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DEVELOPMENT OF PERFORMANCE REQUIREMENTS FOR A RAIL PASSENGER WORKSTATION TABLE SAFETY STANDARD

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ABSTRACT

The American Public Transportation Association's (APTA) Construction and Structural committee, a railroad industry group, with the support of the Federal Railroad Administration (FRA) and the John A. Volpe National Transportation Systems Center (Volpe Center), is creating an industry safety standard for an energy absorbing table. Workstation tables in passenger trains are an increasingly popular seating configuration both in the United States and abroad. Although a well-attached table can provide convenience and compartmentalization for the occupant, there is a risk of abdominal injury during a rail accident.

In Fact, there have been several accidents in the United States in which impacts with workstation tables have severely or fatally injured occupants. In 2006, in response to these injuries, an FRA sponsored program developed a prototype table that distributed load over a wider area of the abdomen and absorbed energy during a collision. This table design was tested with specialized anthropomorphic test devices (ATDs) instrumented to measure abdominal impact response and was shown to decrease injury risk compared to a baseline table design.

Building on the knowledge gained in the development of the prototype table, the proposed standard requires force to the abdomen be limited while energy is absorbed by the table. Since manufacturers do not have access specialized ATDs, , researchers proposed a two part testing requirement. The first part is a quasi-static test which measures the energy absorption capacity of the table with a maximum force level determined from testing with specialized abdominal ATDs. The second part is a sled test with a standard Hybrid III 50th percentile (HIII) ATD to assess compliance with occupant protection standards of compartmentalization and ATD injury assessment reference values (IARVs).

This paper discusses the research performed to develop the performance requirement in the draft standard. Current injury measures, originally developed for the automotive industry, were examined to assess their applicability to workstation table impacts. Multiple Mathematical Dynamic Models (MADYMO) model simulations show the estimated injuries during a simulated sled test scenario. Several force-crush parameters were examined, including the initial stiffness of the force-crush curve, the plateau force and the target energy absorbed by the table, to determined the force-crush design characteristics of a table that are likely to reduce injury risk.

The results of this study, combined with testing of the current prototype table described in a companion paper [1], led to a draft standard that will greatly improve the safety of workstation tables in passenger rail cars.

INTRODUCTION

There have been several accidents in which a passenger sitting at a workstation table suffered severe or fatal abdominal injury after impact. These occurrences led to a research program that produced a prototype table that is better able to protect passengers seated at a table in a collision [2].

FRA tested the prototype table in a full scale train-to-train test with two ATDs with specialized abdominal regions, the Test Device for Human Occupant Restraint (THOR) ATD and the Hybrid III Railway Safety ATD [3]. The tests demonstrated that an energy absorbing workstation table provides improved safety to the passenger in an incident.

After developing and testing the prototype, discussions began with industry members for developing an APTA industry standard for an improved table. Concurrently, the government, university researchers, and private industry groups were developing different methods of testing a workstation table [1]. Existing APTA standards for seats and interior fittings specify impact sled tests using an HIII ATD in order to measure the injury risk during an 8g, 250 ms triangular acceleration pulse. The HIII abdomen is neither biofidelic, owing to the stiff coupled ribcage, nor capable of measuring the severity of impact to the torso at the level of the workstation table. The THOR ATD, on the other hand, is capable of measuring upper abdominal compression and has demonstrated biofidelity in upper abdominal rigid bar impacts. [4]. However, since the THOR ATD is still in development and most widely available to seat and table manufacturers, a two-part standard was devised.

For the first part of the standard, new tables shall be sled tested with a triangular, 8g 250 ms acceleration pulse using HIII ATDs in order to evaluate compartmentalization and to evaluate dummy response relative to existing IARVs for head, neck, chest and lower extremity. However, an additional evaluation is necessary to determine the risk of upper abdominal injury, since the HIII is not capable of measuring the upper abdominal response. Thus, for the second part of the workstation table standard, measurement of the force-crush characteristic of the table edge through quasi-static testing has been proposed. Knowing the force-crush characteristic allows evaluation of upper abdominal injury risk using both comparison to previous testing with advanced ATDs and computational analysis.

The objective of this study is to develop evaluation criteria that define the minimum energy absorption of and the maximum peak force of the force-crush characteristic. The energy absorbed by the table edge during impact must be sufficient to bring the occupant to rest before exhausting the crush element, which would be present a dangerously stiff impact surface. Similarly, the maximum force of the force-crush characteristic must be low enough to prevent injurious compressions and compression velocities to the viscous upper abdomen of the occupant.

These criteria will be developed through a combination of previously-conducted full-scale testing of a prototype design using advances ATDs capable of measuring upper abdominal response, and through a sensitivity analysis carried out using computational techniques. A multi-body model including the THOR ATD was developed in MADYMO and refined based on full-scale test results [3]. This model can be used to predict the upper abdominal injury risk to occupants in a simulated sled test environment using varying table edge force-crush characteristics. This study uses this computational model to evaluate force-crush characteristics of varying peak force and energy absorption to determine the requirements necessary to provide an equivalent level of safety to the existing APTA requirements.

This paper discusses the development of performance requirements for a quasi-static table test that relates peak force and energy absorption to abdominal tolerance. Injury measure, beyond those found in a standard HIII ATD, are researched to provide appropriate injury levels in the abdominal region. A sensitivity analysis carried out using MADYMO 6.4.1 [5] investigates the parameters that affect the occupant response upon impact with a workstation table. The analysis was used to correlate the abdominal IARVs under dynamic test conditions with peak force and energy absorption under quasi-static test conditions.

