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Recommendations for a Sled and Intrusion Pulse in the Study of Injuries to the Lower Extremities

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Abstract

Recent vehicle-to-vehicle frontal impact offset crash tests conducted at Calspan Corporation were studied for an understanding of the dynamic intrusion characteristics of the brake pedal and the toe pan. The instrumentation used in the Calspan tests was inadequate to measure the dynamic intrusion behavior of the brake pedal and the toe pan. However, it was possible to derive a model (approximate) sled pulse and a model (approximate) intrusion pulse of the brake pedal and the toe pan using the information obtained from the static measurements and making simplifying assumptions about the dynamic measurements. This paper presents the development of a model sled pulse and model intrusion pulses for the brake pedal and the toe pan in both the longitudinal and the vertical direction.

Introduction

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. In an extensive survey of the NASS files of frontal impacts, with no rollover, and no occupant ejection, it was noted by Morgan et al. [1] that contact with foot controls was the cause of 43% of ankle injuries of AIS$\geq$2, and 47% of foot injuries of AIS$\geq$2. In the same survey it also was found that contact with the floor pan accounted for 24% of the ankle and foot injuries of AIS$\geq$2. Hence, it is very important to simulate the dynamic intrusion behavior of the brake pedal and the toe pan accurately in sled tests for the study of injuries to the lower extremities.

Recent vehicle-to-vehicle frontal impact offset crash tests conducted at Calspan Corporation provided an opportunity to study the dynamic intrusion behavior of the brake pedal and the toe pan during the crash. These Calspan crash tests were frontal offset crash tests with closing speeds of approximately 115 km/hr and with 60%-70% overlap of the fronts of the vehicles.

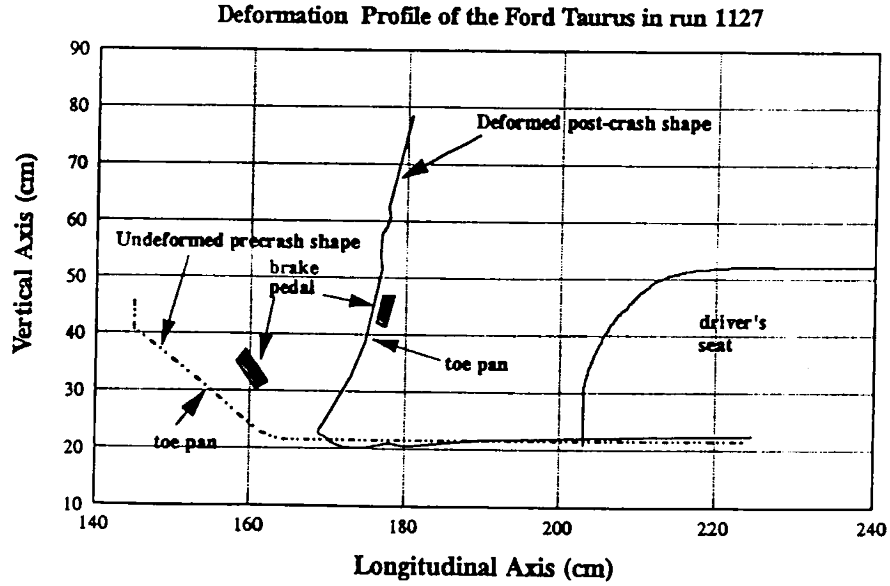
The vehicles were equipped with linear accelerometers in the longitudinal direction at the brake pedal, the toe pan, and the rear of the vehicle. Linear accelerometers in the vertical direction were also available at the brake pedal and the rear of the vehicle. Measurements were made of the pre-test and the post-test distances from the rear of the car to the front of the car, the brake pedal, and the toe pan. Digitized pre-crash and post-crash profiles of the vehicle floor pan were also made by Ford Motor Company. These static pre-test and post-test measurements provide information on the static intrusion of the floor pan.

