



AEROSPACE RECOMMENDED PRACTICE

ARP5765™**REV. B**Issued 2012-10
Revised 2021-03

Superseding ARP5765A

Analytical Methods for Aircraft Seat Design and Evaluation

RATIONALE

The changes in this revision represent the latest agreement obtained by the SAE SEAT Committee to provide the most current information on the topic. This revision adds details on the ES-2re ATD, recommendations on how to document the certification approach, and an analysis checklist. Preexisting sections of the document have been revised to improve clarity and provide additional information or correct errors.

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) defines a means of assessing the credibility of computer models of aircraft seating systems used to simulate dynamic impact conditions set forth in Title 14, Code of Federal Regulations (14 CFR) Parts 23.562, 25.562, 27.562, and 29.562. The ARP is applicable to lumped mass and detailed finite element seat models. This includes specifications and performance criteria for aviation specific virtual anthropomorphic test devices (v-ATDs). This document provides a recommended methodology to evaluate the degree of correlation between a seat model and dynamic impact tests. This ARP also provides best practices for testing and modeling designed to support the implementation of analytical models of aircraft seat systems. Supporting information within this document includes procedures for the quantitative comparison of test and simulation results, as well as test summaries for data generated to support the development of v-ATDs and a sample v-ATD calibration report.

1.1 Purpose

This ARP aims to supplement the information provided in the FAA Advisory Circular (AC) 20-146A. In general, assessing the credibility of modeling and simulation (M&S) is accomplished through the processes of verification and validation (V&V), which are rapidly evolving disciplines within the computational world. The recommended methodology for the successful design and evaluation of aircraft seats using analytical methods is a building block approach comprised of the following steps: software verification, v-ATD calibration, material characterization, subsystem tests, seat system validation, and sensitivity analysis. The v-ATD calibration is seen as the most critical component of the above approach, and as such, the v-ATD performance criteria is a separate section of this document (Section 3). To support the development of v-ATDs, a series of tests of physical ATDs was accomplished and the test information is provided for the Hybrid II (Appendix B) and FAA-Hybrid III (Appendix C). To aid in the completion of the six steps outlined above, the final primary section of the document contains recommended practices for both physical testing and numerical modeling (Section 5).

The uses of M&S in aircraft seat design and evaluation are numerous and begin in the early phases of any development program. Computer aided engineering tools that allow M&S of prototype designs are readily available. The use of M&S here allows tradeoffs to be conducted, evaluation of injury risks, investigation of potential failure areas, and the selection of successful design parameters. Beginning in these early phases will also help develop the future test plans to increase the odds of a successful seat system validation. Once a baseline seat is identified, M&S may be used for determining the critical cases for which testing may be necessary. Using M&S here will potentially reduce the number of required developmental and certification tests. After a baseline seat system is validated, M&S may be applied to investigate installation specific issues and minor modifications without the need to retest.

While there are several advantages of using M&S, it must also be recognized that there are several limitations. Successful validation depends on the quality of the reference test data, modeling techniques and interpretation of the correlation results. The M&S process discussed here relies heavily on the use of test data, and as such, physical testing is still required. Even with a model that is valid for the intended use, there are compliance situations where simulation cannot be applied and further testing will still be required. For example, if the model shows that a design modification significantly increases the stress in critical components where there are no redundant load paths, then a retest may be necessary to ensure that a failure does not occur.

This document is focused on providing guidance to the various stakeholders involved in the M&S process, who may each have different objectives in mind. These stakeholders include the software developers, seat suppliers, seat integrators (usually airframe manufacturers and their certification staff), and regulatory agencies. Their respective primary areas of concern roughly correspond to the different levels of the model validation process. The code developers need to understand the documentation requirements for the code verification and document the limitations of the code. v-ATD model developers need to understand the v-ATD calibration procedure amongst other things, in order to develop models that are useful for customers.

End users for a code or model (v-ATD) need to clearly understand the limitations of the software and any impacts those limitations impart on the use of the models. For example, some v-ATDs may be certified “conditionally compliant” in which the use of the model will only be valid under specific conditions.

The seat suppliers are primarily interested in developing accurate seat models in hopes of reducing the development cycle and the number of certification tests. The airframe manufacturers depend on the integrity of these models to produce reliable interface loads and are responsible to certify the seat for installation into the aircraft. The certification staff and regulatory agencies are concerned with how M&S supports a safe and certified system, as well as the configuration control of the final product. Thus, the goal of this recommended practice is to offer to the seat community a set of potential criteria that may be used to support the creation and documentation of a valid seat system or subsystem in order to support certification efforts and to inform, and potentially streamline, the design process.

1.2 Units

In this document, U.S. customary units (in-lb) and International System of Units (SI) are provided. In all cases, the in-lb units take precedence and the SI (metric) units provided are approximate and conservative conversions. Those who routinely use SI units in practice should ensure that the conversions are accurate.

1.3 Coordinate Systems

The coordinate systems in this document are consistent with SAE J211-1. Reference to x, y, and z dimensions are in the seat or ATD coordinate system and follow standard naming convention.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

2.1.1.1 AS8049, "Performance Standard for Seats in Civil Rotorcraft, Transport Aircraft, and General Aviation Aircraft"

2.1.1.2 SAE J211-1, "Instrumentation for Impact Test - Part 1 - Electronic Instrumentation"

2.1.1.3 SAE J211-2, "Instrumentation for Impact Test - Part 2: Photographic Instrumentation"

2.1.1.4 Gowdy, V., DeWeese, R., Beebe, M., Wade, B. et al., "A Lumbar Spine Modification to the Hybrid III ATD For Aircraft Seat Tests," SAE Technical Paper 1999-01-1609, 1999, doi:10.4271/1999-01-1609

2.1.1.5 Bhonge, P. and Lankarani, H., "Finite Element Modeling Strategies for Dynamic Aircraft Seats," SAE Technical Paper 2008-01-2272, 2008, doi:10.4271/2008-01-2272

2.1.1.6 AS6316, "Performance Standards for Oblique Facing Passenger Seats in Transport Aircraft"

2.1.1.7 AS8043, "Restraint Systems for Civil Aircraft"

2.1.1.8 AS8049/1, "Performance Standards for Side-Facing Seats in Civil Rotorcraft, Transport Aircraft, and General Aviation Aircraft"

2.1.2 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

- 2.1.2.1 Title 14 Part 23 (§ 14 CFR Part 23), "Airworthiness Standards: Normal, Utility, and Acrobatic Category Airplanes"
- 2.1.2.2 Title 14 Part 25 (§ 14 CFR Part 25), "Airworthiness Standards: Transport Category Airplanes"
- 2.1.2.3 Title 14 Part 27 (§ 14 CFR Part 27), "Airworthiness Standards: Normal Category Rotorcraft"
- 2.1.2.4 Title 14 Part 29 (§ 14 CFR Part 29), "Airworthiness Standards: Transport Category Rotorcraft"
- 2.1.2.5 Title 49 Part 572, "Anthropomorphic Test Devices"
- 2.1.2.6 FAA AC 20-146A, "Methodology for Dynamic Seat Certification by Analysis for Use in Parts 23, 25, 27, 29 Airplanes and Rotorcrafts," 2018
- 2.1.2.7 DOT/FAA/AR-05/5, "Development and Validation of an Aircraft Seat Cushion Component Test Volume 1"
- 2.1.2.8 DOT/FAA/AR-11/24, Certification by Analysis: Hybrid II and FAA Hybrid III Virtual Anthropomorphic Test Devices Validation and Verification Methodology"
- 2.1.2.9 FAA AC 25.562-1B Change 1, "Dynamic Evaluation of Seat, Restraint Systems and Occupant Protection on Transport Airplanes," 2015
- 2.1.2.10 FAA PS-ANM-25-03-R1, "Technical Criteria for Approving Side-Facing Seats," 2012
- 2.1.2.11 DOT/FAA/AM-2/11, "Human Factors Associated with the Certification of Airplane Passenger Seats: Seat Belt Adjustment and Release," 2002
- 2.1.2.12 "Metallic Materials Properties Development and Standardization (MMPDS - 14)," 2019

2.1.3 European Union Aviation Safety Agency (EASA) Publications

Available from European Union Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany (for visitors and for mail over 1 kg) and Postfach 10 12 53, D-50452 Cologne, Germany (for mail 1 kg or less); Tel: +49 221 8999 000, www.easa.europa.eu.

- 2.1.3.1 EASA CS 25, "Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes"

2.1.4 Industry Publications

- 2.1.4.1 Bathe, K.J., "Finite Element Procedures, Prentice Hall publication," 1996
- 2.1.4.2 "Mark's Standard Handbook for Mechanical Engineers," 10th edition, 1999
- 2.1.4.3 ASTM E8/E8M-09, "Standard Test Methods for Tension Testing of Metallic Materials," American Society for Testing Material, 2008
- 2.1.4.4 ASTM D3574-03, "Standard Test Methods for Flexible Cellular Materials, - Slab, Bonded, and Molded Urethane Foams," American Society for Testing Material, 2003
- 2.1.4.5 ASME V&V10-2019, "Standard for Verification and Validation in Computational Solid Mechanics," 2019
- 2.1.4.6 Sprague, M.A. and Geers, T.L., "A Spectral-Element Method for Modeling Cavitation in Transient Fluid-Structure Interaction, International Journal for Numerical Methods in Engineering," 60 (15), 2467-2499, 2004

