UM-HSRI-80-52-1

REVIEW OF LITERATURE AND REGULATION RELATING TO HEAD IMPACT TOLERANCE AND INJURY CRITERIA

Robert L. Hess
Kathleen Weber
John W. Melvin

HIGHWAY SAFETY RESEARCH INSTITUTE
THE UNIVERSITY OF MICHIGAN

July 1980

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UM-HSRI-80-52-1		

4. Title and Subtitle	5. Report Date
Review of Literature and Regulation Relating to Head Impact Tolerance and Injury Criteria	July 1980
	6. Performing Organization Code
7. Author(s) Robert L. Hess, Kathleen Weber, John W. Melvin	8. Performing Organization Report No. UM-HSRI-80-52-1
9. Performing Organization Name and Address Highway Safety Research Institute, The University of Michigan, Ann Arbor, Michigan 48109	10. Work Unit No.
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address Motor Vehicle Manufacturers Association, 320 New Center Building, Detroit, Michigan 48202	13. Type of Report and Period Covered Special Report 7/78 - 6/80
	14. Sponsoring Agency Code

15. Supplementary Notes

This volume includes the main text and Appendices A and B. Appendix C is contained in a companion volume.

16. Abstract

Regulation that relates to head injury protection of motor vehicle occupants is examined in relation to head injury biomechanics research. The development of both is presented in a historical review. Recommendations are made for more effective use of the experimental and analytical techniques already available and for further research in these areas.

17. Key Words	18. Distribution Statement
Head Brain Impact Injury Mechanisms Injury Criteria	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
		102	

TABLE OF CONTENTS

1.0 Introduction. 1

2.0 Early Period: 1960-1970. 2

2.1 Wayne State Tolerance Curve. 2

2.2 Severity Index 5

2.3 FMVSS 201. 5

2.4 Injury Mechanisms. 7

2.5 Mathematical Modeling. 8

2.6 FMVSS 208. 10

3.0 A Period of Transition: 1970-1973. 13

3.1 Alternate Views of Head Injury 13

3.2 Head Injury Criteria 15

3.3 Developments in Mathematical and Mechanical Models . . 17

3.4 HIC Extensions 20

4.0 Later Period: 1974-1980. 21

4.1 Finite Element and Kinematic Models. 21

4.2 Experimental Advances and Model Validation 23

5.0 Conclusions 27

6.0 References. 29

Appendix A: Federal Register Excerpts 35

Appendix B: Bibliography. 75

Appendix C: NCSS Head Injury Accident Data. UM-HSRI-80-52-2

1.0 Introduction

Protecting the head from irreversible brain damage is one of the most critical tasks of the automotive safety design engineer and of the regulator who sets Federal Motor Vehicle Safety Standards (FMVSS). Both have based their work on human performance and injury data from a variety of sources. Although field accident data are available in large volume, very little have been able to provide the level of detail necessary to study actual mechanisms of injury. Regulators and engineers concerned with occupant protection have instead used the more scientific data coming from laboratory impact experiments with animals and cadavers, as well as from acceleration experiments with human volunteers, to determine an acceptable level of protection and to measure whether or not a system achieves this level.

The intent of this study is to review the development of biomechanical knowledge about skull/brain injury tolerance to impact and other accelerations, to examine the degree to which this knowledge has been used by the National Highway Traffic Safety Administration (NHTSA) in setting occupant protection standards, and to focus attention on that portion of the evidence that has not been effectively tapped. This latter body of information has been developed primarily in the period beginning 1972, the year in which the Head Injury Criterion (HIC) was incorporated into FMVSS 208 and a court decision was made requiring NHTSA to precisely specify its anthropomorphic test device. Finally, suggestions are made for further research that would enhance our understanding of head injury mechanisms and protection.

The main body of the report contains a review of landmark literature and regulations relating to head injury, along with a list of the primary references. Appended to the report are excerpts from the Federal Register referred to in the review and an extensive bibliography. An additional appendix presents illustrations of head injury accident data from NHTSA's National Crash Severity Study (NCSS).

2.0 Early Period: 1960-1970

2.1 Wayne State Tolerance Curve

The Wayne State Tolerance Curve (WSTC), first suggested by Lissner, Lebow, and Evans (1960)[1*] is the foundation upon which most currently accepted indexes of head injury tolerance are based. As originally presented, the "curve" included six points that represented the relationship between acceleration level and impulse duration (in the range of 1 to 6 ms) found to produce linear skull fracture in embalmed cadaver heads. Simply put, short pulses of high acceleration will cause injury, while lower acceleration levels require longer duration to do harm. The curve was later extended to pulse durations above 6 ms with comparative animal and cadaver impact data and with human volunteer acceleration test data. The details of the history of the WSTC are described in SAE J885b (1980)[2] and will not be repeated here.

The reader should be aware, however, of the physical nature of the experiments of Lissner et al. that produced the first data points to be used in the WSTC. Embalmed human cadavers were used as opposed to fresh cadavers or severed heads. Instrumentation consisted of pressure transducers in the right temporal and left posterior regions of the skull and an accelerometer on the center rear of the skull. The impact

---

*Superscript numbers refer to citations listed in section 6.0: References. Citations may also be identified by author(s) and date in Appendix B: Bibliography.

was on the forehead. The membranes surrounding lobes of the brain were mechanically punctured and torn to allow all parts of the cranial cavity to communicate. The impacts were accomplished by dropping the cadavers onto automotive instrument panels, damped steel plates, steel anvils, and padded steel anvils.

The important points for the present discussion are that (1) pressure change gradients in the region of the foramen magnum were understood to be the primary brain stem injury mechanism; (2) the original WSTC reported peak accelerations and peak pressures for translational impact with hard, flat surfaces in the anterior-posterior direction; (3) the authors cautioned that much data was needed to validate the curve, but (4) it was the first graphical representation of critical injury threshold based on impact conditions. The authors also provided insight into the goal for energy absorbing materials or structures:

> Any padding arrangement or reduction in stiffness of the [instrument] panel, or both, which increases the time duration of impact in an equal or diminished ratio to the decrease in acceleration or pressure produced, will be an improvement with regard to prevention of injury.

The relative decreases and increases necessary are described by a curved line, such as the WSTC.

Soon thereafter, Gadd (1961)[3] suggested plotting the injury threshold curve on logarithmic scales to achieve a straight line fit. The extent to which the slope of this line was steeper than -1 would indicate a greater dependence of injury on the intensity of loading, as opposed to dependence on time of loading. He also suggested that multiple impulses could be analyzed for injury potential by integrating the acceleration over the entire impulse profile, using the power weighting factor, derived above from the slope, on the acceleration portion of the profile. This fundamental engineering advice for those thinking of establishing an index of injury tolerance was later to be developed into the Gadd Severity Index, discussed below.

Before this index was finalized, however, changes were made in the WSTC. To make the triangular peak acceleration levels compatible with irregular wave forms and with the trapezoidal waves of human volunteer tests summarized by Eiband (1959)[4], the ordinate of the curve was changed to "effective" or average acceleration. A plot in this form appears in Patrick, Lissner, and Gurdjian (1963)[5]. The asymptote of the curve, or the low-level acceleration threshold for very long time durations, was given as 42 g. The authors stated, however, that humans are known to have withstood considerably higher accelerations in cases where there was no impact. They suggested then a threshold of from 60 g to 80 g, and they themselves used 80 g as the upper safe limit on effective acceleration for impacts with a padded surface. This figure was later incorporated into FMVSS 201 instrument panel tests and an early version of FMVSS 208. It must be remembered, however, that for non-rectangular wave forms, peak accelerations can be higher than 80 g. The authors cited permissible peaks of 110 g for sinusoidal pulses and 160 g for triangular.

Other concepts coming from this paper that were to emerge later in standards were (1) the avoidance of high acceleration peaks lasting longer than 1 ms and (2) the use of interior impact test velocities of one half the probable vehicle velocity at impact. The reader is cautioned that the latter concept may not be valid in real crashes. Velocities chosen for impact tests should be reevaluated as occupant protection systems change, because interior structures and restraint systems influence occupant kinematics and thus interior impact velocity.

2.2 Severity Index

At the Tenth Stapp Car Crash Conference, Gadd (1966)[6] brought to maturity the ideas presented in 1961. Although a log-log plot of the WSTC resulted in a somewhat curved line, Gadd felt his straight-line approximation was "sufficient at this time" because of the scatter of the data. The slope of his line was -2.5, and thus 2.5 became his power weighting factor. Using the Severity Index (SI) formula $\int a^{2.5}\,dt$, Gadd showed that a triangular pulse having the same area as a square pulse would have an injury potential 1.61 times as great. Near the end of his paper, Gadd returned to the question of his straight line approximation and suggested that, as more data became available, a curve of arbitrary shape could be constructed. He credited J. P. Danforth with the suggestion that the weighting exponent need not be constant but could vary as a function of acceleration.

2.3 FMVSS 201

On December 3, 1966, the proposed initial Federal Motor Vehicle Safety Standards appeared in the Federal Register [1]*. FMVSS 201, "Occupant Protection in Interior Impact," was among those proposed. Using the general test procedures and 15-pound, 6.5-inch diameter headform from SAE J921 (1965)[7], 15 mph impacts with the "head impact area" of the instrument panel were to be performed.

The test criteria were as follows:

---

*Bracketed numbers refer to excerpts in Appendix A of this report.

a) The deceleration of the head form shall not exceed 80g for 1.0 millisecond or more; and,

b) The pressure in the area of contact shall not exceed 100 p.s.i.

The proposed regulation did not apply to areas within 5 inches of the door nor closer to the windshield than could be contacted by the headform. It should be noted that the 80 g effective acceleration limit suggested by Patrick, et al. (1963)[5] was incorporated here as a maximum, except for peaks of very short duration that were also allowed by these authors. The pressure limit of b) was included to control for impacts with protrusions that could be injurious at low acceleration levels. Two months after the initial proposal, the rule was issued with the same provisions, except that the concept of contact-area pressure was dropped [2].

At the request of petitioners, hearings were held in May 1967 regarding the provisions of FMVSS 201. The resulting revised regulation [3], issued in August eliminated areas of the instrument panel below an upper lip from any impact testing and lengthened the duration of allowable deceleration above 80 g to 3 ms. Although no limit was placed on the peak allowable during the 3 ms window, it would be reasonably difficult to achieve an injurious level of acceleration during this short a period if the impacted surface were padded. Using current methods to calculate injury threshold (HIC<1000, to be discussed below), a peak of 280 g would still be within the safe limit.

In October of the same year, another proposal [4] was issued that indicated NHTSA was considering additional areas to be covered by FMVSS 201, including "A" and "B" pillars, windshield headers, sun visors, rearview mirrors, roofs, etc. Comments were also requested on "the need for specifying more stringent impact deceleration-time requirements..."

2.4 Injury Mechanisms

During this time, when tolerance curves and injury indexes were being developed and government standards were trying to reflect these developments, laboratory research continued to be concerned with the actual mechanisms within the skull that produce brain injury and with quantifying the mechanical properties of the skull/brain system. The eventual goal of this research would be the development of sophisticated analytical models to predict injury from impact and acceleration.

The WSTC was based on translational motion data, but rotation had also long been known to effect injury (Holbourn, 1943[8]; Gurdjian, Webster, and Lissner, 1955[9]). Gurdjian, Roberts, and Thomas (1966)[10] observed that the "line of action" of a blow to the head had a significant effect on the resulting injury. If "an impact provides an unusually abrupt rotation of the skull, severe effects can occur in areas not immediately adjacent to the point of impact." Ommaya, Hirsch, and Martinez (1966)[11] found that a cervical collar reduced the rotational acceleration of monkey heads and raised the concussion threshold for occipital impacts. The authors also found that abrupt rotation without impact could affect sensory responses.

A brief paper by Gurdjian, Hodgson, et al. (1968)[12] summarized the state of understanding at that time of brain injury mechanisms from head impacts. Specifically the paper mentioned (1) direct contusion from deformation at the point of impact; (2) indirect contusion produced by negative pressure on the side opposite the impact; (3) brain deformation as it responds to pressure gradients, causing shear stresses at the craniospinal junction; (4) contusion from movement of the brain against rough and irregular interior skull surfaces; and (5) subdural hematoma from movement of the brain relative to its dural envelope, resulting in tears of connecting blood vessels.

2.5 Mathematical Modeling

Early modeling efforts included the work of Hodgson and Patrick (1968)[13], who developed a simple one-degree-of-freedom model to predict the response of the occipital bone to frontal bone impact. The model was based on data from mechanical impedance tests of a human cadaver and two living human subjects in the range of 0 to 5000 Hz. Mechanical impedance measurements involve determining the ratio of a sinusoidal force, applied to a specimen, to a particular mechanical response of that specimen. As the frequency of the applied force varies, both the magnitude and the phase of the response vary. Once the impedance function is known, the impact response can be calculated. The results can also be used to develop and validate simple lumped parameter models of the head, both mathematical and physical, incorporating the same mechanical impedance in the frequency range of interest. The particular response used by Hodgson and Patrick was the amplification of acceleration at a point on the head opposite the applied force. This response of the cadaver head was found to be similar to that of a simple spring-mass system with an antiresonant frequency at 313 Hz and a resonant frequency at 900 Hz. At frequencies below 100 Hz, the response was that of a rigid body.