LITERATURE REVIEW

A review of the literature was conducted to determine appropriate injury assessment reference values (IARVs) for blunt thoracic and abdominal impact [6]. Unfortunately, there have been no experiments performed using human volunteers or post-mortem human surrogates (PMHS) that appropriately characterize the impact of the edge of a workstation table with the upper abdomen. A majority of the experiments presented in the literature address either seat belt loading to the front of the thorax and abdomen or generic surface loading on the side of the thorax and abdomen [7,8]. Furthermore, PMHS are poor models [9] of the types of injuries (lacerations and contusions of the organs in the thoracoabdominal cavity) that have been associated with workstation tables [10]. Because of the lack of appropriate and agreed-upon IARVs for the upper abdomen, this study will use conservative IARVs based on existing metrics to evaluate table performance. Note that for the purpose of this study, the mean bilateral chest deflection measures at the 8^{th} anterior rib of the THOR ATD is used to define upper abdominal compression.

Injury Assessment Reference Values

Injury risk functions have been developed to relate measurements of occupant response using a test dummy to the risk of injury based on the Abbreviated Injury Scale (AIS) [11]. An AIS score classifies the survivability of injuries on a scale from 1 (minor) to 6 (un-survivable) [9]. Researchers have found relationships between dummy-based measurements and injury risk, which are used to define tolerance levels. In the automotive industry, these tolerance levels are referred to as injury assessment reference values (IARVs).

The Code of Federal Regulations, Title 49, Part 571, Section 208 (also referred to as the Federal Motor Vehicle Safety Standards 208, or FMVSS 208), tolerance levels are specified based on a given percentage risk of certain AIS score, though the percentage risk or AIS values are not consistent across different injury measurements. For instance, FMVSS 208 specifies a maximum sternal deflection of 76 millimeters, which corresponds to a 50 percent risk of an AIS score of 3 or greater [12]. The head injury criterion tolerance level of 700 corresponds to a 31 percent risk of an AIS 2 or greater injury, the neck injury criterion tolerance level of 1.0 corresponds to a 22 percent risk for an AIS 3 or greater injury, and the femur axial load criterion tolerance level of 10 kilonewtons represents a 35 percent risk of an AIS 2 or greater injury [13]. These values are consistent with the standards for row-to-row seating specified by APTA [14]. These values are measured using the HIII, in the sled test portion of the standard.

For the purpose of this analysis, each abdominal region IARV will be chosen to correspond to a 25 percent risk of an AIS 3+ injury unless otherwise noted. For injury metrics in which only an AIS 4+ risk is available, the IARV is chosen at the 5 percent risk level. Injury risk functions vary depending on the power of the statistical analysis and difference in the classified injury types. A 25 percent risk of an AIS 3+ injury is more or less equivalent to a 5 percent risk of an AIS 4+ injury. For example, a chest deflection value of 55 millimeters corresponds to a 25 percent risk of an AIS 3+ injury, while the same value corresponds to a 7.7 percent risk of an AIS 4+ injury.

Chest

Injury risk functions have been developed for chest deflection (Figure 1a), spinal acceleration (Figure 1b), and the Combined Thoracic Index (CTI) [13]. Since the CTI was developed specifically to predict injury in cases of combined seat belt and air bag restraints, it is not included in this analysis. The risk function for chest deflection relevant to an AIS 3+ injury risk (1), where D_{max} is the maximum sternal deflection.

$$p(AIS \geq 3) = \frac{1}{1 + e^{(3.7124 - 0.0475 D_{\max})}} \quad (1)$$

The risk function for chest acceleration relevant to an AIS 3+ injury risk (2), where A_c is the peak 3ms acceleration of the thoracic spine.

$$p(AIS \geq 3) = \frac{1}{1 + e^{(3.1493 - 0.0630 Ac)}} \quad (2)$$

Solving for a value of 25 percent, the IARV for chest deflection is 55 millimeters and the IARV for spinal acceleration (i.e. Chest 3ms acceleration) is 32.5 g. Injury risk functions for the viscous criterion have only been developed at an AIS 4+ level, where a viscous criterion of 1.0 meters per second corresponds to a 25 percent risk of an AIS 4+ injury. Based on the regression presented by Viano (1988) [15] (), a 5 percent risk of an AIS 4+ injury would occur at a viscous criterion value of 0.8 meters per second.

