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**EVALUATION OF TESTING METHODS
TO DEVELOP TEST REQUIREMENTS
FOR A WORKSTATION TABLE SAFETY STANDARD**

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ABSTRACT

Investigations of passenger train accidents have revealed serious safety hazards associated with the thin, rigid tops of workstation tables, which are common fixtures aboard rail cars. Thoracic and abdominal injuries caused by occupant impact with workstation tables have been cited as the likely cause of two fatalities during a 2002 accident in Placentia, CA [1]. Additionally, workstation tables have been cited as the cause of injury in reports on accidents in Intercession City, FL [2], and Burbank, CA [3].

Currently there are no regulations or safety standards governing the crashworthiness of tables in passenger trains beyond attachment strength requirements. However, research sponsored by the Federal Railroad Administration (FRA) and in collaboration with the American Public Transportation Association (APTA) Passenger Rail Equipment Safety Standards (PRESS) Construction & Structural working group is underway to develop a mandatory industry safety standard for tables to ensure that they will be designed to provide a minimum level of safety during a train accident

FRA's Equipment Safety Research Program has already developed and tested a prototype table design to demonstrate the improved occupant protection provided by an energy-absorbing table. The prototype table design was tested using a THOR [4] and an H3RS [5], which are advanced anthropomorphic test devices (ATDs), onboard a 35 mph full-scale train-to-train impact test of rail cars modified to incorporate crash energy management (CEM) [6]. Test results demonstrated that the Injury Assessment Reference Values (IARVs) measured by the instrumented ATDs were within human tolerance levels established by the National Highway Traffic Safety Administration (NHTSA) for automotive crashworthiness for the head, neck, chest, abdomen, and femur.

Having demonstrated the effectiveness of an energy-absorbing table, the next step is developing a performance-based safety standard for tables that ensures a minimum level of crashworthiness. The safety standard would employ the use of

an 8G dynamic sled test with instrumented ATDs to evaluate occupant injury and structural integrity of the table, similar to the seat test requirements in APTA-SS-C&S-016-99 [7], which is the industry safety standard for passenger seats in rail cars. Normally, advanced ATDs like the THOR would be required to measure abdominal and thoracic loads caused by the table impact during the sled test. However, use of these experimental ATDs for table qualification testing is not feasible due to their limited availability. Therefore, alternative test methods must be developed to evaluate the crashworthiness of workstation tables.

This paper evaluates several potential methods to measure table crashworthiness, including quasi-static crush testing, pendulum impact testing, drop tower testing, and sled testing with standard Hybrid III 50th percentile ATDs. The pros and cons of these tests are also described. After evaluating the various testing methods, test conditions for two separate tests are proposed for an industry table standard. A companion paper [8] describes analysis results used to establish performance requirements proposed for evaluating table crashworthiness for the safety standard, in accordance with the test conditions proposed in this paper.

INTRODUCTION

Traditionally workstation tables have been designed for function and aesthetics. Typical construction may include a plywood table top covered with a laminate surface. Tables are usually fastened to the wall with a bracket and screws, and supported vertically by a table leg near the aisle-side of the table.

These types of tables have been shown to convey concentrated abdominal loads to occupants during train collisions. Accident investigations have also determined that these tables can sometimes detach from the wall and floor mounts under the force of occupant loading, cause a loss of occupant compartmentalization, and even trap an occupant in the facing seat pair.

The results of this modeling, which are described in the companion paper [8], indicate that kinetic energy absorbed by the table provides a meaningful correlation with abdominal injury. Generally, abdominal injury indices decrease as energy absorbed via table crush increases, provided that the peak contact force between the ATD and the table is limited.

A number of different tests have been explored to assess table crashworthiness. The following sections will survey the information gathered during this testing. The test measurements and results will be described, along with the pros and cons of each method in terms of measuring energy absorbed via table crush and peak contact force.

QUASI-STATIC TESTING

Several quasi-static tests have been performed on the FRA prototype table to characterize its force-crush behavior. Preliminary analysis and quasi-static testing led to design modifications to increase confidence that the table design would perform as desired during the more complicated and expensive full-scale train-to-train test with the THOR ATD. After the full-scale tests indicated that the table met the test objectives, another quasi-static test was conducted to verify the force-crush behavior of the final design. The test conditions, test measurements, and test results are described below.

