THE PROCESS OF EVALUTION AND DOCUMENTATION OF CRASH TEST DUMMIES FOR PART 572 OF THE CODE OF FEDERAL REGULATIONS

Daniel Rhule
Heather Rhule
Bruce Donnelly
National Highway Traffic Safety Administration
United States

Paper Number 05-0284

ABSTRACT

A candidate anthropometric test device (ATD), or crash test dummy, must undergo a rigorous evaluation and documentation process before it can be considered for incorporation into Part 572 of the Code of Federal Regulations. This process has been developed over many years and includes (1) thorough dummy and drawing inspection, (2) establishment of dummy certification criteria, (3) evaluation of the dummy's durability, biofidelity, repeatability, and reproducibility, and (4) the generation of a detailed manual for dummy assembly procedures. The evaluation process will be outlined and explained in detail. Recent dummy evaluations for the Thor Lx, the ES-2re and the Ten-year-old HIII dummies will be utilized as examples of the various parts of the process.

INTRODUCTION

The National Traffic and Motor Vehicle Safety Act of 1966 (the Safety Act) [1] authorizes the National Highway Traffic Safety Administration (NHTSA) to prescribe motor vehicle safety standards to reduce deaths and injuries resulting from traffic accidents. The Act requires that each Federal Motor Vehicle Safety Standard (FMVSS) shall be practicable, meet the need for motor vehicle safety, and be stated in objective terms.

NHTSA's FMVSSs generally consist of three groups of regulations: 1) the 100-series dealing with pre-crash avoidance requirements, 2) the 200-series dealing with crashworthiness requirements and 3) the 300-series dealing with post-crash requirements. Many of the 200-series crashworthiness standards specify dynamic crash tests, either full-scale vehicle crash testing or sled crash simulations, that replicate real-world crash scenarios. Anthropomorphic test devices (ATDs or test dummies) are used in these dynamic tests as measuring tools that render repetitive and correlative results under similar test conditions and to reflect the protective performance of a vehicle or item of motor vehicle equipment with respect to human occupants. NHTSA enforces the FMVSSs by testing vehicles or equipment as described in the test procedures contained in the FMVSSs.

In 1970, NHTSA amended Federal Motor Vehicle Safety Standard 208 (FMVSS 208) to require automatic crash protection for all passenger cars as of July 1, 1973 and for most light trucks and vans as of July 1, 1974. Compliance would have been determined by a crash test with ATDs in the front outboard seats. Shortly after the March 10, 1971 final rule, Chrysler, et al. [2] filed lawsuits in the U.S. Court of Appeals for the Sixth Circuit challenging the automatic crash protection requirements. The plaintiffs argued that the automatic crash protection requirement were: (a) not "practicable," as required by the Safety Act, because the technology needed to comply with automatic protection was not sufficiently developed at the time; (b) did not "meet the need for motor vehicle safety," as required by the Safety Act, because seat belts offered better occupant protection than automatic protection; and (c) were not "objective," as required by the Safety Act, because an ATD built to the existing SAE Recommended Practice [3] did not produce consistent, reliable or repeatable test results.

In Chrysler v. DOT, the Sixth Circuit announced its decision on the lawsuits. The court ruled in favor of NHTSA on the first two arguments, but found in favor of the manufacturers on the third argument that the ATD specified by the standard did not meet the criterion of objectivity. The court remanded the case to NHTSA with instructions that further specification be made in objective terms to assure comparable results among test sites. The court further noted that, "The importance of objectivity in safety standards can not be overemphasized." Objective in the context of this case means that (1) the tests and dummies used to determine compliance or non-compliance with the standard produce identical results when the test conditions are duplicated (repeatability and reproducibility), (2) that the accuracy of the tools be demonstrable in a reasonable

test procedure and (3) that vehicle compliance be based upon instrument readings (crash test dummies) as opposed to the opinions of human beings.

NHTSA developed new specifications for the anthropometric test dummy following the Chrysler decision. In 1973, the agency created Part 572 under Title 49 of the Code of Federal Regulations [49 CFR 572], to be a repository for specifications of crash test dummies and similar test devices. At the same time, the agency issued much more detailed test dummy specifications for the ATD to be used in FMVSS 208 testing. That first crash test dummy was the Hybrid II Part 572 Subpart B, 50th Percentile Male.

Since the time of the Chrysler decision, NHTSA has sought to ensure that any candidate ATD considered for possible use in a Federal Motor Vehicle Safety Standard undergoes a rigorous evaluation and documentation process to determine the ATD's suitability for incorporation into Part 572 of 49 CFR. This process includes, as a minimum, the assurance that the dummy meets:

- dimensional, mass, and construction specifications as contained in a drawing set
- performance requirements based on test procedures, also called certification procedures, that assure the dummy responds accurately and repeatably under specified loading conditions
- documented procedures for the assembly, disassembly, and inspection (PADI) of the dummy such that any users performing an FMVSS crash test are able to prepare the dummy before and after testing
- documentation that the dummy is sufficiently durable, repeatable, reproducible, and biofidelic to be used as a test instrument, in combination with appropriate injury criteria, to assess the potential for injury in an FMVSS crash test.

Of these elements, the drawing part numbers as well as the certification test procedures and performance specifications appear in Part 572 of 49 CFR. The PADI and the supporting documentation are placed into the docket. Injury criteria, which are part of the FMVSS, appear in Part 571 of 49 CFR.

