PARAMETRIC STUDY OF SIDE IMPACT THORACIC INJURY CRITERIA USING THE MADYMO HUMAN BODY MODEL

Richard Kent, Edwin Sieveka, Jeff Crandall
Automobile Safety Laboratory
University of Virginia
United States of America
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ABSTRACT

This paper presents a computational study of the effects of three parameters on the resulting thoracic injury criteria in side impacts. The parameters evaluated are a) door velocity-time (V-t) profile, b) door interior padding modulus, and c) initial door-to-occupant offset. Regardless of pad modulus, initial offset, or the criterion used to assess injury, higher peak door velocity is shown to correspond with more severe injury. Injury outcome is not, however, found to be sensitive to the door velocity at the time of first occupant contact. A larger initial offset generally is found to result in lower injury, even when the larger offset results in a higher door velocity at occupant contact, because the increased offset results in contact later in the door V-t profile - closer to the point at which the door velocity begins to decrease. Cases of contradictory injury criteria trends are identified, particularly in response to changes in the pad modulus. Maximum chest deflection and maximum viscous criterion gradually decrease as the padding modulus increases. TTI, however, increases with some increases in pad modulus. Complex interactions among the three parameters are observed, and their interpretation is shown to depend on the specific injury criterion analyzed.

INTRODUCTION

Federally mandated crash tests are currently performed in the United States and in Europe to evaluate the side impact characteristics of new vehicles. The European thoracic injury criteria, test dummy, and test conditions, however, differ from those used in the U.S. The U.S. injury criterion is the thoracic trauma index (TTI): an acceleration-based criterion measured using a U.S. Side Impact Dummy (USSID) (Morgan et al. 1986). The European dummy, EuroSID, has additional capability to measure deformation-based criteria, including the maximum change in the lateral chest dimension (maximum chest deflection, C_{max}), the maximum time rate of this change (maximum deflection velocity, V_{max}), and the maximum of the product of deflection and deflection velocity (maximum viscous criterion, VC_{max}) (Viano and Lau 1985). A necessary, though insufficient, requirement for global harmonization of safety standards, therefore, is an increased understanding of the efficacy of these thoracic injury criteria.

Near-side occupant loading occurs as the door is driven into the occupant by the impacting vehicle. The door velocity-time (V-t) profile can be estimated by integration of data from an accelerometer mounted on the door structure and oriented laterally to a vehicle in a full-scale vehicle crash test (Figure 1). The U.S. National Highway Traffic Safety Administration (NHTSA) performs side impact tests under the Side Impact New Car Assessment Program (SINCAP). In these tests, the inner door panel

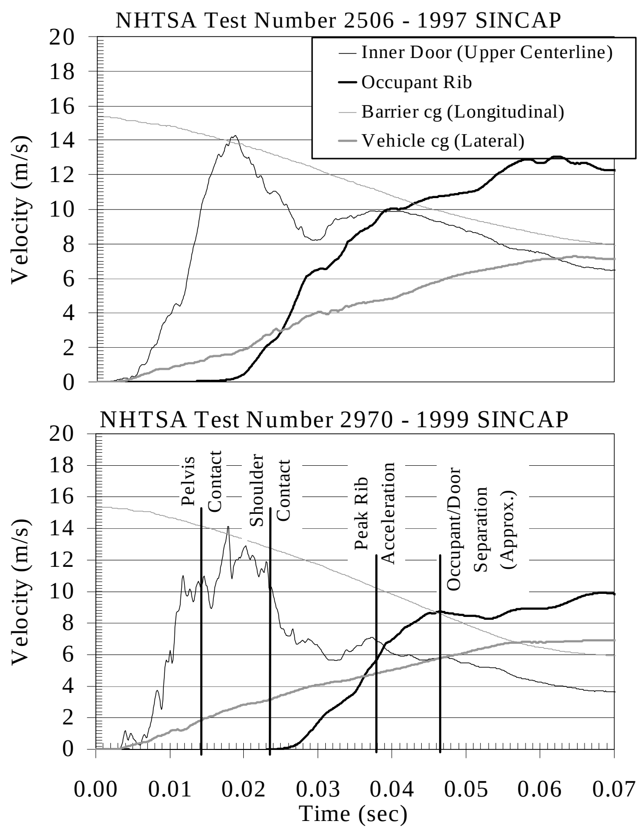


Figure 1. Velocity-time profiles at selected locations on the barrier, struck vehicle, and occupant in two SINCAP tests.

velocity builds to a maximum that has approximately the magnitude of the barrier center of gravity (cg) longitudinal velocity at that time. This initial peak occurs 10 ms to 25 ms after the barrier first contacts the vehicle; approximately the same time the door strikes the occupant. The door velocity then decreases while the door is in contact with the occupant.

With the increased introduction of side airbags, an understanding of the relative benefits of padding versus additional space between the occupant and interior door panel is of critical importance. Analytical, experimental, and computational studies have shown that complex interactions exist among the door V-t profile, the thickness and stiffness of padding at the door-occupant interface, and the initial distance (offset) between the occupant and door. Further, because current injury criteria are imperfect predictors of injury risk, the specific criterion used to indicate thoracic injury risk can influence the interpretation of these interactions (Lau et al. 1991, Payne and Allan-Stubbs 1997, Allan-Stubbs 1998, Morris et al. 1999, Kent et al. 2001).

It is necessary, therefore, to consider door dynamics, padding, and offset when evaluating the efficacy of a thoracic injury criterion. The Automobile Safety Laboratory at the University of Virginia has designed and manufactured a sled system that can reproduce a realistic door velocity-time profile throughout the duration of occupant loading as well as incorporate a range of padding types (including a side airbag) and initial occupant-to-door offsets (Kent et al. 2001).

The purpose of the current study is not to determine optimal padding or other vehicle crashworthiness design properties. Rather, the goal is to elucidate how the door V-t profile, padding modulus (σ), and initial door-to-occupant offset (δ) influence C_{max}, V_{max}, VC_{max}, and TTI**.** Of specific interest is an understanding of how these parameters may influence the criteria differently (e.g., an increase in padding modulus may result in lower TTI but higher VC_{max}). The results presented herein provide a computationally based justification for a series of human cadaver tests to be performed for the evaluation of thoracic injury criteria. In the case of contradictory trends in the different injury criteria, the injuries sustained by a cadaver provide a means of evaluating the relative efficacy of the criteria.