Test Conditions

The workstation table was fastened to a rigid test fixture using the same attachment mechanism planned for rail service. The table was destructively tested under a quasi-static loading condition in which longitudinal, loads were applied simultaneously to the table at both seat positions, to evaluate the crashworthiness of the table at each seat position under combined loading.

The loads were applied to the table by two hydraulic cylinders, which were attached to rigid body blocks 15 in wide by 8 in high, approximating the size of a human torso. The vertical sides had a radius of three in. The body blocks were aligned laterally at the center of each seat position and centered vertically on the table edge. The displacement rate of the cylinders was approximately 1 in/minute.

Test Measurements

The force-time history and displacement-time history of the independent loading rams were measured. The longitudinal displacement of the table top was measured on the side opposite the load applications, in line with the applied loads, using a string potentiometer. To assess encroachment, table penetration into the passenger space on the opposite side of the table was calculated by subtracting the longitudinal displacement of the table (measured by string potentiometers) from the initial longitudinal distance between the table edge and the seat back.

Three-axis reaction loads were also measured at the attachment points between the table and the test sled via three load cells, two at the wall mount and one under the support leg at the floor mount. Still photographs of the table were taken

pre- and post-test. The progress of the test was also documented using a digital video camera at two locations (top and side views). A pre-test photo of the quasi-static test set-up is shown below in Figure 3.



FIGURE 3. PRE-TEST PHOTO OF QUASI-STATIC TEST

Test Results

The loading rams were deployed nearly 8 in during the test. The wall-side ram was stopped after 7 in of ram displacement because the honeycomb was fully crushed and the load in the steel frame was increasing rapidly. The aisle-side ram was allowed to continue until approximately 8 in of ram displacement, at which point the honeycomb on this side was also exhausted. The difference in peak displacement of the two rams is due to the elastic bending of the center I-beam of the table.

A post-test photo of the table crush is shown in Figure 4, depicting the permanent table crush on the wall-side (top of photo) and aisle-side (bottom of photo).

The force-crush plots for the aisle-side and the wall-side load applications are shown in Figure 5. The force is that measured in the loading ram at each table position. The crush is the displacement of each loading ram, which were actuated to displace together.

When the rams had displaced about 0.3 in and the applied load reached approximately 1,300 lbf, the honeycomb began to crush plastically. The load then gradually increased to about 2,200 lbf and then began to increase rapidly as the honeycomb consolidated. The measured load for the wall-side loading ram eventually reached 4,800 lbf at a displacement of 7 in. The measured load for the aisle-side loading ram reached 4,200 lbf at a displacement of 8 in.



FIGURE 4. POST-TEST PHOTO OF QUASI-STATIC TEST

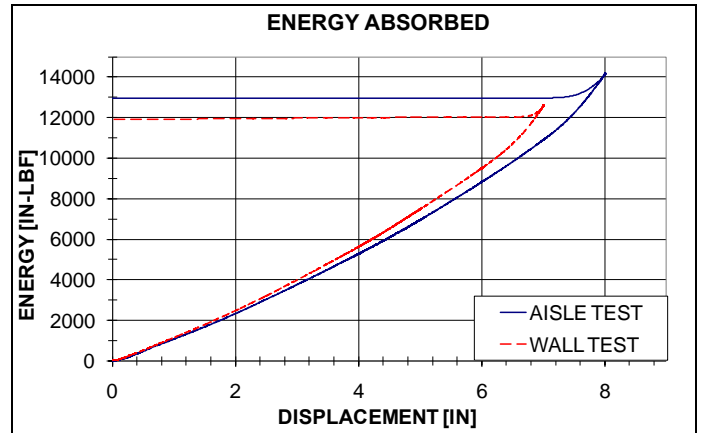


FIGURE 6. ENERGY ABSORPTION PLOTS

A disadvantage of the quasi-static test is that it is not dynamic like a rail accident, and doesn't account for any strain rate sensitivities or other dynamic effects, which may or may not exist in a particular table design.

DYNAMIC PENDULUM TESTING

Two separate dynamic pendulum tests were performed on the FRA prototype table to characterize its force-crush behavior under dynamic loading conditions. The test conditions, test measurements, and test results are described below.

