DYNAMIC MOTION OF THE FLOOR PAN AND AXIAL LOADING THROUGH THE FEET IN FRONTAL CRASH TESTS

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ABSTRACT

Data from frontal crash tests involving a Ford Taurus in various configurations were examined to characterize the dynamic response of the floor pan and the brake pedal during impact and associate their behavior with the axial loads transmitted through the dummy feet.

Analysis of the data from these crash tests suggests that there are floor pan acceleration pulses of high amplitude and short duration which are associated with small floor pan intrusion and high distal tibia axial loads. Conversely, there are floor pan acceleration pulses of low amplitude and long duration which are associated with large floor pan intrusion and low distal tibia axial loads.

The axial loads measured by the load cells just above the ankles in the dummies were highly correlated with the peak acceleration of the floor pan or brake pedal. However, these axial loads did not correlate well with the amount of floor pan/brake pedal intrusion.

Occupant simulations using crash pulses identified in the actual crashes suggested that compressive axial loading through the ankle can be reduced by including several centimeters of suitable energy absorbing padding on the floor pan.

THOUGH LOWER EXTREMITIES INJURIES are not life threatening, they have been reported to represent the second most important source of disability for individuals who survive traumatic injury. Pletchen et al. (1990) examined the injuries of 143 belted drivers of Mercedes-Benz cars and ranked lower extremities injuries as number two in priority based on injury costs. Morgan et al. (1991) examined the 1979-1986 NASS files for frontal impact and found that lower extremities injuries are about 26 percent of the total moderate or greater injuries (AIS$\geq$2 count) for both belted and unbelted occupants. Stucki et al. (1995) revisited the NASS accident data files for the years 1988-1993 and again found that, in frontal crashes, approximately 25 percent of AIS$\geq$2 injuries are to the lower extremities.

In a more detailed look at the NASS files of frontal impacts, with no rollover and no occupant ejection, it was noted by Morgan et al. (1991) that contact with foot controls was the cause of 43 percent of ankle injuries of AIS$\geq$2, and 47 percent of foot injuries of AIS$\geq$2. In the same survey it also was found that contact with the floor pan accounted for 24 percent of the ankle and foot injuries of AIS≥2.

In a survey of lower extremity trauma to vehicular front-seat occupants admitted as patients to a level 1 trauma center, Dischinger et al. (1994, 1994) noted that axial loading through the floor pan accounted for over 30 percent of ankle/foot injuries. Case studies of trauma patients suggested that ankle/foot injuries were possible with minimal or no intrusion of the floor pan. Patients in vehicle crashes with minimal floor pan intrusion experienced calcaneus and pilon fractures (intra-articular fracture of the distal tibia due to axial loading through the midfoot and talus into the distal tibia (1994)) similar to those suffered by people who fall from heights and land on their feet. On the other hand, for vehicle crashes with significant floor pan intrusion, the patients experienced ligamentous injuries and multiple fractures of the ankle/foot bones.

The study of ankle/foot trauma due to axial loading goes back to the nascent period of biomechanics. In 1945, Draeger et al. (1945) studied the effect of blast loading on the lower extremities of personnel standing on the ship deck. Draeger exposed standing human volunteers and cadavers to high acceleration imposed axially at the base of the foot and noted the response along with injuries to the lower extremities. Most of the injuries to the human cadavers in the dynamic and static tests were calcaneal fractures. The static load required to fracture the cadaver foot was 6.6 kN.

More recently, Mertz (1993) proposed limits for axial loads on the tibia, although no dynamic laboratory tests were conducted with human surrogates in direct support of these limits.

Kruger et al. (1994) found a correlation between footwell reduction and the measured foot loads in five offset crash tests using subcompact passenger cars. The study also showed that the right foot is subjected to higher loads than the left foot.

Prasad et al. (1995) compared the relative severity of various frontal crash tests currently in use in the U.S.A. and Europe. The relative severity of the crashes in this study were measured with respect to interior intrusion deformations of the car bodies and dummy occupant responses. As in (Kruger, 1994), Prasad also noted that the right tibia responses of the driver are higher than those of the left tibia. For the crash tests examined in his study, Prasad noted that axial loads through the feet and amount of floor pan intrusion were not related.