Another mechanical property important for head injury modeling is the dynamic complex shear modulus, G, of the brain. Technically, G is a vector quantity expressing two perpendicular components: G', the dynamic elastic modulus representing the springlike stiffness of the material under shear stress, and G", the dynamic loss modulus representing the viscous losses in the material. This complex modulus is necessary for a numerical analysis of a viscoelastic material. Fallenstein, Hulce, and Melvin (1969)[14] studied this property as the initial phase of a larger program to completely characterize the material of the human head. In their paper, the authors discussed the work of others who provided guidance for the program and reported their own experimental results. The values obtained for in vitro human brain were just below those of in vivo human muscle tissue. Higher values were found in preliminary in vivo tests on Rhesus monkeys. The authors predicted that further tests and in vitro/in vivo correlations would help resolve questions about the effects of post-mortem changes, blood pressure, and frequency on the dynamic properties of brain tissue.

Driving point impedance tests of the head were conducted by Stalnaker, Fogle, and McElhaney (1970)[15] on a human cadaver and on living and cadaver monkeys. The ratio of the driving force to the velocity at the driven point was measured over the frequency range of 30 to 5000 Hz. The authors' methods for attaching transducers and holding the subjects in place were an improvement over those used in previous impedance tests. A linear two-degree-of-freedom model was developed from the data obtained. The authors found the brain to be very nearly critically damped. Metz, McElhaney, and Ommaya (1970)[16] reported on a new method of measuring the elastic modulus of brain tissue. Values equivalent to G' were found to be somewhat higher than those reported by Fallenstein, et al. (1969)[14].

The mechanical properties of cranial bone were studied by McElhaney, Fogle, et al. (1970)[17]. This work, like that of Fallenstein, et al. (1969)[14], was part of a program to adequately characterize all the materials of the human head so that physical and mathematical models could be constructed for systematic study of head injury mechanisms. This work was sponsored by the National Institute of Neurological Diseases and Stroke. A variety of properties were reported in detail as well as the dependence of these properties on the structural arrangement of the diploe, a characteristic likely to vary considerably over a population of subjects. A model was developed to summarize the variations of mechanical properties with respect to the density of this region.

2.6 FMVSS 208

Getting out of the laboratory for a moment, it is appropriate at this point to discuss the developments in the area of regulation that occurred in 1970. In May, the first proposal to incorporate automatic (passive) crash protection into FMVSS 208 appeared in the Federal Register [6]. To test the effectiveness of these systems, the standard was to establish "basic injury criteria with reference to an anthropomorphic dummy, expressed in terms of maximum forces and pressures on critical parts of the body." The dummy to be used was that described in SAE J963 (1968)[18]. The occupant protection systems would be tested the first year with dummies in a frontal fixed-barrier crash at 30 mph, and lateral and rollover tests would be added the following year. The proposal specified that "the resultant head acceleration shall not exceed 80 g for any continuous period of more than 3 milliseconds." NHTSA admitted that the specified dummy "may not provide totally reproducible results." There was, however, no easily available alternative at the time. It should be noted as well that the test criteria were based on the magnitude of the resultant acceleration rather than on its projection along a single axis, as was used in constructing the original WSTC. An interim option of manual lap/shoulder belts that had to meet the same test conditions was also included in the proposal. Comments on the proposal ensued. A presentation of the arguments on both sides concerning this and later proposals can be found in a report by the U.S. National Transportation Safety Board (1979)[19], and therefore only pertinent highlights will be mentioned here. The primary objection to the injury criteria measurements was that they were beyond the state of the art.

On September 25 a revised proposal [7] was issued stating that "the resultant head acceleration shall not exceed 90 g, and shall not exceed 67 g for a cumulative duration of more than 3 milliseconds." These criteria differed from those of the earlier proposal and FMVSS 201 in that a peak acceleration was established and the 3 ms limit on high accelerations became cumulative rather than continuous. No explanation was given for the changes. The proposal also increased the number of interim options available. For fully automatic systems (first option) and semi-automatic systems in which a manual lap belt could be included (second option), the injury criteria above were to be met under frontal fixed-barrier test conditions. For manual lap/shoulder belts (third option), the test conditions remained the same, but the only criterion for passing the test was that the system "experience no complete separation of any element of a seat belt assembly." This option was given to reduce the cost of complying with interim improved belt systems.

To put FMVSS 201 somewhat more in line with 208, a proposal [8] was made to increase the test velocity for the head impact areas and lower the allowable headform decelerations such that, when these areas were impacted at 25 mph by the standard headform, they could not cause a deceleration of more than 90 g for a cumulative duration of 1 ms nor 67 g for a cumulative duration of more than 3 ms. The proposal also sought to increase the size and number of impact areas covered. These changes, however, were never put into effect, and the current FMVSS 201 remains essentially as it was in 1967.

The first FMVSS 208 rule incorporating automatic restraints was issued November 3, 1970 [9]. The preamble read as follows with regard to permissible head accelerations:

> The levels proposed in the September 25 notice are adopted in this standard, with head accelerations changed from 67 g to 70 g, as the best available criteria for the quantities measured. Consideration will be given to adoption of a severity index or other criteria as further research results become known.

In the same issue of the Federal Register, amendments to the new rule were proposed [10]. Stating that "biomechanical studies indicate that the lateral acceleration tolerance of the head and chest are significantly less than the frontal acceleration tolerance," a requirement was proposed that the lateral component of head accelerations could not exceed 40 g for a cumulative duration of more than 3 ms. The "biomechanical studies" referred to were not identified, but the data were presumably as yet unpublished results from NHTSA's contracted research project entitled "Door Crashworthiness Criteria." (The paper by McElhaney, Stalnaker, et al. (1971)[20] later presented the data base from this project.) The notice also proposed rollover and moving-barrier lateral tests.

3.0 A Period of Transition: 1970-1973

3.1 Alternate Views of Head Injury

While NHTSA was considering injury severity indexes and limits on lateral impact acceleration, interest continued in the contribution of rotational acceleration to head injury. At the Fourteenth Stapp Car Crash Conference, Hirsch (having joined NHTSA's research staff) and Ommaya (1970)[21] reported confirmation of their earlier findings (Ommaya, et al., 1966[11]) that rotational motion appeared to be more critical to the production of brain injury than translational motion. The authors further stated that "no convincing evidence has to this date been presented which relates brain injury and concussion to translational motion of the head for short duration force inputs, whether through whiplash or direct impact." Caution was suggested when using "currently popular head tolerance criteria" based on translational head motion.

Other researchers, however, were using their own experimental data to develop head injury indexes that would approximate the WSTC. These were the J Tolerance Index (JTI) of Slattenschek (described in English in Slattenschek and Tauffkirchen, 1970)[22], and the Effective Displacement Index (EDI) of Brinn and Staffeld (1970)[23]. Both of these indexes were based on single-degree-of-freedom mass-spring-dashpot vibration models.

Stalnaker and McElhaney (1970)[24] further developed their two-mass model, based on data from their driving point impedance tests, and formulated an injury index called the Maximum Strain Criterion (MSC). This was presented in December at the ASME winter meeting. The MSC curve indicated a tolerance threshold significantly lower than did the WSTC, and injury tolerance was found to be dependent on the impact waveform. The MSC for human lateral head impact was also presented for the first time and was shown to be 50 percent lower than that for longitudinal impact.

Five years after Gadd's Severity Index had been adopted as an SAE recommended practice (SAE J885a, 1966)[25], and just as researchers were recommending the use of alternate criteria, NHTSA decided to adopt the SI as the head injury criterion for first and second options of FMVSS 208. In February 1971, a notice [11] was issued stating NHTSA's intent to require completely automatic systems to provide "protection in frontal fixed barrier crash tests up to 30 mph, and up to 30 to either side of the perpendicular, and in lateral and rollover crash tests." The other two options were to be tested only in the frontal perpendicular configuration. The first and second options were to qualify under "a maximum head severity index of 1000, calculated according to SAE J885a." The third option (lap/shoulder belts) was again only required not to sustain structural failure. The rule [12] appeared in March essentially as announced, except that the third option was to be eliminated after August 1973. The preamble to the rule also reaffirmed NHTSA's opinion that the SAE J963 dummy specifications were "the best available." Research was being done, however, "with a view to issuance of further specifications for these devices." Soon thereafter Chrysler initiated legal proceedings that eventually ended the use of the SAE J963 dummy.

In October 1971, various amendments to the rule were issued [13] regarding testing procedures. The preamble, however, responding to comments that the criterion for head injury was too stringent, restated NHTSA's belief that the SI<1000 was the most acceptable criterion at the time and that it would be retained. Responding again to comments that SAE J963 did not "completely define all the characteristics of the dummies that may be relevant to their performance in a crash," NHTSA accepted the validity of the comments but said,

> It would be difficult, if not impossible, to describe the test dummy in performance terms with such specificity that every dummy that could be built to the specifications would perform identically under similar conditions.

NHTSA thus declined to "freeze" dummy construction and performance specifications at that time. In the same Federal Register issue, a proposal [14] was made to ease the timing for mandatory automatic protection systems by extending the third option for two years with, however, the requirement that outboard lap/shoulder belts meet the injury criteria of automatic restraints and include an ignition interlock.

3.2 Head Injury Criteria

The Fifteenth Stapp Car Crash Conference, held in the fall of 1971, included special sessions on head injury and became a forum for the discussion of head injury mechanisms, tolerance thresholds, and test criteria. Translation vs. rotation was again discussed (Unterharnscheidt, 1971[26]; Gennarelli, Ommaya, and Thibault, 1971[27]); Gadd (1971)[28] suggested that, based on rocket sled experiments, the SI<1000 limit was much too conservative for non-contact, whole-body accelerations; and Fan (1971)[29] introduced the Revised Brain Model (RBM), a modification of the JTI. Versace (1971)[30] presented a mathematical critique of the SI and suggested an alternative method for calculating the index number, in which the effective acceleration, defined as $\frac{1}{T} \int a^n \, dt$, was raised to the 2.5 power and multiplied by the time duration. Versace argued the approach was still inadequate because of two factors: (1) biomechanical data were insufficient to accurately arrive at an appropriate exponent, and (2) the index represented only an intermediate stage in the injury chain of events. A measure of the actual response of the brain to head impact would be more relevant.

NHTSA liked Versace's formula because it was able to handle the seemingly high tolerance levels in cases of long duration, low-level acceleration and in cases of two or more high peak accelerations associated with two or more impacts. In March 1972, a proposal [16] was issued to replace the SI in FMVSS 208 with the following expression:

$$\left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a \, dt\right]^{2.5} (t_2 - t_1) < 1000$$

where "a" is the resultant acceleration and "t_1" and "t_2" are any two points in time during the crash. The decision to change was said to be based on research information that "head acceleration exposure is not always additive relative to head injury." Although not formally labeled at that time, the new index soon became known as the Head Injury Criterion (HIC).

In the month prior to the HIC proposal, NHTSA issued the FMVSS 208 rule [15] that extended the injury criteria of automatic restraint systems to the manual lap/shoulder belts of the third option and added the ignition interlock. Vehicle manufacturers commented that, as long as the head does not contact anything, belt systems allow the head to flop loosely forward, creating a high SI value while not contributing significantly to injury. When the HIC was adopted as a rule [18] in June 1972, NHTSA restricted the definition of t_2 and t_1 to be "any two points in time after the head contacts a part of the vehicle other than the belt system." This modification applied only to belt systems allowed under the interim third option. The issue was not resolved yet, however, and in October a further restriction was made to discount the effects of glancing blows. The regulation [19] then specified "any two points in time during any interval in which the head is in continuous contact with a part of the vehicle other than the belt system."

3.3 Developments in Mathematical and Mechanical Models

Although the regulator had updated its injury criterion and testing procedures, research continued to better characterize and predict skull/brain injury and to use this information to develop test dummies having reasonable levels of repeatability and biofidelity. These issues were the subjects of several papers presented at the Symposium on Human Impact Response in October 1972.

At this symposium, McElhaney, Stalnaker, and Roberts (1972)[31] presented further refinements of the MSC and compared its injury predictions to those of the other indexes, i.e., SI, HIC, JTI, EDI, and RBM. The MSC was revised to represent the Mean (rather than maximum) Strain Criterion, where "mean strain" was defined as "the displacement of one side of the head relative to the other, divided by the distance across the cranium." Basing a tolerance curve on average rather than peak acceleration levels was more consistent with other criteria. The mean tolerable strain for human heads was calculated to be .0061 in/in. Comparing the MSC to other indexes for several simulated crashes, the JTI, EDI, and RBM predictions were similar to the MSC, but the SI and

HIC were much more conservative. In the final section of the paper, the authors summarized data from human cadaver impact tests, undertaken to establish force- and acceleration-time histories of the human head, so that dummy head impact reponses could be specified.

The discussion that followed the presentation dealt with the current state of understanding of brain injury mechanisms and the implications for head injury modeling. Part of this discussion is quoted here:

> J.H. McElhaney: The model we propose, which as we see predicts essentially the same things as many other models, is based on information from essentially rigid or almost hard impacts. Under these conditions we get a certain type of injury. We have certain injury mechanisms involved. We're starting to believe more and more, that this mechanism is cavitation whereas at one time we thought it might be just a gross deformation in the brain...We're still staying with a lumped-parameter model, but we're introducing many more parameters in an attempt to build into it the ability to consider different mechanisms of injury. We recognize particularly that as the pulse duration increases, there is a different mechanism of injury; and in fact, in the rigid striker impacts we see predominately contracoup type injuries. When we pad this striker we don't see contracoup injuries anymore. We see minute hemorrhaging in much larger areas in the brain. Both of these injury types cause some difficulty in assessment. If the injuries occur in one region of the brain our pathologist tells us it's of no consequence; but if they occur in another region of the brain or tear a major artery, for example, it's very serious...When we go to long pulse durations where we have a lot of angular displacement of the head or high angular velocity, we see a completely different type of injury mechanism. We see subdural hematomas and brain stem involvement. What I think we will wind up with in the future is either several injury criteria, each relating to a specific injury depending on the mechanism, or possibly one injury criterion that covers all of the injury mechanisms...This is a difficult problem, and its not going to be solved right away; but at the same time the automotive community is also faced with a difficult problem that they have to solve right away, and I don't have much more advice than to go slow until we learn more.