Test Conditions

The conditions for the first test were chosen to approximate the energy associated with the earlier THOR table experiment onboard the full-scale CEM train-to-train test in order to correlate the results of the THOR test with the dynamic pendulum test. The mass of the THOR ATD was 170 lbm. The velocity at the time of impact with the table was about 12 mph. The energy associated with these conditions was approximately 10,000 in-lbf. These initial conditions were therefore used for the first pendulum test.

The conditions for the second pendulum test were chosen to approximate the conditions associated with a standard HIII 50th percentile ATD subjected to an 8G crash pulse. These conditions are also specified in the APTA seat standard. The impact velocity for an ATD under these test conditions is approximately 9-10 mph, resulting in a kinetic energy of about 6,000 in-lbf.

During the period between the first and second pendulum tests, lumped-parameter modeling using MADYMO was conducted to correlate collision conditions between an event defined by an acceleration time history and an event defined by an initial mass and velocity. In order to match the energy absorbed by the table in the two cases, the mass of the pendulum was decreased to 75 lbm for the second test.

Each mass was suspended from the ceiling of the test bay by a set of eight cables that were attached to the pendulum shuttle, four attached to the front of the shuttle, and four attached near the back. The outside cables were suspended at

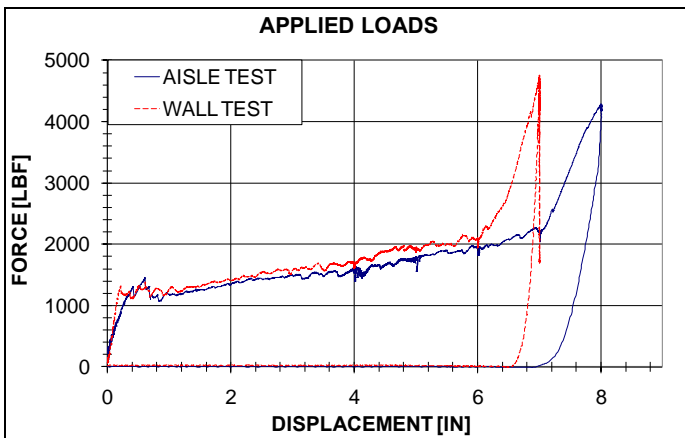


FIGURE 5. TABLE FORCE-CRUSH PLOTS

The largest reaction loads were measured at the wall load cells in the lateral direction. The loads at the two wall-mounted load cells were approximately equal and opposite, with the load cell on the applied load side of the table in tension and the other in compression. The peak load was about 8,000 lbf in tension. The sum of the longitudinal reaction loads measured at the three load cells reached about 7,000 lbf. The peak vertical reaction load was about 430 lbf measured at the attachment of the support leg to the floor.

The energy absorbed by table crush at each table position was calculated by integrating the force vs. displacement plot for each ram from t_0 to t_f , where t_0 is the time that the ram contacts the table, and t_f is the time that the force returns to zero.

The energy absorption plots for each ram as a function of ram displacement are shown in Figure 6. The energy absorbed on the wall-side and aisle-side of the table was approximately 12,000 in-lbf and 14,000 in-lbf, respectively.

The quasi-static test has a number of advantages. It is a relatively inexpensive test. It is also easy to measure the force and displacement time histories and to calculate energy absorbed. The force required to initiate crush, which was a design parameter, is easy to identify. The maximum force allowed can be tied to abdominal tolerance.

an angle of about 30 degrees to provide lateral stability. The inside cables were suspended vertically (i.e., not at an angle like the outside cables) so that the cables did not interfere with one another during the drop. The same rigid body blocks from the quasi-static tests were attached to the leading end of the pendulum shuttle. The freely swinging pendulums were raised to a predetermined height to achieve the required impact velocity, and then released simultaneously. A pre-test photo of the test set-up is shown in Figure 7 (note that the opposite side of the table had been crushed during a previous test).