Every dummy must undergo a rigorous assessment process, often called "federalization," that incorporates these elements. Incorporation of a dummy into Part 572 includes a proposal stage through the publication of a notice of proposed rulemaking (NPRM) in the Federal Register, a public comment stage, and a publication of a final rule that addresses the public comments. Publication of the final rule completes the addition of the ATD into the Part 572 regulation.

THE FEDERALIZATION PROCESS

The Federalization process requires a thorough inspection of the dummy and comparison to the drawings, certification and laboratory testing, sled testing and crash testing. Because of the high cost associated with crash testing and, to a lesser extent, sled testing, it is logical to perform those tests after the less expensive inspection and lab tests. Cost efficiency suggests a sequence of operations moving from inspection through lab testing to sled and crash testing. The various objectives of the Federalization process do not lend themselves to a sequential process because several requirements can only be fulfilled with multiple types of testing. For example, durability of a dummy is tested in the lab, on the sled and in crash tests. Figure 1 shows a chart cross-referencing the objectives of Federalization with the sequential operations of testing. In Figure 1 time and test operations progress from left to right while the functional objectives of Federalization are shown vertically on the left. This chart will be updated in each section of the following discussion indicating under which sequential task each Federalization requirement is met.

FUNCTIONS \ TASKS	Dummy Inspection	Lab Testing	Sled Testing	Crash Testing
Drawing Package				
Certification				
Durability				
R & R				
Biofidelity				
PADI				

TIME →

Figure 1. Federalization objectives versus scheduled tasks matrix.

DRAWING PACKAGE

An engineering drawing package defining the physical dimensions of the dummy assembly, all sub-assemblies and detail drawings of all of the parts is a Federalization requirement and is incorporated into

Part 572 49 CFR by reference. The weight and center of gravity (CG) of the dummy component segments are also specified in the drawing package.

The actual physical drawings reside in the docket room at NHTSA headquarters in Washington, D.C. and are also available from the Docket in electronic graphics format (.pdf). The drawing package is intended to minimally specify the dimensional and mass properties of the dummy and all of the dummy parts.

The drawing package is usually produced by a dummy manufacturer and obtained by NHTSA during the dummy evaluation process. Most dummies are designed and developed in collaboration with national and international organizations such as the SAE, ISO, OSRP, EEVC, etc. Before the dummy is considered for incorporation into Part 572, the agency assures that the drawings and all associated information are accessible and freely available to the public without any restrictions, such as proprietary claims, patent rights, trade names, etc.

Inspection

Several dummies are acquired and completely disassembled and inspected. If more than one manufacturer supplies the dummy, at least one dummy from each supplier will be purchased for inspection and subsequent testing. Physical dimensions of each part of the disassembled dummy will be measured and compared to the drawing package and any discrepancies will be noted. This includes a check on the weights and CGs of component segments. In the case of flesh and foam parts with irregular shapes the critical dimensions are checked against the drawing, allowing for an appropriate tolerance on these soft parts.

The list of discrepancies is brought to the attention of the dummy manufacturer and the party responsible for the drawings. Often the discrepancy is a simple mistake in a drawing and easily corrected; however, sometimes a modification to the physical dummy is required. If a significant modification to the dummy is needed, the dummy may be returned to the manufacturer for correction. In many cases work can continue while the modified part is produced either by working with other dummy components that are not affected by the change or by substituting a prototype part that does not affect the dummy configuration or dynamic response. In the case when there are two, or more, manufacturers of a dummy who make a component part differently, a compromise on the discrepancy is sought. If agreement cannot be reached, NHTSA will make a decision and incorporate a satisfactory design into the Part 572 drawing package.

The Federalization requirement for a drawing package is satisfied in the disassembly and inspection task (See Figure 2).

Modification

Before proceeding on to the testing phases of the evaluation process, the drawing and physical configuration issues must be resolved. Otherwise, it is likely that changes will be made to the dummy after testing has begun and these changes will invalidate the test results and require retesting. This process of examination and testing leading to

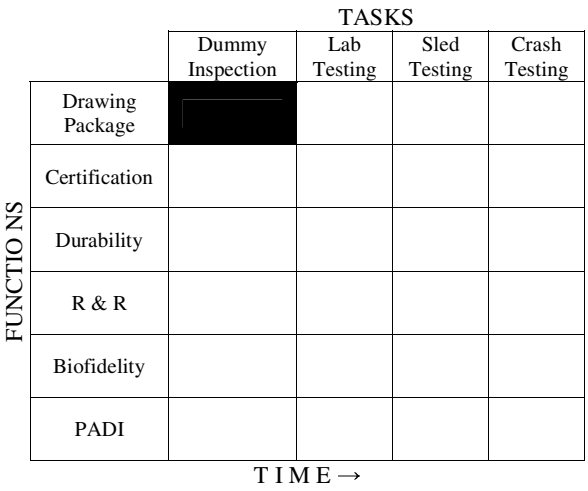

Figure 2. Drawing package requirement satisfied by the dummy inspection task.

modifications continues throughout the evaluation process. It is a time consuming and frequently expensive iterative process. This examination and modification process is the principal reason that the evaluation proceeds from the least expensive to the most expensive type of examination, i.e., inspection, lab testing, sled testing and crash testing. It is quite possible at any point in the Federalization process that a shortcoming of the dummy will become apparent and modification will be required. If this occurs it is often necessary to back up and repeat some, or all, of the testing. This iterative, exacting and often expensive process results in a dummy that meets the Federalization requirements for durability, biofidelity, repeatability and reproducibility.