Intrusion Characteristics of the Brake Pedal and the Toe Pan from Measured Values

<u>Static Measurements:</u> The longitudinal static intrusion was obtained by subtracting the measured post-test distances (longitudinal distance of the brake pedal and the toe pan from the rear of the vehicle) from the corresponding measured pre-test distances. Static intrusion characteristics were also obtained from the digitized pre-crash and post-crash shapes of the floor pan. As an illustration, a digitized pre-crash and post-crash floor pan shape of the Ford Taurus (in Calspan test run 1127) is shown in Figure 1. A point at the rear of the vehicle was selected as the reference point for these digitized shapes since, the rear of the vehicle did not experience any effect of the intrusion and moved during the impact as a rigid body. Figure 1 indicates that there was significant vertical as well as longitudinal intrusion of the floor pan. The intrusion of the brake pedal obtained from Figure 1 is 17.5 cm in the longitudinal direction and 11.4 cm in the vertical direction. The intrusion of the toe pan obtained from Figure 1 is 21.6 cm in the longitudinal direction and 11.4 cm in the vertical direction. The approximate average intrusion of the brake pedal and the toe pan (obtained from all the tests conducted at Calspan) was 22.9 cm in the longitudinal direction and 11.4 cm in the vertical direction. These static intrusion values were taken into consideration while developing the acceleration signals of the brake pedal and the toe pan.

Figure 1

Deformation Profile of the Ford Taurus in run 1127



Dynamic Measurements: The data from the accelerometers was used to obtain the dynamic intrusion characteristics of the brake pedal and the toe pan. The accelerations in the longitudinal direction (obtained from the accelerometers) were integrated twice to obtain the respective displacements. The difference in the displacements of the brake pedal and the rear of the car in the longitudinal direction is the longitudinal intrusion of the brake pedal. The longitudinal intrusion of the toe pan and the vertical intrusion of the brake pedal and the toe pan were also obtained in a similar manner.

The measured static intrusion was compared to the intrusion calculated using the method described above. It was found that there was significant difference in the measured and the calculated values (sometimes as high as 500%). This discrepancy in the measured static intrusion and the corresponding calculated intrusion at the end of the crash (obtained by processing the accelerometer data) could be attributed to the fact that the accelerometers may have rotated during intrusion. Hence, the dynamic intrusion obtained by straight forward integration of the acceleration curves is *not* reliable.

Since direct integrations of the accelerometer data in the Calspan tests can not lead to the correct static intrusion of the brake pedal and the toe pan, it was decided to make simplifying assumptions about the actual brake pedal and toe pan acceleration signals.

Using the actual static and dynamic measurements, an approximate model sled pulse (a model of the sled pulse) and approximate intrusion pulses (models of the true intrusion pulses) of the brake pedal and the toe pan were developed. Since the accelerometers at the brake pedal and the toe pan may have rotated, the true pulses of the brake pedal and the toe pan are different from their actual pulses measured by the accelerometers. Calspan test run 1127 was selected for emulating the behavior of the brake pedal, the toe pan, and the vehicle. Test run 1127 (which is a vehicle-to-vehicle frontal crash test containing a 60% overlapped 1991 Ford Taurus 4-door sedan at 58 kph into a 62.6% overlapped 1991 Honda Accord DX 4-door sedan at 58 kph) was chosen since the accelerometers appeared to rotate at a much later time and to a lesser extent during the crash event.

Model Acceleration of the Sled Pulse

The duration of the pulse, the maximum acceleration value, and the average acceleration are all characteristics of the vehicle impact used in the design of a sled pulse. The characteristics of the basic sled pulse were obtained from the accelerometers at the rear of the vehicle in the Calspan tests, since they appeared to be unaffected by the intrusion during impact. Since the vehicle motion was in the longitudinal direction for roughly the first 200 msec, only the longitudinal acceleration was considered for the sled pulse.