The aggregate of these previous studies suggest three important aspects of lower leg injuries: (1) ankle/foot injuries can be disabling, expensive and constitute a substantial percentage of moderate (AIS≥2) injuries, (2) a major mechanism of ankle/foot injuries is axial loading through the foot, and (3) loading of the lower extremities during the vehicle crash by the brake pedal and the floor pan is associated with this type of ankle injury mechanism. Therefore, our understanding of ankle/foot trauma may be advanced by a better understanding of the dynamic motion of the brake pedal and the floor pan during a crash.

VEHICLE CRASH TESTS

Frontal crash tests were conducted in various configurations at Calspan Corporation (Stucki, 1995). These tests provided an opportunity to study the dynamic and static intrusion behavior of the brake pedal and the floor pan and the associated axial loads transmitted through the ankles of the dummy during a crash.

Five vehicle crash configurations involving the Ford Taurus were considered in this study: (1) Full frontal barrier crash at 48 and 56 km/h, (2) 60 percent overlap collinear car-to-car crash at 100 and 120 km/h closing speed, (3) 50 percent overlap oblique car-to-car crash at 120 km/h closing speed, (4) 50 percent overlap crash into a deformable fixed barrier at 65 km/h closing speed, and (5) 50 percent overlap oblique car crash into a moving deformable barrier.

The details of the seven crash tests examined are shown in Table 1. The change in velocity in Table I is that for vehicle 1. Only vehicle 1 was examined in detail. Figure 1 shows the crash configurations for the tests listed in Table 1.

The vehicles were equipped with accelerometers oriented in the longitudinal direction at the brake pedal, the floor pan, and the support structure under the rear seat of the vehicle as shown in Figure 2.

Measurements were made of the pre and post-crash distances from points at the rear of the car to the brake pedal and to various points on the floor pan. Digitized pre-crash and post-crash profiles of the vehicle floor pan were also made in some crash tests. The static intrusion of the brake pedal and the floor pan in the longitudinal direction was then computed as the difference between the post-crash and pre-crash measurements at these locations.

The Hybrid III dummies in the driver's position in the vehicles under study were all restrained by combined air bags and belt restraints. The dummy instrumentation included load cells just above the ankles to measure axial loads through the dummy feet.

Table I
Details of Vehicle Crash Tests

Test No.	ΔV (km/h)	Overlap %	impact angle	vehicle 1	vehicle 2
TFRB1 (Taurus to Fixed Rigid Barrier crash 1)	56.3	100	0	1993 Ford Taurus 4-door Sedan	Fixed Rigid Barrier
TFRB2 (Taurus to Fixed Rigid Barrier crash 2)	48.4	100	0	1993 Ford Taurus 4-door Sedan	Fixed Rigid Barrier
THCO1 (Taurus to Honda Collinear Offset crash 1)	56.0	60	0	1991 Ford Taurus 4-door Sedan	1991 Honda Accord 4-door Sedan
THCO2 (Taurus to Honda Collinear Offset crash 2)	49.0	60	0	1991 Ford Taurus 4-door Sedan	1991 Honda Accord 4-door Sedan
TTOO1 (Taurus to Taurus Oblique Offset crash 1)	59.4	50	30	1992 Ford Taurus 4-door Sedan	1994 Ford Taurus 4-door Sedan
TFDB1 (Taurus to Fixed Deform. Barrier crash 1)	64.7	50	0	1994 Ford Taurus 4-door Sedan	Fixed Deformable Barrier
TMDB1 (Taurus to Moving Deform. Barrier crash 1)	56.7	50	30	1993 Ford Taurus 4-door Sedan	Moving Deformable Barrier