- 2.1.4.7 Belytschko, T., Liu, W., Moran, B., "Nonlinear Finite Elements for Continua and Structures," John Wiley and Sons Publication, 2000
- 2.1.4.8 Bhonge, P.S. and Lankarani, H.M., "Evaluation of the Input Parameters for the Finite Element Modeling of Aircraft Seats Using Component Level Validation," International Journal of Vehicle Structures and Systems, March 2011
- 2.1.4.9 Moorcroft, D., DeWeese, R., and Taylor, A., "Improving Test Repeatability and Methods," The Sixth Triennial International Fire and Cabin Safety Research Conference, October 25-28, 2010
- 2.1.4.10 Olivares, G., Acosta, J.F., and Yadav, V., "Certification by Analysis I and II," FAA Joint Advanced Materials and Structures (JAMS) Center of Excellence Technical Review Meeting, Seattle, May 2010
- 2.1.4.11 Buechler, M.A., McCarty, A.S., Reding, D., Maupin, R.D., "Explicit Finite Element Code Verification Problems," IMAC Conference and Exposition on Structural Dynamics XXII, 2004
- 2.1.4.12 Bao, Y. and Wierzbicki, T., "On Fracture Locus in the Equivalent Strain and Stress Triaxiality Space," International Journal of Mechanical Sciences, 46 (2004) 81-98
- 2.1.4.13 Bao, Y. and Wierzbicki, T., "A Comparative Study on Various Ductile Crack Formation Criteria," Transactions of the ASME, Vol. 126, July 2004
- 2.1.4.14 Bao, Y., "Dependence of ductile crack formation in tensile tests on stress triaxiality, stress and strain ratios," Engineering Fracture Mechanics 72 (2005) 505-522
- 2.1.4.15 Hooputra, H., Gese, H., Dell, H., and Werner, H., "A Comprehensive Failure Model for Crashworthiness Simulation of Aluminum Extrusions," (2004) International Journal of Crashworthiness, 9:5, 449-464, doi:10.1533/ijcr.2004.0289
- 2.1.4.16 ABAQUS User's Manual
- 2.1.4.17 LS-DYNA User's Manual
- 2.1.4.18 Hinton, M.J. and Kaddour, A.S., "The Second World-Wide Failure Exercise: Benchmarking of Failure Criteria Under Triaxial Stresses for Fibre-Reinforced polymer Composites," 16th International Conference on Composite Materials
- 2.1.4.19 Schweizerhof, K., Wiemar, K., Munz, T., and Rottner, T., "Crashworthiness Analysis with Enhanced Composite Material Models in LS-DYNA Merits and Limits"
- 2.1.4.20 Oberkampf, W.L. and Roy, C.J., "Verification and Validation in Scientific Computing"
- 2.1.4.21 Seidt, J.D., "Plastic Deformation and Ductile Fracture of 2024-T351," Ohio State University Dissertation, 2010
- 2.1.4.22 Pratt, J.D., "Allowables-Based Flow Curves for Nonlinear Finite-Element Analysis," ASM International Journal of Failure Analysis and Prevention 01/2007
- 2.1.4.23 ASTM E8, "Standard Test Methods for Tension Testing of Metallic Materials"
- 2.1.4.24 ASTM E9, "Standard Test Methods of Compression Testing of Metallic Materials at Room Temperature"
- 2.1.4.25 ASTM D3039, "Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials"
- 2.1.4.26 ASTM D3410, "Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading"
- 2.1.4.27 ASTM D6641, "Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture"

- 2.1.4.28 ASTM D5467, "Standard Test Method for Compressive Properties of Unidirectional Polymer Matrix Composite Materials Using a Sandwich Beam"
- 2.1.4.29 ASTM D3518, "Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a $\pm 45^\circ$ Laminate"
- 2.1.4.30 ASTM D7078, "Standard Test Method for Shear Properties of Composite Materials by V-Notched Rail Shear Method"
- 2.1.4.31 ASTM D3574, "Standard Test Methods for Flexible Cellular Materials - Slab, Bonded, and Molded Urethane Foams"
- 2.1.4.32 Huculak, R.D. and Lankarani, H.M., "Methods of evaluating ES-2 leg flail in dynamic evaluation and certification tests of side-facing aircraft seats," (2015) International Journal of Crashworthiness, 20:6, 613-628

2.2 Definitions

2.2.1 ANALYST

The individual creating and running the computer simulation.

2.2.2 CALCULATION VERIFICATION

The process of determining the solution accuracy of a particular approximate numerical solution to the mathematical model (ASME V&V10-2019).

2.2.3 CALIBRATION

The process of adjusting physical modeling parameters in the computational model to improve agreement with experimental results (ASME V&V10-2019).

2.2.4 CODE

The computer implementation of algorithms developed to facilitate the formulation and approximate solution of a class of problems (ASME V&V10-2019).

2.2.5 CODE VERIFICATION

The process of determining that the numerical algorithms are correctly implemented in the computer code and of identifying errors in the software (ASME V&V10-2019).

2.2.6 CONCEPTUAL MODEL

The collection of assumptions and descriptions of physical processes representing the solid mechanics behavior of the reality of interest from which the mathematical model and validation experiments can be constructed (ASME V&V10-2019).

2.2.7 ERROR

The quantitative difference between a measured or calculated value and the referent or true value (ASME V&V10-2019).

2.2.8 INTENDED USE

The specific purpose and conditions for which the computational model is to be used (ASME V&V10-2019).

2.2.9 MODEL

The representation of a system, phenomena, or process under specific physical conditions. The representation includes the conceptual, mathematical, and computational models (ASME V&V10-2019).

2.2.10 PREDICTION

The use of a model to calculate a response where the modeler does not know the experimental outputs (ASME V&V10-2019).

2.2.11 REALITY OF INTEREST

The physical system and its associated environment to which the computational model will be applied (ASME V&V10-2006).

2.2.12 SENSITIVITY ANALYSIS

The general process of discovering the effects of model input parameters on the response features of interest using techniques such as analysis of variance (ANOVA) (ASME V&V10-2006).

2.2.13 SIMULATION

The computer calculations performed with the computational model (i.e., “running the model”) (ASME V&V10-2019).

2.2.14 UNCERTAINTY

The lack of accuracy associated with a measured or calculated value. It is typically a combination of reducible and irreducible uncertainties (ASME V&V10-2019).

2.2.15 VALIDATION

The process of determining the degree to which a model is an accurate representation of corresponding physical experiments from the perspective of the intended uses of the model (ASME V&V10-2019).

2.2.16 VERIFICATION

The process of determining that a computational model accurately represents the underlying mathematical model and its solution (ASME V&V10-2019).

3. VIRTUAL ANTHROPOMORPHIC TEST DEVICE (v-ATD) CALIBRATION

A primary component affecting the response of an aviation seat system is the ATD. The majority of the compliance data channels are either directly measured from the ATD (e.g., HIC, lumbar load, etc.) or greatly affected by the ATD (e.g., floor reaction load). As such, it is imperative for the virtual representation of the ATD to be of as high fidelity as possible. To this end, the purpose of this section is to provide a methodology for evaluating the fidelity of an aviation v-ATD. This evaluation is broken into four parts: mass and geometry evaluation, sub-assembly evaluation, pelvic shape evaluation, and dynamic response evaluation. The subsections include different requirements for v-ATDs used in forward facing seat (Hybrid II and FAA Hybrid III) and side facing seat ATD (ES-2re) configurations. While this section is primarily for v-ATD developers, it contains important information regarding the limitations and related effects on seat system verification and validation.

3.1 Mass and Geometry Evaluation

The virtual anthropomorphic test device (v-ATD) should meet the specifications cited in Title 49 of the Code of Federal Regulations (CFR) Part 572 as appropriate for the physical ATD it is meant to represent. These specifications reference drawings that provide geometry and mass distribution parameters, location of joints and their range of articulation, length, mass, and center of gravity for each segment, assembled dimensions, and general external shape. The mass and dimensions of the v-ATD should fall within the acceptable range cited in the specifications. Where the specifications do not cite a dimensional tolerance, assume that the tolerance is equal to ± 0.1 inch (± 2.54 mm) of the nominal value.

FAA 14 CFR 25.562 specifies a Hybrid II ATD, or equivalent, which has a defined bare (no shoes or clothing) weight of 164 pounds $\pm$ 3 pounds (74 kg $\pm$ 1.4 kg). EASA CS 25.562 specifies 170 pounds (77 kg) ATD when tested. The as-tested ATD includes shoes, which have a combined weight of approximately 2.5 pounds (1.1 kg), and clothing, which has negligible weight. The as-tested weight does not include the weight of the sensor cables. Use of bronze clavicles, allowed by both the FAA and EASA, adds approximately 2.5 pounds (1.1 kg) to the standard Hybrid II. v-ATD developers are encouraged to include the weight of shoes (2.5 pounds total) and the bronze clavicles. If this version of the v-ATD does not weigh 170 pounds (77 kg), the developer is encouraged to increase part weight until the v-ATD equals or exceeds 170 pounds (77 kg). The additional weight should be evenly distributed. Limits on the weight of individual segments should not be exceeded, except for the clavicles. As long as the bare weight of the v-ATD is less than 169.5 pounds (the upper limit plus weight of bronze clavicles, 76.9 kg), the v-ATD would meet the weight requirements of both the FAA and EASA regulations.

The FAA Hybrid III also has a defined weight of 164 pounds $\pm$ 3 pounds (74 kg $\pm$ 1.4 kg). EASA CS 25.562 specifies a 170 pounds (77 kg) ATD when tested. The as-tested ATD includes shoes, which have a combined weight of approximately 2.5 pounds (1.1 kg), and clothing, which has negligible weight. At the upper end, the ATD weight is 169.5 pounds (76.9 kg). The bronze clavicle replacements weigh more than the Hybrid II, adding approximately 9.5 pounds (4.3 kg). Bronze clavicles are not recommended since neither the FAA nor EASA have approved their use for the FAA Hybrid III.

The ES-2re has a defined weight of 159.6 pounds $\pm$ 2.6 pounds (72.4 kg $\pm$ 1.2 kg). Both the FAA and EASA specify the ES-2re for injury criteria tests for side-facing seats. The as-tested ATD is not expected to weigh 170 pounds (77 kg) and therefore no alterations are required.

3.1.1 Sensor Locations

Per SAE J211-1, in order to measure multi-axial accelerations, each acceleration transducer axis must pass within 0.394 inch (10.0 mm) of the point of interest (e.g., the head CG), and the center of the seismic mass of each accelerometer should be within 1.181 inches (30.0 mm) of that point. The orientation of the measurement axis should not be greater than 5 degrees from the reference axis.