On December 5, 1972, the U.S. Court of Appeals, Sixth Circuit, ruled on the Chrysler suit challenging the automatic restraint regulations. The decision rendered the FMVSS 208 test procedures invalid because of an inadequately specified test dummy. In response to this ruling, NHTSA issued a proposal [20] in April 1973 that introduced the General Motors Hybrid II Dummy, a highly repeatable test device, as the new test dummy for the first and second options. In June, a regulation [22] was published that eliminated all dynamic tests for belt systems covered under the third option as a result of further court decisions on test dummy inadequacies. Dynamic tests for third option manual belts were never reinstituted. Automatic belt systems, however, would be covered under the first option test conditions.

In August, a new Part 572 was added to Title 49 of the Code of Federal Regulations [23] that established the previously proposed dummy as NHTSA's test device. The dummy was specified with detailed drawings and performance criteria. The performance specifications of the dummy head were as follows:

> When the head is dropped from a height of 10 inches ...the peak resultant accelerations at the head's center of gravity shall be not less than 210 g and not more than 260 g. The acceleration/time curve for the test shall lie at or above the 100 g level for an interval not less than 1.5 ms.

Except for minor problems with surface texture and accelerometer placement, these specifications were generally accepted by safety engineers.

During this same period, another dummy was being developed that had the joint goals of providing repeatable/reproducible results as well as having a biodynamic performance in frontal impacts closely matching that of unembalmed human cadavers. The dummy was introduced at the Seventeenth Stapp Car Crash Conference as "Repeatable Pete" (McElhaney, Mate, and Roberts, 1973[32]). The development process for the head and thorax of this dummy is significant in that it was the first time a laboratory had made mechanical measurements, designed a physical model, and evaluated the model using the same test equipment, instrumentation, and procedures. This closed-loop process resulted in the first demonstration of a repeatable test device that also had good biomechanical response.

At the same conference, Stalnaker, Roberts, and McElhaney (1973)[33] reported the results of new long-duration lateral head impacts to human cadavers and live infrahuman primates. Using dimensional analysis techniques, the animal data were scaled to estimate the side impact tolerance of the living human. The threshold of human closed-brain injury was reported to be 76 g for a 20 ms impulse. Autopsies showed that long-duration impacts most commonly resulted in brain stem and internal brain hemorrhaging in areas remote from the impact locations.

3.4 HIC Extensions

Returning to regulatory developments, the HIC was being extended into the test criteria of other standards. Shortly after the HIC was proposed for use in FMVSS 208, a proposal [17] was issued for a new standard on motorcycle helmets. Initially, the helmets would meet certain peak and cumulative-duration g criteria, but eventually the standard would be upgraded to require helmets to meet the proposed HIC. When FMVSS 218 [24] was issued in August 1973, however, the latter aspect was deferred pending further research and testing. A comprehensive review of head impact research and injury criteria as they relate to helmet standards can be found in Robbins (1980)[34].

A proposal [25] for a new standard on school bus occupant protection was isssued in July 1973. The proposal applied the HIC to the testing of head impact areas, such that when they were impacted at 15 mph by an 11.5-pound, 6.5-inch-diameter hemispherical headform, the HIC was to be less than 1000, using the resultant acceleration at the headform center of gravity. The proposal also described the force-time history on the headform by stating that the energy absorbed by the impacted material must be greater than 40 inch-pounds before the force level on the impactor exceeded 150 pounds; and it described the load distribution by stating that, at 5-ft/s impacts, the area impacted must be greater than 3 square inches. In April 1975, the proposal [27] was altered to limit the HIC calculation to the use of "axial" or translational acceleration of the headform in its direction of travel. In January 1976, FMVSS 222 [29] was issued with the headform impact requirements included as proposed.

4.0 Later Period: 1974-1980

4.1 Finite Element and Kinematic Models

In the mid-1970's, new modeling efforts were launched using finite element analysis methods. Finite element models differ from traditional "infinitesimal models" primarily in the manner in which continuity is expressed. Generally, the former are more adaptable to digital computation techniques and more readily accept various forms of calculation tolerances. The ability of this type of approach to handle irregular shapes and inhomogeneous materials made it particularly suitable for modeling the mechanical structures and responses of the head. These efforts were hampered, however, by the lack of a complete set of data describing the properties of the various materials of the head.

Chan (1974)[35], following a discussion of shell models and a careful review of the continuum mechanics research on impact loading of head-like forms, presented a finite element model that predicted both shear strain and reduced pressure effects. The model was three-dimensional and had a symmetric axis of revolution. A more complex model, but still of idealized shape, was later developed by Khalil and Hubbard (1977)[36].

Two models reflecting the actual geometry of the head were developed under NHTSA sponsorship. These were reported to the Nineteenth Stapp Car Crash Conference. (Shugar, 1975[37]; Ward and Thompson, 1975[38]). The Shugar model concentrated on the mechanics of skull deformation and fracture, treating the brain as a homogenous, nearly incompressible material. The Ward model, on the other hand, assumed the skull to act as a rigid shell and only addressed the complex effects of impact and abrupt acceleraton on the brain itself. For practical and economic reasons, these two approaches could not be integrated because each had several hundred degrees of freedom. Since the Ward model was more appropriate than the Shugar model for the longer-duration impacts experienced in crash environments having energy absorbing materials and structures, its further development was supported by NHTSA.

Mucciardi, Sanders, and Eppinger (1977)[39] demonstrated an interesting approach to predicting brain injury by analyzing head motion. Data from head impacts to monkeys performed by HSRI were used. Measured translational and rotational acceleration and velocity waveforms were treated by a non-linear Adaptive Learning Network (ALN) program developed to produce empirically-derived predictive models of head injury. The injury criterion was a special computed overall AIS.

Time derivatives were used to create "jerk" waveforms to be used in addition to the measured waveforms. From thirty-four available kinematic parameters, the ALN model successfully predicted the observed integer AIS (using seven parameters), the unconsciousness AIS (using six parameters), and the time of unconsciousness (using seven parameters). The authors concluded that the overall AIS was a function of the total momentum transferred from the impact and the rate of momentum transfer. Their results suggested that rotational motion might be a prominent factor in causing unconsciousness, but that the overall AIS was primarily dependent upon translational motion.

4.2 Experimental Advances and Model Validation

More experimental data were still needed before brain injury could confidently be predicted, and experimental methods also needed to be improved. Nahum and Smith (1976)[40] made contributions to both areas. They performed experimental blunt impacts to the heads of human cadavers whose fluid pressues in the cerebrospinal fluid space and cerebral blood vessels had been raised to simulate realistic levels. Resultant accelerations were obtained from the signals of four head-mounted accelerometers and were used to calculate SI and HIC values. The time histories of the accelerations and impact forces were presented along with autopsy evaluations of the injuries produced. These experiments indicated that laboratory procedures could produce injuries similar to those seen in a clinical practice and that a rough correlation existed between currently used head injury criteria and the intracranial trauma observed.

In a continuation of their work, Nahum, Smith, and Ward (1977)[41] measured intracranial pressures arising from head motion during impact and compared these to pressures predicted by the Ward model. Correlations were generally good, especially in the frontal region of the brain. Modifications to the damping factor and compessibility of the brain model were made to improve the correlations. Additional correlations of model predictions with live monkey tests at HSRI showed the same relationship as those for pressurized cadavers and thus indicated that the experimental procedures adequately simulated the in vivo state. This cooperative experimental/analytical research program was of benefit to both approaches.

Further contributions to experimental procedures were made by Stalnaker, Melvin, et al. (1977)[42]. In a series of head impacts with human cadavers, head motion was measued using a new three-dimensional accelerometry technique that made the calculation of angular accelerations possible for the first time. These data were compared to brain motion observable using a new high-speed cineradiographic system. Brain vascular pressurization methods were also developed and used in some of the tests. Preliminary analysis of the data indicated that the brain was only partially coupled to the skull during impact, resulting in an effective head mass that varied with time during the impact. Pressurization was found to improve skull/brain coupling. In addition, the authors observed a degradation of brain stiffness as time after death increased.

Biomechanical data was also being used by those designing improved physical models. Foster, Kortge, and Wolanin (1977)[43] introduced the new General Motors Hybrid III Dummy, which had been under development since 1975. While retaining the repeatability of the Hybrid II, the Hybrid III provided biomechanical responses, including those of the head, consistent with responses found in published literature. Like "Repeatable Pete," however, biofidelity of this dummy was limited to the frontal impact diection.

In May 1978, a proposal [31] was issued for an upgraded standard on child restraint systems, FMVSS 213. Dynamic tests were to be required for the first time using a "three-year-old" dummy to represent children between 20 and 50 pounds in a 30 mph barrier crash. Lacking biomechanical data for child injury tolerance, NHTSA specified the same HIC threshold as that for "adult" dummies. Restraint systems for infants had only to meet certain head-area padding requirements, because the "infant" test dummies were not suitable for making acceleration measurements. The rule [32] appeared a year and a half later with the injury criterion included as proposed.

In an attempt to determine the validity of the HIC threshold of 1000, Got, Patel, et al. (1978)[44] calculated the HIC for 42 free-fall impacts to the heads of human cadavers. Some were helmeted, some were not. Using their own method of measuring accelerations to calculate the resultant, the authors found that tolerance to head impact without fracture was much greater than the HIC would allow. They suggested that HIC<1500 was appropriate for both frontal and lateral impacts.

At the Twenty-Third Stapp Car Crash Conference, new head rotation experiments were reported, and further experimental validations of the Ward brain model were presented. Gennarelli, Abel, et al. (1979)[45] subjected monkeys to rotational head accelerations and found the threshold for frontal lobe contusion to be less than that for the temporal lobe. The authors attributed this finding to differences in mechanical input to the two regions rather than to differences in tissue properties.

Nahum, Smith, et al. (1979)[46] presented results of impacts to helmeted, human cadavers, finding that the protective device prevented high-magnitude, short-duration intracranial pressures for the first 8 ms. Positive posterior pressures, which seemed to be unique to helmeted-head impacts, developed after 8 ms and were not computed by the model.

Recognizing the fact that head impact tolerance of living humans would never be experimentally measured to the injurious level, Nusholtz, Melvin, and Alem (1979)[47] compared the head impact response of live and post-mortem monkeys and related the results to the earlier cadaver tests of Stalnaker, et al. (1977)[42]. Differences in acceleration- and pressure-time histories were found between the live and unpressurized post-mortem states, the latter resulting in lower peaks and smoother waveforms. Comparisons with the human cadaver tests were complicated by differences in head size and head/neck muscle structure. The authors found, however, that by changing the data parameters from time to path arc length, the head response waveforms for monkeys and humans could be made more congruent.

The epidural pressures measured above were compared to predictions of the Ward model, adjusted for monkey head mass and geometry. The results, reported by Nusholtz, Axelrod, et al. (1979)[48], indicated significant differences between the live and post-mortem brain responses in terms of response time and magnitude, damping, compressibility, and coupling effects between the brain and cervical cord. The authors suggested that further tests and simulations of the impact response of pressurized post-mortem monkeys were needed.

From time to time, Ward has made comparisons between the validated injury predictions of her model and those of the HIC and found the latter index to be unreliable. These comparisons will appear in a paper to be presented at the Twenty-Fourth Stapp Car Crash Conference in 1980.

5.0 Conclusions

Those who know the history and/or participated in the development of the Head Injury Criterion are the first to acknowledge its weaknesses: it was based on sparse experimental data, it is not actually a measure of injury, and it does not necessarily correspond to injuries produced under controlled laboratory conditions. Add to this the fact that the Part 572 Dummy, the test device used to produce the data with which the HIC is calculated, claims only to have repeatability and not biofidelity. Under certain impact conditions, the dummy head, because of its stiffness, produces higher accelerations than should be expected. The question then arises, just what is being measured?

It seems unlikely, however, that NHTSA will exchange the HIC for another index in the near future. Part of the reason for a reluctance to change may be that there is no other completely validated injury prediction tool available. Even though experimental techniques have been refined so that new and better measurements can be made, data analysis methods have been devised to deal with surrogate subjects, and mathematical models have been developed that incorporate the mechanical properties and responses measured in the laboratory, sufficient laboratory head impact research with human cadavers or with animals has not yet been done, and very little is currently being conducted.

Notwithstanding the advent of automatic restraint systems, the head will remain a critical area to deal with in any occupant protection system. Not only will there continue to be head impacts with various interior structures, but the effect of new systems on non-contact head accelerations must not be neglected. Proven laboratory techniques are currently available that can provide for significant progress toward meaningful understanding of human brain injury under impact conditions. In addition to techniques of subject preparation and parameter measurement, a variety of sophisticated methods of analysis have been created and tested. Research should be carried out during the next few years that would pursue a number of these techniques. Lateral impact studies and investigations into the relative influence of subject-to-subject parameter variability should also be conducted.