Figure 1 - Crash Configurations

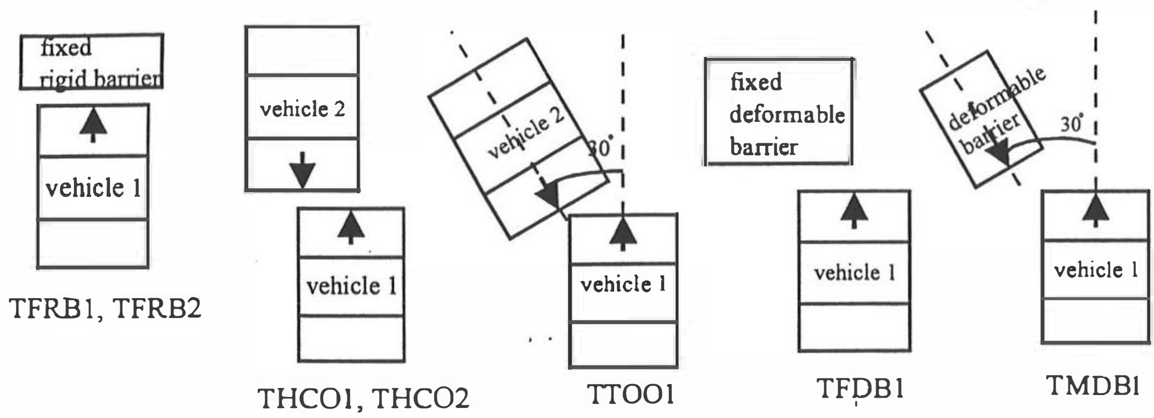
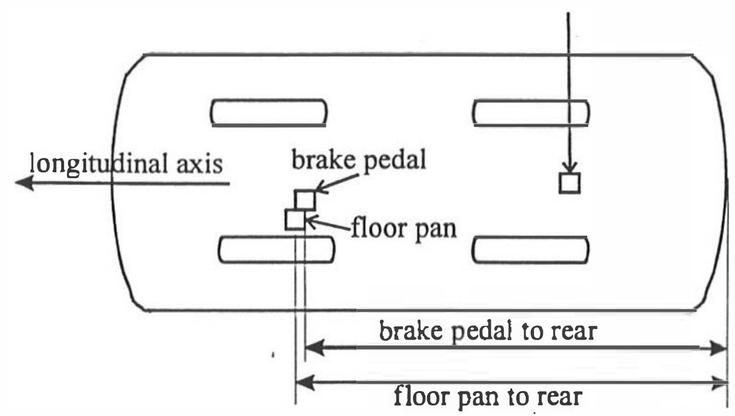


Figure 2 - Location of Accelerometers



This paper analyzes the data from instrumentation (1) at the floor pan, (2) at the brake pedal, and (3) in the Hybrid III's lower leg. The goal of this analysis was to understand the acceleration pulses of the floor pan and the brake pedal and then relate them to the axial loads through the dummy feet measured by the distal tibia load cells.

DYNAMIC MOTION OF THE FLOOR PAN AND THE BRAKE PEDAL

The data from the accelerometers (shown in Figure 2) were used to obtain the dynamic characteristics of the brake pedal and the floor pan. The accelerations in the longitudinal direction were integrated twice to obtain the respective velocities and displacements. The longitudinal intrusion of the brake pedal/floor pan were calculated as the difference between the longitudinal displacements of the brake pedal/floor pan and the rear of the vehicle.

In order to illustrate this procedure of obtaining intrusion, the longitudinal accelerations (processed by an SAE Channel Class 60 filter) of the rear of the vehicle compartment and the brake pedal from the oblique offset crash into a moving deformable barrier, TMDB1, are shown in Figure 3. The corresponding velocities and displacements obtained by integration are shown in Figures 4 and 5, respectively. The static intrusion of the brake pedal for this crash was measured to be 8.5 cm. However, the calculated intrusion obtained as the difference in the displacement between the brake pedal and the vehicle far exceeds the measured value (over 200% error). The velocity profile of the brake pedal suggests that the accelerometer at the brake pedal likely rotated during intrusion causing the discrepancy between the measured static intrusion and the corresponding calculated value. Similar processing of the accelerometer data of the brake pedal and the floor pan for the other crash tests suggested that the rotation of the accelerometers was difficult to quantify and ranged between a minimal to a significant amount.

Figure 3- Longitudinal acceleration of the vehicle and the brake pedal.

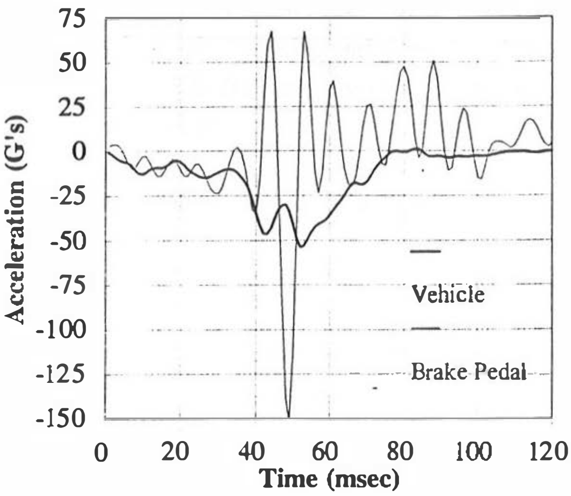


Figure 4- Longitudinal velocity of the vehicle and the brake pedal.