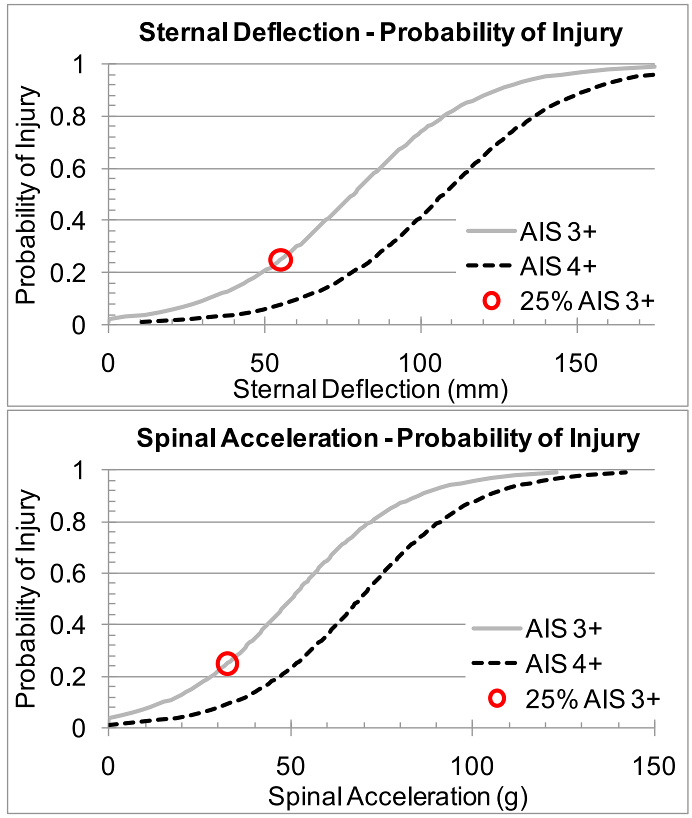


FIGURE 1. INJURY RISK FUNCTIONS TO RELATE TEST DUMMY MEASUREMENTS TO INJURY RISK FOR VARIOUS AIS SCORES (FROM EPPINGER, 1999 [13])

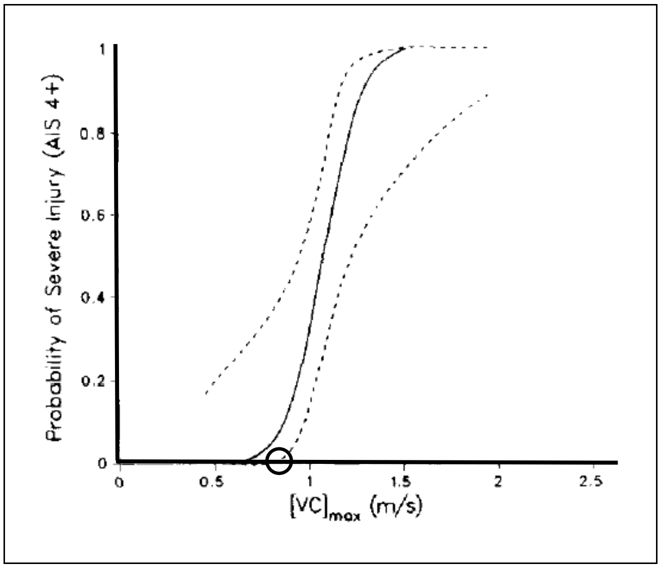


FIGURE 2. INJURY RISK FUNCTION TO RELATE VISCOUS CRITERION TO AIS 4+ INJURY RISK (FROM VIANNO, 1998 [15])

Abdomen

To the knowledge of the authors, relationships of frontal upper abdominal deflection and rate of deflection to injury have not been developed or published. This section proposes frontal upper abdominal compression and viscous criterion limits based on established lower abdominal and chest injury risk functions, supplemented by the previously-developed relationship between external and skeletal deflection and an inferred relationship between frontal- and side-impact tolerances."

A risk function has been developed to relate lower abdominal compression with a probability of an AIS 4+ injury (Figure 3), where a compression value of 50 percent of the un-deformed abdominal depth corresponds with a 25 percent risk of an AIS 4+. Based on the injury risk function presented by Rouhana (1989) [16], a 5 percent risk of an AIS 4+ injury would occur at an external deflection of the upper abdomen of roughly 38 percent, which corresponds to a deflection of 87 millimeters. Since upper abdominal injury risk functions are not currently available, this abdominal risk curve is used henceforth to evaluate upper abdomen injury risk. Correcting to represent skeletal deflection (as opposed to external deflection) measured by the test dummy by dividing by 1.3 (as in Viano, 1988 [15]) as opposed to external deflection, a 5 percent risk of an AIS 4+ injury would occur at a skeletal deflection of 67 millimeters.

The viscous criterion is not well defined for the abdomen in front impact. For side impact, risk functions have been developed for both the thorax and the abdomen, where the 25 percent risk of an AIS 4+ injury occurs at viscous criterion values of 1.47 meters per second and 1.98 meters per second, respectively [17]. Assuming that the relationship between these IARVs holds true for front impact, a 5 percent risk of an AIS 4+ injury would occur at an abdominal viscous criterion value of 1.08 meters per second.

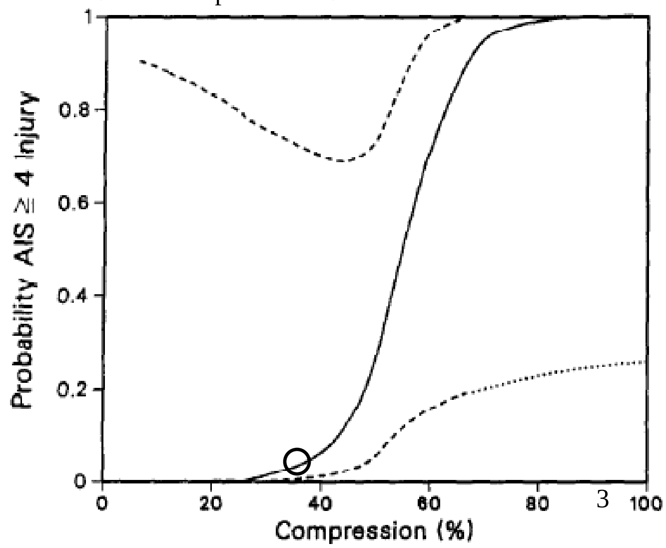


FIGURE 3. RISK OF AN AIS 4+ ABDOMINAL INJURY BASED ON EXTERNAL DEFLECTION (FROM ROUHANA, 1989 [16]).