The question of the relative roles of pressure and shear strain seems answerable, at least for midplane impacts, and it is reasonable to believe that the variable relationship found between actual injury and HIC values can be explained to some extent. An evolutionary type of injury criteria for the head should then result, that can change as our knowledge and understanding changes. The utility of the HIC as a reasonable tool for regulation would not be seriously threatened by such research, while the conditions for survival under impact loading of the head would be better understood.

6.0 References

1. Lissner, H.R.; Lebow, M.; Evans, F.G. 1960. Experimental studies on the relation between acceleration and intracranial pressure changes in man. Surgery, Gynecology, and Obstetrics 111:329-338.

2. Society of Automotive Engineers. 1980. Human tolerance to impact conditions as related to motor vehicle design. New York: SAE Handbook Supplement J885 APR80.

3. Gadd, C.W. 1961. Criteria for injury potential. In Impact Acceleration Stress Symposium, 27-29 November 1961, Brooks AFB, Tex., pp. 141-144. Washington, D.C.: National Academy of Sciences--National Research Council publication no. 977, 1962.

4. Eiband, A.M. 1959. Human tolerance to rapidly applied accelerations: A summary of the literature. Cleveland: NASA Lewis Research Center. NASA Memorandum 5-19-59E.

5. Patrick, L.M.; Lissner, H.R.; Gurdjian, E.S. 1963. Survival by design-head protection. In 7th Stapp Car Crash Conference Proceedings, 11-13 November 1963, Los Angeles, pp. 483-499. Springfield, Ill.: Charles C. Thomas, 1965.

6. Gadd, C.W. 1966. Use of a weighted impulse criterion for estimating injury hazard. In 10th Stapp Car Crash Conference Proceedings, 8-9 November 1966, Alamogordo, N.M., pp. 164-174. New York: SAE paper no. 660793, 1967.

7. Society of Automotive Engineers. 1965. Instrument panel laboratory impact test procedures. In SAE Handbook 1966, pp. 862-865. New York: SAE J921.

8. Holbourn, A.H.S. 1943. Mechanics of head injuries. Lancet, 245:438-441.

9. Gurdjian, E.S.; Webster, J.E.; Lissner, H.R. 1955. Observations on the mechanism of brain concussion, contusion and laceration. Surgery, Gynecology, and Obstetrics 101:680-690.

10. Gurdjian, E.S.; Roberts, V.L.; Thomas, L.M. 1966. Tolerance curves of acceleration and intracranial pressure protective index in experimental head injury. Journal of Trauma 6(5):600-604.

11. Ommaya, A.K.; Hirsch, A.E.; Martinez, J.L. 1966. The role of whiplash in cerebral concussion. In 10th Stapp Car Crash Conference Proceedings, 8-9 November 1966, Alamogordo, N.M., pp. 314-324. New York: SAE paper no. 660804.

12. Gurdjian, E.S.; Hodgson, V.R.; Thomas, L.M.; Patrick, L.M. 1968. Significance of relative movements of scalp, skull, and intracranial contents during impact injury of the head. Journal of Neurosurgery 29(1):70-72.

13. Hodgson, V.R.; Patrick, L.M. 1968. Dynamic response of the human cadaver head compared to a simple mathematical model. In 12th Stapp Car Crash Conference Proceedings, 22-23 October 1968, Detroit, pp. 280-301. New York: SAE paper no. 680784.

14. Fallenstein, G.T.; Hulce, V.D.; Melvin, J.W. 1969. Dynamic mechanical properties of human brain tissue. Journal of Biomechanics 2(3):217-226.

15. Stalnaker, R.L.; Fogle, J.L.; McElhaney, J.H. 1970. Driving point impedance characteristics of the head. American Society of Mechanical Engineers Biochemical and Human Factors Conference, 31 May - 3 June 1970, Washington, D.C. New York: ASME paper no. 70-BHF-14.

16. Metz, H.; McElhaney, J.H.; Ommaya, A.K. 1970. A comparison of the elasticity of live, dead, and fixed brain tissue. Journal of Biomechanics 3(4):453-458.

17. McElhaney, J.H.; Fogle, J.L.; Melvin, J.W.; Haynes, R.R.; Roberts, V.L.; Alem, N.M. 1970. Mechanical properties of cranial bone. Journal of Biomechanics 3(5):495-511.

18. Society of Automotive Engineers. 1968. Anthropomorphic test device for dynamic testing. SAE Handbook 1969, pp. 977-980. New York: SAE J963.

19. U.S. National Transportation Safety Board. 1979. Safety effectiveness evaluation of the National Highway Traffic Safety Administration's rulemaking process. Vol. II: Case history of Federal Motor Vehicle Safety Standard 208: Occupant crash protection. Washington, D.C. NTSB-SEE-79-5.

20. McElhaney, J.H.; Stalnaker, R.L.; Roberts, V.L.; Snyder, R.G. 1971. Door crashworthiness criteria. In 15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif., pp. 489-517. New York: SAE paper no. 710864.

21. Hirsch, A.E.; Ommaya, A.K. 1970. Protection from brain injury: The relative significance of translational and rotational motions of the head after impact. In 14th Stapp Car Crash Conference Proceedings, 17-18 November 1970, Ann Arbor, Mich., pp. 299-328. New York: SAE paper no. 700899.

22. Slattenschek, A.; Tauffkirchen, W. 1970. Critical evaluation of assessment methods for head impact applied in appraisal of brain injury hazard, in particular in head impact on windshields. In 1970 International Automobile Safety Conference Compendium, 13-15 May 1970, Detroit; 8-11 June 1970, Brussels, pp. 1084-1112. New York: SAE paper no. 700426.

23. Brinn, J.; Staffeld, S.E. 1970. Evaluation of impact test accelerations: A damage index for the head and torso. In 14th Stapp Car Crash Conference Proceedings, 17-18 November 1970, Ann Arbor, Mich., pp. 188-220. New York: SAE paper no. 700902.

24. Stalnaker, R.L.; McElhaney, J.H. 1970. Head injury tolerance for linear impacts by mechanical impedance methods. American Society of Mechanical Engineers Winter Annual Meeting, 29 November - 3 December 1970, New York. New York: ASME paper no. 70-WA/BHF-4.

25. Society of Automotive Engineers. 1966. Human tolerance to impact conditions as related to motor vehicle design. SAE Handbook 1968, pp. 911-913. New York: SAE J885a.

26. Unterharnscheidt, F.J. 1971. Translational versus rotational acceleration: Animal experiments with measured input. In 15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif., pp. 767-770. New York: SAE paper no. 710880.

27. Gennarelli, T.A.; Ommaya, A.K.; Thibault, L.E. 1971. Comparison of translational and rotational head motions in experimental cerebral concussion. In 15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif., pp. 797-803. New York: Society of Automotive Engineers.

28. Gadd, C.W. 1971. Tolerable severity index in whole-head, nonmechanical impact. In 15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif., pp. 809-816. New York: Society of Automotive Engineers.

29. Fan, W.R.S. 1971. Internal head injury assessment. In 15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif., pp. 645-665. New York: SAE paper no. 710870.

30. Versace, J. 1971. A review of the severity index. In 15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif., pp. 771-796. New York: SAE paper no. 710881.

31. McElhaney, J.H.; Stalnaker, R.L.; Roberts, V.L. 1972. Biomechanical aspects of head injury. In Human Impact Response--Measurement and Simulation. Proceedings of the Symposium on Human Impact Response, 2-3 October 1972, Warren, Mich., pp. 85-110. New York: Plenum Press, 1973.

32. McElhaney, J.H.; Mate, P.I.; Roberts, V.L. 1973. A new crash test device--"Repeatable Pete". In 17th Stapp Car Crash Conference Proceedings, 12-13 November 1973, Oklahoma City, pp. 467-507. New York: SAE paper no. 730983.

33. Stalnaker, R.L.; Roberts, V.L.; McElhaney, J.H. 1973. Side impact tolerance to blunt trauma. In 17th Stapp Car Crash Conference Proceedings, 12-13 November 1973, Oklahoma City, pp. 377-408. New York: SAE paper no. 730979.

34. Robbins, D.H. 1980. Impact head injury data base. Ann Arbor: University of Michigan Highway Safety Research Institute for the National Institute for Occupational Safety and Health.

35. Chan, H.S. 1974. Mathematical model for closed head impact. In 18th Stapp Car Crash Conference Proceedings, 4-5 December 1974, Dearborn, Mich., pp. 557-578. Warrendale, Pa.: SAE paper no. 741191.

36. Khalil, T.B.; Hubbard, R.P. 1977. Parametric study of head response by finite element modeling. Journal of Biomechanics 10(2):119-131.

37. Shugar, T.A. 1975. Transient structural response of the linear skull-brain system. In 19th Stapp Car Crash Conference Proceedings, 17-19 November 1975, San Diego, Calif., pp. 581-614. Warrendale, Pa.: SAE paper no. 751161.

38. Ward, C.C.; Thompson, R.B. 1975. The development of a detailed finite element brain model. In 19th Stapp Car Crash Conference Proceedings, 17-19 November 1975, San Diego, pp. 641-674. Warrendale, Pa.: SAE paper no. 751163.

39. Mucciardi, A.N.; Sanders, J.D.; Eppinger, R.H. 1977. Prediction of brain injury measures from head motion parameters. In 21st Stapp Car Crash Conference Proceedings, 19-21 October 1977, New Orleans, pp. 369-415. Warrendale, Pa.: SAE paper no. 770923.

40. Nahum, A.M.; Smith, R.W. 1976. An experimental model for closed head impact injury. In 20th Stapp Car Crash Conference Proceedings, 18-20 October 1976, Dearborn, Mich., pp. 783-814. Warrendale, Pa.: SAE paper no. 760825.

41. Nahum, A.M.; Smith, R.; Ward, C.C. 1977. Intracranial pressure dynamics during head impact. In 21st Stapp Car Crash Conference Proceedings, 19-21 October 1977, New Orleans, pp. 339-366. Warrendale, Pa.: SAE paper no. 770922.

42. Stalnaker, R.L.; Melvin, J.W.; Nusholtz, G.S.; Alem, N.M.; Benson, J.B. 1977. Head impact response. In 21st Stapp Car Crash Conference Proceedings, 19-21 October 1977, New Orleans, pp. 303-335. Warrendale, Pa.: SAE paper no. 770921.

43. Foster, J.K.; Kortge, J.O.; Wolamin, M.J. 1977. Hybrid III--a biomechanically-based crash test dummy. In 21st Stapp Car Crash Conference Proceedings, 19-21 October 1977, New Orleans, pp. 975-1014. Warrendale, Pa.: SAE paper no. 770938.

44. Got, C.; Patel, A.; Fayon, A.; Tarriere, C.; Walfisch, G. 1978. Results of experimental head impacts on cadavers: The various data obtained and their relations to some measured physical parameters. In 22nd Stapp Car Crash Conference Proceedings, 24-26 October 1978, Ann Arbor, Mich., pp. 57-99. Warrendale, Pa.: SAE paper no. 780887.

45. Gennarelli, T.A.; Abel, J.M.; Adams, H.; Graham, D. 1979. Differential tolerance of frontal and temporal lobes to contusion induced by angular acceleration. In 23rd Stapp Car Crash Conference, 17-19 October 1979, San Diego, pp. 563-586. Warrendale, Pa.: SAE paper no. 791022.

46. Nahum, A.M.; Smith, R.; Raasch, F.; Ward, C.C. 1979. Intracranial pressure relationships in the protected and unprotected head. In 23rd Stapp Car Crash Conference Proceedings, 17-19 October 1979, San Diego, Calif., pp. 615-636. Warrendale, Pa.: SAE paper no. 791024.

47. Nusholtz, G.S.; Melvin, J.W.; Alean, N.M. 1979. Head impact response comparisons of human surrogates. In 23rd Stapp Car Crash Conference Proceedings, 17-19 October 1979, San Diego, Calif., pp. 499-541. Warrendale, Pa.: SAE paper no. 791020.

48. Nusholtz, G.S.; Axelrod, J.B.; Melvin, J.W.; Ward, C.C. 1979. Comparison of epidural pressure in live anesthetized and postmortem primates. In 7th International Workshop on Human Subjects for Biomechanical Research Proceedings, 16 October 1979, Coronado, Calif., pp. 175-200. Washington, D.C.: Distributed by National Highway Traffic Safety Administration.

APPENDIX A

Appendix A: Federal Register Excerpts

[1] 31 FR 15212, December 3, 1966.
FMVSS 201, proposal; Docket 3, Notice 1.
Occupant Protection in Interior Impact--Passenger Cars

. . .

S3.1 Instrument panels. Except as provided in S3.1.1, when that area of the instrument panel that is within the head impact area, unrestrained child impact area, or knee and leg impact area is impacted by a 15 pound, 6.5-inch-diameter head form at a relative velocity of 15 miles per hour--

(a) The deceleration of the head form shall not exceed 80g for 1.0 millisecond or more; and,

(b) The pressure in the area of contact shall not exceed 100 p.s.i.

S3.1.1 The requirements of S3.1 do not apply to areas--

(a) Less than 5 inches inboard from the juncture of the instrument panel attachment to the body side inner structure; and,

(b) Closer to the windshield juncture than those contactable by the head form with the windshield in place.

[2] 32 FR 2408, February 3, 1967.
FMVSS 201, rule; Docket 3.
Occupant Protection in Interior Impact--Passenger Cars

. . .