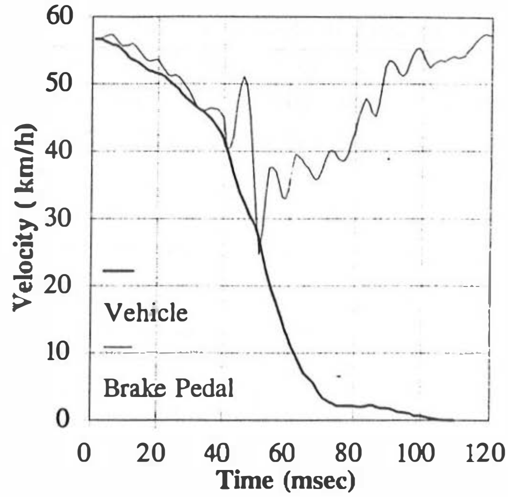
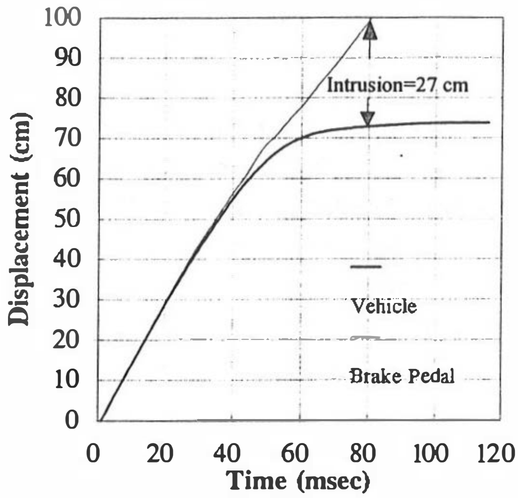


Figure 5 - Longitudinal displacement of the vehicle and the brake pedal.



APPROXIMATE CHARACTERIZATION OF THE BRAKE PEDAL AND THE TOE PAN MOTION

One can conclude from the example in the previous section that, because direct integration of the accelerometer data in the vehicle tests does not lead to the independently measured values of change in velocity and static intrusion of the brake pedal/floor pan, rotation and other factors corrupted the acceleration measurements.

Before floor pan intrusion commences, the actual floor pan/brake pedal acceleration and velocity are essentially identical to the vehicle acceleration and velocity. Once intrusion commences, the floor pan/brake pedal decelerates faster than the vehicle and comes to rest before the vehicle compartment. This higher deceleration is manifested as a greater amplitude floor pan acceleration pulse than that of the vehicle. The corresponding actual floor pan longitudinal velocity-time curve has a larger slope than the vehicle velocity-time curve. The difference in the area between this actual floor pan velocity curve and the vehicle velocity curve represents the amount of floor pan intrusion.

Given the accelerometers at the brake pedal and floor pan likely rotated during intrusion, the measured longitudinal acceleration of the brake pedal and the floor pan are different from the actual acceleration pulses. Therefore, it is necessary develop approximations for the actual brake pedal and floor pan acceleration signals. Measurements of static intrusion and the digitized pre-crash and post-crash shapes of the floor pan provide reliable information that can be used to develop approximate floor pan/brake pedal acceleration signals.

The following guidelines were used to develop approximate longitudinal acceleration curves of the floor pan/brake pedal which preserve the velocity change and match measured static intrusion:

1. The measured floor pan/brake pedal acceleration curves are used to estimate the time of commencement and completion of the intrusion process.
2. The approximate acceleration curve before the commencement of intrusion is assumed to be similar to the vehicle acceleration.
3. The approximate floor pan/brake pedal acceleration curve for the duration of intrusion is modeled as a half sine curve. The width of the sine curve is equal to the duration of intrusion obtained from step 1. The amplitude of the sine curve is adjusted such that the change in velocity of the floor pan/brake pedal is the same as that of the vehicle.
4. The intrusion of the floor pan/brake pedal is calculated by subtracting the area under the approximate velocity curve from the area under the vehicle velocity curve and is compared to the measured intrusion value.
5. If the calculated and measured intrusion are quite different, then steps 1 through 5 are repeated by first making small changes in the time of commencement and completion of the intrusion process.

