records contains fracture injuries of the leg, where the leg is divided in three parts; tibia/fibula, ankle and foot. The ankle injuries are defined as injuries to the talus, caleaneus and malleoleus. A leg injury relative frequency can be calculated from the material, according to the table below.

Table 1.
Leg Injuries where First Figure is Number of Cases and Second Figure is Relative Injury Frequency in % of All Selected Frontal Impacts in this Study.

	Tibia/Fibula	Ankle	Foot
Driver	33 / 0.5%	73 / 1.2%	56 / 0.9%
Pass	6 / 0.3%	13 / 0.6%	11 / 0.5%

The most frequently injured part of the leg is the ankle, which together with the foot represents approx. 80% of all injuries. The driver leg injury frequency (in percent), is about double that of the passenger.

Crash severity

The EBS (Equivalent Barrier Speed, Nilsson-Ehle et al. 1982) measurement was used as a measure of crash severity. With the help of a logistic regression, it can be shown that higher severity, gives a higher risk for leg injury (Figure 1).

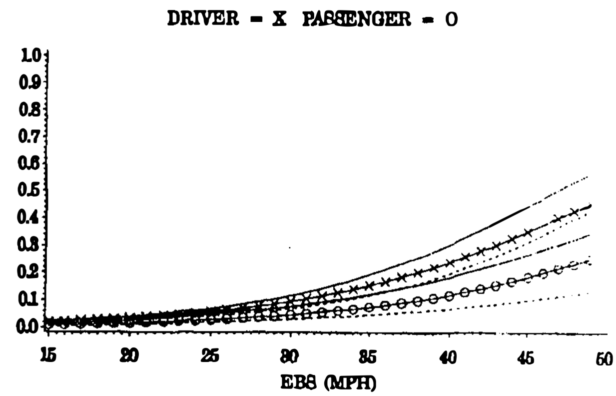


Figure 1. Leg Injury Risk for Driver and Front Seat Passenger as a Function of EBS. Risk Curves Surrounded by 90% Confidence Bands.

Figure 2 illustrates the EBS distribution between driver and front seat passenger.

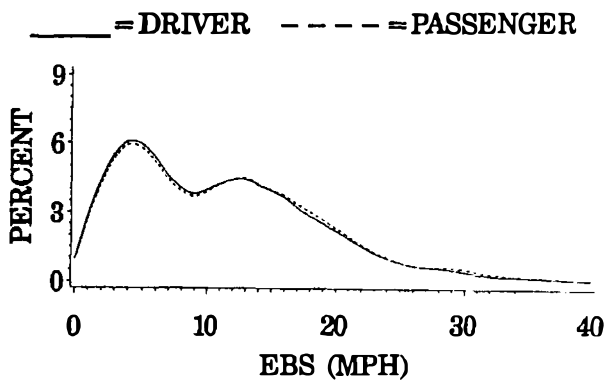


Figure 2. EBS Distributions for Driver and Front Seat Passenger in Frontal Impacts.

The small difference in EBS distribution can not explain the higher injury risk for the driver compared to the passenger. It is clear that increased severity (and thereby to some extent, increased acceleration), results in an increased risk of sustaining leg injury.

Deformation

Another way of quantifying the crash severity, is the deformation of the car. Volvo's database contains the exterior deformation of each car and with the help of laboratory data, it can be shown that intrusion in the footwell area requires an exterior deformation in excess of 50 cm.

A logistic regression, with 90 % confidence limits, shows that greater deformation depth of the car, gives a higher risk of leg injury (Figure 3). For a certain deformation of the car, the driver has a higher risk of leg injury, compared to the front seat passenger.

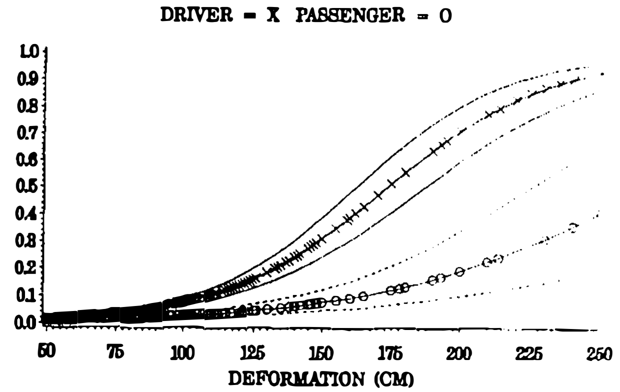


Figure 3. Leg Injury Risk for Driver and Front Seat Passenger as a Function of Exterior Deformation. Risk Curves Surrounded by 90% Confidence Bands.

Figure 4 does not illustrate any significant difference between driver and front seat passenger, regarding the distribution of the deformation.

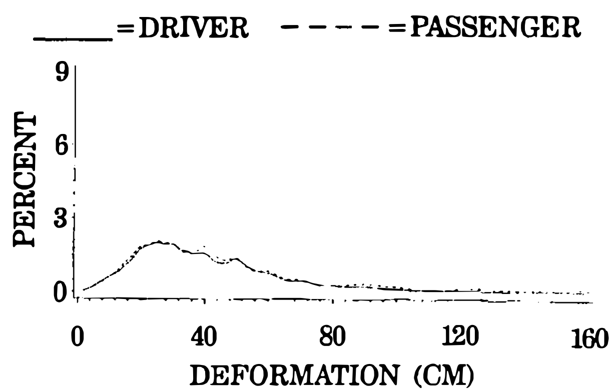


Figure 4. Exterior Deformation Depth Distributions for Driver and Front Seat Passenger in Frontal Impacts.

The higher risk of injury for the driver, compared to the passenger, can not be explained by the small difference in exterior deformation distribution. It is, however, clear that increased deformation (and thereby to some extent, increased footwell intrusion), results in an increased risk of sustaining leg injury.

Severity and Deformation

By plotting the injury cases against EBS and deformation, it is possible to distinguish, if intrusion is a significant parameter, or if there are occurrences without intrusion present. It is also possible to determine whether a higher degree of EBS or deformation, is required to produce a certain type of leg injury. Figures 5 and 6 illustrate the injuries to tibia, ankle and foot, for the driver and front seat passenger respectively, as a function of EBS and deformation of the car.