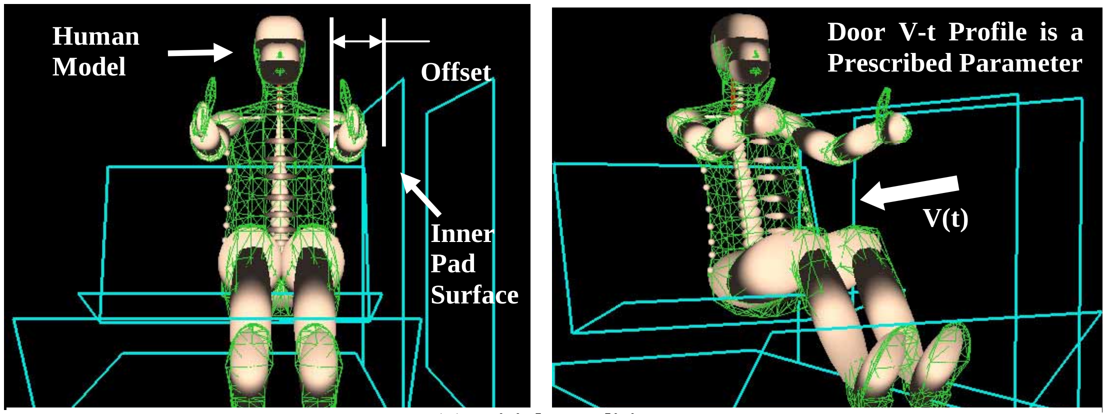
BACKGROUND

Contradictory trends in side impact thoracic injury criteria have been reported in the literature. In 1987 and in 1989, Deng presented a lumped-parameter occupant and vehicle side impact model used to analyze vehicle structural characteristics, padding stiffness, and padding thickness. Deng found that an increase in padding thickness reduced thoracic acceleration levels while increasing thoracic deflection and viscous response. This behavior was attributed to decreased peak force with concomitant increased occupant-to-door contact duration. Lau (1989) confirmed Deng's findings using a series of full-scale vehicle-to-vehicle side impact tests. In these tests, the acceleration-based TTI response of the EuroSID dummy was found to decrease with the addition of padding on the inner door surface. Deflection-based criteria, VC_{max} in particular, did not exhibit this trend and were observed to have a much less repeatable response than TTI. In contrast to the findings of Deng and Lau, Trella and Kanianthra (1987) used a lumped-parameter model to show that acceleration-based criteria and deflection-based criteria yielded similar trends in response to all parametric changes evaluated. Trella and Kanianthra attributed Deng's findings to the "characteristic features of the…model…and the properties used to simulate the dummy." It may be that Trella and Kanianthra did not observe contradictory injury criteria trends because they used a model of the USSID, which is intended to measure chest acceleration but is not designed to measure chest deflection in a biofidelic manner.

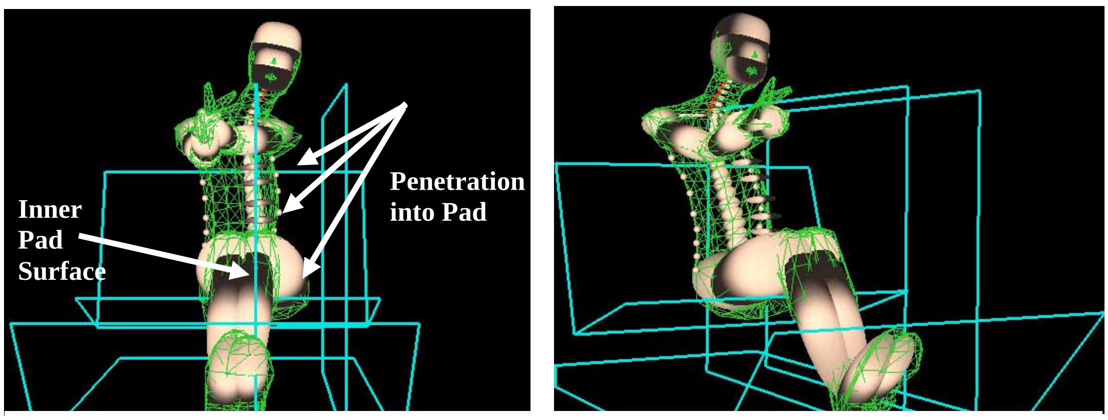
This study will expand on these previous analyses through the use of a state-of-the-art human body model. The MADYMO human body model thorax (Happee et al. 2000) has non-linear stiffness and damping, which have been validated for lateral loading using human cadaver sled tests and human cadaver blunt impactor tests. The modal synthesis method (Koppens et al. 1993) is used to describe the thorax using a series of eight flexible bodies with spring damper models providing coupling and load sharing between the flexible bodies and between the flexible bodies and the spine. The modal method for approximating the motion of a flexible body involves a linear combination of a limited number of predefined modes, which is a limitation of the model. This method of discretization does, however, allow complex geometry and a distributed description of mass and stiffness without the added computational resources required for finite element modeling.

SIMULATION METHODS

Thirty-six near-side impact simulations were performed using the 50^{th} percentile male, multi-directional MADYMO human body model (Figure 2). The model was positioned on a rigid seat with the arms raised in a nominal driving position. A deformable wall was used to simulate an intruding,



(a) Initial Conditions



(b) Maximum Chest Deflection

Figure 2. Frontal and oblique views of MADYMO human body model and simulation setup.

side-struck door loading the thorax. Three door V-t profiles (A, B, C) were chosen to represent a range of profiles observed in SINCAP tests (Figure 3). The V-t profiles differed in the peak velocity (10 m/s, 13 m/s, 16 m/s), the time to peak velocity (9.5 ms, 12.2 ms, 15 ms), and the slope during the deceleration phase of the profile (7.9g, 15.4g, 21.8g).