HIII Ten-year-old Child Dummy

The Ten-year-old Hybrid III child dummy (Figure 3) was developed under the direction of the SAE Hybrid III Dummy Family Task Force and in collaboration with First Technology Safety Systems (FTSS) and Denton Anthropometric Test Devices (DATD). NHTSA participated in this dummy design and evaluation. This dummy was divided into an upper half and a lower half and each half was designed and prototype parts fabricated by different manufacturers. Drawings and computer aided design (CAD) files were then exchanged, through the SAE committee, and each manufacturer then fabricated the other half of the dummy. The result was dummies manufactured by both suppliers that were nearly identical. In the case of the Ten-year-old, NHTSA bought a whole dummy from each manufacturer and also bought the half of the dummy each had designed, assembling the two halves to make a third dummy.

The SAE committee provided the drawings and CAD files to NHTSA for the purposes of inspection. As would be expected under this collaborative design approach, the inspection process for the HIII Ten-year-old yielded only a small list of discrepancies between drawings and dummies. Table 1 shows the segment weight specifications and the actual weights of the dummies from each manufacturer indicating very good compliance with fairly tight tolerances.

Figure 3. The Ten-year-old HIII dummy.

Table 1.
Ten-year-old Segment Weights.

Segment	Part Number	Specification	Dummy 1	Dummy 2	Average
Head Assembly	880105-100X	8.23 +/- 0.10	8.25	8.16	8.21
Neck Assembly	420-2000	1.77 +/- 0.10	1.78	1.80	1.79
Upper Torso Ass'y	420-3000	17.94 +/- 0.30	17.82	17.82	17.82
Lower Torso Ass'y	420-4000	19.21 +/- 0.30	19.16	19.42	19.29
Upper Arm, Left	*420-7000-1	1.78 +/- 0.10	1.66	1.74	1.70
Upper Arm, Right	*420-7000-2	1.78 +/- 0.10	1.71	1.73	1.72
Lower Arm, Left	*420-7000-1	1.35 +/- 0.10	1.33	1.36	1.35
Lower Arm, Right	*420-7000-2	1.35 +/- 0.10	1.34	1.37	1.36
Hand, Left	420-7231-1	0.38 +/- 0.10	0.35	0.46	0.41
Hand, Right	420-7230-2	0.38 +/- 0.10	0.35	0.47	0.41
Upper Leg, Left	*420-5000-1	5.90 +/- 0.15	5.89	6.02	5.96
Upper Leg, Right	*420-5000-2	5.90 +/- 0.15	5.89	6.02	5.96
Lower Leg, Left	*420-5000-1	4.92 +/- 0.15	4.83	4.96	4.90
Lower Leg, Right	*420-5000-2	4.92 +/- 0.15	4.97	4.97	4.97
Foot, Left	420-5500-1	0.90 +/- 0.05	0.90	0.90	0.90
Foot, Right	420-5500-2	0.90 +/- 0.05	0.92	0.88	0.90
TOTAL WEIGHT	420-0000	77.61 +/- 2.00	77.15	78.08	77.62

CERTIFICATION

All regulated dummies are subjected to a series of tests in order to ensure that their components are functioning properly. These tests are typically conducted immediately before and after an FMVSS test is conducted to support the validity of the test results. The certification tests by and large evaluate the dummy's components that have important consequences in their proposed FMVSS applications. With this in mind, the tests are generally designed to load the dummy at a range similar to what it is expected to undergo in the proposed application. The certification tests are also intended to monitor the responses of components that may have a tendency to deteriorate over time. Some typical certification tests include:

- head drop
- neck flexion and extension
- thorax impact
- knee/femur impact
- torso flexion

Generally, by the time the Agency begins the federalization process, a preliminary set of certification procedures have been developed. NHTSA must then acquire or fabricate any new equipment required to conduct the tests. The process of evaluating the certification test procedures can then be initiated. This includes assessing:

- Test procedures. Can the set-up be repeatably achieved? Are the speeds realistic? Is the test user-friendly?
- Response corridors. Can the dummy meet the corridors? Are the corridors reasonable approximations of the loading that the dummy will experience in its intended application? Are the corridors within the dummy's mechanical limits and the instrumentation capacities?
- Repeatability and reproducibility. Does each dummy provide repeatable responses? Do all of the dummies respond similarly?

In some cases, as with the Thor Lx and FLx advanced instrumented lower legs, the Agency has led the development of the design, independent of broad industry involvement. In this instance, there were no preliminary set of certification procedures and thus the Agency independently developed procedures and response corridors.