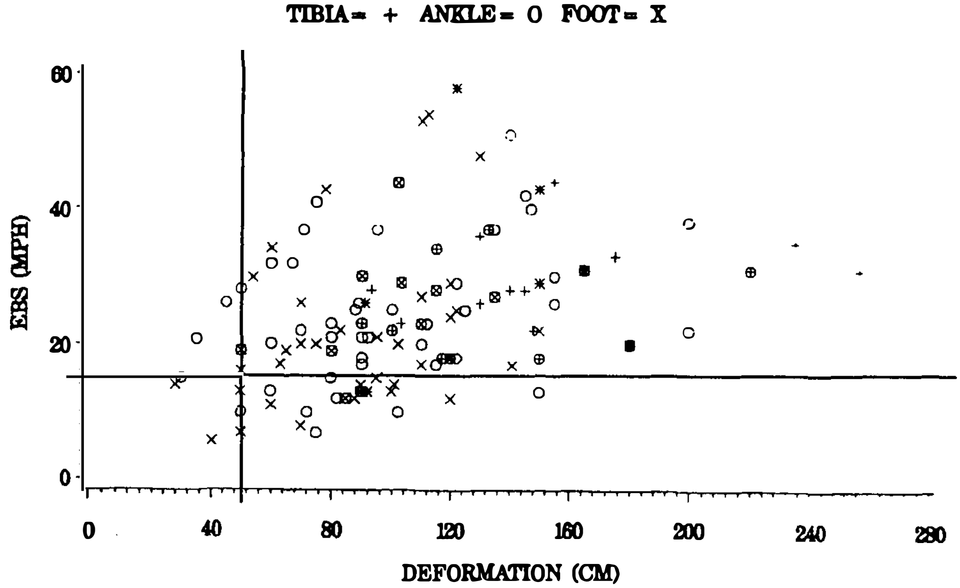


Figure 5. Leg Injuries to Driver.

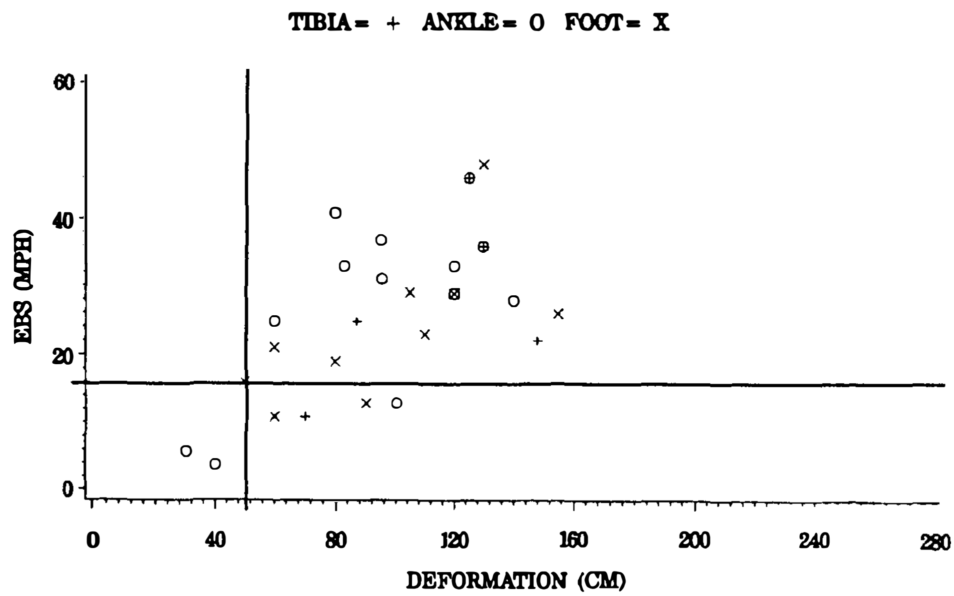


Figure 6. Leg Injuries to Front Seat Passenger.

It is interesting to note that approx. 10% of the cases are foot and ankle injuries where deformation is less than, or equal to 50 cm, i.e. no footwell intrusion is involved and severity is low (< 15 mph). These cases exist for both the driver as well as passenger. All fractures to the tibia have occurred at a deformation of 70 cm or greater and an EBS in excess of 12 mph.

Fractures to the foot and ankle, requires less deformation and EBS.

Higher severity, both in deformation and EBS, is required in order for the front seat passenger to sustain foot fractures.

Impact Area

The impact areas describe how much of the front of the car that has been engaged during the crash. The accidents are divided into three areas. Left offset is defined as all accidents involving less than 33% overlap on the left side. Right offset stands for the same definition on the right side. The remaining impacts, where the overlap is greater than 33% on any side, are defined as frontal impacts.

The percentage of offset impacts, on the left side, is greater for drivers whom have suffered leg injuries, than it is for all drivers in the selected material. See Figure 7.

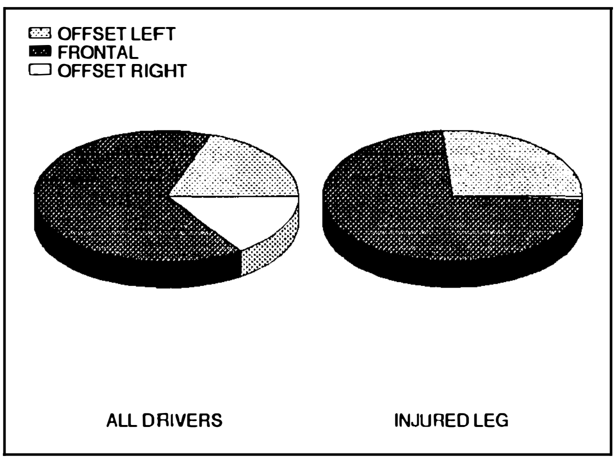


Figure 7. Distribution of Impact Areas for the Driver.

Comparing accidents involving front seat passenger leg injuries to accidents involving all passenger injuries, shows that frontal impacts are more common. It is also interesting to note that passenger leg injuries also have occurred, when the impact has been on the drivers' side.