Three values of door padding modulus were analyzed (σ_A = 165.5 kPa, σ_B = 310.3 kPa, σ_C = 413.7 kPa). These are generic, intended to represent the extremes of the surface against which an occupant may be loaded. The highest modulus represents a stiff door interior panel, while the lowest modulus is intended to represent very soft door padding or, in a highly simplified sense, a side airbag. In order to remove the confounding effect of the pad bottoming out (which is typically modeled as a linear increase in modulus and therefore necessitates additional parameters, namely the depth at which the pad modulus starts increasing and the slope of the line), all pad moduli were modeled as constant over the entire crush

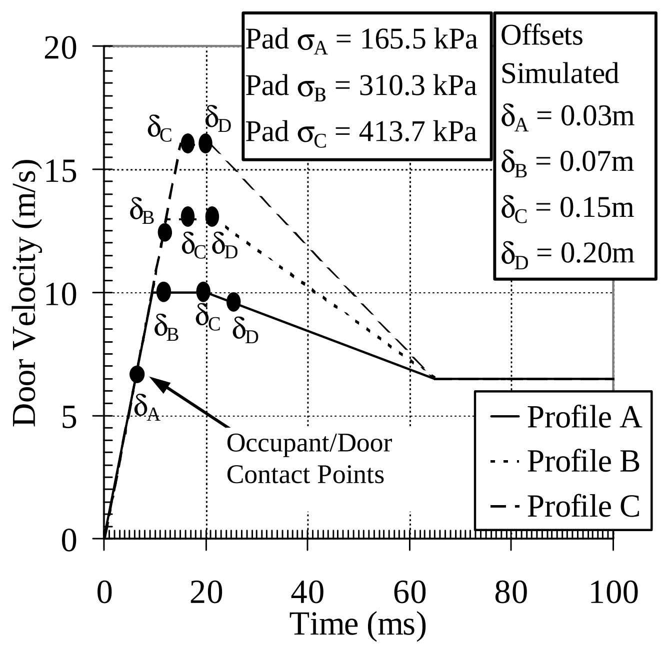


Figure 3. Door V-t profiles, pad moduli, and occupant-door offset distances simulated.

depth. This simplification facilitates interpretation of the results and is of minimal consequence because a) the purpose of this paper is to analyze and to compare the responses of different injury criteria rather than evaluate door design, and b) there were no dimensional absurdities resulting from this description of the door interior (i.e., crush depths were realistic).

The initial lateral position of the occupant was varied so that four values of initial door-to-occupant offset (the distance from the occupant's shoulder to the proximate surface of the pad) were simulated (δ_A = 3 cm, δ_B = 7 cm, δ_C = 15 cm, δ_D = 20 cm). These values were chosen based on a survey of realistic positions that could be obtained in passenger vehicles currently in the U.S. fleet. The effect of increased offset is that the occupant contacts the door later in the door V-t profile (Figure 3). Thus, it was possible to analyze the effect of the door velocity at occupant contact as well as the effect of the point on the V-t profile at which contact occurred.

Every combination of door V-t profile, pad modulus, and offset was simulated. The injury criteria were obtained using post-processing software included in the MADYMO package (MADYMO 1999). The presented values of chest deflection, spinal acceleration, and rib acceleration were calculated at the level of the seventh rib.

SIMULATION RESULTS

The peak pad deformation distance (i.e. pad crush) at the shoulder level was approximately 11 cm for the lowest pad modulus simulated, a reasonable representation of the total deflection of a small thorax airbag. The minimum pad crush was approximately 4.4 cm for the highest pad modulus simulated, a reasonable value for a relatively stiff production interior door panel.

C_{max}, V_{max}, TTI, and VC_{max} were obtained for all sets of input conditions (Table 1). As expected, contradictory trends in injury criteria were observed. In other words, the effects of changes in many of the input conditions would be interpreted differently depending on the specific injury criterion chosen to represent the occupant's actual injury potential. The values of TTI ranged from 103 to 292 [injury reference value (IRV) 90], indicating significant risk of thoracic injury for all sets of conditions. VC_{max}, on the other hand, ranged from 0.48 m/s to 2.91 m/s (IRV 1.0 m/s), indicating a wider range of injury risk. Some of the effects were, however, independent of the criterion analyzed. Greater peak door velocity was found to correspond with higher values of all injury criteria. Further, in general, a larger initial offset resulted in lower values of all injury criteria, even when the larger offset resulted in a higher door velocity at occupant contact (Figure 4 and Figure 5). For example, simulations number 2, 11, 20, and 29 involve pad σ_A and V-t profile B. The values of all injury criteria for these four simulations decrease in magnitude as the offset increases, despite increased door contact velocity from simulation 2 to simulation 11 and from simulation 11 to simulation 20. The decrease with increasing offset did not occur, however, in all cases for all injury criteria. While the mean values of all criteria (averaged across all V-t profiles and pad moduli) did exhibit a decreasing trend with increasing offset (Figure 5), TTI was found to increase with increasing offset for certain pad moduli and V-t profiles. As shown in Figure 4, an increase in TTI as offset increased from 3 cm to 7 cm was observed for V-t profile B (intermediate profile) when the two highest moduli (σ_B and σ_C) were used. This increase was observed with V-t profile C (the most severe) for all pad moduli, while it was not observed in any case with V-t profile A (least severe). Therefore, when an increase in offset resulted in a large increase in door velocity at occupant contact, TTI predicted that the larger offset was more injurious, while all other criteria always decreased with increasing offset.

The magnitude of the decrease in the mean as offset increased depended on the specific criterion analyzed: the mean values of both VC_{max} and TTI decrease by over 30% as the offset was increased from 3 to 20 cm, with most of the decrease occurring as the offset changed from 7 cm to 15 cm. By contrast, mean C_{max} changed by less than 5% as offset increased from 3 cm to 20 cm (Figure 5).

The padding modulus was found to have the greatest potential for generating contradictory trends in injury criteria. The mean values of both C_{max} and VC_{max} gradually decreased as the modulus was increased, but mean TTI increased abruptly as the modulus was changed from 165.5 kPa to 310.3 kPa (Figure 6).

Complex interactions among the door V-t profile, the pad modulus, and the initial offset were found. In addition, these interactions would be interpreted differently depending on the injury criterion analyzed. For example, for the lower-severity door V-t profiles, C_{max} tended to decrease as the pad modulus increased and as the offset increased. This trend was not observed, however, for the most severe door V-t profile analyzed. For the most severe door V-t profile, the intermediate modulus resulted in the highest C_{max} for all values of offset (Figure 7).