FIGURE 7. PRE-TEST PHOTO OF TEST SET-UP

Test Measurements

The time- history of the force between the pendulum and the table was measured by a uniaxial load cell placed behind the impact face of the hollow, rigid body block. The acceleration time history of each pendulum was measured by a three-axis accelerometer mounted to the top of the shuttle. The reaction loads at the table attachment points were measured with three-axis load cells, as per the quasi-static test set-up. The longitudinal displacement time history on the table side opposite each impact mass was measured with string potentiometers. Still photographs of the table were taken pre- and post-test. The progress of the test was also documented using a high-speed digital video camera at two locations (top and side views).

Test Results

In the first pendulum test, which had a kinetic energy of about 10,000 in-lbf, the impact of the pendulums produced about 5 in of permanent deformation on both the wall-side and aisle-side of the table (see post-test photo in Figure 8). The crush on the wall-side of the table was slightly greater than on the aisle side due to the increased rigidity associated with the proximity to the wall mount. The cantilevered aisle-side experienced more elastic deformation of the center I-beam.



FIGURE 8. POST-TEST PHOTO OF DYNAMIC TEST #1

The force time history plots measured from the load cells on the pendulum masses are shown in Figure 9. After the initial dynamic spike, the forces plateau to a relatively constant force level of 1,000 lbf to 1,500 lbf while the honeycomb crushes. These force levels are similar to the average crush force of the honeycomb during the quasi-static test, indicating that there is not a significant strain-rate sensitivity in this table design under these dynamic loading conditions. The honeycomb was not quite fully crushed under these loading conditions.

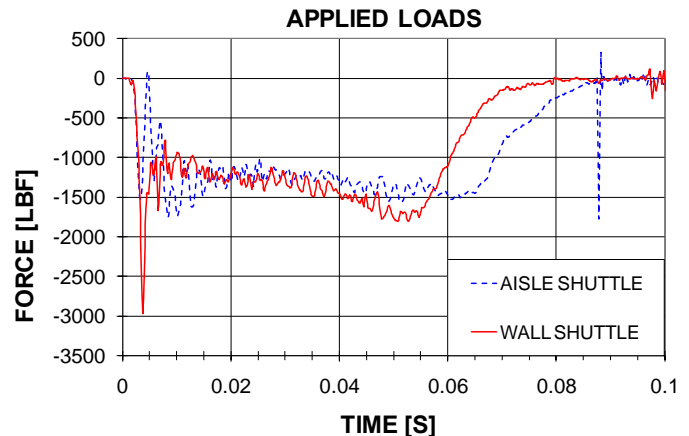


FIGURE 9. TEST #1 IMPACT FORCE TIME HISTORY

In the second pendulum test, which had a kinetic energy of about 6,000 in-lbf and a mass of 75 lbm, the table crush measured after the test was only 1.5 to 2.5 in on both sides of the table (see post-test photo in Figure 10). The crush on the wall-side of the table (left, bottom side in photo) was somewhat less than the aisle-side (right, bottom side in photo) because the rigid body block grazed the steel support structure, which dissipated some kinetic energy. As expected, the crush was significantly less than in the first pendulum test because the kinetic energy was reduced by 40%.



FIGURE 10. POST-TEST PHOTO OF DYNAMIC TEST #2 (BOTTOM SIDE OF PHOTO)

The force time history plots measured from the load cells on the pendulum masses are shown in Figure 11. The initial dynamic spike was less significant in this test and the oscillation in the force was greater due to the lighter masses. The average force due to the aisle-side mass impact was generally between 1,000 lbf and 1,700 lbf. The average force range due to the wall-side mass was much greater because it struck the steel support structure near the wall mount.

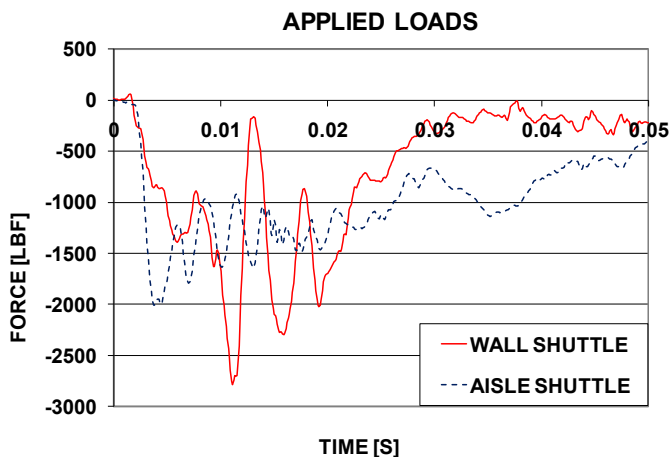


FIGURE 11. TEST #2 IMPACT FORCE TIME HISTORY

The dynamic pendulum tests were performed to determine their suitability for evaluating energy absorption, force levels during crushing, and peak accelerations to correlate with injury indices. Ideally, the pendulum tests would have provided a useful comparison to ATD impacts because the test was dynamic, as are rail vehicle accidents. However, there were several disadvantages to this test method.