S3.1. Instrument panels. Except as provided in S3.1.1, when that area of the instrument panel that is within the head impact area or knee and leg impact area is impacted by a 15 pound, 6.5 inch diameter head form at a relative velocity of 15 miles per hour, the deceleration of the head form shall not exceed 80g for 1.0 millisecond.

S3.1.1 The requirements of S3.1 do not apply to areas--

(a) Less than 5 inches inboard from the juncture of the instrument panel attachment to the body side inner structure; or,

(b) Closer to the windshield juncture than those contactable by the head form with the windshield in place.

. . .

S3.2 Seat backs. Except as provided in S3.2.1, when that area of the seat back that is within the head impact area or knee and leg impact area is impacted by a 15 pound, 6.5 inch diameter head form at a relative velocity of 15 miles per hour, the deceleration of the head form shall not exceed 80g for 1.0 millisecond or more.

[3] 32 FR 11776, August 16, 1967.
FMVSS 201, rule; Docket 19.
Occupant Protection in Interior Impact, Passenger Cars and Related Definitions

. . .

After review of the evidence presented at the hearings ordered by the Federal Highway Administration, the report of the presiding officer, and the Bureau's analysis of the engineering meetings with the industry, I have determined that Standard 201 issued January 31, 1967, should be superseded by a new Standard that specifies initial requirements to afford impact protection for occupants and that certain related definitions should be amended accordingly.

. . .

In 255.3(b):

. . .

3. Revise the definition of "head impact area" to read as follows: "Head impact area" means all non-glazed surfaces of the interior of a vehicle that are statically contactable by a 6.5-inch diameter spherical head form of a measuring device having a pivot point to "top-of-hand" dimension infinitely adjustable from 29 to 33 inches in accordance with the following procedure, or its graphic equivalent:

(a) At each designated seating position, place the pivot point of the measuring device--

(1) For seats that are adjustable fore and aft, at--
(i) The seating reference point; and
(ii) A point 5 inches horizontally forward of the seating reference point and vertically above the seating reference point an amount equal to the rise which results from a 5-inch forward adjustment of the seat or 0.75 inch; and

(2) For seats that are not adjustable fore and aft, at the seating reference point.

(b) With the pivot point to "top-of-hand" dimension at each value allowed by the device and the interior dimensions of the vehicle, determine all contact points above the lower windshield glass line and forward of the seating reference point.

(c) With the head form at each contact point, and with the device in a vertical position if no contact point exists for a particular adjusted length, pivot the measuring device forward and downward through all arcs in vertical planes to 90 degrees each side of the vertical

longitudinal plane through the seating reference point, until the head form contacts an interior surface or until it is tangent to a horizontal plane 1 inch above the seating reference point, whichever occurs first.
. . .

S3. Requirements--S3.1 Instrument Panels. Except as provided in S3.1.1, when that area of the instrument panel that is within the head impact area is impacted in accordance with S3.1.2 by a 15-pound, 6.5-inch diameter head form at a relative velocity of 15 miles per hour, the deceleration of the head form shall not exceed 80 g continuously for more than 3 milliseconds.

S3.1.1 The requirements of S3.1 do not apply to--

(a) Console assemblies;

(b) Areas less than 5 inches inboard from the juncture of the instrument panel attachment to the body side inner structure;

(c) Areas closer to the windshield juncture than those statically contactable by the head form with the windshield in place.

(d) Areas outboard of any point of tangency on the instrument panel of a 6.5-inch diameter head form tangent to and inboard of a vertical longitudinal plane tangent to the inboard edge of the steering wheel; or

(e) Areas below any point at which a vertical line is tangent to the rearmost surface of the panel.

S3.2 Seatbacks. Except as provided in S3.2.1, when that area of the seat back that is within the head impact area is impacted in accordance with S3.2.2 by a 15-pound, 6.5-inch diameter head form at a relative velocity of 15 miles per hour, the deceleration of the head form shall not exceed 80 g continuously for more than 3 milliseconds.

[4] 32 FR 14278, October 14, 1967.
FMVSS 201, proposal; Docket 2-1.
Occupant Protection in Interior Impact--Passenger Cars
. . .

Standard No. 201, issued August 11, 1967 (32 F.R. 11776), specifies initial requirements for instrument panels, seat backs, sun visors, and armrests to afford impact protection for occupants. The Administrator is considering extending the requirements to include additional areas of protection and to increase the level of this protection. Specifically being considered are appropriate requirements for the following: protrusions, windshield header area, "A" and "B" pillars, sun visors and mountings, rearview mirrors and mountings, roofs, instrument panels, consoles, and seat backs.

Comments are also requested regarding the need for specifying more stringent impact deceleration-time requirements or higher impact test velocities or both.

[5] 33 FR 5120, March 26, 1970.
FMVSS 213, rule.
Child Seating Systems

. . .

S4.10 Impact protection.

S4.10.1 Head. Any rigid component of a child seating system that during forward, right-side, left-side, or rearward impact, may contact the head of a child within the weight and height range recommended in accordance with S4.1(h) who is positioned in the system in accordance with the instructions required by S4.2 shall--

(a) have no corner or edge with a radius of less than three-fourth inch; and

(b) be covered with deformable, non-recovery or slow-recovery energy-absorbing material having a thickness of at least one-half inch.

[6] 35 FR 7187, May 7, 1970.
FMVSS 208, proposal; Docket 69-7, Notice 4.
Occupant Crash Protection; Passenger Cars,
Multipurpose Passenger Vehicles, Trucks and Buses

On July 2, 1969, an advance notice of proposed rule making was issued (34 F.R. 11148), requesting comments on systems, including inflatable restraint systems, for crash protection of vehicle occupants that require no voluntary action on their part.

. . .

The purpose of this notice is to propose a motor vehicle safety standard for Occupant Crash Protection, which would specify performance requirements for protection of vehicle occupants in crashes both by systems that do and those that do not require voluntary action. The proposed standard would replace the existing Standard No. 208, Seat Belt Installations.

. . .

The proposed standard establishes basic injury criteria with reference to an anthropometric dummy, expressed in terms of maximum forces and pressures on critical parts of the body. It would require passenger cars manufactured on or after January 1, 1972, to meet these criteria with dummies placed at each designated seating position, in a frontal fixed barrier crash at 30 miles per hour. Since it appears that some manufacturers will be unable to meet these requirements by that date with systems that are purely passive, because of inadequate supplies of such systems, passenger cars manufactured during calendar year 1972 would be permitted to meet the criteria with advanced systems, such as vehicle-sensitive 3-point belts, that do require action by the occupants. On or after January 1, 1973, passenger cars would be required to meet the frontal crash test, and in addition a lateral impact test and a rollover test, by means requiring no action by vehicle occupants.

. . .

The anthropometric dummy is an important part of the test requirements of the proposed standard. The specifications of SAE Recommended Practice J963, "Anthropometric Test Device for Dynamic Testing," are employed for the purposes of this proposal. It is recognized that these specifications, evidently the most complete set available at this time, may not provide totally reproducible results in testing vehicle performance. Further work on this subject is in progress, and comments are specificaly requested on any changes that should be made.

. . .

S4. Occupant protection requirements.

S4.1 Frontal barrier crash. When the vehicle impacts a fixed collision barrier perpendicularly or at any angle up to 30 degrees from the perpendicular in either direction, while moving longitudinally forward at any speed up to 30 miles per hour, it shall meet the injury criteria of S4.4, under the conditions of S6.

S4.2 Lateral barrier crash. When the vehicle impacts a fixed collision barrier perpendicularly, while moving laterally at 15 miles per hour, it shall meet the injury criteria of S4.4, under the conditions of S6 except that all adjustable vehicle windows are fully open.

S4.3 Rollover. When the vehicle is subjected to 2 complete rollovers on level ground from a forward speed between 30 and 60 miles per hour, under the conditions of S6 except that all adjustable vehicle windows are fully open, no anthropometric test device shall be ejected from the passenger compartment.

S4.4 Injury criteria. The following injury criteria apply to each anthropometric test device placed in a designated seating position of the vehicle under the conditions of S6.

S4.4.1 The device shall not be ejected from the vehicle passenger compartment.

S4.4.2 The resultant head acceleration shall not exceed 80 g for any continuous period of more than 3 milliseconds.

[7] 35 FR 14941, September 25, 1970.
FMVSS 208, Docket 69-7, Notice 6.
Occupant Crash Protection, Passenger Cars, Multipurpose Passenger Vehicles, Trucks, and Buses

The purpose of this notice is to propose requirements for occupant crash protection for vehicles manufactured on or after Jauary 1, 1972. A previous notice published on May 7, 1970 (35 F. R. 7187) proposed requirements for both "passive" crash protection and for interim "active" systems, and a public meeting was held on June 24 and 25, 1970, to discuss the contents of that proposed standard. On the basis of comments and information received since the earlier notice, this notice proposes modified requirements for the interim systems effective January 1, 1972.

. . .

Under this proposed standard, manufacturers of passenger cars would be given three options under which they could provide occupant crash protection in vehicles manufactured on or after January 1, 1972.

The first option would be a passive protection system that requires no action by vehicle occupants. A variety of systems may be used to meet this requirement, among which are passive cushioning of the vehicle interior, self-fastening belt systems, crash deployed nets, "blankets," and air bags.

The second option would require a Type 1 lap belt in all positions, and would either (1) be tested by a 30-m.p.h. barrier crash with anthropometric dummies restrained by lap belts in the front outboard seating positions, with the same injury criteria as the passive system; or (2) conform to the updated requirements proposed in the notices of proposed amendment to Motor Vehicle Safety Standards No. 201 and 203 (35 F.R. 14936, 35 F.R. 14940).

The third option would be an improved combination of lap-and-shoulder belt system in the front outboard seating positions, with lap belts in other positions. The front outboard systems would be tested by a 30-m.p.h. crash in which belt systems, used with test dummies, would be required to remain intact.

. . .

Several comments were received concerning the injury criteria specified for passive systems. Most commenters felt that the force and pressure measurements specified were beyond the state of the art. It has been determined that an adequate measurement of injury can be made in terms of head acceleration, chest acceleration, and the force transmitted through each femur, and values for each of these injury criteria are specified in this notice.

. . .

S3.1 First option--passive protection system. When the vehicle perpendicularly impacts a fixed collision barrier, while moving longitudinally forward at any speed up to 30 m.p.h., it shall meet the injury criteria of S5, under the test conditions of S4 using unrestrained anthropomorphic test devices, by means that require no action by vehicle occupants.

S3.2 Second option--combination system. The vehicle shall--

. . .

(d) Meet either--

(1) The injury criteria of S5, under the test conditions of S4 with anthropomorphic test devices at each front outboard position restrained only by Type 1 seat belt assemblies, when the vehicle perpendicularly impacts a fixed collision barrier while moving longitudinally forward at any speed up to 30 m.p.h.; or

(2) The requirements proposed, as an amendment to Standard No. 201 (35 F.R. 14936) for the windshield header, the A-pillar, and Zones 1, 2, 3, and 4; and the requirements proposed, as an amendment to Standard No. 203 (35 F.R. 14940) for the steering control assembly.

S3.3 Third option--belt system. The vehicle shall--

(a) Except in convertibles and open-body type vehicles, have a Type 2 seat belt assembly, with either an integral or detachable upper torso portion, at each front outboard seating position, that conforms to Standard No. 209 and S3.4 and S3.5 of this standard;

(b) Have a seat belt warning system at each front outboard seating position that conforms to S3.6;

(c) Have either a Type 1 or a Type 2 seat belt assembly that conforms to S3.4 and S3.5 at all designated seating positions, and other than those specified in S3.3 (a); and

(d) When the vehicle perpendicularly impacts a fixed collision barrier, while moving longitudinally forward at any speed up to 30 m. p. h., under the test conditions of S4 with anthropomorphic test devices at each front outboard position restrained by Type 2 seat belt assemblies, experience no complete separation of any element of a seat belt assembly.

. . .

S5. Injury criteria. When testing conformity to S3.1 or S3.2(d)(1), the following injury criteria shall apply to each anthropomorphic test device placed in the required designated seating positions of the vehicle, under the conditions of S4.

S5.1 No portion of the test devices shall protrude beyond the boundaries of the vehicle passenger compartment.

S5.2 The resultant head acceleration shall not exceed 90 g , and shall not exceed 67 g for a cumulative duration of more than 2 milliseconds.

S5.3 The resultant chest acceleration shall not exceed 40 g for a cumulative duration of more than 2 milliseconds.

S5.4 The axial force transmitted to the pelvis through each femure shall not exceed 1,400 pounds.

[8] 35 FR 14936, September 25, 1970.
FMVSS 201, proposal; Docket 2-1, Notice 2.
Occupant Protection in Interior Impact

Standard No. 201 presently requires instrument panels and seat backs to afford occupants a certain measure of impact protection in a crash. This notice proposes to increase that protection by enlarging the surface area subject to the standard's requirements, by lowering the permissible decelerations, by increasing the test velocity in some areas, by requiring extensive use of force-distributing material, and by setting limitations on protruding surfaces within specified areas.

In place of present references to instrument panels and seat backs, six impact zones are established and defined. In addition to the areas included in the present standard, the zones include a larger portion of the seat back area, the lower surface of the instrument panel on the passenger's side, and the upper surface and part of the lower surface of the instrument panel on the driver's side.