Table 1.
Input Parameters and Results

Simulation Number	Offset	Pad	Door V-t Profile	Door Velocity at Shoulder Contact (m/s)	Time of Shoulder Contact (ms)	Offset + Pad Crush, Ψ (mm)	C_{max} (cm)	V_{max} (m/s)	3-ms peak spine accel. (g)	TTI	VC_{max} (m/s) (full thorax)
1	δ_A	σ_A	A	7.5	7.5	115	6.7	8.2	51.6	149	0.83
2	δ_A	σ_A	B	6.4	6.0	130	8.7	12.1	73.1	209	1.82
3	δ_A	σ_A	C	4.3	4.0	137	9.5	11.8	80.3	192	1.84
4	δ_A	σ_B	A	7.5	7.5	84	6.1	9.3	55.4	173	0.73
5	δ_A	σ_B	B	6.4	6.0	96	8.3	12.8	85.2	227	1.93
6	δ_A	σ_B	C	4.3	4.0	110	9.7	16.5	98.2	249	2.89
7	δ_A	σ_C	A	7.5	7.5	74	5.7	9.9	59.0	177	0.68
8	δ_A	σ_C	B	6.4	6.0	85	8.1	11.9	89.8	221	1.57
9	δ_A	σ_C	C	4.3	4.0	97	9.3	16.5	104.8	257	2.91
10	δ_B	σ_A	A	10.0	12.5	154	6.5	7.0	49.9	127	0.70
11	δ_B	σ_A	B	12.8	12.0	170	8.1	11.6	69.4	204	1.56
12	δ_B	σ_A	C	10.7	10.0	179	9.0	12.6	77.8	227	2.02
13	δ_B	σ_B	A	10.0	12.5	123	5.9	7.4	53.4	143	0.50
14	δ_B	σ_B	B	12.8	12.0	129	7.9	13.1	74.3	237	1.32
15	δ_B	σ_B	C	10.7	10.0	135	9.4	16.6	86.6	292	2.08
16	δ_B	σ_C	A	10.0	12.5	116	5.5	6.3	55.0	127	0.48
17	δ_B	σ_C	B	12.8	12.0	118	7.6	14.5	76.9	260	1.51
18	δ_B	σ_C	C	10.7	10.0	124	9.0	15.2	90.8	275	1.88
19	δ_C	σ_A	A	10.0	20.0	233	6.4	6.1	48.9	121	0.60
20	δ_C	σ_A	B	13.0	18.0	247	8.0	9.0	60.9	159	1.16
21	δ_C	σ_A	C	16.0	17.0	258	8.9	11.2	71.6	197	1.74
22	δ_C	σ_B	A	10.0	20.0	204	5.7	5.6	51.6	105	0.53
23	δ_C	σ_B	B	13.0	18.0	210	7.5	9.8	69.9	188	0.90
24	δ_C	σ_B	C	16.0	17.0	216	9.2	11.8	84.4	225	1.35
25	δ_C	σ_C	A	10.0	20.0	196	5.4	6.5	55.8	103	0.51
26	δ_C	σ_C	B	13.0	18.0	201	7.2	8.8	67.8	169	0.83
27	δ_C	σ_C	C	16.0	17.0	203	8.7	13.4	84.3	230	1.12
28	δ_D	σ_A	A	9.5	26.0	282	6.3	6.0	48.1	117	0.57
29	δ_D	σ_A	B	13.0	22.0	296	8.0	8.7	60.1	153	1.11
30	δ_D	σ_A	C	16.0	20.0	307	8.9	11.0	70.9	196	1.70
31	δ_D	σ_B	A	9.5	26.0	253	5.6	5.5	50.8	104	0.51
32	δ_D	σ_B	B	13.0	22.0	259	7.5	8.9	69.3	168	0.83
33	δ_D	σ_B	C	16.0	20.0	266	9.2	11.1	84.8	205	1.34
34	δ_D	σ_C	A	9.5	26.0	246	5.2	6.5	55.1	104	0.49
35	δ_D	σ_C	B	13.0	22.0	250	7.1	8.3	68.2	159	0.81
36	δ_D	σ_C	C	16.0	20.0	254	8.7	11.5	87.0	215	1.17

TTI exhibited a different trend. When the lowest severity door V-t profile was used, TTI increased with increasing pad modulus for small offsets, but decreased for larger offsets. With the intermediate door V-t profile, maximum TTI occurred at offset δ_B (7 cm) and increased with increasing modulus for this offset. For all other offsets, however, maximum TTI occurred with the intermediate value of modulus. The most severe door V-t profile resulted in yet another trend – the peak TTI occurred at the intermediate offset (δ_B) and the intermediate pad modulus (σ_B).

VC_{max} exhibited trends different from both TTI and C_{max}. For door V-t profile A (least severe), VC_{max} was greatest with the lowest modulus and the smallest offset. The intermediate V-t profile yielded similar trends. When the most severe V-t profile was used, however, the highest value of VC_{max} corresponded with the highest modulus.