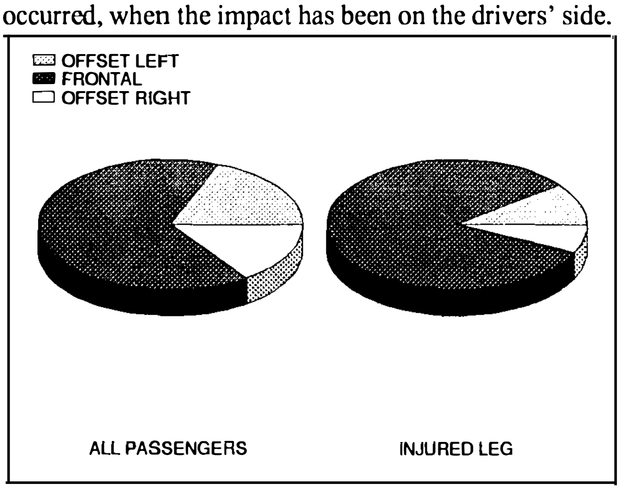


Figure 8. Distribution of Impact Areas for the Front Seat Passenger.

The injury frequencies, with respect to the three impact areas, are displayed in Figures 9-11.

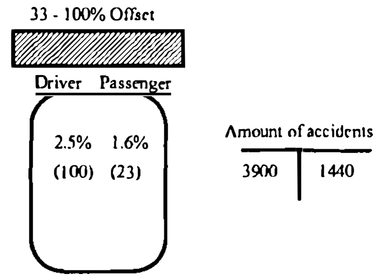


Figure 9. Leg Injury Frequency of Driver and Passenger at 33% -100% Overlap Frontal Accidents.

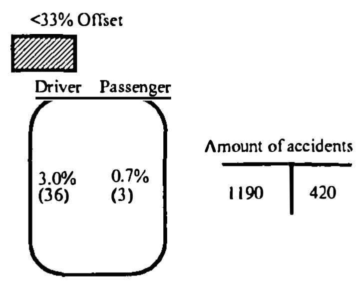


Figure 10. Leg Injury Frequency of Driver and Passenger at <33% Overlap Left Hand Offset Accidents.

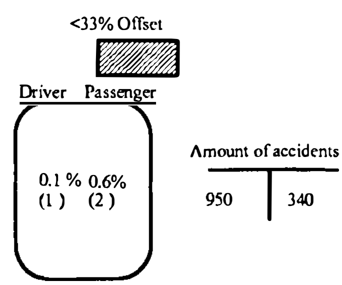


Figure 11. Leg Injury Frequency of Driver and Passenger at <33% Overlap Right Hand Offset Accidents.

Comparing similar impact situations for the driver and front seat passenger means comparing a left offset for the driver, with a right offset for the front seat passenger. There is a higher frequency of driver leg injuries in a left offset impact (3%), than there is for a front seat passenger in a right offset impact (0.6%).

The distribution of EBS and exterior deformation for left and right offset impacts and frontal collisions are displayed in Figures 12 and 13.

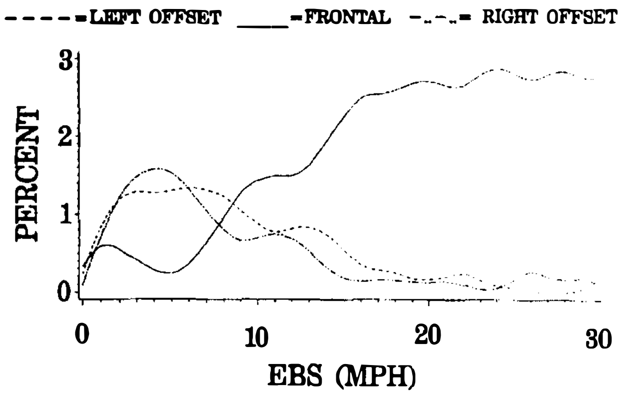


Figure 12. EBS Distribution for Left and Right Offset, and Frontal Impacts.

Offset collisions are more common at lower EBS, while frontal impacts tend to increase above 8 mph EBS.

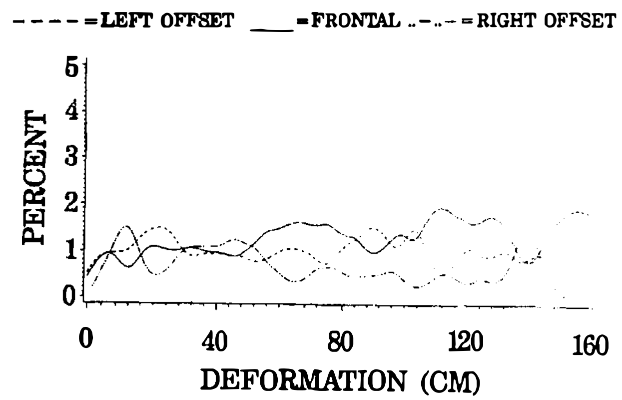


Figure 13. Exterior Deformation Distribution for Left and Right offset, and Frontal impacts.

There are no significant differences in the deformation distribution between the three impact types.

Brake Pedal Use

There is a separate indication in the Volvo database concerning use of the brake pedal. The distribution is displayed in Figure 14.

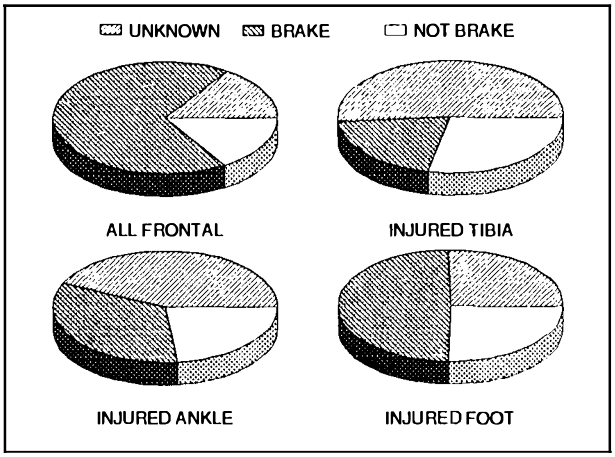


Figure 14. Distribution of Brake Pedal Use of the Driver in Frontal Collisions Including Driver Injury to Tibia, Ankle and Foot.

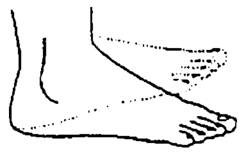
There is a higher frequency of "not brake" for those who have sustained injury to the leg, compared with all frontal accidents in this study. There is, however, a rather large portion of "unknown", making this parameter difficult to analyse.

INJURY TYPES

As a complement to the accident data, a more detailed study has been conducted on the different types of injuries, notably injuries to the ankle. As basis for the assumptions below, experiences from Volvo's accident research provide the major source of input. This input is complemented by results from externally published studies.