To establish certification procedures for the Thor Lx/FLx lower legs, the Agency developed preliminary test procedures based around the following biomechanical response requirements:

- quasi-static response characteristics for:
  - axial loading at the heel (force-deflection)
  - dorsiflexion/plantarflexion response (torque-angle)
  - inversion/eversion response (torque-angle)
- dynamic response characteristics for
  - axial loading at the heel (force-deflection)
  - dorsiflexion response (torque-angle)

After fabricating the necessary hardware, a preliminary test procedure was developed for each of these biomechanical requirements. Initial testing, however, revealed that the quasi-static testing was time consuming and difficult to set-up. Further development led to a dynamic inversion/eversion test procedure and thus the quasi-static tests were relegated to the status of design guidelines, which are used in the development of the design, but not required for certification purposes. As a result, all of the certification tests would be dynamic impact tests – a heel of foot impact; a ball of foot impact; and an inversion/eversion impact.

After establishing the test procedures, the next step was to determine the response corridors. To accomplish this, multiple leg samples were acquired from several manufacturers and each leg was subjected to three repeats of the test procedures. From the data collected, the mean values of the significant responses were computed. Finally, the response corridors were constructed using a tolerance of 10% of the mean response value - the upper limits were set at 110% of the mean and the lower limits were set at 90% of the mean.

The final step is to document the certification test procedures in sufficient detail including:

- identification of the components included in each test
- a description of the test set-up geometry, speed, and orientation
- a diagram which supports the text description of the set-up
- definition of test probe properties including geometry and mass moment of inertia
- clearly stated response requirements

The Federalization requirement of developing certification procedures and response requirements is achieved through lab testing as shown in Figure 4.

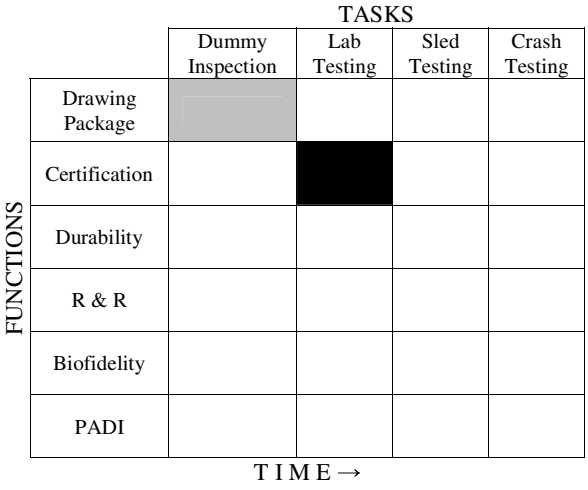

Figure 4. Certification requirement is satisfied by the Lab testing.

DURABILITY

A dummy intended for use in an FMVSS crash test must be durable on several levels. To be valid as a regulatory test instrument that makes measurements to be used to pass or fail a vehicle it is desirable, although not necessarily mandatory, that the dummy survives the crash event intact and still be able to make accurate measurements. This durability is normally ascertained by performing dummy certification tests both before and after the crash test. It is important to recognize that a dummy used in FMVSS testing is intended to identify those vehicles having unacceptable occupant protection capability and to provide data to indicate whether or not the vehicle fails the crash performance test. The dummy needs to be durable at, and above, the failure injury criteria levels. This is likely to be at the upper end of the dummy's mechanical and electronic limitations. Further, the use of dummies in New Car Assessment Program (NCAP) testing at high crash energy levels requires a dummy to be durable well above the FMVSS crash test energy level. Finally, for cost reasons it is desirable that a dummy be sufficiently durable to be used for many years in many tests with only a reasonable level of maintenance and repair.

It is interesting to note that in addition to the durability requirements discussed in the previous paragraph, a dummy is expected to be sensitive to variations in crash loading ranging from low energy levels to high energy levels and to distinguish among good and poor restraint systems of widely varying design.

Certification Testing

Dummy durability assessment begins with certification laboratory testing. A typical thorax certification test setup is shown in Figure 5. The dummy designers generally provide certification test procedures and performance specifications, as was discussed in the previous section. These recommended test procedures serve as the starting point for assessment of dummy durability. The recommended certification tests will be performed repeatedly on several dummies, preferably made by different manufacturers. This testing will also serve as repeatability and reproducibility testing, as will be discussed in the next section.

As the evaluation progresses, the dummy will be visually inspected after each test for damage or excessive wear. Should a change in response data be observed, either sudden or gradual, the dummy will

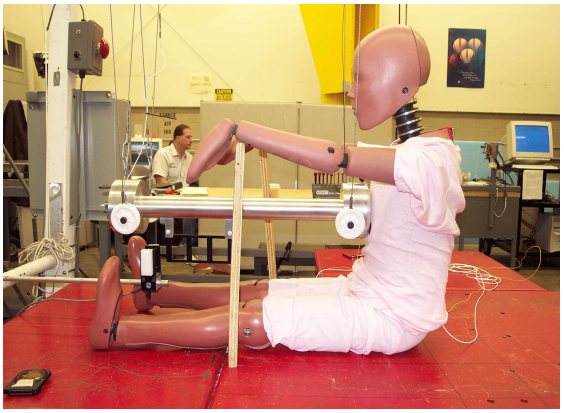

Figure 5. Ten-year-old dummy thorax impact.

be disassembled to ascertain if the reason for the change is breakage or wear. If breakage or wear of a dummy part is found, a decision must be made as to whether this is a tolerable situation and parts should be replaced as routine maintenance or an intolerable situation requiring either dummy modification or abandonment as a candidate test device.