Figures 6 and 7 show the measured and approximate longitudinal acceleration curves of the floor pan for tests THCO1 (collinear offset crash of a Taurus into a Honda) and TFRB1 (crash of a Ford Taurus into a fixed rigid barrier). The percentage error between the calculated intrusion (using the approximate acceleration curves) and the measured intrusion is small and the change in velocity of the floor pan/brake pedal is the same as that of the vehicle. The characteristics of the approximate acceleration pulses of the brake pedal and the floor pan and the measured and calculated intrusions for the crash tests examined are shown in Table A-I of Appendix A. The calculated intrusion from the approximate acceleration pulses is the same or slightly greater than the measured intrusion values. The calculated intrusion need not match the measured intrusion exactly since some rebound of the floor pan/brake pedal is expected after intrusion.

Figure 6- Approx. and measured accel. of the floor pan in test THCO1.

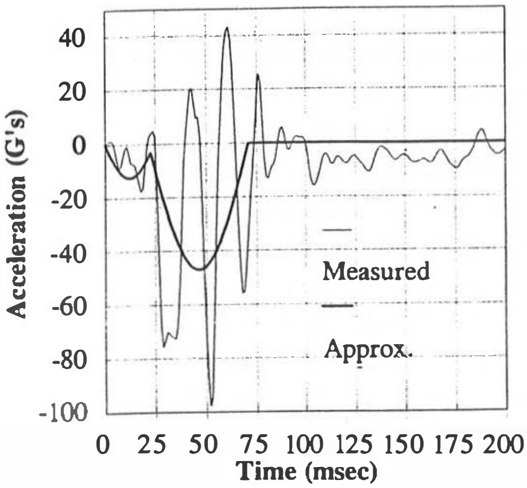


Figure 7- Approx. and measured accel. of the floor pan in test TFRB1.

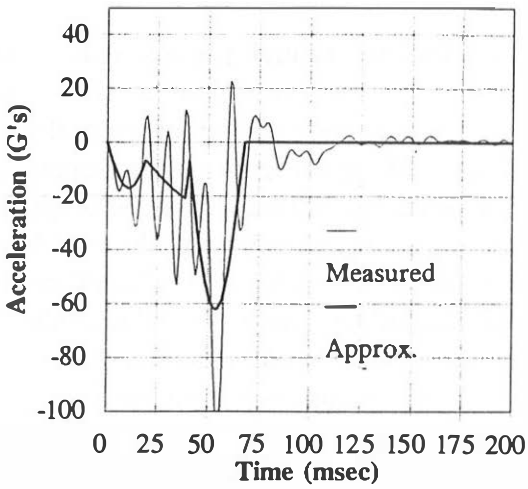
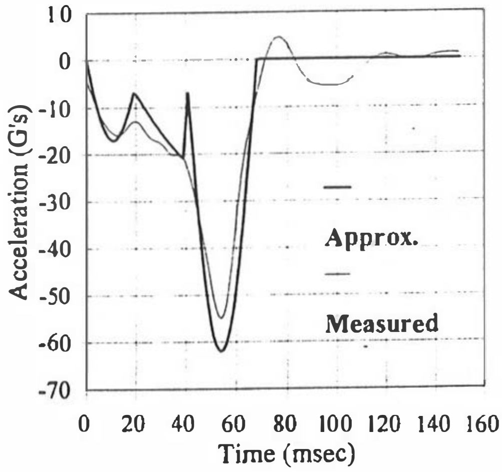


Figure 8 - Approximate floor pan acceleration and measured acceleration filtered to 30 Hz for test TFRB1.



The floor pan approximate acceleration curve for the vehicle to vehicle offset test (THCO1) has a small amplitude but a large width as shown in Figure 6. This offset test showed significant floor pan intrusion. In contrast, Figure 7 shows that the floor pan acceleration curve in the full barrier crash test (TFRB1) has a large amplitude but a small width. This barrier crash test showed very little floor pan intrusion. The intrusion process starts later and has a shorter duration in TFRB1 than in THCO1.

In crash tests where the accelerometers at the brake pedal/floor pan did not rotate significantly, it was found that the developed approximate acceleration curves were similar to the actual acceleration curves filtered to 30 Hz. For example, Figure 8 is an overlay of the measured acceleration curve of the floor pan filtered to 30 Hz and the corresponding approximate acceleration curve for the test TFRB1.

The developed approximate acceleration curves provide a better understanding of the dynamic intrusion characteristics of the brake pedal/floor pan in different crash configurations.