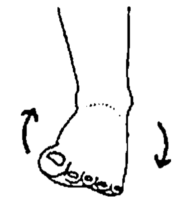
Foot Injuries

Foot injuries AIS2+, are mainly tarsal and metatarsal fractures. The fractures are probably the result of a dorsiflexion motion (Figure 15), induced by the body load, with or without combination of uneven support under the foot. There are also cases of foot injuries resulting from jamming under the pedals, e.g. case no. 10 in the in-depth ankle study described below.

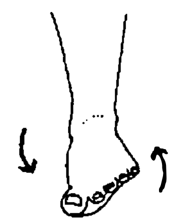


Dorsiflexion: an upward flexion of the foot.

Figure 15. Dorsiflexion.



Inversion: an inward rotation of the foot, with elevation of the medial edge.



Eversion: an outward rotation of the foot, with lowering of the medial edge.

Figure 16. Inversion and eversion.

Ankle Injuries

Ankle injuries account for the majority of AIS2+ leg injuries in Volvo's database.. The mechanisms of the ankle injuries, can be of many different types. To facilitate the understanding of the mechanisms and parameters which influence the occurrence of ankle injuries, an in-depth study was performed. This study involved 12 frontal collisions in Volvo cars (referred to as "cases"). Occupants had a total of 20 injured ankles of type AIS2+. These injuries were analysed in detail. The cases were chosen to be representative of the ankle injuries in the data and valid for the study of injury mechanisms. Each of the cases had detailed descriptions of the vehicle and the accident, as well as medical records including x-rays of the occupants. The cases were studied in a group, consisting of orthopedic experts and car crash experts. The goal was to clarify the motion of the foot and leg and to identify the cause of injury for each specific case. The cases are presented in Appendix 1.

Inversion or eversion of the foot with varying degrees of axial load through the ankle and tibia, accounted for the major injury type (Figure 16). There were 6 cases in the study, in which there was little or no intrusion of the footwell, low crash severity, but with injuries resulting from this mechanism. The bending of the foot at impact, as well as the design of the footwell area, including the pedals, were identified as the important injury factors.

Footwell intrusion and the intrusion of the pedals increases the relative foot impact speed. This often results in a more complex fracture picture (cases no. 2 and 5). If the foot is angled at impact or placed without support under the whole foot, the tolerances for fracture are very low and the inertia body load of the occupant, due to the crash, is enough to sustain a fracture (case no. 12).

Pilon Fracture - Another frequent characteristic ankle injury type in the in-depth study, was a fracture to the neck of the Talus (collum tali), also called "Pilon fracture" (Peterson 1974). This injury is a typical "braking injury" (cases 8 and 11a), but can also occur without brake pedal involvement, as in case no. 10. This fracture will occur *if* the foot is subjected to a local impact, slightly in front of the forces acting through the tibia *and* the ankle muscles are tensed, as shown in Figure 17.

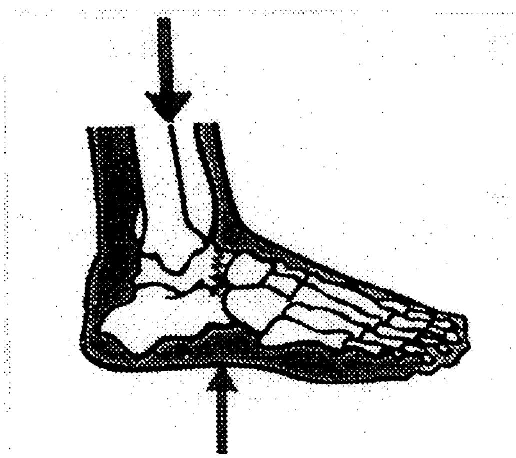


Figure 17. Collum Tali Fracture "Pilon Fracture"; the Ankle Muscles must be Tensed! (ref. Peterson 1974)

Tibia injuries

Injuries to the tibia usually occur in crashes with large intrusion where both the knee and foot are jammed, complemented with a perpendicular impact inducing bending of the bones.

This type of mechanism was also seen in the in-depth ankle study showing fractures induced by axial loads of the tibia, as well as perpendicular impact to the tibia while the leg was under axial loading. The mechanism could lead to ankle fractures, as well as fractures in the tibia and fibula. The fractures induced by axial loading occurred even with minor intrusion, indicating that the acceleration part of the severity should be studied separately from intrusion.

INJURY FACTORS

Having evaluated the statistical material as well as the different types of leg injuries occurring in the field, the main factors of leg injuries, may now be identified. The four main factors and the estimated influence of these factors as a function of speed, is schematically represented in Figure 18

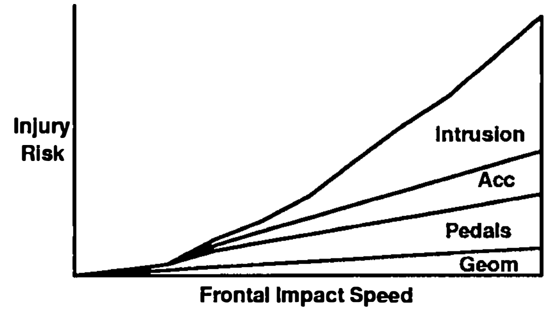


Figure 18. Distribution of Leg Injury Factors in Frontal Impact, with Respect to Impact Speed.

Although difficult to quantify, the existence of these factors may be identified from the accident data and injury types studies as follows:

Geometry

At lower speeds, the main factor is the geometry of the footwell area. There are a number of cases where foot and ankle injuries have occurred at low impact speeds (<15 mph) and where footwell intrusion is not expected. As illustrated in Figure 19, this represents about 10% of the AIS2+ injuries.

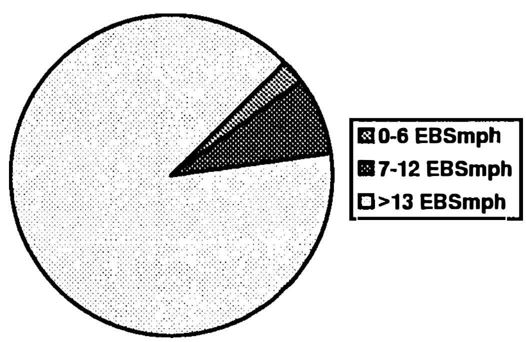


Figure 19. Leg Injury Distribution with Respect to Equivalent Barrier Speed EBS in mph

These cases are all either injuries to the foot or to the ankle. This, coupled with the fact that the foot and ankle tolerances are significantly reduced, if angled, indicates that the footwell geometry is the injury factor in these cases.