It is proposed to test two of these zones--the upper surface of the passenger's side of the instrument panel, and the top of the seat back--at 25 m.p.h., and to test the remaining zones at 15 m.p.h. For any zone, the deceleration would not exceed 67 g for a cumulative duration of more than 3 milliseconds nor exceed 90 g for a cumulative duration of more than 1 millisecond, a restriction on the shape of the deceleration curve not found in the existing standard.

This notice proposes to require force-distributing material on the door pillars, roof interiors, and windshield headers, in addition to altering the requirements presently applicable to sun visors and arm rests. In places where padding is not required, as on door latch releases and window and other controls, the notice proposes surface area and minimum diameter requirements to lessen the hazard to occupants.

Within the impact zones, the notice proposes to prohibit protruding surfaces that can penetrate a specified head form more than 0.375 inch under a 90-pound load. It is proposed that protruding surfaces on the roof interior, console, or seat backs must also meet specified safety requirements.

. . .

S4.1 Impact zones.

S4.1.1 When any point in the area of the motor vehicle interior in impact zones 1, 2, 5, or 6, as specified in S4.1.6 and Figure 1, or any point on a console assembly not in a zone, is impacted by a rigid, 6.5-inch diameter, 15-pound spherical head form with its leading point traveling in a direction normal to the surface at the velocity specified below, the deceleration of the head form shall not exceed 67 g for a cumulative duration of more than 3 milliseconds, and shall not exceed 90 g for a cumulative duration of more than 1 millisecond, when measured at frequencies between 0.5 and 1,000 cycles per second.

(1) For impact zone 1, at 25 miles per hour;
(2) For impact zone 2, at 15 miles per hour;
(3) For impact zone 5, at 15 miles per hour;

(4) For impact zone 6, at 25 miles per hour;

(5) For any part of a console assembly not within an impact zone, at 15 miles per hour.

. . .

S4.1.4 The contactable surface of impact zones 1 and 2 shall be covered with force-distributing material having a thickness of at least 1.5 inches and meeting the requirements of S4.2.

. . .

(a) Impact zone 1 is the area of the instrument panel between the passenger's windshield pillar reference plane and the steering wheel plane, and forward of the instrument panel contour line up to and including the rearmost contactable surface rearward of the juncture of the panel and the windshield.

. . .

(b) Impact zone 2 is the area of the instrument panel between the driver's windshield pillar reference plane and the steering wheel reference plane, and forward of the instrument panel contour line up to and including the rearmost contactable surface rearward of the juncture of the panel and the windshield.

. . .

(e) Impact zone 5 is the area of each seat back, excluding the seat back of a rearmost, side-facing, back-to-back, folding auxiliary jump, or temporary seat, inboard of its seat back reference plane or planes, that is below the seat back contour line and above a horizontal plane passing through the seat back at a point 10 inches vertically above the seating point.

(f) Impact zone 6 is the area of the seat back, including head restraints in their highest design adjustment position but excluding the seat back of a rearmost, side-facing, back-to-back, folding auxiliary jump, or temporary seat, inboard of its seat back reference plane or planes, and above and forward of the seat back contour line.

[9] 35 FR 16927, November 3, 1970.
FMVSS 208, rule; Docket 69-7, Notice 7.
Occupant Crash Protection in Passenger Cars, Multipurpose Passenger Vehicles, Trucks, and Buses

The purpose of this amendment to Standard 208 is to specify occupant crash protection requirements for passenger cars, multi-purpose passenger vehicles, trucks, and buses, manufactured on or after July 1, 1973, with additional requirements coming into effect for certain of those vehicles manufactured on or after July 1, 1974.

. . .

The notice of proposed rulemaking published on September 25, 1970 (35 F.R. 14941), proposed injury criteria that are modified from the May 7 notice. These criteria would limit head accelerations to 67 g except for cumulative periods of 3 milliseconds with a maximum of 90 g, limit chest accelerations to 40 g, except for cumulative periods of 2 milliseconds, and limit the axial force through each upper leg to 1,400 pounds. Comments to the May 7 and the September 25 notices varied widely in their recommendations. Some advocated the use of severity indices, while others disputed the methods or the quantitative levels of the indices. The levels proposed in the September 25 notice are adopted in this standard, with the head acceleration changed from 67 g to 70 g, as the best available criteria for the quantities measured. Consideration will be given to adoption of a severity index or other criteria as further research results become known. Research results and comments related to the problem indicate, however, that human tolerances for lateral accelerations on the head and chest are significantly lower than for forward ones, and the separate notice issued today (35 F.R. 16937) proposes additional injury criteria with respect to the lateral component of head and chest accelerations.

. . .

On consideration of all available data, it has been determined that dummies conforming to the SAE specifications are the most complete and satisfactory ones presently available. More complete specification have been added for the configuration of the pelvis, the positioning of the dummies in the vehicle, and the instrumentation techniques. The positioning of instrumentation within the dummies is specified to insure more consistent and repeatable results. A requirement that acceleration data be filtered to exclude frequencies higher than 250 cycles per second has been added, in response to several comments, to eliminate sharp spikes due to electronic noise and dummy resonance that are not considered significant with respect to injury.

[10] 35 FR 16937, November 3, 1970.
FMVSS 208, proposal; Docket 69-7, Notice 8.
Occupant Crash Protection In Passenger Cars,
Multipurpose Passenger Vehicles, Trucks, and Buses

The purpose of this notice is to propose amendments to the revised Motor Vehicle Safety Standard No. 208, Occupant Crash Protection, issued today (35 F.R. 16926), that would add additional injury criteria for lateral acceleration of the head and chest, specify test conditions for the lateral moving barrier crash test and the rollover test, omit the exception of openbody type vehicles from the rollover requirement that was proposed in the notice of May 7, 1970 (35 F.R. 7187), and establish a minimum vehicle speed for actuation of crash-deployed protection systems.

The standard as issued provides that the resultant accelerations of the head of an anthropomorphic test device in the specified crashes shall not be more than 70 g, except for a cumulative duration of 3 milliseconds, with an absolute maximum of 90 g.

. . .

Biomechanical studies indicate that the lateral acceleration tolerance of the head and chest are significantly less than the frontal acceleration tolerance. It is accordingly proposed that in addition to the criteria described above for resulant accelerations, a requirement be added limiting the lateral component of head accelerations to 40 g, except for a cumulative period of 3 milliseconds.

. . .

A moving barrier test is proposed in place of the fixed barrier collision. The moving barrier speed is set at 20 m.p.h., a speed calculated to approximate the impact of a 15-mile-per-hour fixed barrier impact, or a 30-mile-per-hour car-to-car collision.

. . .

This notice proposes a procedure for rollover testing whereby the vehicle is launched transversely with a specified deceleration pulse from a raised carriage-type platform onto a concrete surface.

. . .

To avoid variable results from collisions between dummies, the standard provides that dummies are to be positioned only in the outboard positions on the side of the impact, for the lateral impact test, and only in the outboard positions on the lower side of the vehicles as mounted on the test platform, for the rollover test.

. . .

A final proposed amendment concerns the minimum vehicle speed for deployment of crash-deployed systems. Comments on the May 7 notice and other information indicate that fixed energy-absorption materials are capable of meeting the occupant protection requirements at low speeds. It is therefore proposed to raise the minimum deployment speed for crash-deployed systems to 15 miles per hour. It is proposed to retain the requirement that the minimum deployment speed be applicable at any angle of impact, since presently available sensors can provide the necessary directional-velocity discrimination, and it is important that crash-deployed systems do not deploy except in crash situations for which they are designed.

[11] 36 FR 2815, February 10, 1971.
FMVSS 208, notice.
Occupant Crash Protection, Notice of 1972 Requirements

This notice is issued as advance public information, for the purpose of informing motor vehicle manufacturers of the main highlights of the Occupant Crash Protection standard (No. 208) that will apply to passenger cars beginning January 1, 1972, to enable them to initiate preparation for production with minimum loss of the remaining leadtime. The features of the standard set forth herein represent final decisions with respect to the standard, which is presently being prepared for issuance in the near future.

Passenger cars, at each designated seating position, must meet at least one of three sets of requirements, or options, as follows:

First Option--Complete Passive Protection System

1. The vehicle shall provide passive protection in frontal fixed barrier crash tests up to 30 m.p.h., and up to 30 degrees to either side of the perpendicular, and in lateral and rollover crash tests. Seat belts are not required, and except for the completely passive type belt system, may not be used for testing.

2. The test dummy is as described in SAE J963, with instrumentation as described in SAE J211.

3. The injury criteria are (a) a maximum head severity index of 1,000, calculated according to SAE J885a, (b) a maximum chest acceleration of 60g, except for periods with cumulative duration of not more than 3 milliseconds, and (c) a maximum upper leg force of 1,400 pounds.

Second Option--Lap Belt Protection System with Belt Warning

. . .

4. For front outboard seats, the vehicles shall meet a perpendicular 30 m.p.h. fixed barrier crash test with instrumented test dummies and injury criteria as described in the first option, but with the dummies lap-belted. No shoulderbelt is required, and even if furnished is not used for testing under this option.

. . .

Third Option--Lap and Shoulder Belt Protection System with Belt Warning

1. The vehicle shall provide a lap and shoulder belt assembly for the front outboard seats, and lap belts at the other seating positions.

2. A belt warning system as described above is required for the lap-belt portions of the front outboard seating positions. Requirements for lap-belt retractors, method of release, and for ranges of adjustment are the same as in the second option.

3. The lap and shoulder belts in the front outboard positions are tested with dummies in a perpendicular 30-m.p.h. fixed barrier crash, with the requirement that there be no structural failures of the restraint system.

[12] 36 FR 4600, March 10, 1971.
FMVSS 208, rule; Docket 69-7, Notice 9.
Occupant Crash Protection in Passenger Cars,
Multipurpose Passenger Vehicles, Trucks, and Buses

The purpose of this amendment to Standard No. 208, 49 CFR 571.21, is to specify occupant crash protection require-ments for passenger cars, multipurpose passenger vehicles, trucks, and buses manufactured on or after January 1, 1972, with additional requirements coming into effect for certain of those vehicles on August 15, 1973, August 15, 1975, and August 15, 1977. The requirements effective for the period beginning on January 1, 1972, were the subject of a notice of proposed rulemaking published September 25, 1970 (35 F.R. 14941), and appear today for the first time in the form of a rule. The requirements for subsequent periods were issued in rule form on November 3, 1970 (35 F.R. 16927), and are reissued today in amended form as the result of petitions for reconsideration.

. . .

The standard establishes quantitative criteria for occupant injury, as determined by use of anthropomorphic test devices. For the head, the criterion is a severity index of 1,000, calculated according to SAE Information Report J885a.

. . .

On January 1, 1972, a passenger car will be required to provide one of three options for occupant protection: (1) Passive protection system that meets the above injury criteria in all impact modes at all seating positions; (2) lap belts at all positions, with a requirement that the front outboard positions meet the injury criteria with lap-belted dummies in a 30-m.p.h. barrier crash without belt or anchorage failure, and lap belts in other positions.

. . .

On August 15, 1973, a passenger car will be required to provide one of two options for occupant protection: (1) Passive protection that meets the injury criteria in all impact modes at all seating positions; or (2) a system that provides passive protection for the front positions in a perpendicular frontal fixed barrier crash, that includes lap belts at all seating positions such that the injury criteria are met at the front positions both with and without lap belts fastened in a perpendicular frontal fixed barrier crash, and that has a seat belt warning system at the front outboard positions.

On and after August 15, 1975, a passenger car will be required to meet the injury criteria in all impact modes at all seating positions by passive means.

. . .

The third option proposed in the September 25 notice has been adopted with some changes. It consists of an improved combination of lap and shoulder belts in the front outboard seating positions, with lap belts in other positions. The belts and anchorages at the front outboard positions must be capable of restraining a dummy in a 30-m.p.h. frontal perpendicular impact without separation of the belts or their anchorages.

. . .

The date on which a passenger car must provide passive means of meeting the injury criteria in a side impact is changed to August 15, 1975, to reflect the greater leadtime needed to develop such passive systems. To provide uniform phasing, and allow time for development of passive protection in the angular-impact and rollover modes, the effective dates for these requirements is also set at August 15, 1975.

Thus, after August 15, 1975, each passenger car must meet the crash protection requirements at each seating position in all impact modes by means that require no action by vehicle occupants.

. . .

A number of petitions objected to the requirement for a minimum speed below which a crash-developed system may not deploy. Upon consideration of the petition, it has been determined that it is preferable to allow manufacturers freedom in the design of their protective systems at all speeds, and this requirement is hereby deleted from the standard.

The injury criteria specified in the November 3 amendment were the subject of numerous petitions. The basic objections to the head injury criteria were that the 70g-3-millisecond requirement was too conservative, with respect to both acceleration levels and time factors. Review of these objections and a reevaluation of the information available to the Administration leads to the conclusion that the head injury criteria can be more appropriately based on the severity index described in the Society of Automotive Engineers Information Report J885a, June 1966. Accordingly, the standard adopts as the criterion for head injury a severity index of 1,000 calculated by the method in the SAE report.

. . .

The use of the anthropomorphic test device described in SAE J963 was objected to by several petitioners, on the grounds that further specifications are needed to ensure repeatability of test results. The Administration finds no sufficient reason to alter its conclusion that the SAE specification is the best available. The NHTSA is sponsoring further research and examining all available data, however, with a view to issuance of further specifications for these devices.