When an intolerable durability problem is observed, the dummy manufacturer and the dummy designers are generally contacted in an effort to resolve the issue in the optimum manner: modification of the dummy, the test procedure or the maintenance procedure. With relatively new dummy designs it is not uncommon to discover durability problems due to extensive repeat testing of the dummy.

Note that at this point a modification to the dummy may be required and the certification testing will likely have to be repeated with the new part, which may be a prototype. This is the same iterative process discussed previously. When this occurs the NHTSA evaluation testing has effectively become part of the development process. It should also be noted that repeat certification tests with multiple dummies will provide repeatability and reproducibility data.

High-Energy Laboratory Testing

Following satisfactory performance in the certification testing, sets of high-energy certification tests are performed. These high-energy tests typically involve raising the kinetic energy of the impact in order to expose the dummy to impact severities slightly greater than those that might be expected in crash tests. Care must be taken in selecting which tests should be performed, e.g., a high-energy chest impact to the Ten-year-old dummy might be excessively severe for a dummy intended to

be loaded with a three-point belt restraint in a booster seat. Also, the process of careful inspection and possible modification is again followed with the possibility of iteratively repeating previous tests always present.

Out-of-Position Testing

In the case of small adult dummies or some child dummies, out-of-position (OOP) testing is performed. In these cases the OOP tests are performed with known aggressive airbag restraint systems to assure that the dummy can withstand severe loading to the head, neck and thorax. Figure 6 is an example of the Ten-year-old child dummy in the head-to-bag OOP position.

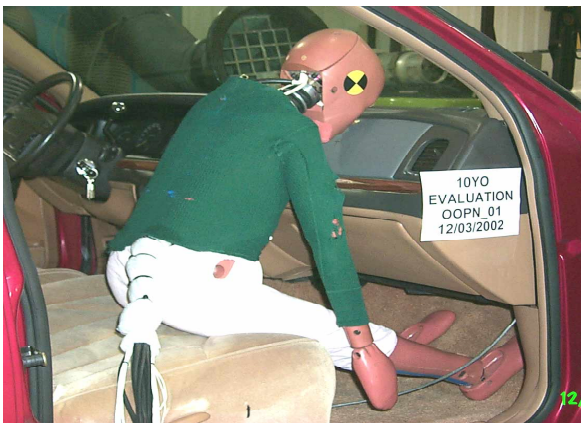

Figure 6. OOP testing for the Ten-year-old child dummy.

Sled Testing

Sled testing of the dummies is performed at FMVSS and at NCAP crash test energy levels. For frontal dummies sled testing is normally performed in a sled buck modeling a typical vehicle in the current fleet. For side impact dummies sled testing is normally performed in a flat wall sliding hard-seat type buck with and without wall padding. For child dummies the stylized FMVSS 213 bench seat is normally used with a Child Restraint System (CRS) or a booster seat. Note that the sled testing used to assess dummy durability may also be used to assess dummy repeatability and reproducibility.

Among other considerations, the typical sled testing matrix will be designed to subject the dummy to various seating positions and test conditions that may expose potential weaknesses of the dummy design.

Crash Testing

Crash testing in the anticipated FMVSS configuration is the final phase of durability assessment. If a dummy is to be used in NCAP testing, the higher energy crash test would be performed on the assumption that a durable dummy at NCAP speed would also be durable at the lower FMVSS crash speed.

Federalization Requirement

The Federalization requirement for dummy durability is satisfied by laboratory testing, sled testing and crash testing (See Figure 7).

TASKS

FUNCTIONS	Dummy Inspection	Lab Testing	Sled Testing	Crash Testing
Drawing Package				
Certification				
Durability				
R & R				
Biofidelity				
PADI				

T I M E →

Figure 7. Durability requirement satisfied by the lab, sled, and crash testing.

REPEATABILITY AND REPRODUCIBILITY

Repeatability and reproducibility (R&R) are important considerations in the evaluation of a dummy. In the context of dummy evaluation, repeatability is defined as the similarity of responses from a single dummy when subjected to multiple repeats of a given test condition. Reproducibility is defined as the similarity of test responses from multiple dummies when subjected to multiple repeats of a given test condition. Any ATD that is to be used for federal regulatory testing must have an acceptable level of R&R to ensure confidence in the responses provided by the dummy.

R&R analysis requires the replication of tests on multiple samples of a dummy, preferably samples from multiple manufacturers. Clearly, the R&R results will depend largely on the dummy's ability to provide similar responses to each test. However,

several external factors may also play a role in the R&R results, such as the repeatability of the dummy's setup or the impact speed. In order to provide a meaningful R&R analysis, control of the test conditions must be exercised. Component tests, such as the certification tests, are more readily controlled and thus may be expected to provide the best estimates of a dummy's R&R. Sled testing provides an efficient alternative to vehicle crash testing and offers insight into the dummy's performance as a complete system. Full vehicle crash testing does not provide a desirable environment for R&R testing as the variation in structural materials of the crash vehicle are difficult to account for.

Additionally, the severity of the test conditions utilized for R&R assessment must also be considered. For example, if the test conditions are so severe that the responses are near or beyond the dummy's mechanical limits or electronic capacity, then the corresponding R&R analysis may not be meaningful. Consider a dummy that is mechanically limited to 50 mm of rib displacement. The rib is impacted repeatedly and the dummy measures rib displacements of 50 mm for each test. The analysis would indicate excellent R&R; however, due to the dummy's mechanical limitations, it is unknown whether this response is truly repeatable. A better evaluation might seek to impart, for example, 40 mm of rib deflection so that the mechanical limits are not approached.