Considering the fact that the pedals may also be an injury factor, we can specifically look at the passenger side, since there is no chance of pedals being involved here. As illustrated in Figure 6, the same type of injuries are present here. This verifies the geometry as a main injury factor.

Pedals

Pedals may contribute to leg injuries in mainly two ways: Pedal geometry and Pedal intrusion. A general indication of the influence of pedals, can be seen by comparing the passenger and driver's side with corresponding impact types; left and right offset. As illustrated in Figures 1 and 3, the driver is at a higher risk of sustaining foot injuries in general, when compared to the front seat passenger. This is an indication that pedals are a source of leg injury.

A stronger indication, however, may be seen when comparing two asymmetrical impact types; the overlap situation where the intrusion is on the driver's side and where it is on the passenger's side. This comparison can be made due to the symmetrical structure and packaging of the Volvo 200 and 700/900 series.

The difference in injuries, both in the full frontal case (Figure 9) and in the corresponding offset cases (Figure 10,11), indicate that pedals are a source of injury.

Pedal geometry - At low speeds, the pedals are believed to cause injuries by twisting the ankle, the foot slipping off the pedals or being subjected to a local load combined with tense muscles from braking. The in-depth ankle study gave examples of such cases, where there was little or no intrusion and injuries still occurred (see INJURY TYPES).

Pedal intrusion - When the intrusion of the firewall starts, the brake pedal booster may also be affected. The booster is contacted by the engine, or other objects in front of the firewall, causing the booster rod to be pushed inwards into the footwell. This, in turn, means that the pedal itself will be pushed into the footwell and due to geometry, pedal intrusion will be greater than the booster intrusion.

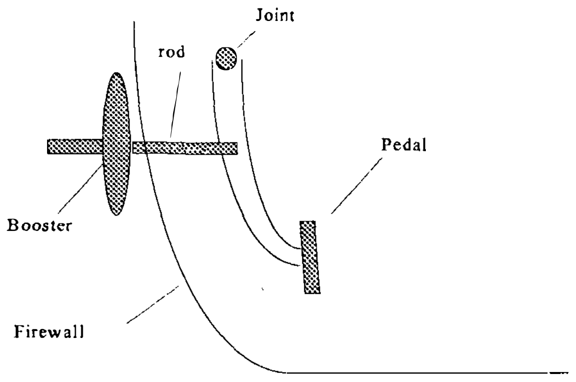


Figure 20. Typical Brake Pedal Configuration.

Acceleration

At higher speeds, the front of the car will be crushed far enough for the engine, or other objects in front of the firewall, to hit the firewall. When this occurs, intrusion in the footwell area will start. When the foot hits the firewall, the difference in speed between the foot and the firewall (delta V), is reduced to zero. Depending on the magnitude of this difference and how quick the reduction is (acceleration), a force will act on the foot.

This quick reduction of delta V (acceleration), may be shown to induce high force levels (see Simulation and Crash Test Studies) and this, in turn, increases the risk of injury.

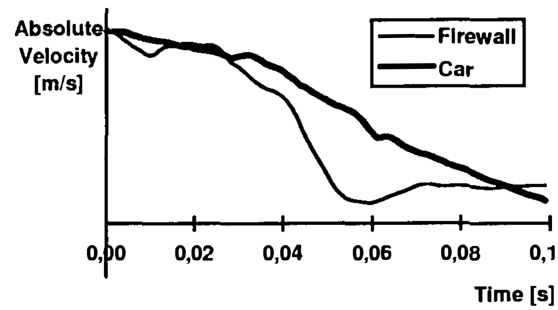


Figure 21. Absolute Car- and Firewall Velocity during a Crash Test.

Measurements from crash tests with dummies show that the contact force induced by a large delta V and acceleration, may be high (Figure 22).

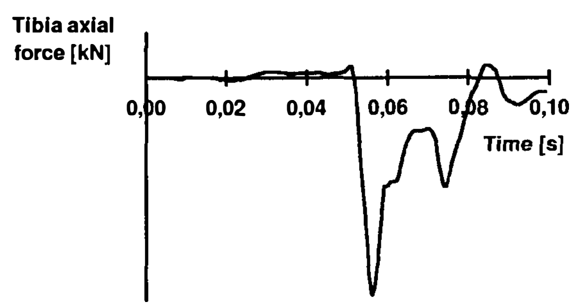


Figure 22. Typical Tibia Axial Force due to Foot Impacting the Firewall in a Crash Test.

Statistically, these acceleration related injuries are found in an area where intrusion is relatively small (<150 mm) and with reference to accident data, these represent approximately 22% of the injuries. The majority of these cases are foot and ankle injuries and the distribution is summarised in Figures 5 and 6.

Intrusion

The leg injury cases, which involve intrusion in excess of 150 mm, constitute 78% of the leg injuries. Most of these cases occur at high speeds and statistics show, that these injuries do not only involve foot and ankle injuries, but also fractures of tibia and/or fibula.

There are many possible reasons for injuries in these severe situations. The in-depth ankle study showed that jamming of feet and legs are common factors. It is also reasonable to assume that many of these injuries may be initiated at the start of intrusion due to geometry, pedals, high acceleration, etc.

If risk of injury is plotted against deformation, the curve rises along with the deformation / intrusion (see Figure 3). It could be said that this is an indication that intrusion is a main factor of injury. However, it is important to remember that as deformation increases, so does the number of factors contributing to an injury i.e. Geometry, Pedals and Acceleration. Therefore, it is difficult to determine the number of injuries which are directly related to intrusion alone.

It is important, however, that intrusion is reduced enough to avoid jamming effects, trapping of feet etc.

SIMULATION AND CRASH TEST STUDIES

Based mainly on the material from the in-depth ankle study and crash tests, there were indications that the quick velocity change (acceleration), occurring when the foot impacts the firewall, may be an injury factor. In order to verify this and also to find out how a suitable padding solution could be configured, a series of mathematical simulations and physical tests were conducted.

Since the acceleration at impact is a direct consequence of the delta V between foot and firewall, a second group of simulation runs were made, in order to find the influence of this parameter.

Simulation model

A sled test model, consisting of rigid bodies in the crash victim program MADYMO2D, was used to evaluate suitable padding characteristics and thickness. The input data such as interior geometry, crash pulse etc. represent a large Volvo car. The model was validated for a 50th percentile belted dummy, with airbag in driver position, in a 35 mph full frontal sled test. Pedals were excluded in the test and simulation.