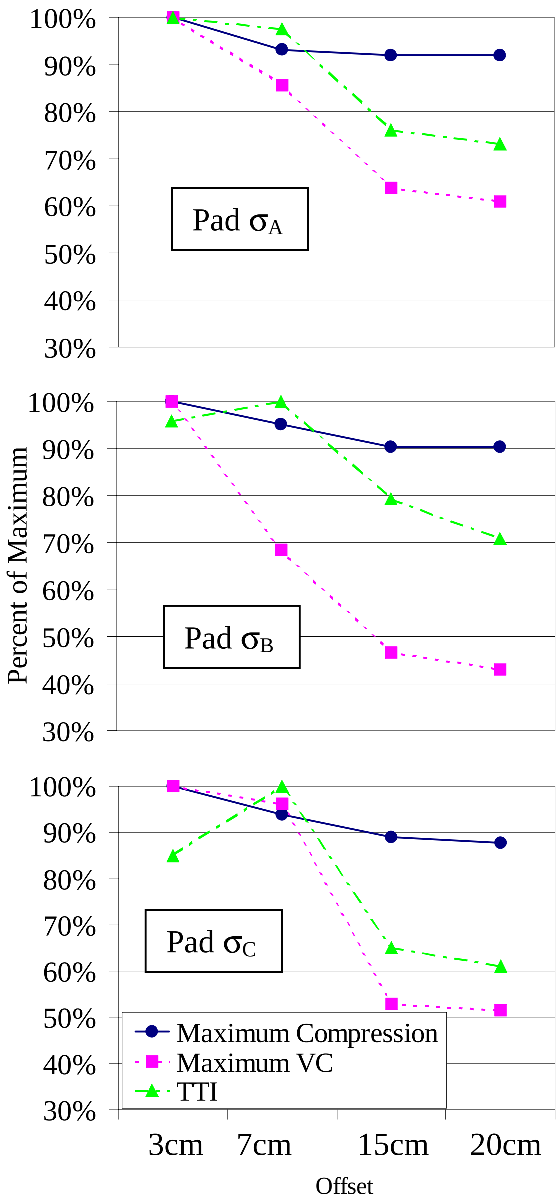


Figure 4. V-t profile B - effect of offset for each pad modulus.

DISCUSSION OF SIMULATION RESULTS

The criteria evaluated in this study exhibit different trends because they reflect the inherent properties of the thorax. On a macroscopic level, the thorax is a deformable, rate-sensitive, nonlinear, inertial structure. As a result, the peak acceleration of the structure's cg and the amount that the structure deflects, for example, will not be affected by a change in loading condition in the same way. The peak spinal acceleration (one component of TTI) is sensitive to the inertia of the torso, the rate at which a force is applied to the thorax (which affects the velocity-sensitive characteristics of the thorax), and the magnitude of the applied force. The acceleration

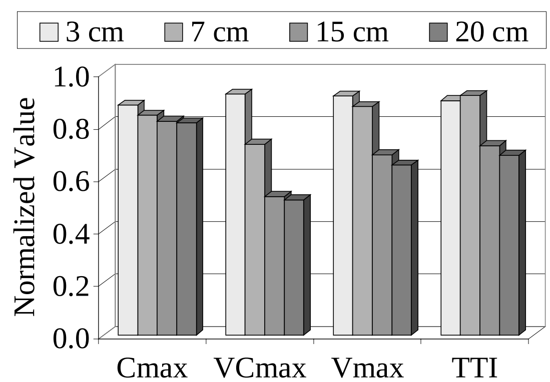


Figure 5. Mean injury criteria trends with changes in offset. Values are normalized as a ratio of the highest value obtained in any simulation.

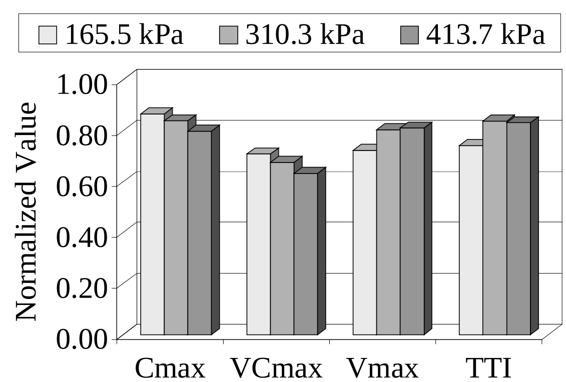


Figure 6. Mean injury criteria trends with changes in pad modulus. Values are normalized as a ratio of the highest value obtained in any simulation.