A smoothed out sled pulse looks approximately like a sine wave. Hence, the sled pulse was modelled using a sine curve such that:

1. The total area under the model curve is approximately equal to the total area under the actual vehicle acceleration curve.
2. The velocity versus time history curves of the two signals are similar.
3. The displacement versus time history (over the ground motion) curves of the two signals are similar.

4. The total area under the actual and model velocity curves (the crush of the vehicle) are approximately equal.

The model acceleration curve and the actual vehicle acceleration curve (obtained from the accelerometer data) are shown in Figure 2. (The actual acceleration pulse has been filtered by an SAE Class 60 filter.) The velocity of the vehicle during the crash test and the model velocity (obtained by integrating the acceleration curves) are shown in Figure 3. The displacement of the vehicle and the model displacement during impact are shown in Figure 4.

The velocity and displacement curves obtained from the integration of the model acceleration curve are quite similar to the corresponding curves obtained by integrating the actual acceleration curve. The actual crush of the vehicle (obtained by integrating the actual velocity curve) is 87.6 cm while the model crush of the vehicle (obtained by integrating the model velocity curve) is 82.5 cm-- see Figure 4. The difference in the actual and model crush of the vehicle is only 6% of the actual crush value. This indicates that the sine approximation of the actual acceleration curve is quite reasonable.

Figure 2
Model and Actual Long. Accel. Curve of the Vehicle

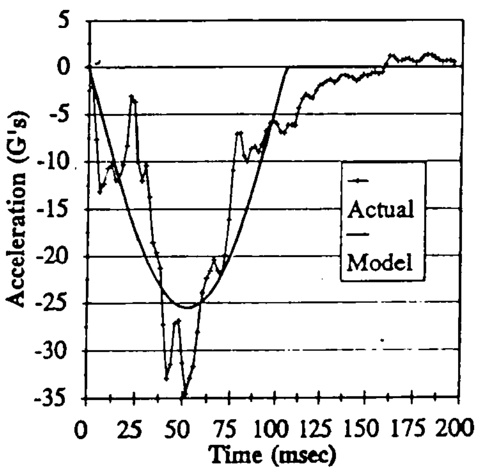


Figure 3
Model and Actual Long. Velocity Curve of the Vehicle

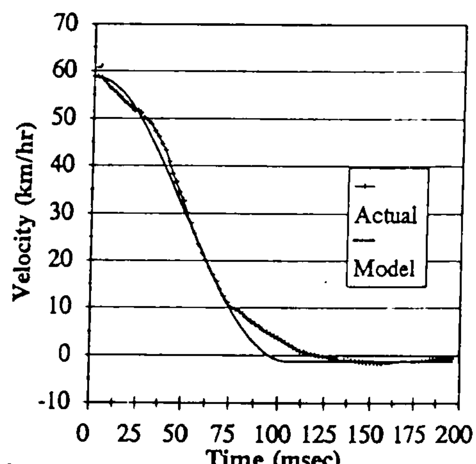
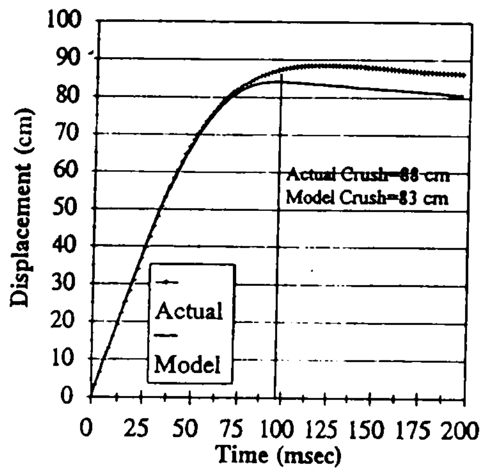


Figure 4
Model and Actual Long. Disp. Curve of the Vehicle



Model Acceleration Pulses of the Brake Pedal and the Toe Pan

Because the front of the vehicle experiences intrusion, the acceleration signals at the front of the vehicle are different from those at the rear of the vehicle. Hence, an acceleration pulse different from the vehicle crash pulse is required for the brake pedal and the toe pan. The intrusion of the brake pedal and the toe pan is in the longitudinal as well as in the vertical direction (Figure 1). Hence, two separate acceleration signals --one in the longitudinal direction and one in the vertical direction-- are required to model the intrusion of the brake pedal and the toe pan.