A quantitative assessment of R&R is achieved using a statistical analysis of variance. The coefficient of variation (CV) is a measure of variability expressed as a percentage of the mean. CV is calculated according to the formula below:

$$CV = \frac{\sigma}{\overline{X}} \times 100\%$$

where

σ = standard deviation of responses

$\overline{X}$ = mean of responses

Historically, NHTSA has categorized the CV scores according to Table 2.

There are several considerations that must be taken into account when CV scores are interpreted. One such consideration would be the relevance of the response. For example, the lateral shearing forces measured in a dummy designed for frontal impacts are generally considered to be of less significance. In this scenario, a poor CV score may not provide sufficient reason for concern. Consideration must also be given to the magnitude of the response. If the mean response is small, then even a small number for the standard deviation can result in a large CV. This consideration is closely related to the first one, in that responses which exhibit a low mean generally have less relevance to the given test condition.

Table 2.
Assessment of CV Scores.

CV Score	Assessment
0 – 5%	Excellent
>5 – 8%	Good
>8 – 10%	Marginal (Acceptable)
>10%	Poor (Unacceptable)

As an example, the agency recently initiated an evaluation of the EuroSID-2re (ES-2re) dummy. To that end, the ES-2re was subjected to repeated certification and sled tests to establish its repeatability and reproducibility as a test tool.

To assess the ES-2re's R&R in certification tests, two sample dummies were each subjected to five repeats of each of the certification tests. The response data was collected and filtered according to the test procedures. Next, statistical analysis of the response criteria resulted in CV scores of repeatability for each dummy and reproducibility for both dummies. Table 3 presents a summary of the ES-2re's R&R analysis for certification tests. It is observed that the vast majority of the responses would be considered excellent, with only four CV scores falling in the 'good' range and just one score in the 'marginal' range.

The Federalization requirement for repeatability and reproducibility is satisfied by laboratory and sled testing (See Figure 8).

BIOFIDELITY

Biofidelity is a measure of how well a dummy replicates the response of a human. If a dummy replicates the human response quite well, it is said to have good biofidelity, or be quite biofidelic. Although not a requirement in Part 572, the dummy's biofidelity is an important consideration in the decision of whether or not the dummy is suitable for incorporation into Part 572.

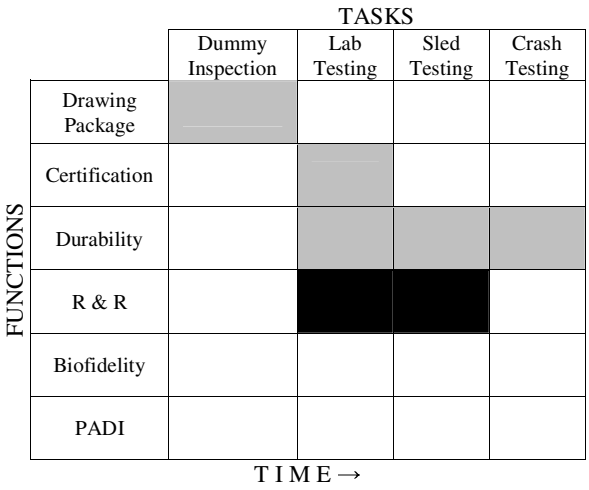

Figure 8. The Lab and Sled testing satisfy the R & R requirement.

Until recently, NHTSA assessed dummy biofidelity based on subjective, qualitative analysis of dummy data fit within cadaver response corridors. Two methods are currently available for assessing the biofidelity of a dummy in side impact testing: 1) the ISO 9790 Biofidelity Classification System [4] and 2) the Biofidelity Ranking System developed by Rhule et al in 2002.

Although the ISO Biofidelity Classification System is well known and accepted within the biomechanics community, it contains several subjective features that limit its capability for impartial evaluation of the biofidelity of dummies that are to be considered for incorporation into Part 572. The ISO System utilizes

Table 3. ES-2re Certification Test R&R Analysis (ref. Docket # NHTSA-2004-18864-15).

Test/Criteria	Dummy S/N 070	Dummy S/N 071	Both
	CV (%)	CV (%)	CV (%)
Head Drop			
Peak Resultant Acceleration	1.1	1.6	**5.4**
Neck Flexion			
Flexion Angle	0.9	0.5	0.9
Time of Flexion Angle	2.3	2.7	2.4
A Angle	0.7	0.5	0.9
Time of A Angle	2.2	1.4	1.8
B Angle	0.7	0.5	0.9
Time of B Angle	1.6	2.6	2.5
Shoulder Impact			
Impactor Acceleration	2.7	**9.3**	**6.9**
Thorax – Rib Impacts			
Upper Rib Def. - 815 mm Drop Height	1.5	3.9	3.1
Middle Rib Def. - 815 mm Drop Height	0.3	0.3	0.3
Lower Rib Def. - 815 mm Drop Height	0.4	0.0	0.5
Abdomen Impact			
Maximum Impactor Force	2.1	2.0	1.9
Time of Max. Impactor Force	0.7	1.2	1.1
Maximum Abdomen Force	**6.9**	3.8	**6.4**
Time of Max. Abdomen Force	1.7	1.0	1.6
Lumbar Spine Flexion			
Flexion Angle	0.8	1.4	1.1
Time of Flexion Angle	1.7	1.9	1.7
A Angle	0.9	1.5	1.5
Time of A Angle	1.4	2.3	1.8
B Angle	0.3	1.3	0.9
Time of B Angle	1.8	.7	1.3
Pelvis Impact			
Maximum Impactor Force	3.5	1.3	2.8
Time of Max. Impactor Force	3.1	4.4	3.6
Max. Pubic Symphysis Force	4.0	1.1	3.1
Time of Max. Pubic Symphysis Force	3.4	4.6	4.2