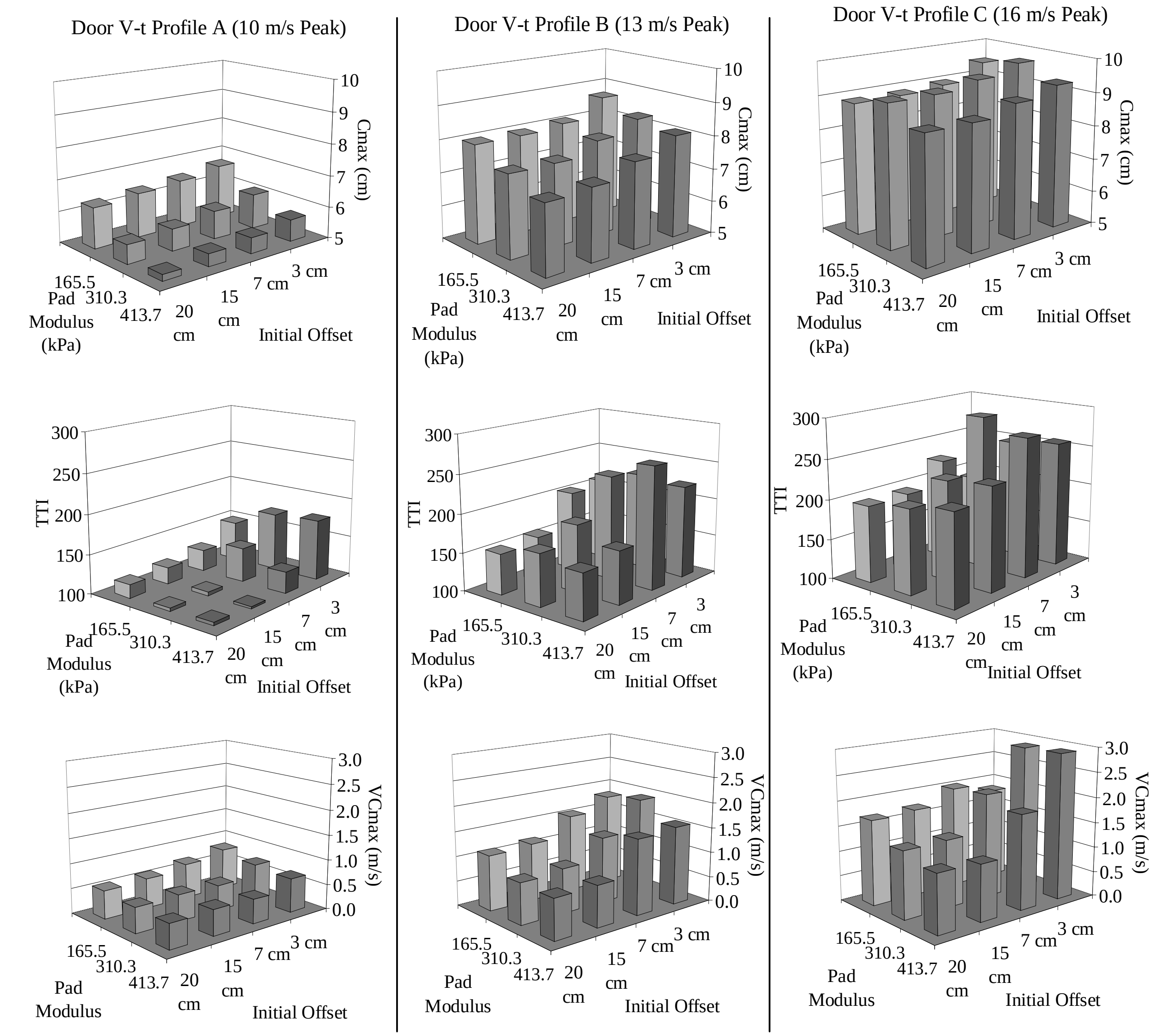


Figure 7. C_{max}, TTI, and VC_{max} as functions of door V-t profile, pad modulus, and initial offset.

of the near-side rib (the other component of TTI), however, is not as sensitive to the characteristics of the torso since the internal elastic and damping do not have time to generate significant force before the near-side rib achieves its maximum acceleration prior to reaching a common velocity with the intruding door. There are interactions among the door modulus, door motion, and the mechanical properties (stiffness, damping, inertia) of the torso, which affect thoracic injury criteria. For the range of conditions evaluated in this study, however, the peak near-side rib acceleration is dominated by the characteristics of the door (padding modulus and V-t profile).

In contrast, the maximum chest deflection and the rate of deflection, and hence VC_{max}, are dependent on the energy stored in the elastic elements of the thorax and on the energy dissipated by the viscous elements of the thorax (see Lau and Viano 1986 and Wang 1989 for a discussion of this dependence). These criteria are therefore sensitive to the duration of the door-to-occupant contact. According to Lau et al. (1991), an increase in contact time, even if it is accompanied by a decrease in peak force on the thorax, can result in an increase in work done on the thorax and therefore an increase in deformation-based injury criteria.

A partial explanation for the observed effects of the pad modulus and the initial occupant-to-door offset can be found by considering TTI as a loading rate and applied force-dependent criterion, while C_{max} and VC_{max} are applied work-dependent criteria. As the pad modulus increases, the magnitude of the applied force increases, as does the rate at which the force is applied (though this effect is offset somewhat by the decreased load distribution associated with a higher pad modulus – the load distribution effect is probably small, however, compared to the effect of the change in modulus). This increase in force and loading rate results in generally higher accelerations and higher values of TTI. In contrast, a higher pad modulus results in a decreased time of occupant-to-door contact and less work done on the thorax. As a result, VC_{max} and C_{max} generally decrease as modulus increases.

When an increase in offset resulted in a large increase in door velocity at occupant contact, TTI predicted that the larger offset was more injurious, while all other criteria always decreased with increasing offset. This may be due to the near-side rib acceleration's sensitivity to the impact velocity and the spinal acceleration's sensitivity to large increases in loading rate.

The results of this study indicate the importance of a biomechanically robust thoracic injury criterion and reveal that the choice of criterion can result in diametrically opposed interpretation of occupant protection countermeasures. Each injury criterion evaluated in this study was, however, developed using a different test methodology and the criteria were not necessarily developed to predict the same type of injury. For example, TTI was developed using human cadavers, which generally sustain only hard tissue (i.e., bony) thoracic injuries, while the viscous criterion was developed using animal models that sustained soft tissue (i.e., organ) injuries. As a result, it may be reasonable to expect that these criteria would exhibit contradictory trends if the mechanisms of the specific injuries they are intended to predict exhibit contradictory trends. The use of a selected criterion in a compliance test, however, contains an inherent assumption that the criterion is a good predictor of overall injury potential in a given impact – regardless of the specific injury type. Because European and U.S. compliance tests specify different criteria, it is desirable to know which of these criteria is a better predictor of injury. One approach to this problem is to identify sets of input conditions (including door V-t profile, pad modulus, and initial offset) that result in contradictory trends in these criteria, perform human cadaver tests, animal tests, or both, to identify the injury-causing potential of these sets of inputs, and identify which criterion is a better predictor of the actual injury outcome. It may be necessary to mandate minimum values of more than one criterion if the criteria are found to correlate with different injury types (e.g., soft tissue and hard tissue) so that the potential for both types of injury is reduced.

The findings of this study are also useful for determining the relative benefits of additional padding (such as that provided by a side thorax airbag) compared to additional space between the door and the occupant (analogous to an increase in offset, which allows a later contact between the door and occupant). Table 1 contains the sum of the initial offset and the amount of pad crush generated in each simulation. This sum, Ψ, represents, in a simplified sense, the distance available between the occupant and the outer surface of the door (if the occupant deforms the entire door width) and is thus a characteristic of a vehicle. For example, a large vehicle may have a Ψ value over 300 mm (large occupant-to-door offset and large door thickness), while a small vehicle may have less than 150 mm (occupant relatively close to door and less door thickness). With this fixed amount of space available between the occupant and the outer door surface, is it more beneficial to fill this space with padding or leave it empty so that the occupant contacts the door later in the door V-t profile? By comparing the injury criteria trends for comparable values of Ψ for each door V-t profile, it is possible to evaluate the case of thick, lower modulus padding (i.e. "airbag-like") against the case of less, higher modulus padding with an accompanying larger initial offset (i.e. "non-airbag-like"). For V-t profile A, simulation 1 (airbag-like) and simulation 16 (non-airbag-like) result in similar values of Ψ (115 mm and 116 mm). All injury criteria are higher for simulation 1 than for simulation 16, indicating that the increased offset provides more benefit than would be gained by filling that space with a soft pad. For V-t profile B, simulation 2 (airbag-like) and simulation 14 (non-airbag-like) have similar values of Ψ (130 mm and 129 mm), as do simulation 20 (airbag-like) and simulation 35 (non-airbag-like) (247 mm and 250 mm). In both instances, the airbag-like simulation resulted in higher values of C_{max} and VC_{max}. On the other hand, TTI was either higher in the non-airbag-like simulation (simulation 14 > simulation 2), or equal (simulation 20 = simulation 35). Finally, for door V-t profile C, simulation 3 (airbag-like) and simulation 15 (non-airbag-like) had similar values of Ψ (137 mm and 135 mm), as did simulation 21 (airbag-like) and simulation 36 (non-airbag-like) (258 mm and 254 mm). Consistent with the findings for V-t profile B, simulation 3 resulted in higher values of C_{max} and VC_{max} than simulation 15, while TTI was higher in simulation 15. Comparison of simulation 21 against simulation 36, however, reveals a different trend. C_{max} was slightly higher in simulation 21 than in simulation 36, while VC_{max} and TTI were both substantially higher in simulation 36 (Table 2).