Parameter Study with Padding and Toepan Angle

All simulations were conducted under the same conditions as the validated model. Two different toepan angles relative to the floor plane, were simulated:

- 38°, undeformed geometry.
- 63°, intruded geometry.

Five different floor characteristics were included in the study as follows:

- A reference characteristics including floor, carpet, shoe and foot deformation which represent the floor without extra padding (K0).
- Four theoretical padding characteristics, which deforms at a constant force level combined with the reference characteristics (K0), shown in Figure 23 (K1-K4).

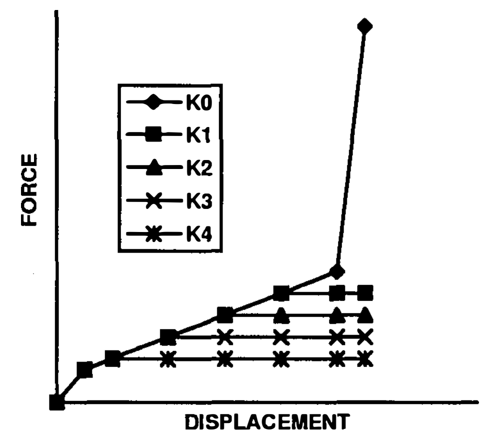


Figure 23. Floor and Padding Characteristics.

Results from Padding Study

The Tibia axial load was reduced by 35% using 15 mm of effective padding (constant force/deformation characteristics) and undeformed foot area geometry. The required physical padding thickness was estimated as the effective thickness plus 15 mm, which includes force build-up and remaining thickness at full compression.

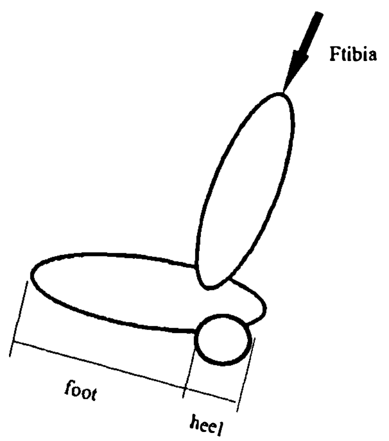


Figure 24. Madymo2d-foot. Definition of Contact Surfaces Foot and Heel in the Model.

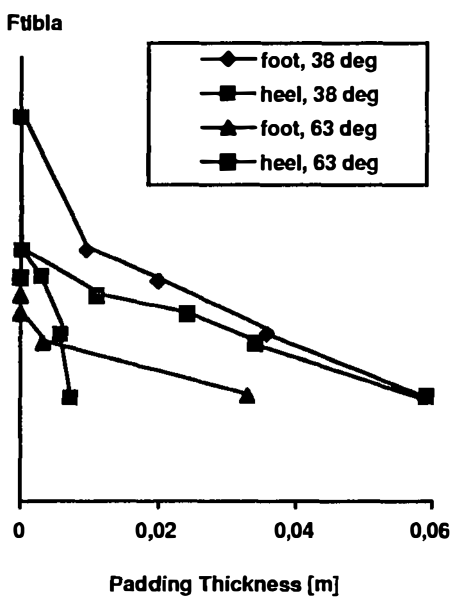


Figure 25. Tibia Load as a Function of used Padding Thickness.

Results showed that the padding was efficient even at a very low thickness. By increasing the thickness, the tibia load was reduced even further although not as much as it was by the first 10 millimetres.

Results also showed that the foot joint angle was mainly dependent on the foot area geometry. The effect of padding stiffness had a minor influence due to local deformation in the area where the foot loads the toepan

Sled Test Results

In order to verify the mathematical model, a series of sled tests were conducted, using the same padding characteristics as in the mathematical model. The tests were performed with an unbelted passenger dummy and airbag, at 30 mph. One reference test with only a steel floor and a carpet, was initially conducted. Padding materials, with a 30 mm thickness were positioned in the footwell in the two remaining sled tests.

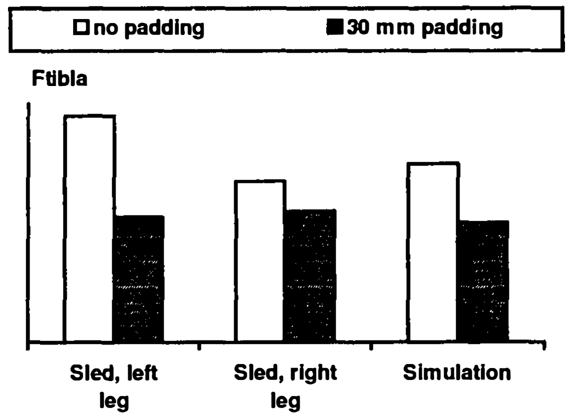


Figure 26. Tibia Load in Sled Test, With and Without 30 mm Thick Padding.

The Tibia axial load was, on average, reduced by 45% in the left leg and 20% in the right leg for the best padding selection. The improvement seen in the simulations was also seen in the tests.

Mathematical Study of Foot position and Relative Foot velocity

A second study was performed to relate the impact speed of the foot, when it contacts the toepan, to Tibia axial force. The same conditions were chosen as above, but padding was not included in these three simulations. The 63° toepan was used with three different positions translated in the x-direction:

- Nominal position.
- +50 mm in the x-direction. Moved rearwards towards the dummy so that the foot rests on the toepan.
- -50 mm in the x-direction. A distance of 100 mm between foot and toepan is obtained at the start of the simulation.

The speed of the car and foot as a function of time, is shown in Figure 27. As the speed of the car is decreased, the foot is moved forward, towards the footwell. When impact between foot and footwell occurs, the difference in speed (delta V in figure 27) is reduced to zero (the point where the lines cross), and some rebound occurs (foot speed lower than car speed).

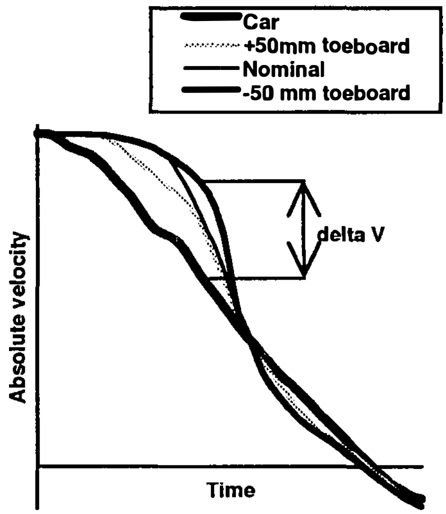


Figure 27. The Car and Foot Absolute Velocity for the Three Different Toepan Positions.