assigned weights for the response measurements, test conditions and body regions. The weights were determined by averaging results of a poll of the ISO members. Since the responses of the poll may or may not be in line with the philosophies of the NHTSA, and since all body regions must pass their individual injury criteria in an FMVSS test, all body regions should be equally weighted when assessing dummy biofidelity. Moreover, the dummy responses are subjectively assigned a numeric value based on the qualitative assessment of the data fit within the cadaver corridors.

As the Biofidelity Ranking System [5] quantifies the biofidelity of a dummy in an objective manner, it was used by NHTSA to evaluate recent dummy biofidelity. The Biofidelity Ranking System is comprised of multiple tests of various types that have associated human response corridors. Each test is assigned a test condition weight in an objective manner that gives the highest weights to those tests that are most representative of the intended dummy test environment and that have response corridors developed from a large number of human subjects. For each measurement of each test, the dummy and human responses are compared over time and their differences quantified, where a lower number indicates better response similarity between the dummy and human. External and Internal biofidelity ranks, which are both deemed equally important for a dummy to possess, are computed to assess the overall biofidelity of a dummy.

As an example, the ES-2re dummy biofidelity was evaluated and found to be relatively good when compared to the SID-HIII, which is currently in Part 572. Tables 4 and 5 show the External and Internal Biofidelity ranks, respectively, for the ES-2re and SID-HIII.

Table 4.
External Biofidelity Ranks for the ES-2re and SID-HIII.
(ref. Docket NHTSA-2004-18865-8)

EXTERNAL BIOFIDELITY	ES-2re	SID-HIII
Overall Rank	**2.6**	**3.8**
Head/Neck Rank	3.7	1.0
Shoulder Rank	1.4	5.1
Thorax Rank	2.9	6.1
Abdomen Rank	2.6	3.0
Pelvis Rank	2.7	3.8
	re - rib extensions	

Table 5. Internal Biofidelity Ranks for the ES-2re and SID-HIII. (ref. Docket NHTSA-2004-18865-8)

INTERNAL BIOFIDELITY	ES-2re	SID-HIII
Overall Rank with abdomen	n/a	n/a
Overall Rank without abdomen	**1.6**	**1.9**
Head Rank	1.0	1.1
Thorax Rank	1.9[1]	2.2[2]
Abdomen Rank	n/a	n/a
Pelvis Rank	2.0[3]	2.5[3]
n/a - not applicable (No human subject internal force data for comparison with the ES-2re; SID-HIII dummy does not make a measurement in the abdomen.)		
re - rib extensions		
1. Upper & lower thorax rib deflections & T-12 lateral acceleration		
2. TTI		
3. Pelvis lateral acceleration		

The biofidelity requirement is satisfied in lab and sled testing as shown in Figure 9.

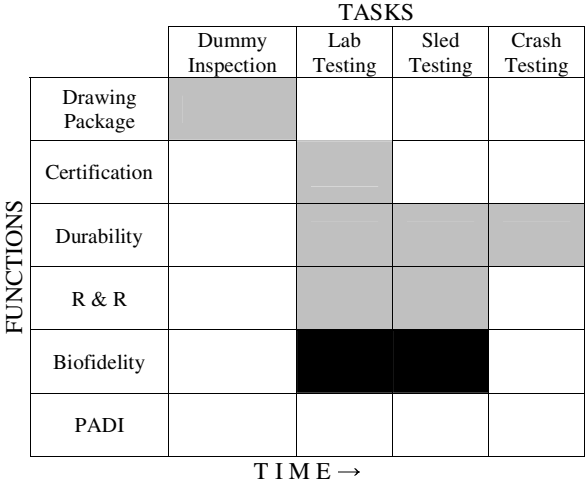

Figure 9. The lab and sled testing satisfy the biofidelity requirement.

PROCEDURES FOR ASSEMBLY, DISASSEMBLY AND INSPECTION

When a dummy is federalized it is necessary to document how the dummy is assembled, disassembled and inspected so that contractors who perform the FMVSS tests can put the dummy and its instrumentation together appropriately. This document, referred to as the Procedures for Assembly, Disassembly and Inspection, or PADI, is

incorporated by reference into Part 572. The PADI serves as a manual that illustrates how the dummy is put together and taken apart, as well as where and how the instrumentation is installed, and where to route the sensor cables within the dummy. It also includes procedures for inspection to aid in determining if certain parts are worn or damaged and need to be replaced.

Procedures for measuring external dimensions, segment weights and sensor output polarity for the dummy and free air resonant frequency and mass moment of inertia of the certification probes are also integral parts of the PADI.