Load cell sensors should match the location indicated on the drawing to within 0.2 inch (5.08 mm). The orientation of the measurement axis should not be greater than 2 degrees from the reference axis.

3.2 Sub-Assembly Evaluation

The ATD specifications include static and dynamic sub-assembly tests. The results of simulations of these tests using the v-ATD (or sub-assemblies) should fall within the tolerance ranges cited in the specifications.

3.2.1 Hybrid II ATD

3.2.1.1 Hybrid II Regulations

The Hybrid II is defined in § 49 CFR Part 572 subpart B. The following regulations define the sub-assembly evaluations:

Head - § 49 CFR Part 572.6

Neck - § 49 CFR Part 572.7

Thorax - § 49 CFR Part 572.8

Limbs - § 49 CFR Part 572.10

Since no tolerance is given for the probe velocity in § 49 CFR Part 572.8 and § 49 CFR Part 572.10, it is suggested to use the tolerance cited in subsections § 49 CFR Part 572.34 and § 49 CFR Part 572.35.

3.2.1.2 Hybrid II Pelvic Compression

In order to determine the amount of material under the ischial tuberosities, perform a simple static compression test. For the Hybrid II physical ATD, place the pelvis buttocks up onto a 5.362 inch (136.19 mm) tall pedestal that bolts to the lumbar load cell mounting surface of the pelvis as shown in Figure 1. Place a 75 pound (34 kg) object onto the pelvis and wait 5 minutes. Measure the distance from the top surface of the pelvis to the bottom surface of the pedestal. This distance must be between 10.402 inches (264.21 mm) and 10.802 inches (274.37 mm).

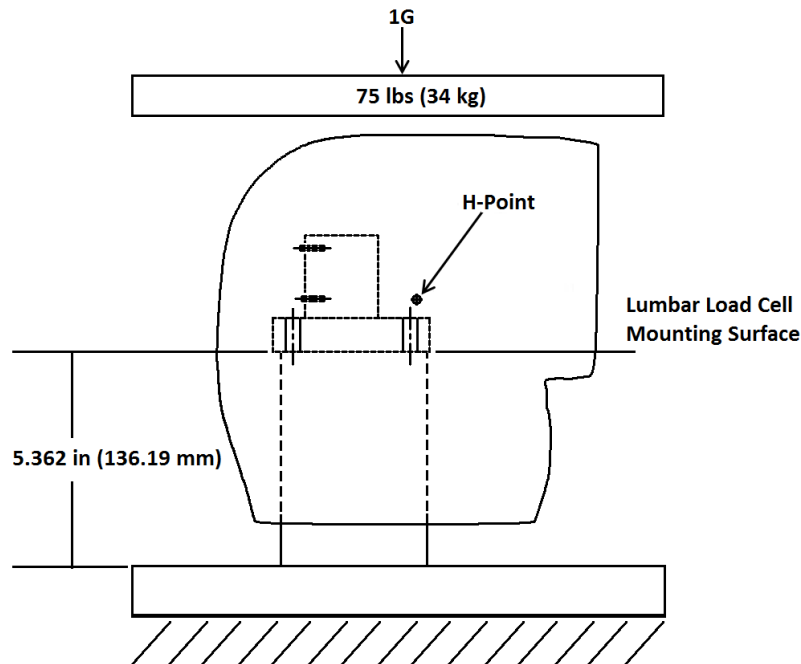


Figure 1 - Pelvis compression illustration

For the Hybrid II v-ATD, the pedestal may be simulated by locking the pelvis (i.e., allowing 0 degrees of freedom) such that the lumbar load cell mounting surface is 5.362 inches (136.19 mm) above a reference plane. Place a 75 pound (34 kg) object above the pelvis and apply a gravity load to the object. A rectangular plate with width and depth greater than the size of the pelvis is sufficient. Once equilibrium is reached, the distance measurement can be made; it is not necessary to simulate the 5-minute wait time. A plot of the position of the 75 pound (34 kg) object or the contact force between the object and the pelvis should be used to demonstrate equilibrium.

If the lumbar load cell mounting surface is not explicitly modeled in the v-ATD, the pedestal height can be modified to account for the distance between the mounting surface and the H-pt. This distance is 1.344 inches (34.14 mm) for the Hybrid II.

3.2.2 FAA Hybrid III ATD

3.2.2.1 FAA Hybrid III Regulations

The FAA Hybrid III ATD contains parts from the Hybrid II and Hybrid III ATDs. Details on the construction of the ATD can be found in SAE 1999-01-1609. As a composite ATD, not all specifications listed in the CFR will be applicable. To evaluate the FAA Hybrid III sub-assembly tests specified in § 49 CFR Part 572 subpart B and § 49 CFR Part 572 subpart E are used; however, neither thorax test is applicable. The following regulations define the applicable sub-assembly evaluations:

Head - § 49 CFR Part 572.32

Neck - § 49 CFR Part 572.33

Limbs - § 49 CFR Part 572.35

3.2.2.2 FAA Hybrid III Pelvic Compression

In order to determine the amount of material under the ischial tuberosities, perform a simple static compression test. For the FAA Hybrid III physical ATD, place the pelvis buttocks up onto a 5.362 inch (136.19 mm) tall pedestal that bolts to the lumbar load cell mounting surface of the pelvis as shown in Figure 1. Place a 75 pound (34 kg) object onto the pelvis and wait 5 minutes. Measure the distance from the top surface of the pelvis to the bottom surface of the pedestal. This distance must be between 10.222 inches (259.63 mm) and 10.362 inches (263.19 mm).

For the FAA Hybrid III v-ATD, the pedestal may be simulated by locking the pelvis (i.e., allowing 0 degrees of freedom) such that the lumbar load cell mounting surface is 5.362 inches (136.19 mm) above a reference plane. Place a 75 pound (34 kg) object above the pelvis and apply a gravity load to the object. A rectangular plate with width and depth greater than the size of the pelvis is sufficient. Once equilibrium is reached, the distance measurement can be made; it is not necessary to simulate the 5-minute wait time. Equilibrium can be shown with a plot of the position of the 75 pound (34 kg) object or the contact force between the object and the pelvis.

If the lumbar load cell mounting surface is not explicitly modeled in the v-ATD, the pedestal height can be modified to account for the distance between the mounting surface and the H-pt. This distance is 1.320 inch (33.53 mm) for the FAA Hybrid III.

3.2.3 ES-2re ATD

3.2.3.1 ES-2re Regulations

The ES-2re is defined in § 49 CFR Part 572 subpart U. The following regulations define the sub-assembly evaluations:

Head - § 49 CFR Part 572.182
Neck - § 49 CFR Part 572.183
Shoulder - § 49 CFR Part 572.184
Thorax (upper torso) - § 49 CFR Part 572.185
Abdomen - § 49 CFR Part 572.186
Lumbar spine - § 49 CFR Part 572.187
Pelvis - § 49 CFR Part 572.188

3.2.3.2 ES-2re Pelvic Compression

There is no standard test for pelvic compression for the ES-2re.

3.3 Pelvis Shape Evaluation

The shape of the ATD's pelvis can significantly affect how it interacts with the seating surface. The following procedure is used to evaluate the v-ATD pelvis shape for the Hybrid II, FAA Hybrid III, and ES-2re:

- 3.3.1 The physical ATD used for this evaluation should have a pelvis that is new or in good condition (no deterioration of the foam or rubber flesh). The joint stiffness for all joints should be adjusted per AS8049.
- 3.3.2 The seat cushion material and geometry used for this evaluation should be a soft, open cell foam with a low initial stiffness (DAX 26 or equivalent per ASTM D3574-11), at least 4.0 inches (101.6 mm) thick, and have x and y dimensions that are greater than or equal to the x and y dimensions the seat pan defined in Figure 2A for the Hybrid II and FAA Hybrid III and Figure 2B for the ES-2re.
- 3.3.3 The finite element (FE) representation of the seat cushion should have the same dimensions as the actual cushion, material properties that are based on measured material properties for that cushion, and appropriately defined FE parameters (such as mesh density and time step). The material properties should be determined by a quasi-static test that loads the center of the physical cushion with a round flat platen 8.0 inches (203.2 mm) in diameter. Only the loading portion of the response is needed for the purposes of this procedure. The FE cushion model should be evaluated by simulating the quasi-static test of the physical cushion. The force on the plate calculated by the cushion model should be within 5% of the measured force for cushion engineering strain values of 10%, 20%, 30%, 40%, 50%, 60%, 70%, and 80%.

- 3.3.4 Position the physical ATD as specified in § 49 CFR Part 572.11 for checking dimensions (other than the head position which should be at the nominal location) and measure the H-point location (x and z) and pelvis orientation (angle about the y-axis) when seated on a rigid surface and when seated on the cushion. The rigid surface should have a pan angle of 0 degrees, a back angle of 0 degrees, and a footrest height 16.0 inches (406.4 mm) below the pan-back intersection for the no cushion seatings. Note that the footrest height must be adjusted (by the difference in the H-pt heights, with and without the cushion) after the cushion is installed to maintain the same pelvis and upper leg angle for both conditions. For consistency in the location of the x component of the H-pt, apply approximately 20 pounds (89 N) to the ATD's knees and keep the upper legs horizontal by supporting them just behind the knees while lowering the ATD into the seat. Seat and measure the ATD three times with no cushion and three times with the cushion (six total seatings). Calculate the H-pt vertical height difference by subtracting the average H-pt z-position on the rigid surface from the average H-pt z-position with the cushion. Calculate the H-pt horizontal depth difference by subtracting the average H-pt x-position on the rigid surface from the average H-pt x-position with the cushion. The pelvic orientation should be within 2 degrees for all six seatings and the average angle should be recorded.
- 3.3.5 Perform a simulation with the v-ATD in the same position as specified in § 49 CFR Part 572.11 for checking dimensions (other than the head position which should be at the nominal location) with a 1 g vertical load applied. Determine the H-point location (x and z) and pelvic orientation (angle about the y-axis) when seated in equilibrium on a rigid surface and when seated on the cushion. Note that the footrest height must be adjusted (by the difference in the H-pt heights) after the cushion is installed to maintain the same pelvis and upper leg angle for both conditions. Calculate the H-pt height difference by subtracting the H-pt z-position on the rigid surface from the H-pt z-position with the cushion. Calculate the H-point depth difference by subtracting the H-pt x-position on the rigid surface from the H-pt x-position with the cushion. The difference between the average H-pt height difference of the ATD and the v-ATD should be no greater than 0.2 inch (5.08 mm). The difference between the average H-pt depth difference of the ATD and the v-ATD should be no greater than 0.2 inch (5.08 mm). The difference between the average pelvis orientation (angle about the y-axis) of the ATD and of the v-ATD when seated on either the rigid surface or the soft cushion should be no greater than 2 degrees.