The abdominal injury values that are used as upper limits in this study are summarized in Table 1.

TABLE 1. SUMMARY TABLE FOR ALLOWABLE ABDOMINAL INJURY VALUES

IARV	Value	AIS risk function used	Probability of injury
Peak Upper Abdomen V(t)C(t)	1.08 m/s	4+	5%
Peak Chest V(t)C(t)	0.8 m/s	4+	5%
Upper Abdomen Compression	67 mm	4+	5%
Chest Compression	55 mm	3+	25%
Chest 3ms Acceleration	32.5 g	3+	25%

MODEL DESCRIPTION

The model tested in this analysis was developed and refined based on the results of a full-scale test of a proof-of-concept design that was carried out on the train-to-train test of Crash Energy Management (CEM) equipment [3]. This model includes a pair of facing seats, which correspond to the geometry of the METROLINK multi-level facing seats, with an intervening workstation table. The top of the table has a height of 32 in from the floor and a thickness of 3.5 in. The table edge is modeled as a lumped mass, of 10 kilograms to represent a worst-case contribution of inertial force to the occupant response. Additionally, the tabletop is connected to a center support structure by a non-linear spring. The non-linear spring has a damping coefficient of 10 Ns/m, which assumes that a relatively rate-insensitive material such as aluminum honeycomb is used in the crush element. A THOR dummy is initially positioned in the window seat facing the table (Figure 4). An 8g, 250 millisecond acceleration pulse is applied to the environment.

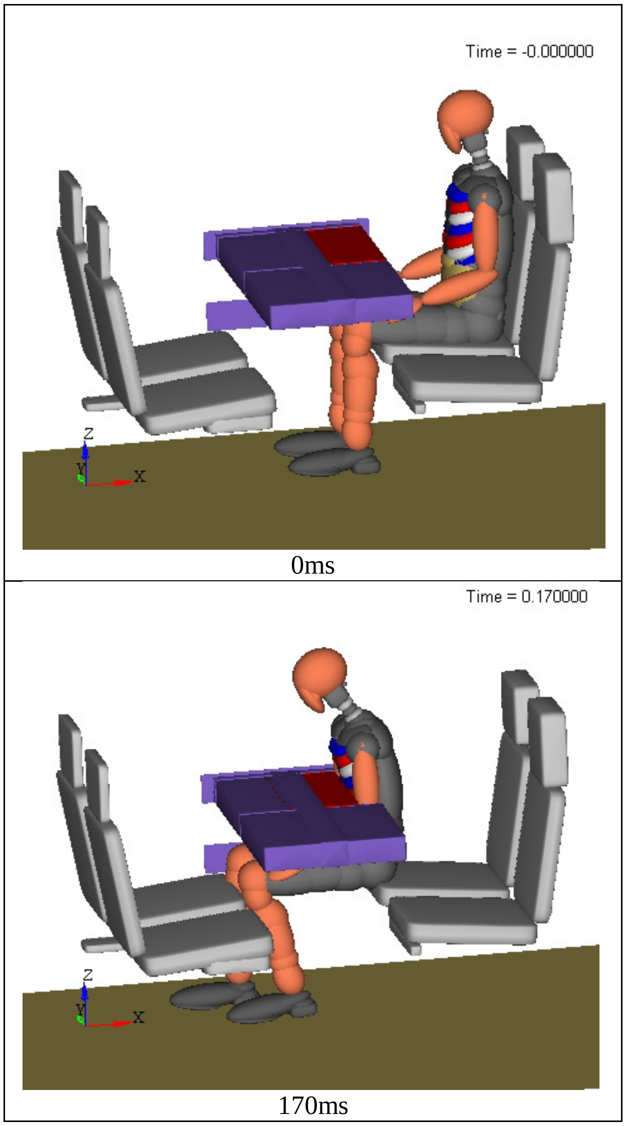


FIGURE 4. MADYMO MODEL OF THE IMPACT OF A THOR TEST DUMMY WITH A WORKSTATION TABLE

The key input into the table model is the force-displacement characteristic. The graph in Figure 5 shows a force-displacement characteristic taken from a quasi-static test of the prototype table. This table has a cantilevered design, so the aisle measurement has an additional inch of displacement due to the rotation of the table. This characteristic shows an initial stiffness for 0.2 in. After the initial stiffness, the crushable honeycomb is crushed at a force level of 1200 lb at an increasing rate. Once the force reaches approximately 2200 lb, the crush element has been exhausted and the force increases rapidly.