[13] 36 FR 19254, October 1, 1971.
FMVSS 208, rule; Docket 69-7, notice 12.
Occupant Crash Protection for Passenger Cars, Multipurpose Passenger Vehicles, Trucks, and Buses

The purpose of this notice is to respond to petitions filed pursuant to Part 553.35 of Title 49, Code of Federal Regulations, requesting reconsideration of Motor Vehicle Safety Standard No. 208, Occupant Crash Protection (49 CFR 571.21), published on March 10, 1971 (36 F.R. 4600).

. . .

The use of the severity index of 1000 as the criterion for head injury was objected to as too stringent, and a more lenient index requested. Considering the present state of the art in head injury measurement, it has been determined that a Severity Index of 1000 is the most acceptable criterion at this time, and it has therefore been retained.

. . .

Several petitioners noted that the requirements for anthropomorphic test devices specified in the standard, mainly those set forth in SAE Recommended Practice J963, do not completely define all the characteristics of the dummies that may be relevant to their (and the vehichle's) performance in a crash test. The NHTSA considers the comment valid. It would actually be difficult, if not impossible, to describe the test dummy in performance terms with such specificity that every dummy that could be built to the specifications would perform identically under similar conditions. Of course, since the dummy is merely a test instrument and not an item of regulated equipment, it is not necessary to describe it in performance terms; its design could legally be "frozen" by detailed, blueprint-type drawings and complete equipment specifications. Such an action does not, however, appear to be desirable at this time. Considerable development work is in process under various auspices to refine the dynamic characteristics of anthropomorphic devices, to determine which designs are most practicable, offer the most useful results, and best simulate the critical characteristics of the human body. The NHTSA is monitoring this work (and sponsoring some of it), and intends to propose amendments of the standard in accordance with it to add more detailed performance and descriptive specifications for the test dummies, although no changes are being made in that respect by this notice.

[14] 36 FR 19266, October 1, 1971.
FMVSS 208, proposal; Docket 69-7, Notice 13.
Occupant Crash Protection in Passenger Cars

. . .

In response to requests by several manufacturers for a delay in the date by which passive protection must be provided in passenger cars, for the reasons discussed in the notice of action on the petitions, it is hereby proposed that a third option be allowed for the period from August 15, 1973, to August 15, 1975.

. . .

(7) All belts would be required to conform to Standard No. 209; the front outboard belts, whether lap belts or nondetachable lap and shoulder belt combinations, would have to meet the injury criteria of the standard when tested with dummies in a 30-m.p.h. frontal barrier crash; and the lap belts in the front center position (if any) must remain intact in the same crash test. Although a detachable shoulder belt is not prohibited at the front outboard positions, an assembly with a detachable shoulder belt would have to meet the injury criteria with the lap belt alone.

. . .

S4.1.2 Passenger cars manufactured from August 15, 1973 to August 14, 1975.

. . .

S4.1.2.3 Third option--lap and shoulder belt protection system with ignition interlock and belt warning.

. . .

(d) At each front outboard designated seating position meet the frontal crash position requirements of S5.1, in a perpendicular impact, with the test device restrained by a Type 1 seatbelt assembly or a Type 2 seatbelt assembly with a nondetachable upper torso portion; and

(e) When it perpendicularly impacts a fixed collision barrier, while moving longitudinally forward at any speed up to and including 30 m.p.h., under the test conditions of S8.1, with an anthropomorphic test device at any front-center seating position restrained by a Type 1 or Type 2 seatbelt assembly, experience no complete separation of any load-bearing element of the seatbelt assembly or anchorage.

[15] 36 FR 3911, February 24, 1972.
FMVSS 208, rule; Docket 69-7, Notice 16.
Occupant Crash Protection

The purpose of this notice is to amend Standard No. 208, Occupant Crash Protection, as proposed September 29, 1971 (36 F.R. 19266, October 1, 1971) with respect to the occupant protection options available between August 15, 1975. The amendments proposed on September 29 are adopted essentially as proposed, with minor modifications.

The notice proposed a third occupant protection option (S4.1.2.3) for passenger cars manufactured between August 15, 1973 and August 15, 1975. The salient feature of the new option was the use of seat belts equipped with an ignition system that would prevent the engine from starting if any front seat occupant did not have his belt fastened. The belts at the front outboard positions would have to meet the injury criteria of the standard in a 30-m.p.h. frontal barrier crash, and any lap belt in the center position would have to remain intact in the same crash. If shoulder belts were provided at the front positions, they would have to be nondetachable and have emergency locking retractors.
. . .

4. A new section S4.1.2.3 is added, reading as follows:

S4.1.2.3 Third option--lap and shoulder belt protection system with ignition interlock and belt warning.
. . .

(d) At each front outboard designated seating position, meet the frontal crash protection requirements of S5.1, in a perpendicular impact, with the test device restrained by a Type 1 seat belt assembly or a Type 2 seat belt assembly with a nondetachable upper torso portion; and

(e) When it perpendicularly impacts a fixed collision barrier, while moving longitudinally forward at any speed up to and including 30 m.p.h., under the test conditions of S3.1, with an anthropomorphic test device at any front center seating position restrained by a Type 1 or Type 2 seatbelt assembly, experience no complete separation of any load-bearing element of the seatbelt assembly or anchorage.

[16] 37 FR 5507, March 16, 1972.
FMVSS 208, proposal; Docket 69-7, Notice 17.
Occupant Crash Protection--Head Injury Criterion

The purpose of this notice is to propose an amendment to the head injury criterion in S6.2 of Motor Vehicle Safety Standard No. 208, Crash Protection, 49 CFR 571.203.

The proposed criterion differs from its predecessors in that it is based on average acceleration. Expressed verbally, the criterion is that the resultant acceleration at the center of gravity of the head during the crash shall be such that when the average acceleration (expressed in g's) during any time interval is raised to the 2.5 power and multiplied by the length of the interval in seconds, the product shall not exceed 1,000. In mathematical terms: The resultant acceleration at the center of gravity of the head shall be such that the expression:

$$\left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a \, dt\right]^{2.5} (t_2 - t_1)$$

where "a" is the resultant acceleration expressed as a multiple of "g" (the acceleration of gravity), and "t_1" and "t_2" are any two points in time during the crash, shall not exceed 1,000.

The intent of the standard's head injury criterion is to set limits on the acceleration exposure of the head that reflect the available biomechanical data in terms that can be satisfactorily measured by a test dummy. The rule published November 3, 1970 (35 F.R. 16927), specified an acceleration level of 70 g that could not be exceeded for a cumulative duration of more than 3 milliseconds and a maximum peak acceleration of 90 g. In the issuance of March 10, 1971 (notice 9, 36 F.R. 4600), the criterion for head injury was changed to the SAE Severity Index system originally developed by C. W. Gadd. The Severity Index is computed by taking the head acceleration at each instantaneous point during the crash event, raising it to the 2.5 power and integrating over the entire time interval. The acceptable index level established in the standard was 1,000, on the basis of data from head impact tolerance studies at Wayne State University and wholebody acceleration tolerance data from A. M. Eiband.

The Severity Index format had several advantages over the earlier criteria. It derived more closely from human data, it took into account the effects of acceleration outside the intervals of peak acceleration, and it had obtained a degree of acceptance in the biomechanical research community and in the automotive industry, as evidenced by its appearance in the SAE Handbook as Recommended Practice J885a.

There are indications, however, that the Severity Index has some shortcomings as a predictor of head injury. The Severity Index is an additive measure, that is, it treats the acceleration exponentially, multiplies by the time duration ($a^{2.5}t$) and adds the resulting products to arrive at the index number. The Severity Index is calculated on the basis of the entire event, including the initial deceleration as the occupant is stopped and the subsequent acceleration as he rebounds against the seat back. This impact-rebound sequence is characteristic of the performance of most restraint systems.

Recent data suggest that head acceleration exposure is not always additive relative to head injury. For example, in human volunteer tests conducted by the NHTSA at Holloman Air Force Base, the volunteers were not injured in air bag tests at speeds up to 30 m.p.h., but the Severity Indices calculated from the test data exceeded 1,000 in several cases, where it was the addition of the rebound phase that produced the excessive Severity Index. The addition of the two phases does not, therefore, appear to be appropriate.

In considering a substitute for the whole-event Severity Index, the NHTSA has utilized, inter alia, the original data from which the Severity Index was derived. The Wayne State study, a direct source of head injury (skull fracture) data, was based on "effective acceleration," i.e., average acceleration. A similar procedure was followed in the Eiband evaluation of whole-body acceleration tolerance data from human volunteer tests. The formulation of the Severity Index does not employ average acceleration. The new approach employs an average acceleration formulation similar to that used in the original presentation of injury tolerance data. It thus avoids the inappropriate accumulation of independent subinjury exposures which is inherent in the Severity Index.

Although the use of average acceleration avoids the additive effects of the Severity Index, there must be limits to the period over which the acceleration is to be averaged. Otherwise, the average can be lowered to unreasonable levels. The proposed amendment therefore establishes as the criterion the highest value achieved by raising the average acceleration over any interval to the 2.5 power and multiplying by the duration of the interval. By and large, this value will be achieved over the interval that includes the highest acceleration peak, which may fall in either the initial portion or the rebound portion of the crash. Isolated peaks generally would not combine to produce a maximum, due to the averaging effect of the lesser accelerations in between. However, successive acceleration with sharp peaks close together could produce a high value. Each of those results seems appropriate from what is known of the mechanics of head injury. Although the proposed computation would be difficult if performed by traditional analytical methods, it is routine when performed by electronic computer, as is commonly available to those who currently conduct this type of testing.

It is therefore proposed that S6.2 in Motor Vehicle Safety Standard No. 208 (49 CFR 571.208) be amended to read as follows:

S6.2 The resulant acceleration at the center of gravity of the head shall be such that the expression

$$\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a\,dt\right]^{2.5}(t_2-t_1)$$

where "a" is the resultant acceleration expressed as a multiple of "g" (the acceleration of gravity), and "t_1" and "t_2" are any two points in time during the crash, shall not exceed 1,000.

[17] 37 FR 10079, May 19, 1972.
FMVSS 218, proposal; Docket 72-6, Notice 1.
Motorcyle Helmets

. . .

The impact attenuation test would establish the maximum acceleration which can be imparted during guided-fall drop tests to a test headform on which the helmet is mounted. The requirements under this test that would be effective March 1, 1973, are based in large part on the American National Standard specifications for Protective Headgear for Vehicular Users, ANSI Z90.1-1971. Each test article would be impacted with two successive impacts on four test sites, two of which are upon a fixed, rigid flat steel anvil and two of which are upon a hemispherical steel anvil. During these impacts peak accelerations experienced by the test headform and headgear combination could not exceed 400 g. Also, accelerations would not be permitted to exceed 200 g. for a cumulative duration of more than 2 milliseconds or 150 g. for more than 4 milliseconds.

Effective September 1, 1974, the requirements would be upgraded to require that the impacts meet the higher performance levels of the proposed head injury criterion of Federal Motor Vehicle Safety Standard No. 208, Occupant Crash Protection.

. . .

S5.1 Impact attenuation.

S5.1.1 With respect to helmets manufactured from March 1, 1973, to August 31, 1974, when an impact attenuation test is conducted in accordance with S7.2, all of the following requirements shall be met:

(a) Peak accelerations shall not exceed 400 g.;

(b) Accelerations in excess of 200 g. shall not exceed a cumulative duration of 2 milliseconds; and

(c) Accelerations in excess of 150 g. shall not exceed a cumulative duration of 4 milliseconds.

S5.1.2 With respect to helmets manufactured on or after September 1, 1974, when an impact attenuation test is conducted in accordance with S7.2, the resultant acceleration shall be such that the expression

$$\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a\,dt\right]^{2.5} (t_2-t_1)$$

where "a" is the resultant acceleration expressed as a multiple of "g" (the acceleration of gravity), and "t_1" and "t_2" are any two points in time during the crash, shall not not exceed 1,000.

[18] 37 FR 12393, June 23, 1972.
FMVSS 208, rule; Docket 69-7, Notice 19.
Occupant Crash Protection

The purpose of this notice is (1) to adopt the method of calculating head injury proposed in Notice 17 of Docket 69-7 (37 F.R. 5507) as an amendment to S6.2 of Motor Vehicle Safety Standard No. 208, Occupant Crash Protection, 49 CFR 571.203, and (2) to respond in part to petitions for reconsideration of the amendments to the standard published in Notice 16, February 24, 1972 (37 F.R. 3911). The issue involving Notice 16 addressed by this notice is the applicability of the head injury criterion of S6.2 to seat belt restraint systems. Action on the remaining issues has been scheduled for completion not later than July 1, 1972.

I. <u>Calculation of head injury criterion</u>. Some substantive objections were raised to the proposed method of calculating the head injury criterion. Several comments questioned the use of resultant accelerations rather than the anterior-posterior accelerations used in the original development of the Wayne State University tolerance curve. Although the curve was originally based on anterior-posterior acceleration data, its validity for resultant accelerations appears to be confirmed by subsequent tests using resultant accelerations computed from biaxial accelerometers. Resultant accelerations have therefore been used in the amended criterion.

The question of the permissible level was again raised with some commenters supporting a level of 1,500 even under the revised method of calculation. This agency's position is that adequate justification has not been demonstrated for a numerical increase in the severity level, although adjustments in the method of calculation adopted herein may have the effect of allowing greater cumulative accelerations than would have been allowed under the Gadd Severity Index. With a new calculation, the higher numerical level is less supportable than before and it is accordingly rejected. The amendment to S6.2 is adopted as proposed.