These findings should be interpreted with caution due to the simulation's highly simplified representation of the vehicle environment. Nevertheless, the findings reveal that the potential for conflicting conclusions about the efficacy of side thorax airbags exists, and illustrate the need for a better understanding of how thoracic injury criteria correspond to the actual injury outcome.

Table 2.
Comparison of Injury Measures in Airbag-Like and Non-Airbag-Like Simulations

V-t profile	Ψ (mm) (nom.)	C_{max} higher	VC_{max} higher	TTI higher
A	115	Airbag-like	Airbag-like	Airbag-like
B	130	Airbag-like	Airbag-like	**Non-Airbag-like**
C	137	Airbag-like	Airbag-like	**Non-Airbag-like**
B	250	Airbag-like	Airbag-like	**Equal**
C	254	Airbag-like	**Non-Airbag-like**	**Non-Airbag-like**

DESCRIPTION OF SIDE IMPACT SLED SYSTEM

It is apparent from these simulations that a sled system designed for the evaluation of side impact occupant protection systems or the analysis of occupant response to side-impact loading must, at least, produce a realistic door velocity-time profile from the time of door contact with the occupant to the time of occupant disengagement (approximately 15 ms to 50 ms in Figure 1). If, in addition, the system is intended to study side airbag interaction with an occupant, then the system must also reproduce the motion of the airbag mounting site (door, seat, roof rail, b-pillar, or other location) and any components against which the airbag reacts. Further, this motion must be reproduced from 0 ms through occupant-door separation in order to maintain the proper geometric spacing of the relevant components. Such a system, described below, has been developed at the University of Virginia (UVA). The UVA side impact system (SIS) (Via Systems, Salinas, California, USA), which has been designed to mount on an existing frontal impact deceleration sled and track, allows for independent control of the seat and door velocity-time profiles. SIS comprises three sleds (Figure 8): a door sled, to which a door, roof rail, or other vehicle components can be mounted; a seat sled; and a variable-mass bullet sled, which serves as the power source for the system. This system is capable of controlling the door motion through the three critical stages of the door V-t profile:

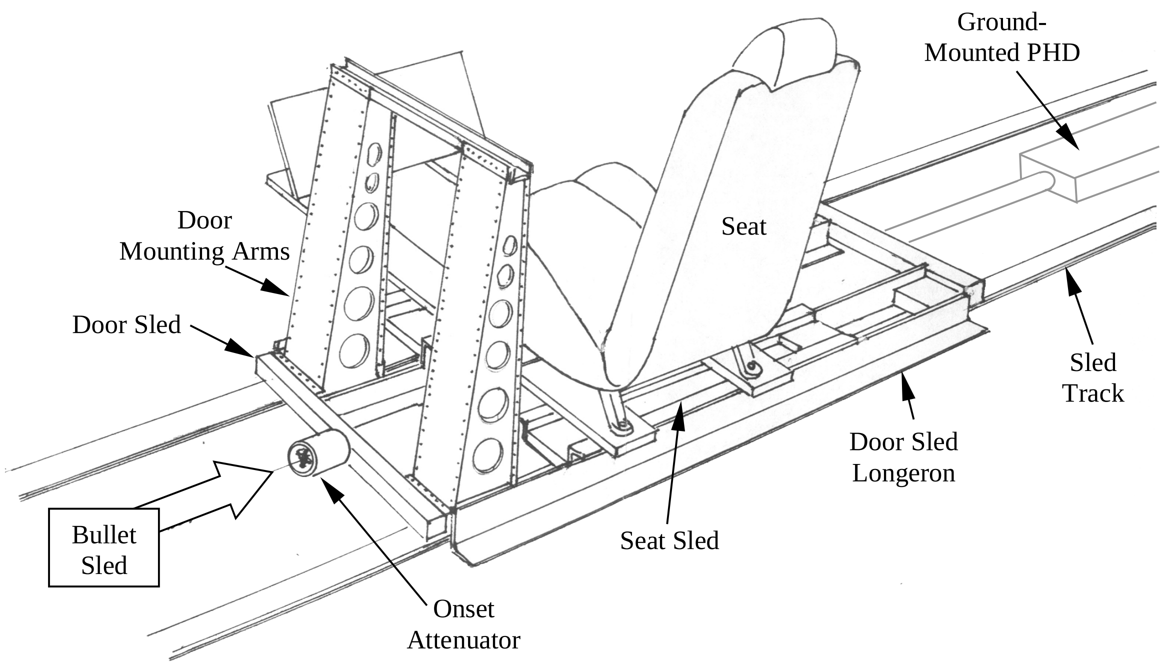


Figure 8. Schematic depiction of UVA Side Impact System.

1. The initial onset in door velocity (e.g., approximately 0 ms to 18 ms on the upper plot in Figure 1).
2. A constant door velocity regime (e.g., approximately 18 ms to 22 ms on the lower plot in Figure 1).
3. The door deceleration until occupant disengagement (e.g., approximately 22 ms to 50 ms on the lower plot in Figure 1).

The shape of the door V-t profile during stage 1 is dictated by the onset attenuator, which consists of an inelastic crushable element contained within a steel cylinder. A probe mounted to the leading edge of the bullet sled mates with the cylinder. The shape and duration of the onset door velocity profile are controlled by the shape of the probe and the geometry of the crushable element's cross-section. The magnitude of the door sled velocity at the end of stage 1 is dictated by the bullet sled velocity at impact and the relative masses of the bullet sled and door sled. The peak door velocity is readily predicted using conservation of momentum since the onset attenuator is designed to store no energy and thus ensure a plastic collision between the bullet sled and the door sled.