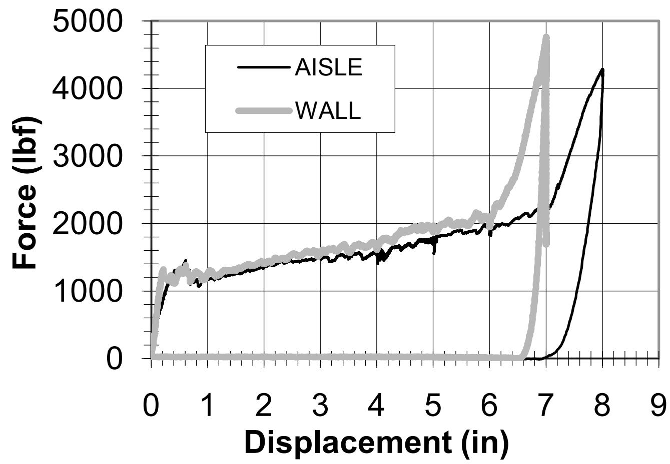


FIGURE 5. FORCE-DISPLACEMENT CHARACTERISTIC OF A PROTOTYPE TABLE MEASURED IN A QUASI-STATIC TEST

Although this analysis employed a force plateau to represent the table edge crush element, it is understood that real-world designs will not be as idealized. For such designs, the target energy absorption value is determined through quasi-static testing by loading up to the point where the maximum force level is reached, then unloading. The target energy absorption value is calculated by integrating the measured force-crush characteristic with respect to crush over the entire time history to remove any stored elastic energy from the system.

METHODOLOGY

In order to assess the sensitivity of the occupant response to changes in the design of the table, a sensitivity analysis was carried out. For this analysis, the table is assumed to follow an idealized force-crush characteristic (Figure 6). In this analysis the force-crush characteristic of the table was varied in plateau force (6 values), and target energy absorbed (5 values), as described in Table 2. Also examined was the initial stiffness of the curve, between no force and the plateau force (5 values). This measure was not found to have any effect and results are not presented here. One hundred and fifty (150) parameter combinations comprise the full-factorial design array.

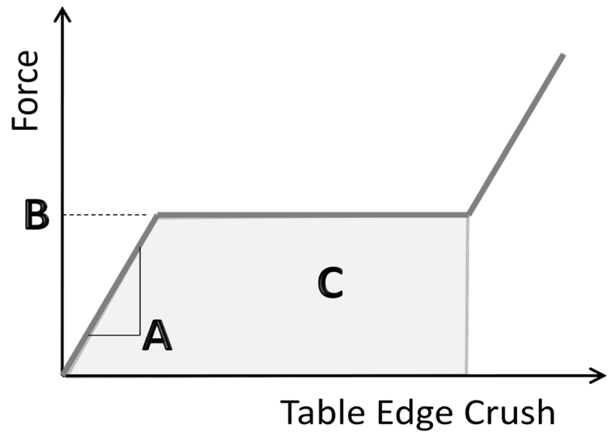


FIGURE 6. IDEALIZED FORCE-CRUSH CHARACTERISTIC

TABLE 2. DESCRIPTION OF THE INPUT PARAMETERS TO THE SENSITIVITY STUDY

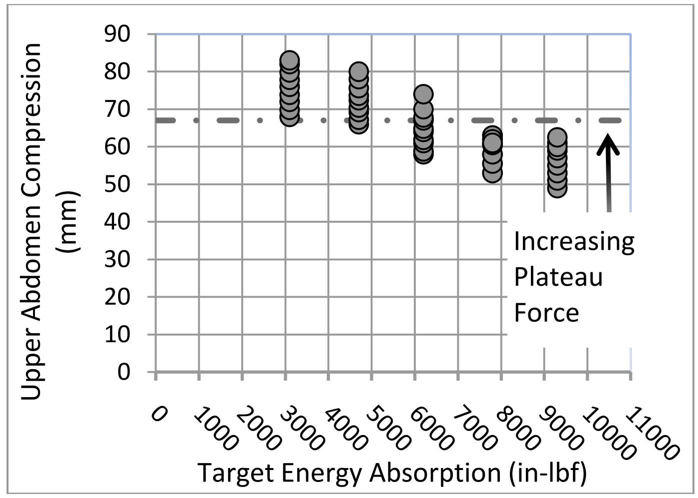
(A) Plateau Force	(B) Target Energy
1000 lbf	3100 in-lbf
1250 lbf	4650 in-lbf
1500 lbf	6200 in-lbf
1750 lbf	7750 in-lbf
2000 lbf	9300 in-lbf
2250 lbf	