3.4 Dynamic Response Evaluation

Existing ATD specifications and calibration tests do not directly evaluate the ATD's response to all of the loading conditions that can occur during aircraft seat dynamic tests. To ensure that v-ATDs adequately emulate the physical ATDs when subjected to these unique loading conditions, comparisons with results of representative full scale sled tests are needed. The test parameters specified herein are designed to produce the range of ATD articulation, force application points and force magnitudes that are typical of those observed during tests of actual aircraft seats. To minimize as many variables as possible, a rigid seat and restraint systems with fixed anchorages are recommended.

3.4.1 General Dynamic Response Test Requirements

- 3.4.1.1 Rigid seat geometries including anchorage points, contact surface locations, load cell locations are provided in Figure 2A for forward facing seat ATD (Hybrid II and FAA Hybrid III) and Figure 2B for side facing seat ATDs (ES-2re).
- 3.4.1.2 The contact surfaces should be rigid, flat, and smooth. The seat pan and floor should be covered with two layers of Teflon sheet.
- 3.4.1.3 The ATD used for these evaluations should meet its design and calibration specifications as defined in § 49 CFR Part 572. Forward facing seat ATD (Hybrid II and FAA Hybrid III) should be clothed per AS8049 and side facing seat ATDs (ES-2re) should be clothed per AS8049/1. Clothing may be cut away as necessary to avoid obscuring photometric targets.
- 3.4.1.4 Photometric target markers should be placed as per SAE J211-2 and Tables 1A or 1B depending, on the specific ATD.
- 3.4.1.5 Place the ATD in the seat consistently. Forward facing seat ATD (Hybrid II and FAA Hybrid III) should be placed per AS8049 and side facing seat ATDs (ES-2re) should be placed per AS8049/1.
- 3.4.1.6 Each test condition should be repeated a minimum of three times.

3.4.1.7 Restraint Systems

3.4.1.7.1 Forward facing ATD restraint systems should use 2 inch (50.8 mm) wide nylon webbing and have fixed anchorage points.

3.4.1.7.2 Side facing ATD restraint systems should use 2 inch (50.8 mm) wide polyester webbing and have fixed lap belt anchorage points. The shoulder belt should allow for payout to replicate typical installations.

3.4.1.8 Adjust the lap belt pre-tension per AS8049.

3.4.2 Dynamic Response Test Setup Documentation

3.4.2.1 Document the surface geometry in contact with the ATD and the location of the belt anchors and guides.

3.4.2.2 Document the restraint system geometry (length, width, thickness, and location of both rigid and flexible components).

3.4.2.3 Document the restraint system pre-tension or slack values.

3.4.2.4 Document the initial position of significant ATD anthropometry landmarks defined in Table 2 and all photometric target markers used to track those locations. Also, document the position of photometric reference targets used for scaling and/or validation per SAE J211-2. The origin for these measurements should be the intersection of the seat back and seat pan at the seat centerline.

3.4.3 Dynamic Response Test Data Requirements

3.4.3.1 The data reported should all be in engineering units versus time with 1 kHz sampling frequency for position and 10 kHz for all other channels. Electronic data should be recorded for a minimum of 300 ms after impact. Position data (derived from high speed video) should be recorded for the period of significant occupant response.

3.4.3.2 Record and process all electronic data per SAE J211-1. For the FAA Hybrid III and ES-2re, neck force and moment data recorded should be translated to the occipital condyle location. Perform a tare correction on the seat pan force data to compensate for the forces and moments induced by the mass attached to the load cell. Record seat pan forces in the local (seat pan) coordinate system. Seat pan moments recorded should be translated to the top of the seating surface at the center of the seat pan.

3.4.3.2.1 For the ES-2re, the neck forces should be filtered at CFC 600 per AS8049/1.

3.4.3.3 Record and process all photometric data per SAE J211-2. The accuracy of photometric length calculations should be determined per SAE J211-2 and reported. The origin for the position data should be the intersection of the seat back and seat pan at the seat centerline.

3.4.4 Specific Test Requirements

A minimum data set for each test condition should be defined such that the relative importance of each type of measurement is considered. Occupant kinematics are given the highest priority since they are directly related to head strike potential and are the product of the forces and accelerations measured. Forces produced are next in priority since they directly assess occupant interaction with restraint systems and seating surfaces. Acceleration measurements are lowest in priority and typically only used to provide a means of comparing occupant response for regions of the body where kinematic or force measurements are not possible. Example datasets are noted in Appendices B, C, and G.

3.4.4.1 Specific Test Requirements for Forward Facing ATDs

- The minimum data set to be gathered for each test condition is defined in Table 3 with an X notation. Cells left blank are intentionally blank.
- Scenario 1: Forward facing test with a two-point belt and without a toe stop. The input acceleration pulse is the 16 g, with a velocity change of 44 ft/s (13.41 m/s) defined in Part 25.562 for the horizontal test condition.
- Scenario 2: 60 degree pitch test with a two-point belt. The input acceleration pulse is the 19 g, with a velocity change of 31 ft/s (9.45 m/s) defined in Part 23.562 for the combined horizontal-vertical test condition.
- Scenario 3: Forward facing test with a three-point belt. Adjust shoulder belt to produce 1.25 inches (31.75 mm) of initial slack. The input acceleration pulse is the 21 g, with a velocity change of 42 ft/s (12.8 m/s) defined in Part 23.562 for the horizontal test condition. The geometry of the three-point restraint system should be such that the shoulder belt to lap belt attachment point is 4 inches (101.6 mm) to the right of the ATD centerline.
- Scenario 4: Forward facing test with a four-point belt. Adjust shoulder belt to produce 1.25 inches (31.75 mm) of initial slack. The input acceleration pulse is the 21 g, with a velocity change of 42 ft/s (12.8 m/s) defined in Part 23.562 for the horizontal test condition.

3.4.4.2 Specific Test Requirements for Side Facing ATDs

- The minimum data set to be gathered for each test condition is defined in Table 6 with an X notation. Cells left blank are intentionally blank.
- Scenario 1: Side-facing test with a three-point, body-centered belt. The input acceleration pulse is the 9 g, 80 ms rise time, and a velocity change of 26 ft/s (13.41 m/s).
- Scenario 2: Side-facing test with a three-point, body-centered belt and an armrest. The input acceleration pulse is the 9 g, 80 ms rise time, and a velocity change of 26 ft/s (13.41 m/s).

3.4.5 Simulation of the Dynamic Evaluation Tests

3.4.5.1 Each of the tests specified in 3.4.4 should be simulated using the v-ATD being evaluated. Simulation parameters should reflect the general and specific test requirements specified in 3.4.1 and 3.4.4. However, the actual values recorded per 3.4.2 should be used to compensate for setup variability. The v-ATD should be positioned in the equilibrium position that most closely matches the pre-test location of the ATD. This will require some engineering judgment since v-ATD dimensions typically vary somewhat from the ATD. The difference in achieved ATD initial position and test acceleration pulse during each repeated test should be minimal. The v-ATD developer is encouraged to use the initial conditions and sled pulse from one of the repeated tests as the input to a single simulation to compare to the repeated tests. However, if the variability of the test initial positions or sled pulses cause a poor test-simulation comparison, the v-ATD developer may run additional simulations using the specific test inputs for the simulation. The v-ATD developer and anyone reviewing the results of the v-ATD evaluation is encouraged to use engineering judgment during each phase of creating the model and the reviewing the results.

3.4.5.2 Simulation parameters not directly measured during the tests should be derived as follows:

- Static and dynamic force-deflection characteristics of the restraint used for the tests should be determined by a component test. This should include loading, unloading and hysteresis characteristics.
- The average friction coefficient between the ATD and the contact surfaces should be 0.2. Since friction is in practice difficult to quantify, this nominal value will be assumed for consistency.
- A value of 0.35 should be used for the average friction coefficient between the ATD and the restraint system. Since friction is in practice difficult to quantify, this nominal value will be assumed for consistency.

3.4.5.3 Simulation data produced should meet the same requirements and have the same data origins as the test data specified in 3.4.3 to facilitate direct comparison.

3.4.6 Comparison of Test and Simulation Results

The comparison of model results to full-scale tests should be done using quantitative error metrics. For each test and simulation pair, calculate the error for the parameters being evaluated using the procedures contained in Appendix A. The maximum error for each parameter should be calculated from three repeated test and simulation pairs. If one simulation is used to match three (or more) tests, that simulation should be compared to each test. If individual simulations are executed for each test, only the matched test and simulation need to be compared.

3.4.6.1 Forward Facing ATD Test and Simulation Comparison

The minimum data channels considered necessary to fully evaluate the dynamic performance of ATD are listed in Table 3. The parameters in Table 3 were examined to determine the type of evaluation (peak, curve shape, or both) that was appropriate for each data channel. Maximum values for acceptable error on the peak are specified in Table 4, with a notation that the peak of interest is either positive or negative. The number listed in each cell is the relative error (expressed as a percentage) for accelerations and forces or magnitude error (expressed as a scalar in inch [millimeters] or degrees) for position and angles. Maximum values for curve shape error are specified in Table 5. The number listed in each cell is the Sprague and Geers comprehensive error (expressed as a percentage). For each parameter identified in Tables 4 and 5, the error between each test and simulation result should be calculated and the maximum error from the repeated tests should be recorded. Standard rounding practice should be employed.