It was desirable to allow as many degrees of freedom as reasonable to assess occupant compartmentalization; however the freedom of motion made it difficult to precisely control the point of impact. Although the effective mass of a HIII 50th percentile ATD was found to be 75 lbf via MADYMO modeling, the lower mass caused more oscillation and noise in the data signals. There were also complications associated with correlating the results from an initial velocity test condition with

results from an ATD subjected to a prescribed acceleration time history. Additionally, the pendulum test cannot assess ATD kinematics or injury indices.

DYNAMIC DROP TOWER TESTING

Drop tower testing is similar to pendulum testing, but it is simplified to allow only one degree of freedom. With proper instrumentation, drop tower testing can be used to evaluate table crashworthiness under dynamic loading conditions in terms of energy absorption behavior of the table, and peak and average forces generated by the mass impact. The test conditions and test measurements are described below. Selected results from drop tower testing conducted by students on a table designed by students at California Polytechnic State University at San Luis Obispo are also presented.

Test Conditions

As in pendulum testing, the table can be fastened to a test fixture as it would be mounted in rail service. The table would be rotated 90 degrees to perpendicular so that the masses would drop onto the edge of the table top. The rigid blocks representing a human torso (described above) would be secured to additional mass that is equivalent to the mass of an HIII 50th percentile ATD. The impact masses would be centered at each seat position. The drop height would be calculated to achieve the desired kinetic energy upon impact. The masses would be released at exactly the same time, but would fall independently once released.

Test Measurements

The test set-up would include instrumentation to measure the acceleration-time history of each mass. A load cell would be placed in front of the impact mass to measure the impact load. The filtered acceleration time histories could be multiplied by the masses to estimate the force time history. If there was good correlation between these two results, it would increase the confidence in the accelerometer data, such that it could be integrated to estimate velocity and displacement of the masses. The integrated velocity and displacement data could be compared to the estimated impact velocity and initial drop height to verify the accuracy of the data. String potentiometers could also be used to measure displacement of both the leading and aft edges of the table top, which could be used to calculate table crush and bending. These results could be used to evaluate energy absorbed by table crush and average and peak table forces.

The force time history plots shown in Figure 12 correspond to the acceleration time history data multiplied by the impact mass of 170 lbf for each mass during the drop tower test conducted by students at Cal Poly. There is an initial dynamic spike, but the average force after the spike is relatively constant at around 1,000 lbf. The Cal Poly drop tower testing did not include additional instrumentation to directly measure force or displacement during the test so energy absorbed by table crush cannot accurately be calculated.

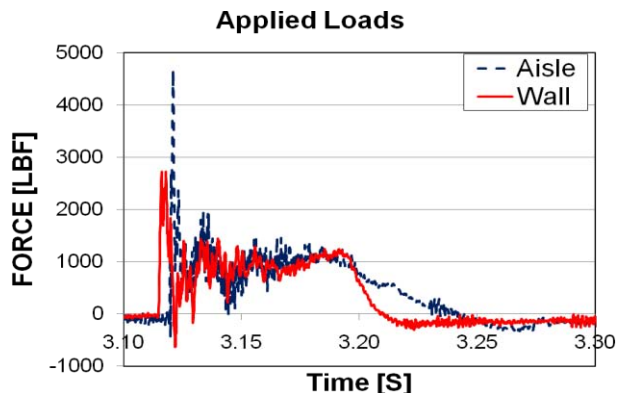


FIGURE 12. FORCE TIME HISTORY FOR CAL POLY TABLE

A drop tower test is a dynamic event and it is easy to precisely control the impact, but it still has many of the same issues as pendulum testing related to equivalent mass, energy correlation, ATD kinematics and injury indices. There are additional issues associated with energy loss due to friction between the dropped masses and the guideposts and accurately measuring the impact velocity and associated kinetic energy.