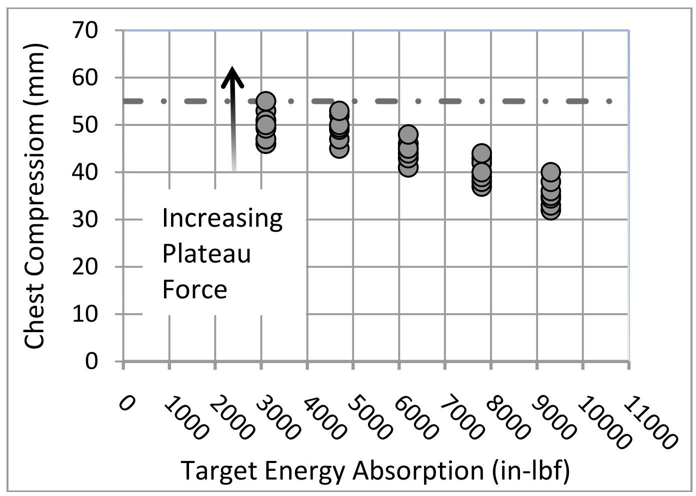
RESULTS

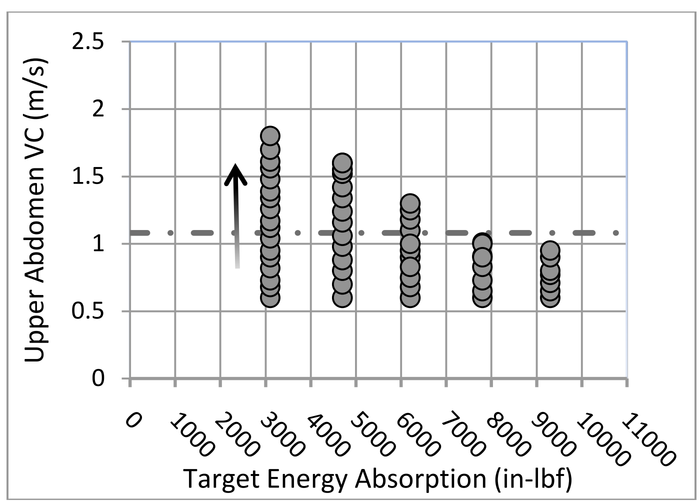
Overall, the results show that the occupant response is sensitive to both of the input parameters. Throughout the results section, the plots shown follow the same legend. Each marker represents one simulation. Where applicable, a dash-dot line indicates the IARV for the given injury criterion.

Target Energy Absorption

Of the three input parameters, the occupant response is the most sensitive to target energy absorption. There are decreasing trends of all five injury measurements with increasing energy absorption. In all but one case, both the minimum and maximum values of the injury metrics for each group of designs decrease at similar rates. For each graph in Figure 7, the injury measure is on the Y-axis and the target Energy Absorption is on the X-axis. For each target energy absorption level, several cases were run with different initial stiffness values and different plateau forces. The arrow on the graphs indicates that the cases with higher plateau forces have the higher injury values within each target energy absorption value. The dashed line on each graph indicates the allowable injury value.







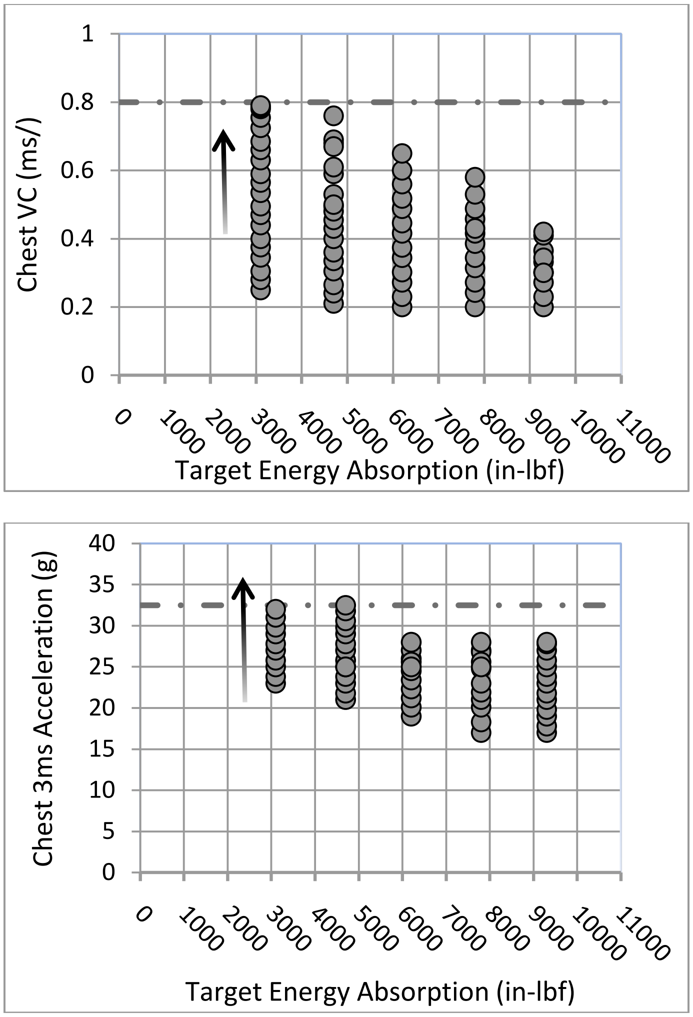
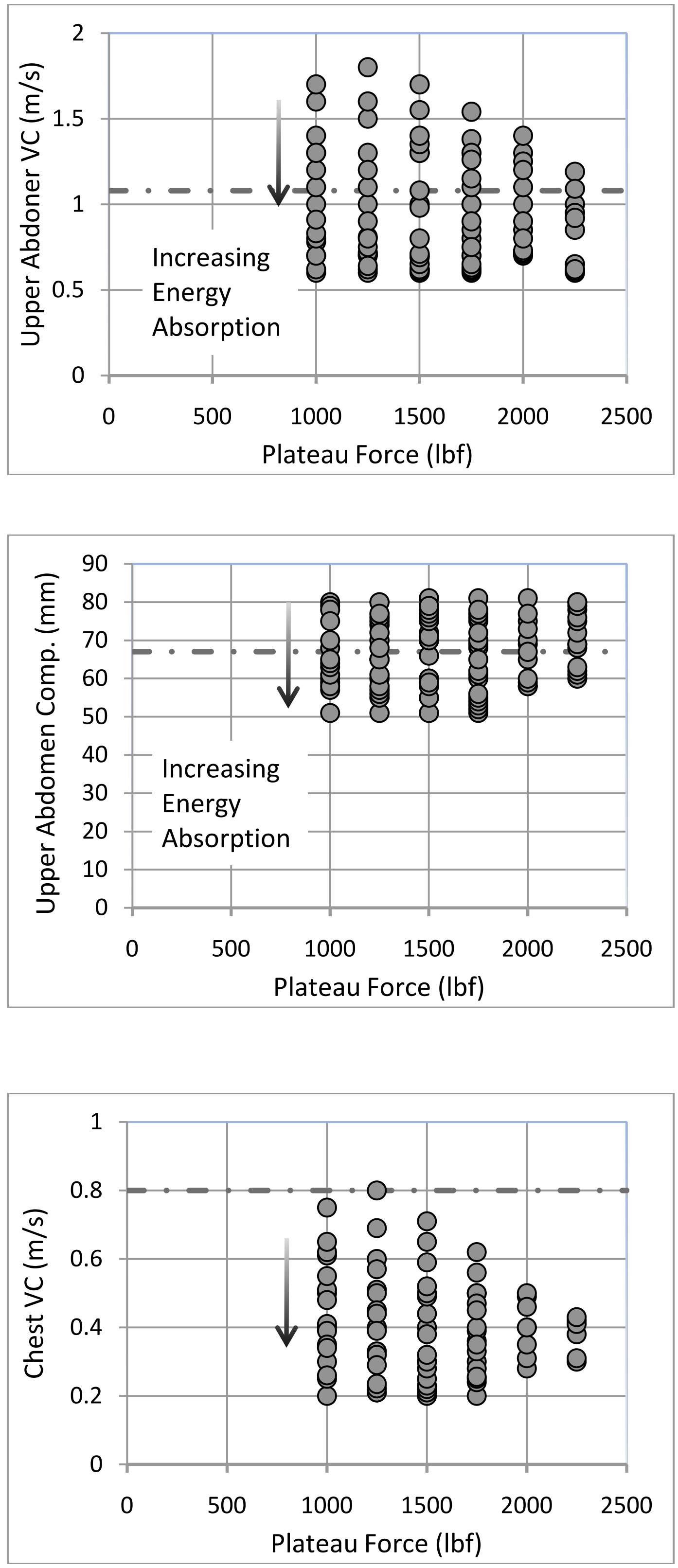