It is difficult to get a clear picture of the dynamic intrusion characteristics of the brake pedal and the toe pan since the accelerometers at the brake pedal and the toe pan have rotated during impact. However, the measurements of static intrusion and the digitized pre-crash and post-crash shapes of the floor plan (Figure 1) provide some information on the static intrusion. This partial information was used to model the acceleration signals of the brake pedal and the toe pan.

<u>Acceleration Signals in the Longitudinal Direction:</u> The acceleration signals of the brake pedal and the toe pan in the longitudinal direction were modelled by a sine curve in a similar manner to that done for the acceleration at the rear of the vehicle. However, one has to be cautious in matching the accelerations and the velocities exactly since the accelerometers may have rotated. Hence, the model acceleration curve was constructed such that: (1) the velocity obtained by the integration of this curve matches the initial portion of the actual velocity curve and (2) the final intrusion (obtained by subtracting the model displacement curve of the brake pedal or the toe pan from that of the rear of the car) is similar to the measured static intrusion value. Some intuition and judgement (obtained from looking at acceleration and velocity curves of the brake pedal and the toe pan from many vehicle crash tests) has gone into the selection of the model acceleration curve to emulate the behavior of the brake pedal and the toe pan, i.e., the authors used a heuristic argument.

The actual acceleration curves of the brake pedal and the toe pan (obtained from the accelerometers) and the corresponding model acceleration curves are shown in Figures 5 and 6. (The actual acceleration pulse has been filtered by an SAE Class 60 filter.) The actual velocity curves and the model velocity curves of the brake pedal and the toe pan (obtained by the integration of the corresponding acceleration curves) are shown in Figures 7 and 8. The actual displacement curves and the model displacement curves of the brake pedal and the toe pan are shown in Figures 9 and 10.

The intrusion of the brake pedal and the toe pan was obtained by subtracting the displacement of the brake pedal and the toe pan from the actual displacement of the rear of the vehicle. The intrusion of the brake pedal and the toe pan is shown in Figure 11. The intrusion obtained from the model displacement curves is 18.0 cm for the brake pedal and 21.3 cm for the toe pan. The measured static intrusion is 17.5 cm for the brake pedal and 21.6 cm for the toe pan. This indicates that the sine approximation of the brake pedal and the toe pan acceleration signal is reasonably accurate with respect to the post-test measured crush.

Table III summarizes the characteristics of the model acceleration curves and the actual acceleration curves of the vehicle, the brake pedal, and the toe pan in the longitudinal direction.

As can be seen from Table III, the peak acceleration of the model acceleration curves are smaller than the actual acceleration curves. However, these model acceleration curves produce the closest approximation of the velocities, the displacements, and the intrusion values. The average acceleration values are provided to assist in the design of an alternate, approximate model acceleration signal such as, a square or trapezoidal wave (which are experimentally easier to generate than a sine wave at some laboratories). The average acceleration was obtained by taking the area under the acceleration curve and dividing by the duration of the pulse. The model average accelerations are slightly higher (9% to 17%) than the actual average accelerations.