If the dummy appears to be a reasonable tool for use in FMVSS and NCAP testing with regard to durability, biofidelity, repeatability and reproducibility, the documentation of the PADI becomes necessary. Since project engineers and technicians become expert at assembling and disassembling the dummy as the dummy evaluation progresses, it makes sense to document the procedures for assembly, disassembly and inspection after most of the evaluation is complete.

The PADI is organized into sections for each body segment: head, neck upper torso, lower torso, arms, legs and feet. Each section contains procedures for removal of the segment from the dummy, disassembly, inspection, assembly and attachment to the dummy. Exploded views of the body segment with its individual parts identified help to illustrate its construction. A table in each section identifies the parts of the body segment, with part number and title that match those of the Drawing Package. The dummy is disassembled from the head down in a piecewise fashion, with instructions, figures, and photographs shown to illustrate each step of the disassembly. Specific instructions on inspection of parts for wear and replacement are included, as well as procedures for assembling the segment and attaching it to the dummy.

Once the disassembly, inspection and assembly sections are complete, then the instrumentation installation and sensor cable routing sections of the PADI are written. These sections are also separated by body segment with photographs to illustrate specific steps to be taken.

Experience obtained during all phases of the evaluation process - inspection, lab testing, sled testing and crash testing - contributes to the development of the PADI (Figure 10).

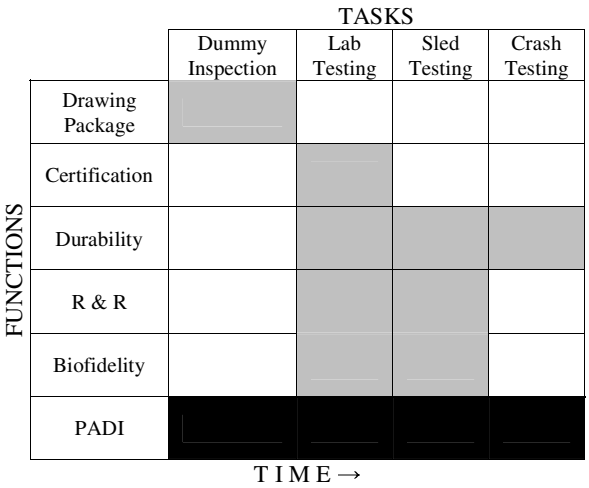

Figure 10. The experience gained in all phases of the evaluation process contributes to the PADI.

SUMMARY

A dummy that is a candidate for incorporation into part 572 49 CFR for potential use in a FMVSS performance standard must undergo a rigorous evaluation process: this process is often referred to as the Federalization process. This process is a standardized set of inspections and tests that result in quantified measures and corresponding documentation of the dummy's assembly and disassembly, drawing package, certification test procedures, durability, repeatability, reproducibility and biofidelity. Although no two dummy designs are identical and; therefore, no two dummy evaluation processes are identical, the skeleton of the process and the expectation for performance of the dummy remain constant.

It is important to recognize that a critical aspect of the evaluation process is the assessment of dummy suitability for the intended use. For example, a dummy designed for frontal impacts may not provide meaningful responses when tested in a side impact condition. This suitability evaluation is part of the entire process although it is not specified as an evaluation task. Further, it is important to be constantly aware of dummy behavior that is not suitable or human-like but may not be exposed in the scheduled testing. A recent example of this type of non-suitability was the lateral load path caused by the ES-2 back plate. This non human-like load did not become evident except after extensive crash testing with multiple vehicles.

Many new dummies are being developed by committee or consortium (HIII Ten year-old, SID IIs

and WorldSID) and it is important for those organizations to realize that the products of their extensive efforts must still undergo the rigorous Federalization process if the dummy is to be considered for use in the FMVSS. Further it is required that NHTSA possess, without restriction of any kind, an accurate and complete drawing package for the dummy for incorporation into part 572 by reference.

Similarly, vehicle manufacturers can be assured that a dummy that is incorporated into part 572 has been rigorously evaluated and is a dependable and reliable test tool that can be used in regulatory compliance testing (FMVSS), market incentive testing (NCAP) and will also be useful for research testing in other test configurations.

The details of the Federalization process outlined here will be continually updated as new techniques are developed and new biomechanical data becomes available. Examples of this are the Bio Rank approach [5] recently developed to quantify the assessment of biofidelity and the ongoing development of R&R procedures that are time history based rather than maximum value based. Nonetheless, the essential framework of Federalization will remain and the need to rigorously evaluate a dummy before it is used in testing will remain.

REFERENCES

[1] Highway Safety Act of 1966, Public Law 89-564

[2] Chrysler Corporation v. Department of Transportation, 472 F.2d 650 (1972), pg 659-693; United States Court of Appeals, Sixth Circuit, December 5, 1972.

[3] Anthropomorphic Test Device for Dynamic Testing SAE J963, SAE Recommended Practice, Society of Automotive Engineers, June 1968.

[4] International Standards Organization, "Technical Report 9790: Road Vehicles – Anthropomorphic Side Impact Dummy – Lateral Impact Response Requirements to Assess the Biofidelity of the Dummy," American National Standards Institute, New York, NY, 1999.

[5] Rhule, H., Brunner, J., Bolte, J., Donnelly, B., Maltese, M., Eppinger, R., "Development of a New Biofidelity Ranking System for Anthropomorphic Test Devices," Stapp Car Crash Journal, Vol. 46 2002.