FIGURE 7. SUMMARY OF THE INJURY METRICS WITH RESPECT TO THE TARGET ENERGY ABSORPTION OF THE FORCE-CRUSH CHARACTERISTIC

Plateau Force

The plateau force was varied between 1000 lb and 2250 lb. For these force ranges, the occupant response is generally insensitive to the plateau force of the input force-crush characteristic. While the minima remain relatively constant, the maxima decrease with increasing plateau force. Again, the designs that absorb the least amount of energy show the highest viscous criterion values. The graphs in Figure 8 show the injury values seen for different values of the plateau force. For the graphs of upper abdomen viscous criterion and upper abdomen compression, it appears that no force level will meet the acceptable values. However, when tables with low target energy absorption values are removed from the chart, the criteria are within acceptable limits.



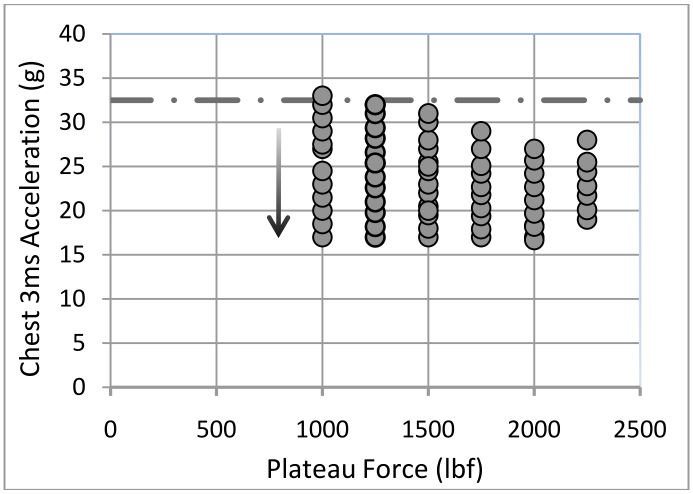


FIGURE 8. SUMMARY OF THE INJURY METRICS WITH RESPECT TO THE PLATEAU FORCE OF THE FORCE-CRUSH CHARACTERISTIC

The upper force was determined through full-scale testing of the prototype table design (Figure 5), which resulted in injury risk similar to the proposed IARVs (Table 1) [2]. Additional analyses using higher force values showed that peak forces greater than 2,250 pounds were unlikely to achieve the target upper abdominal compression limit (Figure 9). The target energy absorption value is calculated by integrating the measured force-crush characteristic with respect to crush over the entire time history to remove any stored elastic energy from the system.