3.4.6.2 Side Facing ATD Test and Simulation Comparison

The minimum data channels considered necessary to evaluate the dynamic performance of v-ATD are listed in Table 6. The parameters in Table 6 were examined to determine the type of evaluation (peak, curve shape, or both) that was appropriate for each data channel. Maximum values for acceptable error on the peak are specified in Table 7, with a notation that the peak of interest is either positive or negative. The number listed in each cell is the relative error (expressed as a percentage) for accelerations and forces. Maximum values for curve shape error are also specified in Table 7. The number listed in each cell is the Sprague and Geers comprehensive error (expressed as a percentage). For each parameter identified in Table 7, the error between each test and simulation result should be calculated and the maximum error from the repeated tests should be recorded. Standard rounding practice should be employed.

3.5 Compliance Criteria

In order to be fully compliant, a v-ATD must meet all requirements in 3.1 to 3.4 with no deviations from the specified maximum error values. No distinction is made between over and under predicting. A v-ATD that cannot meet all of the defined requirements may be deemed conditionally compliant with corresponding limits imposed on the use of the model. The effect of any deviations from the specified requirements should be addressed. The determination of conditionally compliant, the specification of the v-ATD's limitations, and the use of a conditionally compliant v-ATD will require sound engineering judgment, and the rationale of these decisions should be thoroughly documented. When using the seat system model to support certification, it is recommended that the user engage the regulatory authority early in the process to ensure acceptance of the v-ATD.

3.5.1 Conditionally Compliant Examples (Non-Exhaustive List)

1. A Hybrid II v-ATD that meets all performance requirements in dynamic test scenarios one, three, and four, but cannot meet the performance requirements for scenario two, would only be approved for simulations matching the restraint and load application direction of scenarios one, three, and four.
2. A FAA Hybrid III v-ATD with acceptable correlation for a significant portion of the head path in scenario one could be approved on the condition that the model can only be used in installations where the head path is prevented from exceeding the correlated area by external factors such as structural monuments.
3. A Hybrid II v-ATD that does not meet the shoulder belt loads for scenarios three and four could be allowed with the proper application of engineering judgment. For instance, if the v-ATD greatly over-predicts the belt load, it would not be appropriate for a simulation focused on determining head path since the extra belt load would most likely shorten the head trajectory. Conversely, if the v-ATD significantly under-predicts the shoulder belt load, the v-ATD may still have utility in a head path simulation, where it would likely produce a conservative result. However, this v-ATD would not be recommended for situations where the belt loads are close to the regulatory limits.

3.6 Documentation

Documentation showing compliance with all evaluations contained in this section should be available to all users of the v-ATD. This documentation should be analogous to the certification report that accompanies a physical ATD. An example v-ATD calibration report is contained in Appendix D. As with physical ATDs, it is important to have configuration control over the v-ATD. As such, all documentation should make clear the version of the v-ATD, the software platform used, and what parameters can be updated without invalidating the model. All evaluations detailed in this section need to be included in the documentation, as specified below.

3.6.1 Software and Hardware Platform Documentation

As in all computational models, the numerical accuracy of the v-ATD may be dependent on the specific configuration of the hardware and operating system used. In addition, experience suggests that results of any computational software may deviate with release of newer versions of the same software. Therefore, the v-ATD developer should ensure that, regardless of the release versions of software, the performance of the v-ATD meets the requirements defined in this document. When calibrating the v-ATD, either to the complete or partial calibration set defined in 3.1 to 3.4, the v-ATD developer should document the version of the v-ATD, the version of the simulation software, the operating system, and the computer hardware platform that accomplished the calibration for knowledge transfer to the end-users.

3.6.2 Mass and Geometry Evaluation Documentation

The following mass and geometry information should be included in the v-ATD calibration report:

- Table of external dimensions: Citing the specification, tolerance, and actual value.
- Table of total and segment weights: Citing the specification, tolerance, and actual value.
- Table of the centers of gravity for segments: Citing the specification, tolerance, and actual value.
- Table of sensor location of v-ATD in comparison to physical ATD, including notation of the node, joint, or body used to calculate the output.

3.6.3 Sub-Assembly Evaluation Documentation

The following sub-assembly information should be included in the v-ATD calibration report:

- Specification, test results, and corridor plots (where appropriate).

3.6.4 Pelvis Shape Evaluation Documentation

The following pelvis shape evaluation documentation should be included in the v-ATD calibration report:

- Table of measurements versus test data .
- Details of foam properties as used.

3.6.5 Dynamic Response Evaluation Documentation

The following dynamic response evaluation information should be included in the v-ATD calibration report:

- Tables 4 and 5 error information with simulation results.
- Plots of data for each channel.
- Details of belt properties as used.

3.6.6 Conditionally Compliant v-ATD Documentation

For models that do not meet all the requirements, the documentation should clearly list the limitations and intended use of the v-ATD. The effect of any deviations from the specified requirements should be addressed.

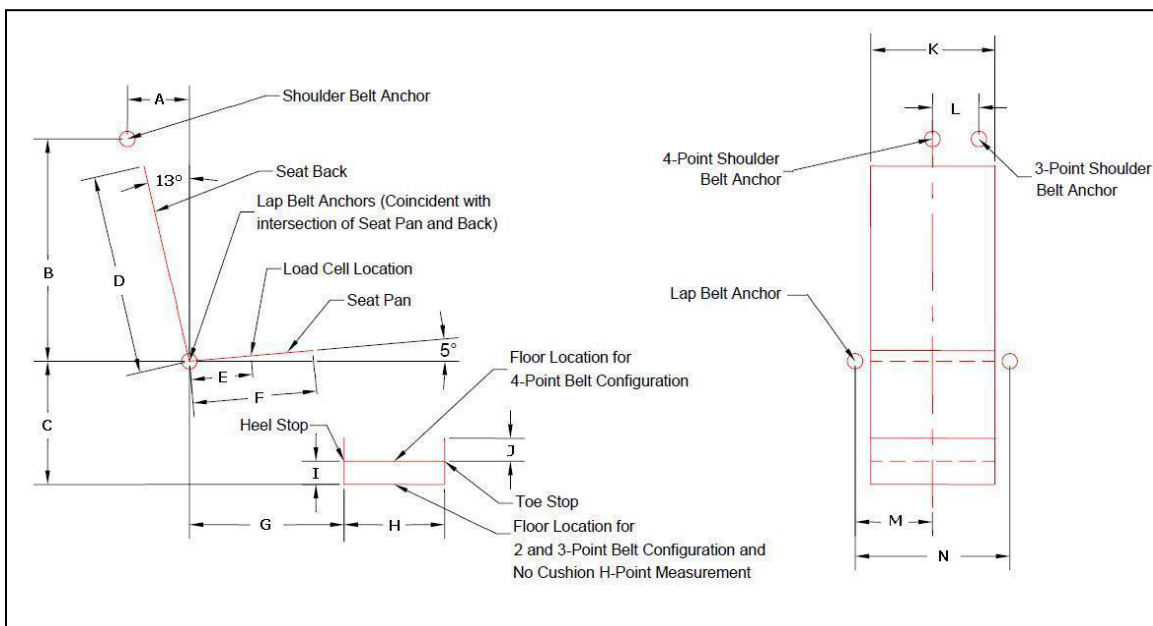


Figure 2A - Seat dimensions for tests of forward facing ATDs

Table 1A - Seat dimensions for tests of forward facing ATDs

Dimension	Letter	Distance (inch)	Distance (mm)
Shoulder belt anchor depth	A	8	203
Shoulder belt anchor height	B	29	737
Seat pan-back intersection height	C	16	406
Seat back length	D	26	660
Pan-back to load cell center	E	8	203
Seat pan length	F	16	406
Pan-back to heel stop length	G	20	508
Heel stop to toe stop length	H	13	330
Floor height (four-point belt configuration)	I	3	76
Toe stop height	J	3	76
Seat width (minimum)	K	18	457
Seat centerline to three-point shoulder belt anchor	L	7	178
Seat centerline to lap belt anchor	M	10	254
Lap belt anchor width	N	20	508

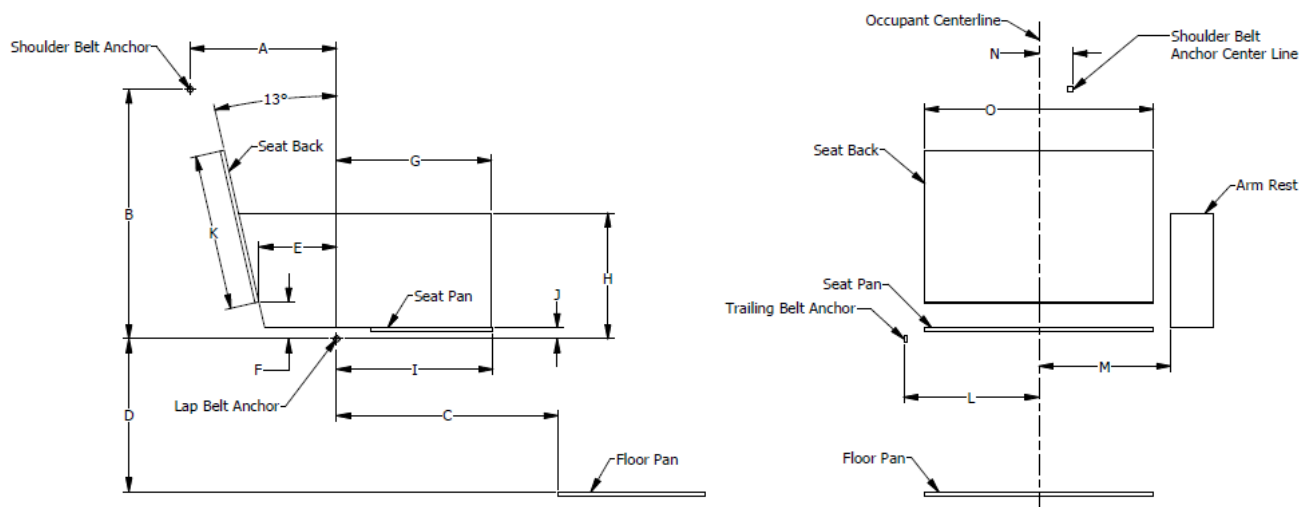


Figure 2B - Seat dimensions for tests of ES-2re

Table 1B - Seat dimensions for tests of ES-2re

Dimension	Letter	Distance (inch)	Distance (mm)
Shoulder belt anchor depth	A	13	325
Shoulder belt anchor height	B	22	554
Floor depth	C	19	493
Floor height	D	13	340
Lower seat back depth	E	7	173
Lower seat back height	F	3	82
Front of armrest depth	G	14	343
Top of armrest height	H	11	279
Front of seat pan depth	I	14	348
Seat pan height	J	1	25
Seat pan length	K	14	345
Seat centerline to lap belt anchor	L	12	300
Seat centerline to armrest	M	12	292
Seat centerline to three-point shoulder belt anchor	N	3	76
Seat width (minimum)	O	20	508