The slope of the absolute foot velocity represents the foot deceleration. The resultant foot deceleration and axial Tibia forces are illustrated in picture 28 and 29.

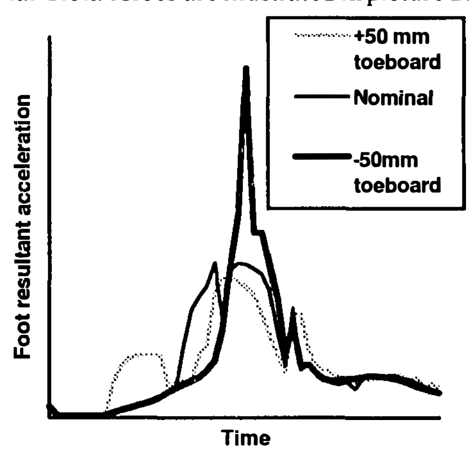


Figure 28. Foot Deceleration for the Three Different Toepan Positions.

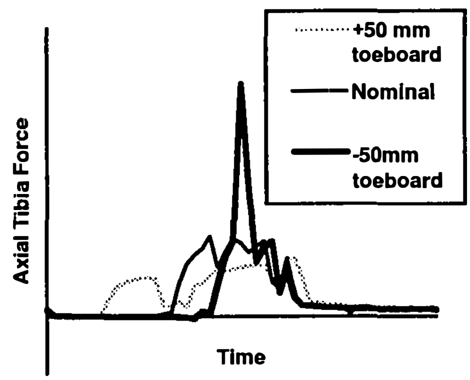


Figure 29. Tibia Axial Forces for the Three Different Toe Board Positions.

The similar curve shapes display the connection between resultant foot deceleration and Tibia axial forces. An increased distance between foot and toepan, leads to a higher impact speed. The following parameters affect the tibia force:

- Foot relative impact speed at the toepan.
- Stop-distance at the toepan.

The results show that the initial position of the foot is an important parameter since it affects the amount of load in the leg (foot, ankle and tibia). If delta V is high enough, the floor, carpet, shoe and foot will 'bottom out' and as a result, the load in the leg will rapidly increase.

CONCLUSIONS

The mechanisms behind leg injuries are complex and difficult to understand. In this paper an attempt has been made to point out the main factors by using statistical material, case study, simulation, testing and expert judgement. The main factors have been shown to be:

- Geometry - based on a number of cases occurring at low severity (< 15 mph EBS) and no footwell intrusion. Reference also to case 11b in the in-depth ankle study.
- Acceleration - based on a number of cases occurring with moderate intrusion (< 15 cm) and no pedal involvement. References also to cases in the in-depth ankle study, simulation and crash test studies, showing that impact leads to high forces in foot and tibia. Simulation and crash tests also show that delta V and padding are sensitive parameters for the resulting load.
- Pedals - based on higher statistical injury risk for the driver, coupled with the driver / passenger comparisons conducted in the injury factors' section

of the paper. Clear indications were also seen in the in-depth ankle study.

- Intrusion - based on the connection between increased intrusion and increased risk of injury. Tibia injuries due to jamming effects were also seen in the in-depth ankle study.

These factors are distributed with respect to impact speed in accordance with Figure 18. As the speed increases, a greater number of these factors contribute to the likelihood of an injury. With the knowledge that leg injuries are not the result of a single injury factor, it is easier to understand that in order to achieve any significant improvements in this field, improvements have to be made in all areas. In other words, it is not enough, just to reduce intrusion or acceleration; leg fractures will still occur due to pedals and / or geometry.

A logical continuation of this study, will be to quantify the influence of the four injury factors, as a function of impact severity.

Preventing injuries

In order to reduce the risk of a leg injury, it is important that all factors are taken into consideration. Regarding each factor, the following general design guidelines are suggested:

Geometry

- Attempt to make the footwell as smooth and flat as possible. Avoid having local differences in height and width.
- Place pedals as close to the footwell as possible. Ultimately, remove the pedals.

Acceleration

- Avoid placing solid objects in front of the footwell, which may cause increased stiffness of firewall when intruded.
- Design the footwell so that it will be shock absorbing, in order to reduce foot acceleration at impact.
- Allow for the feet to be placed close to the firewall in order to limit the delta V at impact.

Pedals

- Place the pedals as close to the firewall as possible.
- Design the pedals so that the brake booster intrusion will have limited effect on pedal intrusion.

Intrusion

- Limit intrusion
- When intrusion occurs, the footwell area should stay flat in order to avoid trapping the feet.
- Instrument panel and knee bars should be designed in such a way that the possibility of jamming the leg during impact, is reduced.