FLOOR PAN/BRAKE PEDAL INTRUSION AND AXIAL LOADING THROUGH THE ANKLE IN VEHICLE CRASHES

The axial loading through the ankle/foot of the dummy were measured by a triaxial load cell located at the lower tibia on each leg of the dummy. Assuming the developed approximate acceleration curves for the brake pedal/floor pan are reasonable representations of the actual floor pan response, associations between characteristics of these approximations and axial loads through the dummy feet will be sought.

Figure 9 presents an overlay of the axial loads through the left and right foot along with the longitudinal acceleration pulse of the floor pan for test THCO1 (Taurus to Honda collinear offset crash). In all the vehicle crashes examined, the maximum axial loads measured by the distal tibia load cells in the Hybrid III dummy were concurrent with the peak of the approximate acceleration pulse of the brake pedal or the floor pan as shown in Figure 10. This suggests that the axial loads through the feet of the dummy are caused by the dynamic motion of the surface on which the feet rest.

Figure 9- Overlay of approx. floor pan accel. and axial loads through the feet.

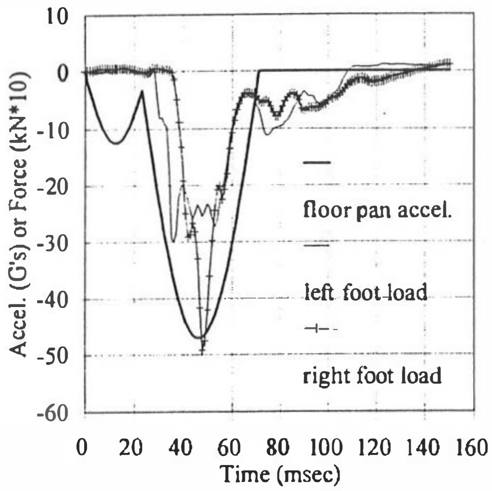
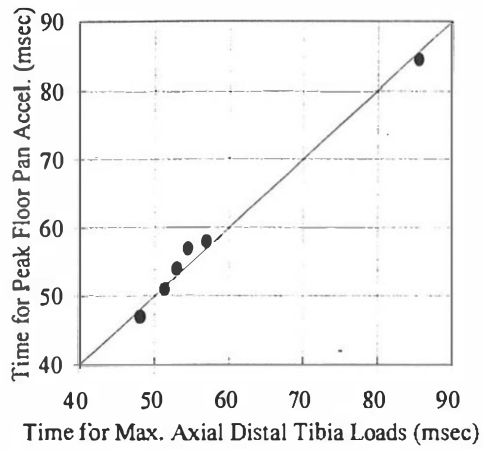


Figure 10- Time of max. distal tibia axial loads and peak approx. floor pan accel.



The maximum axial loads through the left and right feet of the dummy and the residual intrusion measured at the brake pedal and the floor pan for the seven tests listed in Table I are presented in Table B-I of Appendix B. The data in Appendix B suggest that there are high acceleration-short duration floor pan pulses (perhaps 65 G's in 20 msec as in Figure 7) that lead to low levels of floor pan intrusion but result in high (over 7 kN) axial loads through the dummy feet. Conversely, the data suggests there are low acceleration-long duration floor pan pulses (perhaps 50 G's in 40 msec as in Figure 6) that lead to high levels of floor pan intrusion but result in low (under 5 kN) axial loads through the dummy feet.

The maximum axial loads measured by the distal tibia load cell versus the static intrusion measured at the floor pan are shown in Figure 11. Figure 11 and Table B-I suggest that the distal tibia axial load is not related to the amount of floor pan/brake pedal intrusion. The intrusion of the floor pan and brake pedal is relatively high for vehicle to vehicle offset test, THCO1, while the distal tibia loads are relatively low. The intrusion of the barrier crash test, TFRB1, is very small while the distal tibia loads are quite large.

These observations are in agreement with the clinical studies described by Dischinger et al., (1994,1994) where ankle injuries similar to those suffered by people who fall from heights and land on their feet were found among patients in vehicle crashes with minimal intrusion. The high amplitude and short duration acceleration pulse transmitted to the ankle by the intruding floor pan was the possible cause of such injuries.

High acceleration-short duration pulses of the brake pedal/toe pan were associated with axial loads above the 6.6 kN critical load suggested by Draeger (1945) for humans and cadavers, while the long low acceleration pulses were associated with axial loads below the 6.6 kN critical load.