Figure 5
Model and Actual Long. Accel.
Curve of the Brake Pedal

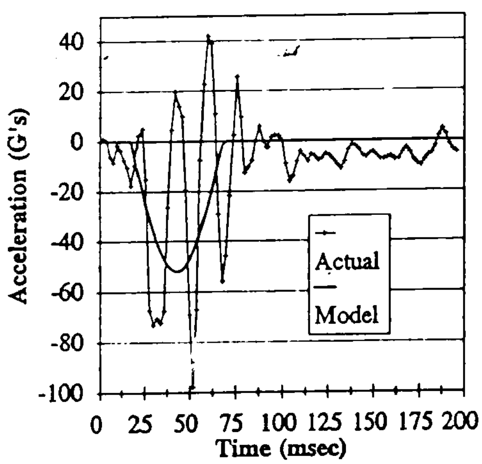


Figure 6
Model and Actual Long. Accel.
Curve of the Toe Pan

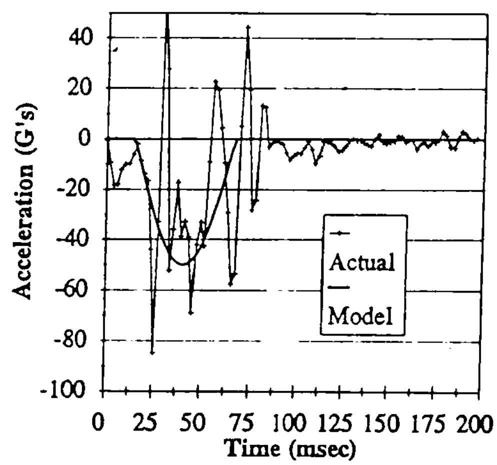


Figure 7
Model and Actual Long. Velocity
Curve of the Brake Pedal

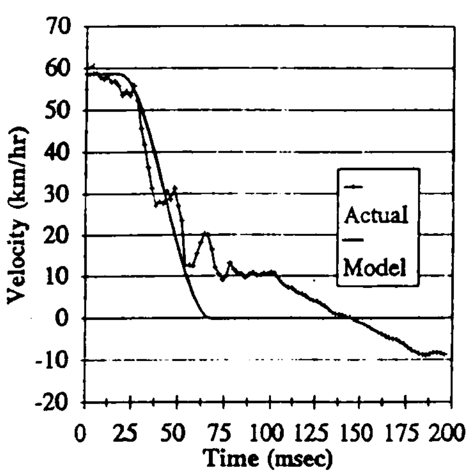


Figure 8
Model and Actual Long. Velocity
Curve of the Toe Pan

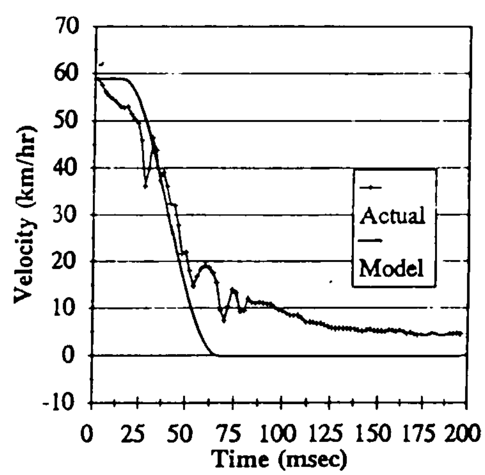


Figure 9
Model and Actual Long. Disp.
Curve of the Brake Pedal

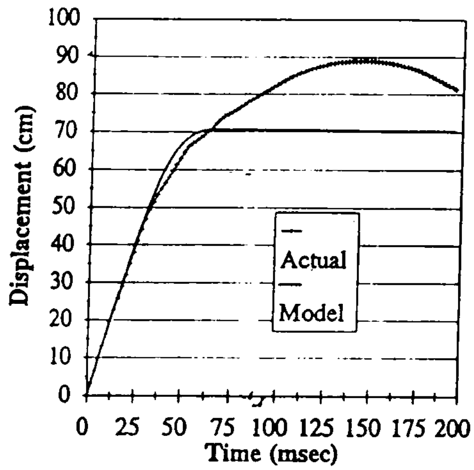


Figure 10
Model and Actual Long. Disp.
Curve of the Toe Pan

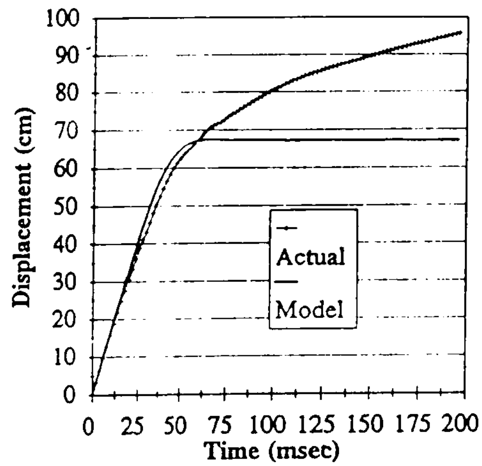
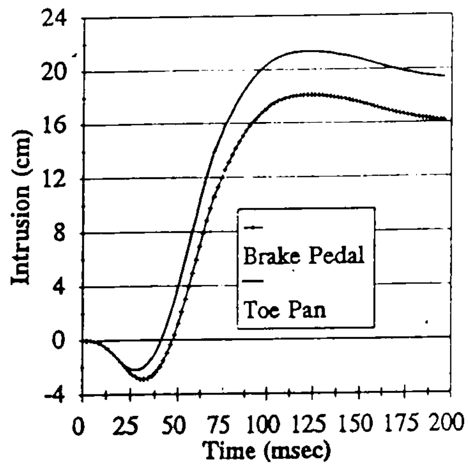


Table III

Characteristics of the Model Acceleration Curves in the Longitudinal Direction

	Vehicle		Brake		Toe Pan	
	Actual	Model	Actual	Model	Actual	Model
Peak acceleration (G's)	35.0	25.5	100.0	52.0	85.0	50.0
Duration of pulse (msec)	130.0	105.0	50.0	50.5	50.0	52.5
Start of pulse (msec)	0.0	0.0	20.0	18.0	20.0	15.0
End of pulse (msec)	130.0	105.0	70.0	68.5	70.0	67.5
Ave. acceleration (G's)	13.6	15.8	28.0	32.8	28.8	31.5

Figure 11
Model Long. Intrusion Curve of
the Brake Pedal and the Toe Pan



Acceleration signals in the Vertical Direction: The vertical acceleration of the brake pedal and the toe pan were also modelled by a sine curve. There is an accelerometer in the vertical direction only on the brake pedal and none on the toe pan. Hence, the vertical intrusion characteristics of the toe pan were approximated to be the same as that of the brake pedal. Since the accelerometers on the brake pedal may have rotated, it is not possible to match the model curves with the corresponding actual curves. However, an estimate of the static vertical intrusion of the brake pedal was obtained from the digitized pre-crash and post-crash floor pan shapes. The vertical static intrusion of the brake pedal and the toe pan for test run 1127 is approximately 11.4 cm.

The initial vertical velocity of the vehicle is zero. During the impact, the brake pedal and the toe pan experience a vertical acceleration pulse which causes the brake pedal and the toe pan to have an upward velocity for the duration of the acceleration pulse. This upward velocity results in an upward displacement (intrusion) of the brake pedal and the toe pan. The characteristics of the model acceleration signal were developed such that:

1. The static vertical intrusion is matched.
2. The duration of the vertical acceleration pulse is within that of the corresponding longitudinal acceleration pulse.
3. The vertical acceleration pulse commences after the beginning of the longitudinal acceleration pulse.

The model vertical acceleration pulses of the brake pedal and the toe pan and the actual vertical acceleration pulse of the brake pedal are shown in Figure 12. The corresponding model velocity and actual velocity of the brake pedal and the toe pan (obtained by integrating the corresponding acceleration curves) are shown in Figure 13. The model and actual displacement curves (intrusion curves) of the brake pedal and the toe pan (obtained by integrating the corresponding velocity curves) are shown in Figure 14. The final intrusion value obtained from the model displacement curve is 11.2 cm which is approximately equal to the static vertical intrusion obtained from Figure 1. The characteristics of the model vertical acceleration curve of the brake pedal and the toe pan are shown in Table IV.