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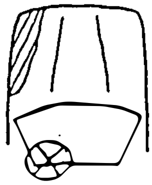
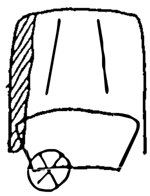
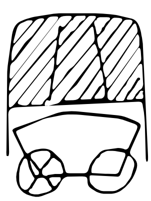
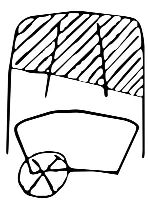
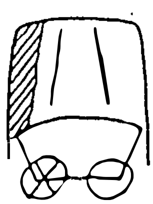
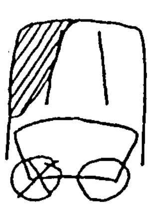
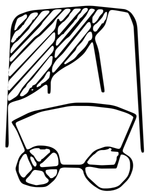
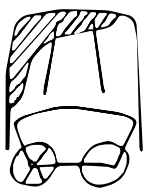
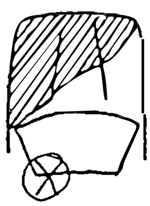
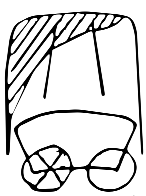
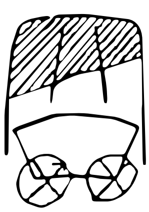
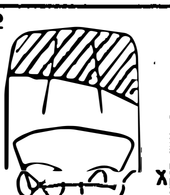
Case no	*Vehicle data*	*Injured occ.*	*left ankle*	*right ankle*	*comments*
1 	**Model:** Volvo 244 **CDC:** 11FLAN35 **Intrusion of** **wheel:** yes **side member:** no **foot well:** minor **Pedals:** deformed	**Position:** driver **Age:** 38 years old **Sex:** male **Braking:** no	**Injuries:** • ligament torn off lateral side of talus • small fracture talus lateral side **Mechanisms:** • inversion	**Injuries:** • fractures medial and lateral malleolus • (fibula fracture 5cm above ankle) **Mechanisms:** • inversion combined with axial load	• occupant jammed
2 	**Model:** Volvo 744 **CDC:** 11FLAW70 **Intrusion of** **wheel:** yes **side member:** no **foot well:** yes **Pedals:** probably deformed	**Position:** driver **Age:** 44 years old **Sex:** male **Braking:** probably not	**Injuries:** • comminuted fracture medial malleolus **Mechanisms:** • eversion combined with axial load • probably also direct impact to malleolus	**Injuries:** • no	• Occupant jammed
3 	**Model:** Volvo 745 **CDC:** 12FDEW45 **Intrusion of** **wheel:** yes **side member:**yes **foot well:** minor **Pedals:** deformed	**Position:** driver **Age:** 48 years old **Sex:** male **Braking:** probably	**Injuries:** • axial fracture of talus **Mechanisms:** • high and distributed axial load	**Injuries:** • fracture medial malleolus **Mechanisms:** • eversion	• passenger no leg injuries though larger wheel intrusion
4 	**Model:** Volvo 745 **CDC:** 12FDEW40 **Intrusion of** **wheel:** no **side member:** no **foot well:** minor **Pedals:** deformed	**Position:** driver **Age:** 45 years old **Sex:** female **Braking:** yes	**Injuries:** • fractures medial and lateral malleolus **Mechanisms:** • inversion combined with axial load	**Injuries:** • open fracture lateral malleolus **Mechanisms:** • eversion combined with axial load	• fracture on right fibula from direct impact, probably by the deformed accelerator pedal • prob. pressed clutch pedal with left foot at impact
5 	**Model:** Volvo 744 **CDC:** 12FLEW50 **Intrusion of** **wheel:** major **side member:** no **foot well:** yes **Pedals:** probably deformed	**Position:** driver **Age:** 40 years old **Sex:** male **Braking:** probably not	**Injuries:** • comminuted fracture medial malleolus **Mechanisms:** • eversion combined with axial load and transverse impact	**Injuries:** • no	• occupant jammed
6 	**Model:** Volvo 764 **CDC:** 12FLEW50 **Intrusion of** **wheel:** yes **side member:**yes **foot well:** yes **Pedals:** deformed	**Position:** driver **Age:** 71 years old **Sex:** male **Braking:** probably not	**Injuries:** • no	**Injuries:** • fracture medial malleolus, low energy **Mechanisms:** • shear forces mainly, probably oblique ankle at impact	• fracture left femur

Case no	*Vehicle data*	*Injured occ.*	*left ankle*	*right ankle*	*comments*
7 	**Model:** Volvo 245 **CDC:** 12FYEW45 **Intrusion of wheel:** major **side member:**yes **foot well:** minor **Pedals:** deformed	**Position:** driver **Age:** 45 years old **Sex:** male **Braking:** probably	**Injuries:** • no	**Injuries:** • horisontal fracture in talus anterior part **Mechanisms:** • load axially-medially	• no injuries to right leg despite major wheel intrusion
8 	**Model:** Volvo 745 **CDC:** 12FYEW35 **Intrusion of wheel:** yes **side member:** no **foot well:** major **Pedals:** deformed	**Position:** driver **Age:** 41 years old **Sex:** male **Braking:** yes	**Injuries:** • collum tali fracture "pilon fracture" **Mechanisms:** • axial impact, tensed muscles	**Injuries:** • collum tali fracture "pilon fracture" • fracture medial malleolus **Mechanisms:** • extensive axial load combined with inversion. Force at the anterior part of calcaneus	
9 	**Model:** Volvo 245 **CDC:** 12FDAW **Intrusion of wheel:** yes **side member:**yes **foot well:** minor **Pedals:** deformed	**Position:** driver **Age:** 20 years old **Sex:** female **Braking:** no	**Injuries:** • fracture medial malleolus **Mechanisms:** • eversion	**Injuries:** • fracture lateral malleolus **Mechanisms:** • inversion	
10 	**Model:** Volvo 744 **CDC:** 12FLEW50 **Intrusion of wheel:** yes **side member:**yes **foot well:** yes **Pedals:** unknown	**Position:** driver **Age:** 46 years old **Sex:** male **Braking:** no	**Injuries:** • subluxation of choupards joint • (fracture of 5th metatarsal) **Mechanisms:** • axial compression, sliding and jamming of foot	**Injuries:** • collum tali fracture "pilon fracture" • (fractures in tibia and fibula 10 cm above ankle) **Mechanisms:** • axial impact, tensed muscles • (lateral load and bending of tibia/fibula)	• fracture right femur
11a 	**Model:** Volvo 244 **CDC:**2FDEW 35 **Intrusion of wheel:** no **side member:** probable **foot well:** no **Pedals:** unknown	**Position:** driver **Age:** 79 years old **Sex:** male **Braking:** probably	**Injuries:** • collum tali fracture "pilon fracture" • fractures at joint tibia/talus **Mechanisms:** • axial load when oblique ankle OR • load axially-medially	**Injuries:** • collum tali fracture "pilon fracture" **Mechanisms:** • axial impact, tensed muscles	• fracture left hipjoint • both ankles probably effected by pedals
11b	**Model:** as 11a **Intrusion of wheel:** no **side member:** no **foot well:** no	**Position:** front passenger **Age:** 78 years old **Sex:** female	**Injuries:** • no	**Injuries:** • fracture lateral malleolus **Mechanisms:** • inversion combined with axial load	
12 	**Model:** Volvo 944 **Intrusion of wheel:** no **side member:** no **foot well:** no **Pedals:** deformed	**Position:** driver **Age:** 48 years old **Sex:** female **Braking:** no	**Injuries:** • no	**Injuries:** • fracture lateral malleolus **Mechanisms:** • inversion	• right foot on acc. pedal • the load in the ankle is induced by body load only