In general, the distal tibia loads are higher on the right leg than on the left leg as was observed by Prasad (1995) and Kruger (1994). The time of occurrence of maximum distal tibia loads was nearly the same for the left and right legs and generally occurred at the time of peak floor pan/brake pedal accelerations.

The maximum axial loads through the dummy feet are highly correlated to the peak approximate acceleration of the brake pedal or the floor pan. Figure 12 is a plot of maximum approximate acceleration of the brake pedal/floor pan versus maximum distal tibia axial load for the seven tests listed in Table I. The axial loads through the feet are proportional to the peak approximate acceleration of the brake pedal/floor pan but not to the amount of intrusion.

Figure 11- Maximum distal tibia axial load vs. floor pan intrusion.

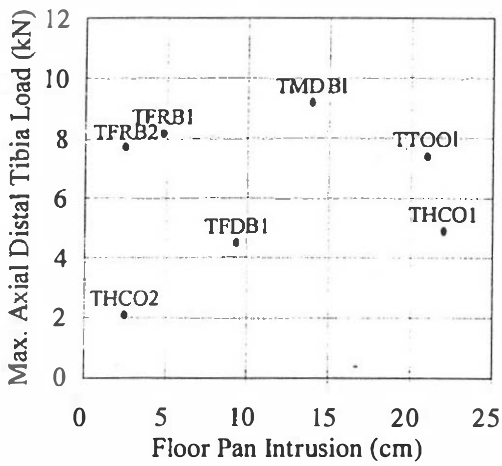
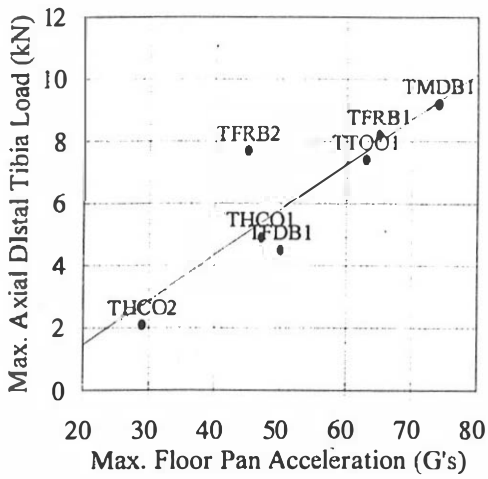


Figure 12- Max. distal tibia axial load vs. max. approx. floor pan acceleration.



SIMULATION

Having associated higher axial loads in the dummy's ankle with a high amplitude/short duration pulse of the floor pan, one would then ask if an energy-absorbing padding material placed over the floor pan can reduce the high forces being transmitted to the dummy's feet. The Articulated Total Body (ATB) occupant simulation program was used to facilitate this study to associate the intrusion characteristics of the padded and unpadded floor pan with the axial loads through the dummy feet.

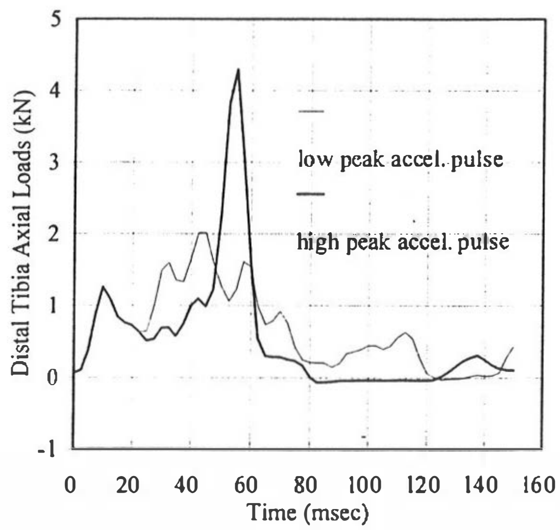
Two simulations were conducted using the same vehicle pulse and different floor pan acceleration pulses. The first simulation used a high amplitude/short duration floor pan acceleration pulse with small amount of floor pan intrusion. The second simulation used a low amplitude/long duration floor pan acceleration pulse with large amount of floor pan intrusion

The axial loads through the dummy feet for these two simulations are shown in Figure 13. The same trend in the axial loads transmitted through the dummy's feet was observed in these simulations as in the actual vehicle crashes.