Table 2 - ATD anthropometry landmarks

#	Name	Definition	Measured Point
1	H-point	Intersection of a line passing through both hip joints and the midsagittal plane of the ATD	Measured at the surface of the hip flesh
2	Head CG	Intersection of a line along the y-axis passing through the head center of gravity and the midsagittal plane of the ATD	Measured at the surface of the head flesh
3	Knee	Intersection of the centerline of the knee pivot and the midsagittal plane knee	Measured at the surface of the knee pivot bolt head
4	Ankle	Intersection of the centerline of the ankle pivot and the midsagittal plane of the ankle	Measured at the surface of the ankle pivot bolt head
5	Shoulder	Intersection of the centerlines of the shoulder horizontal pivot and the fore-aft pivot	Measured at the surface of the shoulder flesh
6	Elbow	Intersection of the centerline of the elbow pivot and the midsagittal plane of the elbow	Measured at the surface of the elbow pivot bolt head for the Hybrid-II or the outboard surface of the elbow flesh for the FAA Hybrid-III
7	Wrist	Intersection of the centerline of the wrist pivot and the midsagittal plane of the wrist	Measured at the surface of the wrist flesh
8	Pelvis angle	The angle that the x-axis of the lumbar spine load cell makes with the seat x-axis	Measured using auxiliary markers placed at known locations relative to the pelvis coordinate system
9	Head angle	The angle that the x-axis of the head accelerometer array makes with the seat x-axis	Measured using auxiliary markers placed at known locations relative to the head coordinate system

NOTES:

1. When the ATD is in a typical seated posture, the location of each of the defined points can be estimated by adding half the breadth (width along y-axis) of the ATD or joint to the measured point's y-dimension.
2. At a minimum, photometric targets should be placed at measured points 1 through 5 and as necessary to calculate head angle and pelvis orientation throughout the test.
3. The seat coordinate system does not include the seat pan angle. In the current rigid seat configuration, the seat coordinate system is equivalent to the sled or laboratory coordinate systems for the 0 degree test conditions.

Table 3 - Dynamic calibration channel set for forward facing ATD

Channel Description	Forward Facing Two-Point Belt	Forward Facing 60 Degree Two-Point Belt	Forward Facing Three-Point Belt	Forward Facing Four-Point Belt
Sled Ax	X	X	X	X
Upper Neck Fx *			X	X
Upper Neck Fy *			X	
Upper Neck Fz *			X	X
Upper Neck Mx *			X	
Upper Neck My *			X	X
Chest Ax (CFC 180)			X	X
Lumbar Fz		X		
Lumbar My		X		
Right Lap Belt Load	X		X	X
Left Lap Belt Load	X		X	X
Right Shoulder Belt Load				X
Left Shoulder Belt Load			X	X
Seat Pan Fx	X	X	X	X
Seat Pan Fz	X	X	X	X
Seat Pan My	X	X	X	X
Head CG X Position	X	X	X	X
Head CG Z Position	X	X	X	X
H-point X Position	X		X	X
H-point Z Position	X	X		
Knee X Position	X			X
Knee Z Position	X			X
Ankle X Position	X			
Ankle Z Position	X			
Shoulder X Position			X	X
Shoulder Z Position			X	X
Opposite Shoulder X Position			X	
Opposite Shoulder Z Position			X	
Head Angle **	X			X
Pelvis Angle **	X	X		X

NOTES:

* FAA Hybrid III only.

** Angle can be determined using photometrics or angular rate sensors.

Blank cells intentionally left blank.

Table 4 - Maximum allowable peak error for forward facing v-ATD**

Channel Description	Forward Facing Two-Point Belt		Forward Facing 60 Degree Two-Point Belt		Forward Facing Three-Point Belt		Forward Facing Four-Point Belt	
Upper Neck Fx *					10%	-	20%	-
Upper Neck Fy *					30%	-		
Upper Neck Fz *					15%	+	30%	+
Upper Neck Mx *					25%	-		
Upper Neck My *					10%	+	20%	+
Chest Ax (CFC 180)					10%	-	10%	-
Lumbar Fz			10%	-				
Lumbar My								
Right Lap Belt Load	10%	+			10%	+	10%	+
Left Lap Belt Load	10%	+			10%	+	10%	+
Right Shoulder Belt Load							10%	+
Left Shoulder Belt Load					10%	+	10%	+
Seat Pan Fx								
Seat Pan Fz	25%	-	10%	-	25%	-	10%	-
Seat Pan My	20%	-	10%	-	10%	-	20%	-
Head CG X Position	0.5 inch (12.7 mm)	+			1.75 inches (44.45 mm)	+	0.25 inch (6.35 mm)	+
Head CG Z Position							0.3 inch (7.62 mm)	-
H-point X Position	0.25 inch (6.35 mm)	+			1.25 inches (31.75 mm)	+	0.5 inch (12.7 mm)	+
H-point Z Position	0.2 inch (5.08 mm)	+	0.1 inch (2.54 mm)	-				
Knee X Position	0.5 inch (12.7 mm)	+					0.5 inch (12.7 mm)	+
Knee Z Position								
Ankle X Position								
Ankle Z Position								
Shoulder X Position					2.0 inches (50.8 mm)	+	0.5 inch (12.7 mm)	+
Shoulder Z Position							0.5 inch (12.7 mm)	-
Opposite Shoulder X Position					0.5 inch (12.7 mm)	+		
Opposite Shoulder Z Position								
Head Angle ***							8 degrees	-
Pelvis Angle ***	7 degrees	-	3 degrees	+			5 degrees	+

NOTES:

* FAA Hybrid III only.

** Column with plus or minus denotes peak of interest is either a global maxima or minima.

*** Angle can be determined using photometrics or angular rate sensors.

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Table 5 - Maximum allowable curve shape error for forward facing v-ATD

Channel Description	Forward Facing Two-Point Belt	Forward Facing 60 Degree Two-Point Belt	Forward Facing Three-Point Belt	Forward Facing Four-Point Belt
Upper Neck Fx *			10%	10%
Upper Neck Fy *			30%	
Upper Neck Fz *			20%	25%
Upper Neck Mx *			40%	
Upper Neck My *			10%	40%
Chest Ax (CFC 180)			10%	15%
Lumbar Fz		15%		
Lumbar My		25%		
Right Lap Belt Load	15%		10%	10%
Left Lap Belt Load	15%		10%	10%
Right Shoulder Belt Load				10%
Left Shoulder Belt Load			10%	10%
Seat Pan Fx	20%	5%	15%	10%
Seat Pan Fz	20%	5%	15%	10%
Seat Pan My	20%	10%	10%	15%
Head CG X Position	10%	10%	10%	10%
Head CG Z Position	10%	15%	30%	10%
H-point X Position	10%		20%	10%
H-point Z Position	10%	15%		
Knee X Position	10%			10%
Knee Z Position	10%			10%
Ankle X Position	15%			
Ankle Z Position	20%			
Shoulder X Position			15%	15%
Shoulder Z Position			40%	15%
Opposite Shoulder X Position			10%	
Opposite Shoulder Z Position			75%	
Head Angle **	10%			10%
Pelvis Angle **	10%	20%		10%

NOTES:

* FAA Hybrid III only.

** Angle can be determined using photometrics or angular rate sensors.
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Table 6 - Dynamic calibration channel set for side facing v-ATD

Channel Description	Side Facing with Armrest	Side Facing No Armrest
Sled Ax	x	x
Left Leg Rotation	x	
Right Leg Rotation	x	
Upper Neck Shear *	x	x
Upper Neck Fz	x	x
Upper Neck Mx	x	x
Upper Neck My	x	x
Upper Neck Mz	x	x
Shoulder Belt Load	x	x
Right Lap Belt Load	x	x
Center Lap Belt Load	x	x
Shoulder Belt Payout	x	x
Wall Load Fy	x	

NOTES:

- * Neck shear is the resultant of the X- and Z-components as defined in AS8049/1.
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Table 7 - Maximum allowable peak and curve shape error for side facing v-ATD

Channel Description	Side Facing					
	Peak Magnitude Error				Shape Error	
	w/Armrest		No Armrest		w/Armrest	No Armrest
Left Leg Rotation (degrees)					20% **	
Right Leg Rotation (degrees)					20% **	
Upper Neck Shear Force *	15%	+	15%	+	15%	15%
Upper Neck Fz	15%	+	15%	+	15%	15%
Upper Neck Mx	15%	+	15%	+	15%	15%
Upper Neck My	30%	-	30%	-	30%	30%
Upper Neck Mz	30%	+	30%	+	30%	30%
Shoulder Belt Load	15%	+	15%	+	15%	15%
Center Belt Load	30%	+	30%	+	30%	30%
Shoulder Belt Payout	***		***			
Wall Load Fy	30%	+			30%	

NOTES:

- * Neck shear is the resultant of the upper neck Fx and Fy.
 ** Due to the looseness of the ES-2re hip joint, the evaluation should demonstrate the the leg freely rotates from zero to 45 degrees.
 *** The maximum belt payout should fall within the range of the test data scatter.