SUGGESTED TEST REQUIREMENTS

Based on the above survey of several testing methods, and in conjunction with results from testing and MADYMO modeling with a THOR ATD, the following two tests, with associated test conditions, measurements, and performance requirements, are proposed for an industry table safety standard.

Test #1 - Dynamic Sled Test with HIII 50th Percentile ATD

This proposed test would be nearly identical to the sled testing specified in the APTA seat standard, with the addition of a workstation table. Some modifications are made to the injury measurements and performance requirements.

Test Conditions

A passenger seat (single, double, triple, etc. to represent the intended service conditions) would be fastened to the test sled at the nominal location relative to the table for the intended rail service. A facing seat on the opposite side of the table would be optional. A workstation table would be fastened to the test sled as it would be mounted to a rail car. Instrumented HIII 50th percentile ATDs would be placed, one in each seat position, facing the direction of travel. The test fixture would act as a rigid mounting point for the table and seats.

The test sled would be subjected to an 8G, 250 millisecond crash pulse in the shape of an isosceles triangle.

Test Measurements

The test measurements would be similar to those measured in the APTA seat standard, with the addition of chest deflection. Below is a list of suggested test measurements:

- Triaxial head acceleration-time history for each ATD
- Triaxial chest acceleration-time history for each ATD
- Axial left and right femur force-time history for each ATD
- Upper neck extension/flexion bending moment, M_y , for each ATD
- Upper neck axial force, F_z , for each ATD
- Upper neck shear force, F_x , for each ATD
- Chest deflection, measured at sternum, for each ATD
- Longitudinal acceleration-time history of the test sled

The longitudinal distance from the forward-most location on the table to the front of the facing seat back (or theoretical position if a facing seat is not used) would be measured post-test to evaluate entrapment due to table displacement on the far edge of the table:

The following injury criteria would be computed in accordance with 49 CFR 571.208 [11]:

- HIC15
- 3ms chest Gs
- Axial femur load
- Peak upper neck axial tension/compression forces
- Nij
- Chest deflection, measured at the sternum

Still photographs of the table would be taken pre- and post-test. The progress of the test would be documented using a high-speed digital video camera at two locations (overhead and side views).

The performance requirements would include ATD compartmentalization, positive table attachment, and injury indices requirements per those in the APTA seat standard, with an additional requirement for chest deflection, chest viscous criterion, and a different IARV for the chest deceleration criteria.

Chest deflection was originally used in the automotive industry to assess direct impact between an automobile steering column and an ATD's chest. The sensor for chest deflection is located behind the ATD's sternum, which is generally located near the point of impact with a steering column, but not with a workstation table. The measurement would provide additional information related to the table impact, particularly if the table engages part of the rib cage. A stricter requirement will be specified for table testing than for automotive testing since chest compression in table testing will be referred from an impact not directly in line with the sensor, whereas the chest deflection sensor is generally in line with the steering column in automotive testing.

Performance Requirements

For a successful test, the following requirements must be met:

- The table and any table components must remain attached to the test fixture or simulated rail car structure.
- The crush of the table edge shall not result in any exposed sharp edges or spaces capable of entrapping an occupant during a rail accident.
- During and after the test, the table shall not penetrate the survival space reserved for occupants in the facing seat, where applicable, so as not to entrap the facing passengers or prevent egress. The survival space shall not be less than 15 inches, as measured in the horizontal plane from the forward-most location on the table to the front of the facing seat back.
- The ATDs shall be compartmentalized between the initially occupied seat and the table.
- All injury measurements must meet the following injury criteria in Table 2, most of which are the same as those defined in CFR 49 Part 571, Standard No. 208: Occupant Crash Protection [11]. The chest deceleration and deflection criteria are more restrictive than the automotive standard to compensate for the fact that the contact between the ATD and the table is not in line with the chest sensors.