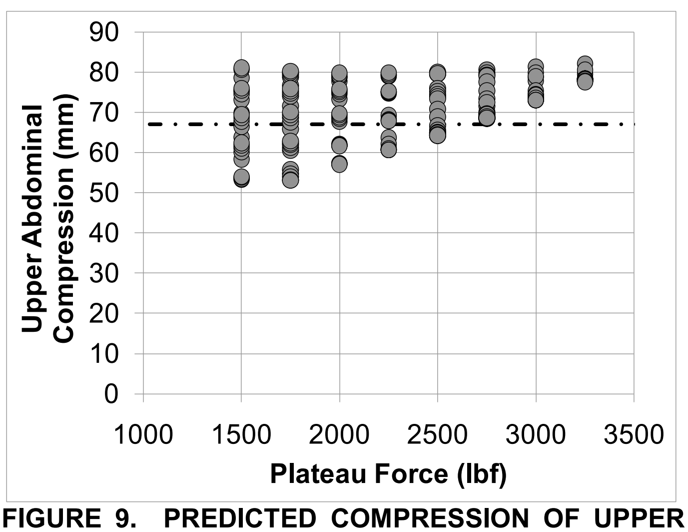


FIGURE 9. PREDICTED COMPRESSION OF UPPER ABDOMEN RELATIVE TO MAXIMUM FORCE

DISCUSSION

Overall, the target energy absorbed by the table is the best predictor of occupant response. As implemented in this study, the target energy absorbed represents the amount of energy dissipated before a defined peak load is reached, as would be measured in a quasi-static test. The target energy absorbed does not include any energy dissipated through contact of the occupant with the seat, floor, or facing seat. A knee bolster on the facing seat, for instance, could reduce the severity of the occupant response by reducing the kinetic energy of the occupant without loading the thorax or abdomen.

The target energy absorbed by the table edge is important to the occupant response because it dictates the kinetic energy of the occupant at the point of exhaustion of the energy-absorbing element. The kinetic energy of the occupant, however, is difficult to quantify, as the mass of the occupant does not act the same as a lumped mass. A majority of the injury predictors occur at the point of peak table crush, and a majority of the designs crush past exhaustion of the energy absorbing element. In only nine of the designs, the energy-absorbing element was not exhausted. One of these designs had target energy absorption of 7,750 inch-pounds, while the other eight had a target energy absorption of 9,300 inch-pounds. Thus, the total kinetic energy that must be dissipated to bring the occupant to rest using the current table geometry under an 8g, 250 millisecond pulse is likely to be between 7,750 and 9,300 inch-pounds.

These designs, however, do not result the lowest injury risk primarily due to the high plateau force. As shown in Figure 8, most of the minima of the metrics (aside from the upper abdominal viscous criterion) begin to increase at a plateau force of 1,750 pounds through 2,250 pounds. Thus, there are designs that absorb a lower amount of energy, yet result in a lower injury risk due to a decreased peak force. . All of the minima occur at or below a plateau force of 1,750 pounds, while the compression values are minimized at 9,300 inch-pounds of energy absorption capacity and viscous criterion values are minimized at as low as 6,200 inch-pounds of capacity, as long as the initial stiffness is no greater than 2,300 pounds per inch.

This study looked at variations on the force crush curve, but it did not cover all the variations possible in a table design. The model had two seated dummies, but there exist workstation tables with one or three people seated. This table was cantilevered from the wall, whereas most table designs have a supporting pole at the aisle end. Variations in the height of the table were also studied and did not affect injury values. Differently sized occupants, including children were not studied. The effect of the thickness of the table on the injury imparted to occupants is not readily measured by a lumped mass model. These are all items that could be studied in the future.

SUCCESSFUL DESIGNS

The designs characterized as successful in protecting the occupant are those that result in injury metric predictions of less than or equal to the IARVs presented in Table 1. Successful table designs result in a maximum injury risk of either a 25 percent risk of AIS 3+ injury or a 5 percent risk of an AIS 4+ injury. The minimum target energy absorption value that meets all of the IARVs is 6,200 inch-pounds. The maximum plateau force that meets all of the IARVs is 2,000 pounds. Values of all initial stiffnesses are included in the successful designs, which indicate that as long as the energy absorption is at least 6,200 inch-pounds, the response is insensitive to initial stiffness.

CONCLUSION

The results of this analysis indicate that the injury risk from impact with a workstation table is minimized when the energy absorption capacity is equal to the kinetic energy of the occupant, minus losses from external forces. Table edge energy absorbing capacities of 9,300 inch-pounds, specifically with a peak force at or below 1,750 pounds, minimized the upper abdominal compression and chest compression. Chest acceleration and viscous criterion are minimized by designs with the plateau forces up to 2,000 pounds, and energy absorption capacities at or above 6,200 inch-pounds.

In order to meet the IARVs for upper abdominal compression, chest compression, upper abdominal and chest viscous criterion, and chest acceleration simultaneously, the energy-absorbing capacity of the crush element of the table must be at least 6,200 inch-pounds with a maximum plateau force of 2,000 pounds.

Achievement of the IARVs represents a level of safety of at most a 25 percent risk of an AIS 3+ injury, or a 5 percent risk of an AIS 4+ where AIS 3+ risk functions are unavailable, which provides a level of safety at least equivalent to the existing automotive and passenger rail regulations.

This information will be incorporated into an APTA standard to evaluate the risk of upper abdominal injury based on the measured force-crush characteristic of the table edge. For such designs, the target energy absorption value is determined through quasi-static testing by loading up to the point where the maximum force level is reached, then unloading. Based on the result of this study, the recommended minimum target energy absorption value is 6,200 in-lbf and the recommended maximum force level is 2,250 lbf. In concert with a sled test of the workstation table with a HIII ATD to evaluate compartimentalization and head, neack and lower extremity injury risk, this standard will provide a level of safety to occupants equivalent to the existing APTA standards.

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