4. SEAT SYSTEM VERIFICATION AND VALIDATION

The purpose of a model is the accurate representation of a real-world system, where the accuracy required is dependent on the intended use of the model. The processes used to evaluate the accuracy of the computer model in representing both the real world and the underlying mathematical model are called verification and validation (V&V). The V&V process generates evidence and establishes credibility that the computer model has the adequate accuracy and level of detail to support certification by analysis (CBA), and this evidence is included in a verification and validation report (VVR). This section provides suggestions for the information to be included in VVR.

By following the V&V process, the modeler improves the likelihood that the model will accurately predict the response of the seat system and will generate the necessary documentation to substantiate its use for certification. The method recommended in this section is based on ASME V&V10-2019 with modifications that tailor this guidance to better apply to aviation seats. Figure 3 shows the suggested V&V approach. Activities appear in plain text, and the products of these activities are shown in rounded boxes. First, the reality of interest is defined, which is the physical system and its associated environment to which the computational model will be applied (i.e., its intended use). While the intended use of the model will affect many decisions, the basic concepts of V&V are the same regardless of model use. Next, the physical system is abstracted into a conceptual model, which includes the descriptions of the physical processes and assumptions.

At this point in the process, two parallel paths are formed to separate modeling and simulation (M&S) activities from physical testing activities. In the M&S branch, the conceptual model is described by a set of mathematical equations and modeling data that approximate the physical reality. The terms code, model, and simulation have specific, complementary definitions taken from ASME V&V10-2019. Code refers to the computer implementation of algorithms, i.e., software. The model is the conceptual, mathematical, and numerical representation of the physical phenomenon. The simulation is the execution of a model. Thus, a model can be run multiple times, often with minor changes to initial conditions, generating multiple simulation results.

The first step is to determine whether the software solves the model properly. This process is called code verification. Next, it is important to determine that the numerical error, from the time step and mesh resolution (for finite element models), is low. This process is called calculation verification. The results of the model are then quantitatively compared to the results of the physical experiment. When acceptable agreement is observed, the model can then be used to predict the system response to an untested, but similar, scenario. Sensitivity analysis is recommended to guide the extent of extrapolation and to define limitations on the model.

This method can be applied to a model that is intended to show full seat system compliance to one or more of the three basic test configurations (combined horizontal-vertical, structural, or occupant injury). This method may also be applied to component models intended to show some specific behavior. The method includes baseline material characterization along with traceability of material properties, component level response (when applicable), use of calibrated v-ATDs, and integrated seat system responses, which includes the interaction with the v-ATD. Sensitivity analysis is recommended throughout the process to determine the sensitivity of model inputs that are difficult to measure (e.g., friction) or inputs that are not known with high certainty.

Verification and validation of a complete seat model is a complex task whereby definition of a standardized set of steps cannot be provided as they can be for the v-ATD. It is important to use engineering judgment to identify and evaluate the parameters of importance. In cases, where the models are the primary source of certification data, it is important to obtain concurrence from the regulatory authorities on how to proceed toward validation. It is likely that the specifics will need customization depending on the specific seat model and the availability of test data.

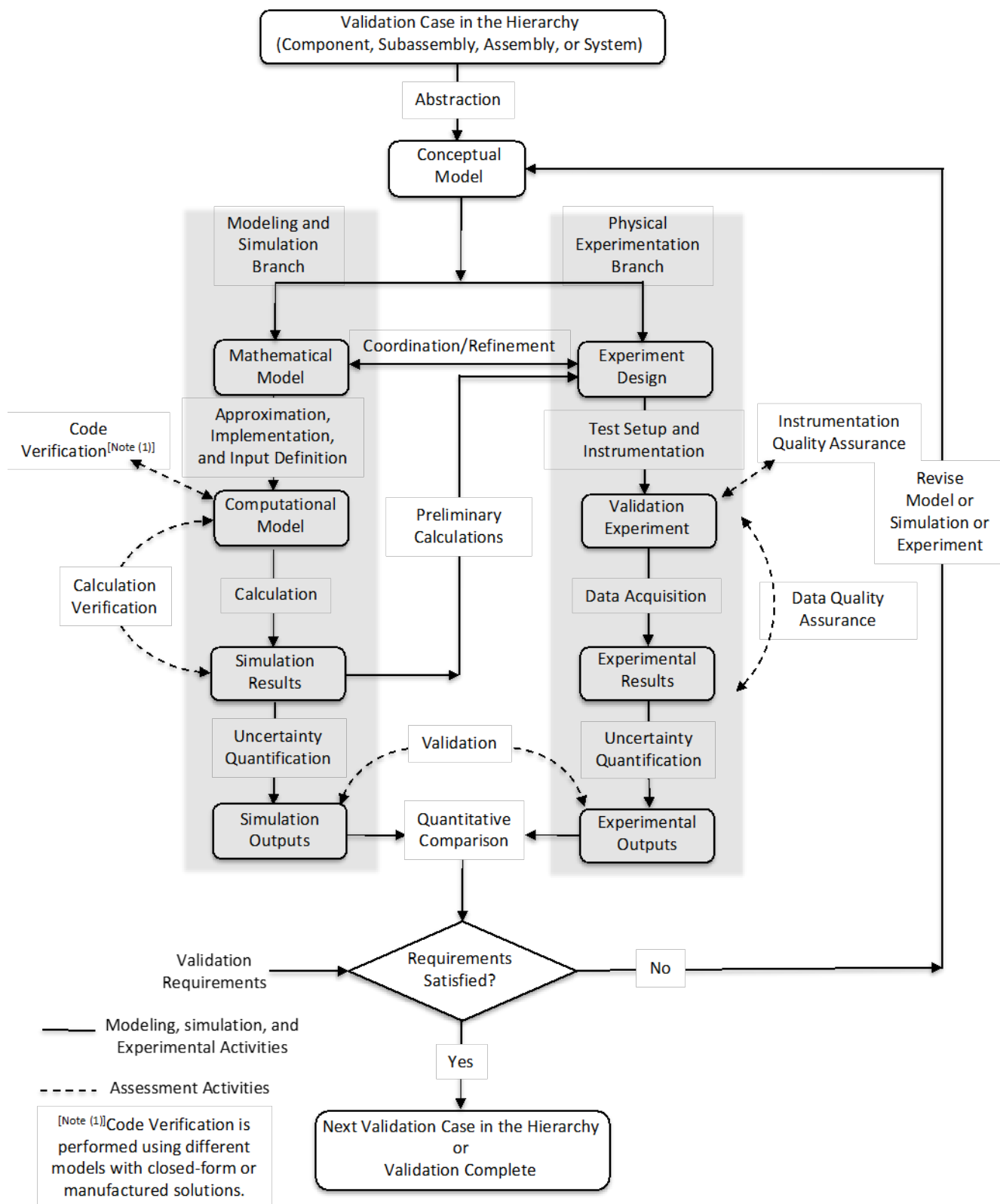


Figure 3 - ASME V&V10-2019 process map (ASME V&V10-2019)

Top-level guidance is provided in FAA advisory circular AC 20-146A which describes the use of computer modeling analysis within seat certification. This includes general guidance on how to validate the computer models and under what conditions the models may be used in support of certification. This section is intended to complement the FAA guidance by providing an overview of several areas to consider when developing a validation plan and evaluating a model. Because the processes of verification and validation are rapidly evolving and highly depend on the specific problem, this section represents a starting point and updates or modifications of the process may need to be considered.

4.1 V&V Plan, Reality of Interest, Intended Use, and System Response Quantities

Prior to model development, it is useful to generate a V&V plan that includes a description of the reality of interest and intended use of the model, definition of the system response quantities of interest, selection of metrics to compare computed results with experimental measurements, code and solution verification requirements, definition of the accuracy requirements, and specification of validation experiments. This will allow the modeling and testing groups to coordinate physical testing requirements. This document can also be used in initial discussions with a regulatory agency if the work is going to be used for certification.

The first piece of the V&V plan is to define the reality of interest and intended use of a model. The reality of interest includes both the system and the environment modeled. An example at the top level of the system hierarchy is a fully loaded triple place passenger seat under combined horizontal-vertical test condition as defined in 14 CFR 25.562. The reality of interest could also be at the component level. The intended use is the application domain over which the model is expected to make predictions. A few examples are a model for initial seat development, a full seat system model for use in a certification package, and a model of part of the seat to show joint stresses. Once the reality of interest and intended use of the model is defined, they are abstracted into a conceptual model. The conceptual model is the collection of assumptions and descriptions of physical processes representing solid mechanics behavior of the reality of interest from which the mathematical model and validation experiments can be constructed (ASME V&V10-2019). From this, the appropriate modeling details, system response quantities (SRQs), and accuracy requirements will be a natural extension. Certification requirements will tend to be more stringent than internal developmental requirements.

The system response quantities can be split into three groups: primary, support, and threshold. A primary SRQ would be a required channel, such as head resultant acceleration, HIC, or lumbar load, or any quantity is considered critical in evaluating the system, such as floor reaction loads in a structural test. A support SRQ is a channel that provides additional confidence that the model is an accurate representation of the reality of interest. In a scenario where HIC needs to be evaluated, support channels could be head impact velocity and head impact angle. A threshold channel is one that is expected to be very low. An example is lap belt load in a combined horizontal-vertical test. During the critical part of the physical test, the belt load is essentially zero. Definition of a simple threshold can show that the model output does not grossly contradict the test data. For any of the three types of SRQs, engineering judgement can be used to determine specific channels for evaluating the reality of interest and intended use. In general, the SRQs can differ greatly between a structural test, an injury criteria test, and a combined horizontal-vertical test. The analyst is encouraged to discuss the collection of support and threshold channels with the test laboratory. Related recommendations are contained in 7.1.