TABLE 2. INJURY CRITERIA REQUIREMENTS

Criteria	Injury Threshold
HIC15	700
Nij	1.0
Neck Axial Tension (Fz)	+937/-899 lbf (4,170/4,000 N)
Chest deceleration over 3 ms clip, Gs	32.5
Chest deflection	2.2 inches (55 mm)
Chest Viscous Criterion	2.6 ft/s (0.8 m/s)
Femur Load	2,250 lbf (10,000 N)

The sled test with an HIII 50th percentile ATD has the benefit of being a dynamic event with a high degree of fidelity to represent the occupant kinematic, compartmentalization, table attachment, and injury assessment for the head, chest, neck, and femur. The only disadvantage is that the HIII ATD cannot measure loads delivered directly to the abdomen. The following test is recommended to assess abdominal injury.

Test #2 – Quasi-Static Test

A quasi-static test is proposed to measure the energy absorbed by table crush without exceeding a peak force limit, which is associated with abdominal tolerance levels.

Test Conditions

A workstation table would be mounted to a rigid test fixture or simulated car structure using the same fasteners or attachment mechanism used in service, i.e., bolts, screws, track, tapping plate, etc. The table would be destructively tested under quasi-static loading conditions. A series of tests would be performed in which a quasi-static load is applied to the table at each seat position, to evaluate the crashworthiness of the table at each seat position.

The load would be applied to the table via a rigid block (depicted in Figure 13) to which the hydraulic cylinder would be attached. The block would be aligned laterally at the center of each seat position for the intended service. The blocks would be centered vertically on the table edge. The displacement rate of the cylinder would be approximately one in/minute. The test would proceed until the applied load reached 2,250 lbf, then the ram would be retracted to remove the applied load.

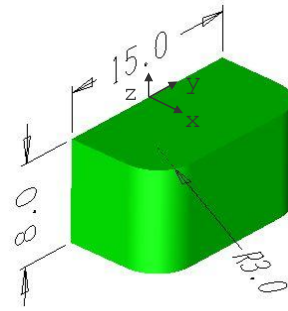


FIGURE 13. LOADING BLOCK (DIMENSIONS ARE IN INCHES)

Test Measurements

The force-time history and displacement-time history of the loading ram would be measured in accordance with SAE J211-1 [13]. The longitudinal displacement of the table top would be measured on the side opposite the load application in line with the applied load using a string potentiometer.

The table penetration into the passenger space on the opposite side of the table would be calculated by subtracting the longitudinal displacement of the table (measured by a string potentiometer) from the initial theoretical longitudinal distance between the table edge and the seat back.

The energy absorbed by plastic (permanent) table crush at each table position would be calculated as follows:

- Plot the applied load vs. displacement of the loading ram
- Integrate the load vs. displacement plot until the applied load returns to zero, thus subtracting the elastic energy stored in the table.

Still photographs of the table would be taken pre- and post-test. The progress of the test would also be documented using a digital video camera at two locations (top and side views).

Performance Requirements

For a successful test, the following requirements must be met:

- The table and any table components must remain attached to the test fixture.
- The crush of the table edge must minimize any sharp edges or points of entrapment which might endanger an occupant.
- During and after crushing of the table, a minimum of 15 in of survivable space must be preserved for facing occupants, based on the predominant seat pitch used for seats surrounding tables.
- The energy absorbed by the plastic (permanent) table crush, as calculated above, must be at least 6,200 in-lbf without the force exceeding 2,250 lbf.

CONCLUSIONS

After evaluating the benefits of several testing techniques, dynamic sled testing with an HIII 50th percentile ATD and quasi-static testing have been proposed to assess compliance with the recommended test objectives. The combination of these two tests can be used to evaluate table attachment, occupant compartmentalization, table encroachment on facing passengers, and injury to critical body parts, including head, neck, chest, abdomen, and femurs. The dynamic sled test can be used to evaluate all of these objectives except for abdominal injury. The quasi-static test can be used to assess the energy absorption capacity of the table without exceeding a defined force limit, which is tied to abdominal injury tolerance levels. The test conditions, test measurements, and performance requirements have been defined for each test. The rationale behind the specific performance requirements for each set of test requirements are explained in detail in the previously mentioned companion paper [8]. These test and performance requirements have been proposed in a draft industry table standard. The requirements in these two tests are expected to significantly improve the collision safety associated with workstation tables.

ACKNOWLEDGMENTS

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