The duration of stage 2 is dictated by the initial standoff between the door sled and the ground-mounted programmable hydraulic decelerator (PHD) (Via Systems, Salinas, California, USA). A low-friction interface is maintained pneumatically between the bullet sled and the sled track. Thus, after the initial collision between the bullet sled and the door sled, these sleds translate at a nearly constant velocity until the door sled contacts the piston of the PHD.

The shape of the door V-t profile during stage 3 is controlled by the orifice array used in the PHD. The bullet sled mass can be set to the same mass as the U.S. or the European side impact barrier (1,360 kg or 950 kg, respectively) or other impacting vehicle, so occupant inertial effects on the door V-t profile are equivalent in the sled test and in the target full-scale impact. Thus, the PHD is used to shape the door V-t profile that would exist in the absence of an occupant. The authors presented finite element simulations of a vehicle-to-vehicle side impact in which we tracked the inner and outer door V-t profiles with and without an occupant (Kent and Crandall 2000). We found that the inner door V-t profile is sensitive to the presence of an occupant, while the outer door V-t profile is not, and concluded that the inner door V-t profile measured in a sled test will be approximately equal to that measured in a target full-scale impact if (1) the inner door V-t profile that would occur if the full-scale test was performed without an occupant is imparted to the sled-mounted door, (2) the bullet sled/occupant mass ratio is approximately equal to the full-scale striking vehicle/occupant mass ratio, and (3) the door used in the sled test has the appropriate inner panel stiffness and geometry. A simulation of the UVA SIS indicates that it is capable of reproducing the no-occupant inner door V-t profile (Figure 9).

The seat sled is mounted on tracks allowing it to move independently of the door sled. Initial door-to-occupant offset is adjusted by moving the initial position of the seat sled relative to the door sled. The seat motion is controlled throughout the test by a velocity-independent brake that generates a prescribed constant force between the door sled and the seat sled.

After stage 3, the PHD brings the entire system to rest at less than 5g, precluding damage to test dummies or artifactual injury to cadaver subjects.

Preliminary tests with the system indicate that door V-t profiles can be reproduced reasonably well and that the system is repeatable and controllable. Figure 10 shows the door sled velocity measured during three development tests performed with no occupant compared to the measured mid-rear door V-t profile obtained in SINCAP test 2994. The effect of the occupant is pronounced in the SINCAP test, but the range of V-t profiles obtained with SIS appear to bound the V-t profile that would have occurred had the SINCAP test been performed without an occupant. While additional tests are necessary, including those with occupants, these preliminary tests indicate that the system is flexible enough to reproduce a range of realistic door V-t profiles. The system appears to be adequate, therefore, for the purpose of evaluating the effects of door V-t profile characteristics, occupant-to-door offset, and padding properties on the comparative efficacy of thoracic injury criteria.

CONCLUSIONS

Pad modulus, initial door-to-occupant offset, and the characteristics of the door V-t profile all influence thoracic injury outcome in a side impact, but the interpretation of injury outcome depends on the specific criterion chosen to represent injury potential. Global harmonization of side impact safety standards therefore requires a better understanding of the efficacy of thoracic injury criteria.

Regardless of the criterion used to assess thoracic injury, higher peak door velocity corresponds with more severe injury. Injury outcome is not, however, sensitive to the door velocity at the time of occupant contact. A larger initial offset

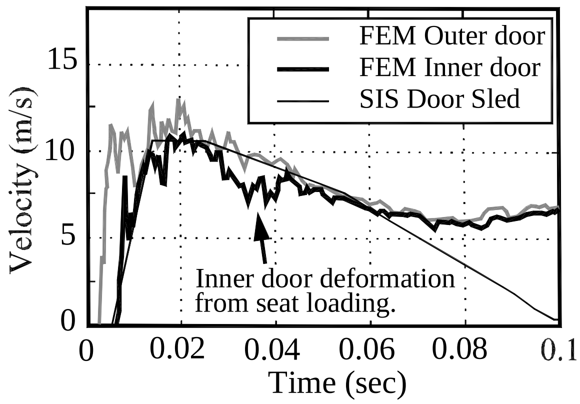


Figure 9. Finite element vehicle door impact response (no occupant) compared to SIS door sled velocity (see Kent and Crandall 2000).

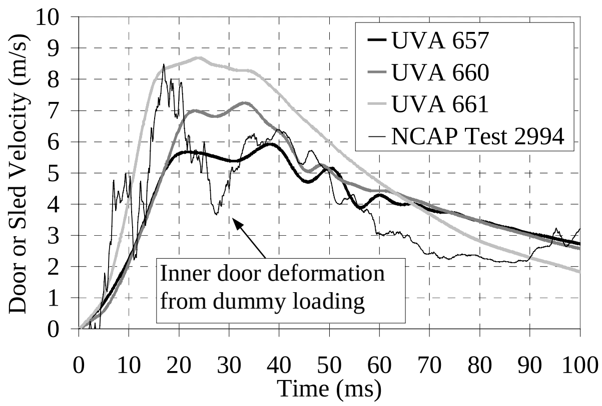


Figure 10. Preliminary SIS test data compared to SINCAP data.

generally is found to result in lower injury, even when the larger offset results in a higher door velocity at occupant contact, because the contact time is closer to the point at which the door sled velocity begins to decrease. The padding modulus is found to exhibit the greatest potential for generating contradictory injury criteria trends. Both maximum chest deflection and maximum viscous criterion, which are sensitive to the duration of occupant loading, gradually decrease as the padding modulus increases. On the other hand, TTI, which is more sensitive to the magnitude and rate of the applied force, increases as the pad modulus increases.

The results of this study provide a computationally based justification for a series of human cadaver tests to be performed for the evaluation of thoracic injury criteria. In the case of contradictory trends in the different injury criteria, the injuries sustained by a cadaver (or an animal model) provide a means of evaluating the relative efficacy of the criteria. A three-sled side impact system is presented which is capable of reproducing realistic ranges of door V-t profile, padding modulus, padding thickness, and initial door-to-occupant offset.

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