4.2 Verification

Verification is the process of determining that a computational model accurately represents the underlying mathematical model and its solution (ASME V&V10-2019). This critical step precedes validation, as it is important to minimize/eliminate errors before progressing. Verification is broken into two components, code verification and calculation verification.

4.2.1 Code Verification

Code verification is the process of determining that the numerical algorithms are correctly implemented in the computer code and of identifying errors in the software (ASME V&V10-2019). It helps to ensure the mathematical model and the solution algorithms are working correctly, i.e., the code solution predicts the analytical solution. This is generally performed by the code developer for commercial off the shelf software during the formulation of the code as well as any subsequent updates, such as during the development of new element, material or contact formulation. Code verification should include a robust software quality assurance system that ensures the traceability of code performances for various release versions. The software performance should be verified on commonly used operating systems and hardware platforms and the end-user should be made aware of any limitations. The code developer should provide the end-user with a theoretical manual that describes the basic software algorithms including formulations for element types, material models, contact methods, etc.

The user is encouraged to verify that the code is tested and complies with acceptable closed form or analytical solution. While the code developer should evaluate all of the implemented algorithms, the end-user should focus on the aspects of the code to be used in the individual simulation. As an example, in a seat model simulated with a multipurpose commercial code, only the algorithms related to structural dynamics need to be evaluated, while the algorithms that are related to fluid dynamics could likely be ignored.

Examples of code verification problems can be found in the referenced paper “Explicit Finite Element Code Verification Problems.”

4.2.2 Calculation Verification

Calculation verification, also called solution verification, is the process of determining the solution accuracy of a particular approximate numerical solution to the mathematical model (ASME V&V10-2019). The goal of calculation verification is to show that the numerical errors (due to incomplete spatial or temporal convergence) in the system response quantities (SRQs) of interest are minor compared to the validation requirements. Evaluation of spatial convergence is necessary in components that are in the critical load path.

4.2.2.1 Temporal Discretization

The dividing of the total time of a simulation into smaller segments is called temporal discretization. Each segment is typically referred to as a time step. The stability of explicit integration methods depends on the time step; if it is too large for a given element size L (minimum characteristic length in the model) the method fails, either due to stability issues or poor accuracy. If the element size is smaller than required, the solution time becomes impractical, thus diminishing the effectiveness of the method. Additional guidance such as critical time step for a given model is provided in 7.2.2.2.

In theory, the most numerically efficient solution is obtained when an integrating time step equivalent to the stability limit is chosen. Codes, attempt to offset the problems of numerical instability by regulating and constantly updating the time interval used throughout the analysis. The time step may be recomputed at each cycle based on the changing mesh size. Nonphysical mass can also be added to the structure in order to artificially increase the time step, thereby reducing the run time. Use of mass scaling require defining a time scale factor, typically in the range of 0.6 to 0.9. The time step, including any scale factor, should be reported in the VVR.

4.2.2.2 Spatial Discretization

The finite element analysis technique divides a continuum into finite elements (volumes, surfaces, and line segments) which are interconnected at a discrete number of points, called nodes, and solves the boundary-value problem. The number of elements and the types of elements used will greatly affect the accuracy of the result. For example, a coarse mesh can produce erroneous results. Construction of a model includes a trade-off between the accuracy of the solution, and the amount of time it takes to run the simulation. Typically, the applicant uses the coarsest mesh that produces a sufficient level of accuracy. As such, evaluation of spatial convergence is necessary in components that are in the critical load path. The criteria used to determine that the discretization was sufficient to resolve the physics of interest should be provided in the VVR.

A quasi-quantitative estimate of the spatial convergence can be generated based on two or more mesh refinements. If the results of the numerical solution do not change significantly from the refinement, the mesh is likely close to the asymptotic region. Exact calculation of the spatial convergence error of an explicit structural analysis is a non-trivial pursuit that is an ongoing research activity.

To aid the end-user in this verification process, 7.2 contains information on standard industry practice that will help the modeler to manage the sources of error and methods to discretize the physical structure to reduce modeling error.

4.3 Validation

Validation is the process of determining the degree to which a model is an accurate representation of corresponding physical experiments from the perspective of the intended uses of the model (ASME V&V10-2019). The ability of the model to represent a physical phenomenon is evaluated by comparing the model predictions with physical test data. This process relies on high quality test data and a quantitative comparison of test and simulation results.

4.3.1 Test Data

In order to generate high quality test data for the purposes of modeling a dynamic sled test, 7.1 details recommended practices that go beyond the basic requirements of AS8049. Early communication between the test engineer and engineering analyst provides an opportunity to determine the desired data and the prioritization of that data based on available resources.

All tests conducted for model validation should be documented with sufficient detail to allow for the recreation of the test. Test documentation in a certification package may be sufficient for full-scale sled tests. Component and material characterization tests will require unique documentation, which should include geometry, initial and boundary conditions, loading rates, and photographs. Additional guidance is provided in 4.5 and 7.1.2.

4.3.2 Validation Metrics

A validation metric is a mathematical calculation that defines the distance between an experimental value and a simulation value. This provides a quantitative evaluation of the agreement between the test and simulation. Appendix A describes one method to calculate the error between the results of a numerical simulation and the results of a physical test. Unless otherwise specified, evaluate magnitude error and curve shape error for each required channel. Time histories should be evaluated at the beginning of the onset of the test pulse through significant system response as seen in the physical test. The most significant system response is often the motion of the anthropomorphic test device(s). Channel inputs should have consistent units, appropriate sampling rates (minimum 10000 Hz for electronic instrumentation data and 1000 Hz for photometric data) and equal time lengths. Test and simulation position data needs to have the same global origin (typically the SRP). If necessary, correct units, data set length, and origin offsets during post-processing.

4.3.3 Uncertainty and Sensitivity Analysis

4.3.3.1 Error and Uncertainty

All tests and numerical models contain errors and uncertainties. Error is the quantitative difference between a measured or calculated value and the referent or true value (ASME V&V10-2019). Typical sources of error include numerical solution error (see 4.2.2) and human error, such as incorrect placement of sensors. Uncertainty is the lack of accuracy associated with a measured or calculated value that is due to inherent variability (aleatory uncertainty) or lack of knowledge (epistemic uncertainty) (ASME V&V10-2019). Uncertainty in similar tests exists because of the differences in material tolerances, initial conditions, material properties, differences between test facilities, and differences in ATDs, among others. Uncertainty in the numerical simulation exists because of input parameters, types of hardware, and software, among others. Some of the variability, such as material properties, affects both the physical model and the numerical model.

Ideally, the uncertainty in the model and experiment is explicitly quantified. This requires repeated testing, knowledge of the material variability, knowledge of manufacturing tolerances, sensor accuracy and calibration data, and other information. When that information is unavailable, subject matter experts could be used to estimate the range of experimental or numerical values. The explicit method provides greater confidence in the results of the uncertainty quantification.

4.3.3.2 Sensitivity Analysis

Sensitivity analysis is closely related with uncertainty analysis; while the latter studies the overall uncertainty in the conclusions of the study, sensitivity analysis tries to identify what source of uncertainty weighs more on the study's conclusions. The practitioner will find that disciplined use of the tools and techniques in sensitivity analysis will provide insight not readily understood by ad-hoc cause and effect studies. Typically, problems of complexity addressed in this document are non-linear in nature and multivariable. The multivariable model inherently leads to a multi-dimensional solution space, which can be difficult to understand without these methods.

Quite often, some or all of the model inputs are subject to sources of uncertainty, including errors of measurement, absence of information and poor or partial understanding of the driving forces and mechanisms. This uncertainty imposes a limit on our confidence in the response or output of the model. Good modeling practice requires that the modeler establish confidence in the model. This requires, first, a quantification of the uncertainty in any model results (uncertainty analysis); and second, an evaluation of how much each input is contributing to the output uncertainty.

Sensitivity analysis addresses the second of these issues, performing the role of ordering by importance the strength and relevance of the inputs in determining the variation in the output. "Sensitivity analysis is the general process of discovering the effects of model input parameters on the response features of interest using techniques such as analysis of variance (ANOVA)" (ASME V&V10-2006).

Furthermore, sensitivity analysis can be useful for a range of purposes, including:

- Model simplification: Fixing model inputs that have no effect on the output, or identifying and removing redundant parts of the model structure.
- Increased understanding of the relationships between input and output variables in a system or model.
- Enhancing communication from modelers to decision makers (e.g., by making recommendations more credible, understandable, compelling or persuasive).
- Finding regions in the space of input factors for which the model output is either maximum or minimum or meets some optimum criterion.
- Testing the robustness of the results of a model or system in the presence of uncertainty.
- Uncertainty reduction: Identifying model inputs that cause significant uncertainty in the output and should therefore become the focus of attention if the robustness is to be increased.
- Searching for errors in the model (by encountering unexpected relationships between inputs and outputs).
- In general, most sensitivity procedures adhere to the following outline:
 - Quantify the uncertainty in each input (e.g., ranges, probability distributions). Note that this can be difficult and many methods exist to elicit uncertainty distributions from subjective data.
 - Identify the model output to be analyzed (the target of interest should ideally have a direct relation to the problem tackled by the model).
 - Run the model a number of times using some design of experiments (DoE), dictated by the method of choice and the input uncertainty.
 - Using the resulting model outputs, calculate the sensitivity measures of interest.

In some cases, this procedure will be repeated, for example in high-dimensional problems where the user has to screen out unimportant variables before performing a full sensitivity analysis. Sensitivity analysis is recommended to guide the extent of extrapolation and to define limitations on the model (2.1.4.21). Sensitivity analysis is recommended throughout the model validation process to determine the sensitivity to model inputs that are difficult to measure (e.g., friction) or inputs that are not known with high certainty (see Figure 4).