Table IV
Characteristics of the Model Acceleration Curves in the Vertical Direction

Peak Acceleration (G's)	Duration of Pulse (msec)	Start of Pulse (msec)	End of Pulse (msec)	Average Acceleration (G's)
45.0	40.0	25.0	65.0	0.0

Figure 12
Model and Actual Vertical Accel. Curve of the Brake Pedal

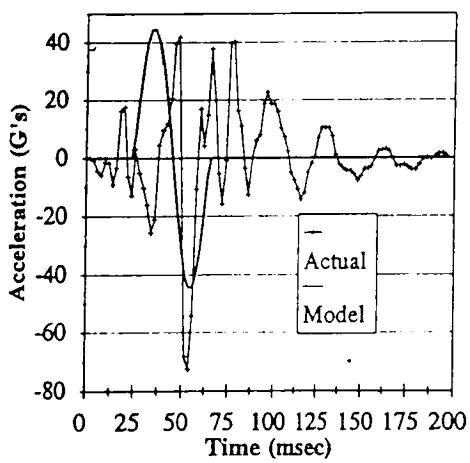


Figure 13
Model and Actual Vert. Vel. Curve of the Brake Pedal

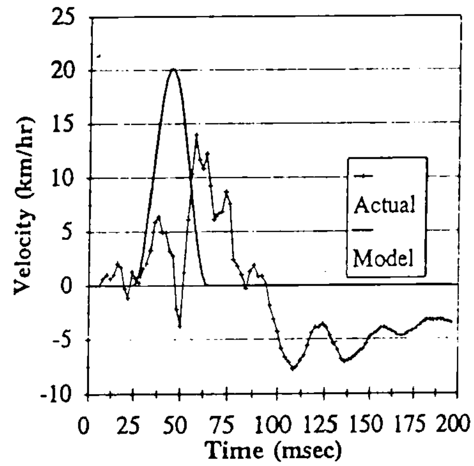
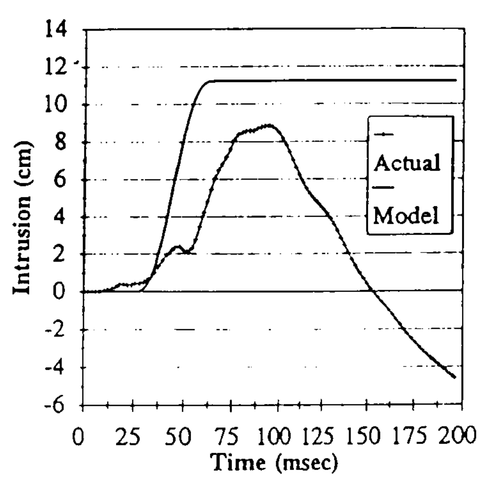


Figure 14
Model and Actual Vert. Intrusion Curve of the Brake Pedal



Conclusions

Recent vehicle-to-vehicle frontal impact offset crash tests conducted at Calspan Corporation were studied to determine the intrusion characteristics of the brake pedal and the toe pan. It was found that there is a significant vertical component of intrusion (average of 11.4 cm) as well as a horizontal component (average of 22.9 cm) as shown in Figure 1. A model, or approximate, sled pulse was developed in the form of a half sine wave and is shown in Figure 2. Model intrusion pulses for the brake pedal and the toe pan were developed in the longitudinal direction. The longitudinal brake pedal and toe pan pulses are shown in Figure 5 and Figure 6 respectively. A model intrusion pulse for the brake pedal and the toe pan in the vertical direction was developed as shown in Figure 12.

Acknowledgement

The authors would like to thank Carl Ragland of NHTSA for his help and support.