Further simulations were conducted using floor pan padding of varying stiffness to determine whether there can be a reduction in the axial loads through the feet. The floor pan pulses were not varied, but only the padding thickness and stiffness was changed. An energy absorbing material of about 150 kN/m stiffness and 2.5 cm thickness reduced the high axial load in the dummy's lower leg by a third.

In summary, the occupant simulations showed similar trends in the axial loading of the feet in different crash configurations as was observed in the actual crashes. The simulations also suggested that there can be a significant reduction in the axial loads by placing 2.5 to 5 cm thickness of the proper energy absorbing padding over the floor pan.

Figure 13- Distal tibia axial loads in simulations using two floor pan acceleration pulses.



CONCLUSIONS

Data from frontal crash tests in various configurations were examined to characterize the dynamic response of the floor pan and the brake pedal. The responses of Hybrid III dummies in the vehicles were also examined to study axial forces being transmitted through the feet.

Analysis of the crash data suggests there are floor pan/brake pedal acceleration pulses of high amplitude and short duration (65 G's in 20 msec) that lead to low levels of floor pan intrusion but result in high, over 7 kN, axial loads through the feet of the Hybrid III dummy.

Conversely, there floor pan/brake pedal pulses of low amplitude and long duration, perhaps 50 G's in 40 msec, that lead to high levels of floor pan intrusion but result in low, under 5 kN, axial loads through the feet of the Hybrid III dummy. The high amplitude short duration floor pan acceleration pulse is a probable cause of calcaneus and pilon fractures that are found in occupants in vehicle crashes with minimal intrusion.

The maximum axial loads through the dummy feet were concurrent with the maximum acceleration of the floor pan/brake pedal suggesting that the axial loads through the feet were driven by the accelerating floor pan/brake pedal.

Poor association was found between maximum axial loads through the feet and the amount of floor pan/brake pedal intrusion. The maximum axial loads through the feet are in general higher for the right leg than the left leg and are highly correlated to the peak acceleration of the floor pan

Occupant simulations suggested that 2.5 cm thickness of suitable floor pan padding can reduce the axial loads through the feet by a third and therefore reduce ankle/foot injuries associated with axial compressive loads.

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APPENDIX A

The purpose of this appendix is to present the characteristics of the approximate acceleration curves of the brake pedal and the floor pan of the Ford Taurus for the different crash configurations found in Figure 1.

Table A-1
Characteristics of the Approximate Acceleration Curves of the Floor pan and Brake Pedal of the Ford Taurus in Various Crash Configurations

Test No.	Location	Measured Intrus. (cm)	Calculated Intrus. (cm)	Approx. Peak Accel. (G's)	Start of intrus. (msec)	Approx. Accel. Durat. (msec)
TFRB1	brake pedal	4.8	6.7	65.0	46.0	20.0
TFRB1	floor pan	4.8	5.4	62.0	40.0	28.0
TFRB2	floor pan	2.5	3.2	45.0	38.0	26.0
THCO1	brake pedal	17.5	18.0	47.0	23.0	48.0
THCO1	floor pan	21.6	21.7	47.0	21.0	49.0
THCO2	floor pan	2.5	2.0	29.0	37.0	42.0
TTOO1	brake pedal	17.5	17.7	63.0	40.0	35.0
TFDB1	brake pedal	4.8	5.4	50.0	66.0	38.0
TMDB1	brake pedal	8.4	8.8	74.0	36.0	24.0

APPENDIX B

The purpose of this Appendix is to present the maximum distal tibia axial loads measured by the load cells just above the ankles of a Hybrid III dummy in a Ford Taurus for the different crash configurations found in Figure 1.

Table B-1
Measured Static Intrusion, Peak Approximate Acceleration of the Floor Pan and Brake Pedal, and Maximum Distal Tibia Axial Loads in Vehicle Crashes

Test No.	Intrusion (cm)		Approx. Peak accel. (G's)		Left tibia Load (kN)	Right Tibia Load (kN)
	Brake	Floor pan	Brake	Floor Pan		
TFRB1	4.8	4.8	65	62	3.3	8.2
TFRB2	2.0	2.5	--	45	4.4	7.7
THCO1	18	22	47	47	3	4.9
THCO2	2.5	2.5	--	29	2.1	0.7
TTOO1	18	21	63	--	5.1	7.4
TFDB1	4.8	9.4	50	--	4.5	2.6
TMDB1	8.4	14.0	74	--	5.4	9.2