Disclaimer

The views presented are those of the authors and are not necessarily those of the National Highway Traffic Safety Administration, U. S. Department of Transportation.

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[1] Morgan, Richard M., Eppinger, Rolf H., Hennessey, Barbara C.: "Ankle Joint Injury Mechanism for Adults in Frontal Automotive Impact," Proceedings of the 35th Stapp Car Crash Conference, pp. 189-198, San Diego, California, 1991.

DISCUSSION

PAPER: **Recommendations for a Sled and Intrusion Pulse in the Study of Injuries to the Lower Extremities**

SPEAKER: Shashi Kuppa, Conrad Technologies, Inc.

CHAIRPERSON: This is an initial effort for what one might do for a sled pulse in a laboratory simulation.

QUESTION: Mark Plaisan, Applied Technologies Associates
I was wondering if the rotational sensor might help, whether there as a rotational component in your measurements?

A: I actually wrote up something about using MHD sensors to put on the brake pedal and since they are so light. It is simple Euler angle theory and you can come up with the rotations, but I'm really not sure how feasible it is and I think also they were running out of channels at Calspan. They didn't have that many channels so it really didn't take off on that. I think on paper it is workable. I've already got all the equations down and everything.

Q: Would a sixth degree of freedom system right on the brake pedal help or you say you are out of channels for that.

A: I think so. I think they are up to the maximum right now.

Q: Ed Kennedy, Farmington Hills
It was thirty-six miles per hour, was it?

A: Yes.

Q: Which is probably one of the worst kinds of impacts especially when it's on the offset and thirty mile per hour barrier based on some statistical data, some years ago. Thirty miles per hour takes care of about ninety-seven percent of the frontals. Thirty-six miles per hour has to be up beyond nine and this is an area to correct the intrusion that you showed. I think it would be beyond what the automotive manufacturers would be doing.

A: I think before they actually ran these crash tests, they did a NASS survey of data about what the velocities were for crash tests of vehicle accidents where there was significant intrusion and they came up with a speed of around thirty-four to thirty-seven miles an hour.

Q: But we're dealing with the top three percent of the accidents though.

A: Maybe. But they were trying to mimmick actual vehicle accidents where there was significant intrusion in these Calspan tests.

Q: Right and they would still be up in that last three percent.

A: Probably. I'm not sure.

Q: I might add that in the actual laboratory experiments, certainly some of them would, a great number of them, would be done with lesser intrusion. In other words, just trying to understand a very violent event for intrusion, but the total matrix that is envisioned to be followed would be at a much lower range of intrusion. Right? This is trying to pick one of the outer ranges.

A: Right.

Q: I'm not trying to discredit what they are looking at but I want to put it into perspective.

A: Absolutely, thank you.

Q: Guy Nusholtz, Chrysler Motors
I'd like to compliment you on addressing an issue that doesn't get addressed very often and we thank you for that. One comment that I'd have is that looking at a lot of vehicles where there is and/or floor board deformation, a lot of times when you see the floor pan pushed back as far as you've analyzed it there, we also get some buckling in the floor pan in addition to that and certainly, depending on how bad the impact is, is going to determine how much of that went on, but that's not an uncommon instance.

A: Yes. I'd like to make a comment. Over the few days that I've been here, I've talked with many people about this and I've got a lot of feedback. I think I can improve on this quite a bit and I think maybe in my paper, when I submit it, it will be a little different.

Q: Jeff Crandall, University of Virginia
I just sort of wanted to make a comment on the levels of intrusion that NASS is showing. We found at the University of Virginia by our analysis of the NASS data, that roughly sixty percent of the accidents that had intrusion were less than two percent, but for the six to eight inch levels that we're talking about here, there were significant numbers somewhere in the vicinity of eight to ten percent.

Q: Bruce Donnelly, Calspan Corporation
In defense of my employer, I don't believe the possible number of channels was exceeded, but rather, although I wasn't involved with these tests, probably the number of channels contracted for.