II. Applicability of the head injury criterion to seatbelt systems. The decision to postpone the date of mandatory installation of passive restraints until August 15, 1975, was made in consideration of the hardship that would have been imposed on many manufacturers by a requirement to provide passive restraints by the original date of August 15, 1973. The injury criteria of the standard, measured in a barrier crash with instrumented dummies, were applied to belt systems as well as passive systems that might be used to meet the requirements of the standard, beginning August 15, 1973.

Several manufacturers have petitioned for the removal of the injury criteria, particularly those for head injury, from the belt system tests. Their concern arises from their test results indicating that in many vehicles currently available belt systems either do not meet or only marginally meet the head injury criteria. They have argued that much, perhaps most, of the acceleration that contributes to the head Severity Index measurement with a shoulder-belted dummy occurs as the head flops loosely forward without striking anything in the vehicle. Actual field collision data, they maintain, does not indicate that this type of head movement by shoulder-belted vehicle occupants in a crash is a serious injury-producing factor. They question the correlation between results of the dummy tests and the actual protective characteristics of the belt systems.

The NHTSA recognizes the uncertainty concerning the significance of head movement by a shoulder-belted occupant whose head does not strike the forward part of the vehicle, although it considers the present evidence too scanty to be conclusive in either direction. It also recognizes that the leadtime for any major design or component changes for the 1974 models has been virtually exhausted. Recent materials submitted to the docket indicate that presently existing inflatable restraint systems can meet the head injury criteria with little difficulty. The inherent limitations in lap-and-shoulder-belt systems make it considerably more difficult for those systems to meet these criteria, although belt systems have been found to provide protection at moderate speeds.

For these reasons, it has been decided that a temporary modification in the head injury measurements for belt systems is justified. The amendment made by this notice in response to the petitions affects vehicles manufactured before August 15, 1975, and provides that measurement of head accelerations begins, for purposes of computing the head injury criterion for belted dummies, only at the moment at which the head strikes some portion of the vehicle other than a belt. The measurement will thus include any contact with the windshield or dashboard, for example, or the effects of rebound against the seat back, but preimpact accelerations of the head will be excluded.

This agency will examine closely the accident data bearing on the traumatic effect of nonimpactive head accelerations, as well as such laboratory data as may be gathered, for example from cadaver studies. Work is also in progress concerning the correlation between dummy and human behavior, with a view to more sophisticated instrumentation and measurement of vehicle performance, and to continued evaluation of the head injury criterion for the entire test crash event.

In consideration of the foregoing, paragraph S6.2 of Motor Vehicle Safety Standard No. 208, Occupant Crash Protection, 49 CFR 571.208, is amended to read as follows:

S6.2 The resultant acceleration at the center of gravity of the head shall be such that the expression:

$$\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a\,dt\right]^{2.5} (t_2 - t_1)$$

shall not exceed 1,000, where "a" is the resultant acceleration expressed as a multiple of "g" (the acceleration of gravity), and "t_1" and "t_2" are any two points in time during the crash. However, in the case of a vehicle manufactured before August 15, 1975, when the dummy is restrained by a seat belt system, t_1 and t_2 are any two points in time after the head contacts a part of the vehicle other than the belt system.

[19] 37 FR 22871, October 26, 1972.
FMVSS 208, rule; Docket 69-7, Notice 23.
Occupant Crash Protection

The purpose of this notice is to reply to petitions filed pursuant to 49 CFR 553-35 requesting reconsideration of the requirements of Motor Vehicle Safety Standard No. 208 relating to seatbelts in vehicles manufactured after August 15, 1973, as amended by Notices 19 and 20 of Docket 69-7 (37 F.R. 12393; 37 F.R. 13265).

1. Seatbelts and the injury criteria of S6. The primary objection raised by petitioners is that Notices 19 and 20 did not altogether revoke the requirement that seatbelts used to meet the 1973 interlock option must be capable of meeting the injury criteria of S6. Although review of the petitions suggests that additional modification of the head injury criterion is advisable, the NHTSA declines to grant petitioners' request for complete relief from the injury criteria.

Review of the petitions for reconsideration of Notice 16 showed that belts would have difficulty meeting the full criteria. Since leadtime was insufficient for major design changes in belts before 1973, it was found necessary either to remove the injury criteria or modify them so that the changes needed to enable belts to conform could be made in 1973.

Upon review, it was concluded that the injury criteria, even in modified form, would have the beneficial effect of regulating the overall protection characteristics of the occupant compartment and belt system. Regulation of the seatbelt as a separate component, as in Standard 209, does not insure that the belt will be installed in a manner calculated to insulate the occupant from injurious contact with the interior of the vehicle. It was therefore decided to retain the injury criteria, with such modifications as seemed necessary to allow manufacturers to conform to S4.1.2.3 by August 15, 1973.

The most significant, though by no means the only, agent of head injury is impact with the vehicle interior. In reviewing the petitions on Notice 16, it was decided that no interim criteria would be acceptable that disregarded any impact-related accelerations. Notice 19 therefore amended the head injury criterion in a manner that was intended to include all impact accelerations and to disregard the effect of nonimpact accelerations. As several petitioners point out, however, the amendment did not fully carry out this intent. S6.2, as amended, would have disregarded only those accelerations occurring before the head impacted the vehicle and would have counted all accelerations after that point. One effect of this formula was that a glancing impact, in itself insignificant, would cause all subsequent nonimpact accelerations to be counted even though such accelerations would be distinguishable in kind from the preimpact acceleration. To avoid this result, the agency has decided to include in the calculation of the head injury criterion only those accelerations that occur while the head is in contact with the vehicle.

Some petitioners suggested that even while the head is touching the vehicle, a significant part of the head's deceleration is due to the restraining action of the belt and not to the surface that head strikes. Although there is undeniably more than one force that contributes to head deceleration, the force produced by the impacted surface becomes increasingly important as the duration of the impact increases. If the accelerations during an impact are of such an amplitude and duration that a HIC value of 1,000 is approached, the acceleration caused by the belt is generaly insignificant. The criterion therefore counts all accelerations during the impact phase.

. . .

In cosideration of the foregoing, Motor Vehicle Safety Standard No. 208, Occupant Crash Protection, 49 CFR 571.208, is amended as follows:

1. S6.2 is amended to read:

S6.2 The resultant acceleration at the center of gravity of the head shall be such that the expression:

$$\left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a \, dt\right]^{2.5} (t_2 - t_1)$$

shall not exceed 1,000, where "a" is the resulant acceleratin expressed as a multiple of "g" (the acceleration of gravity), and "t_1" and "t_2" are any two points in time during the crash. However, in the case of a passenger car manufactured before August 15, 1975, or a truck or multipurpose passenger vehicle with a GVWR of 10,000 pounds or less manufactured before August 15, 1977, when the dummy is restrained by a seatbelt system, t_1 and t_2 are any two points in time during any interval in which the head is in continuous contact with a part of the vehicle other than the belt system.

. . .

Effective date: August 15, 1973.

[20] 38 FR 8455, April 2, 1973.
Part 572, proposal; Docket 73-8; Notice 1.
Occupant Crash Protection--Proposed Test Dummy Specifications.

The purpose of this notice is to propose specifications for the test dummy to be used in testing vehicles for compliance with Motor Vehicle Safety Standard No. 208, Occupant Crash Protection, and to propose an amendment to Standard No. 208 incorporating the new specification.

. . .

The dummy design that has been tentatively selected by the NHTSA, and is hereby proposed, is a composite design using components developed by Alderson Research Laboratories, Sierra Engineering Co., and General Motors. This dummy design has been designated by General Motors as the "GM Hybrid II Dummy," and has undergone extensive testing by GM. In the judgement of the NHTSA, on the basis of information received to date and on the basis of the agency's own test program, it represents the most satisfactory design that is currently commercially available.

. . .

The NHTSA is continuing to support advanced research and development work on devices that simulate the human body. It is widely recognized that the technology in this area is in a relatively early stage of development. In the judgement of this agency, however, the device proposed for use by this notice is fully adequate for the purpose, and it is anticipated that, as finally issued, the proposed dummy specifications will remain stable for several years.

The head proposed for the dummy is the latest in a series of aluminum heads developed by Sierra Engineering Co. After reviewing the impact test data of heads having a variety of designs and compositions, the NHTSA has determined that the aluminum head is less likely to becloud the acceleration data with its own resonances than are heads of other materials.

The performance of the head is evaluated by a test in which the head is dropped forehead first onto a steelplate. The accelerations recorded by the accelerometers in the head must fall within specified limits in order for the head to qualify for use in compliance test.

The neck chosen for the dummy is made of rubber and meets the design specification of General Motors Drawing No. 50-3. Its performance is evaluated by a pendulum impact test, in which the motion of the head allowed by the neck must fall within specified limits during a controlled deceleration of the pendulum. Data from pendulum tests conducted by Calspan Corp., indicate that the test is sensitive to differences in design and repeatable in successive tests of the same neck.

. . .

To reduce variances in performance caused by differences in instrumentation location and mounting, the proposed regulation also specified the manner in which instruments are to be located and mounted.

In light of the above, it is proposed that Chapter V of Title 49, Code of Federal Regulations, be amended by adding a new Part 572, "Test Dummy Specifications" as set forth below.

It is also proposed that section S8.1.8 of Standard No. 208 be amended by substituting a reference to the Part 572 dummy for the present reference to the SAE J963 dummy. It is further proposed that the first and second restraint options available to manufacturers before passive protection becomes mandatory, suspended by the Chrysler decision, be reinstated in the standard, thereby permitting manufacturers to elect to install passive restraint systems during that period.

The NHTSA does not intend hereby to make the Part 572 dummy applicable to seat belts under the third option in 1973 (S4.1.2.3).

[21] 38 FR 9830, April 20, 1973.
FMVSS 208, proposal; Docket 69-7, Notice 26.
Occupant Crash Protection--Proposed Interlock Amendments

. . .

The initial amendment proposed by this notice is the deletion of the injury criteria as applied to belts under the interlock option in 1973. This amendment is proposed as a direct consequence of the decision of the U.S. Court of Appeals for the Sixth Circuit in _Ford v. National Highway Traffic Safety Administration_, No. 72-1179, decided February 2, 1973. The court in _Ford_ ruled that its earlier opinion in _Chrysler v. Volpe_, Sixth Circuit, No. 71-1339 et al., decided December 5, 1973, was dispositive of the _Ford_ petition, and therefore invalidated those portions of the seatbelt interlock option that rely on the test dummy for measurement of injury criteria.

Although under the court's decisions there is no obstacle to the imposition of injury criteria within a reasonable time after the agency specifies a new test dummy, the recently proposed test dummy regulation will not result in a final specification in time for manufacturers to conduct a new series of seatbelt evaluation tests before the 1974 model year. Accordingly, it is proposed that the paragraph requiring belts to meet the injury criteria (S4.1.2.3.1(d)) be deleted.

Also affected by the invalidation of the test dummy is the requirement that the center front seatbelt restrain a dummy in a 30-mi/h barrier test without belt breakage (S4.1.2.3.1(e)). To reinstate this requirement for 1974 models, the agency would need to reestablish a dummy specification in time for certification tests to be run. Present information indicates that the breakage test requirement does not contribute substantially to the performance of belt systems. It is therefore proposed that the requirement be deleted.

[22] 38 FR 16072, June 20, 1973.
FMVSS 208, rule; Docket 69-7, Notice 27.
Seatbelt Interlock Requirements

. . .

As amended, therefore, S4.1.2.3.1(a) provides that at the front outboard positions a manufacturer may install either a Type 2 seatbelt assembly that conforms to standard No. 209, or a type 1 seatbelt assembly that meets the injury criteria of S5.1. Insofar as the injury criteria themselves are contingent upon the establishment of an adequate method of measurement through the adoption of a new test dummy, a manufacturer who intends to produce vehicles with type 1 belts at the front outboard positions will have to await the adoption of the new dummy regulation and its incorporation into the options under S4.1.2.

. . .

S4.1.2.3 Third option--lap and shoulder belt protection system with ignition interlock and belt warning--

S4.1.2.3.1 Except for convertibles and open-body vehicles, the vehicle shall--

(a) At each front outboard designated seating position have a seatbelt assembly that conforms to S7.1 and S7.2 of this standard, a seatbelt warning system that conforms to S7.3 and a belt interlock system that conforms to S7.4. The belt assembly shall be either a type 2 seatbelt assembly with a nondetachable shoulder belt that conforms to standard No. 209 (571.209), or a type 1 seatbelt assembly such that with a test device restrained by the assembly the vehicle meets the frontal crash protection requirements of S5.1 in a perpendicular impact.

(b) At any center front designated seating position, have a type 1 or type 2 seatbelt assembly that conforms to standard No. 209 (571.209) and to S7.1 and S7.2 of this standard, and a seatbelt warning system that conforms to S7.3; and

(c) At each other designated seating position, have a type 1 or type 2 seatbelt assembly that conforms to standard No. 209 (Part 571.209) and to S7.1 and S7.2 of this standard.

[23] 38 FR 20449, August 1, 1973.
Part 572, rule; Docket 73-8, Notice 2.
Anthropomorphic Test Dummy--Occupant Crash Protection

The purposes of this notice are (1) to adopt a regulation that specifies a test dummy to measure the performance of vehicles in crashes, and (2) to incorporate the dummy into Motor Vehicle Safety Standard No. 208 (49 CFR 571.208), for the limited purpose of evaluating vehicles with passive restraint options between August 15, 1973, and August 15, 1975. The question of the restraint system requirements to be in effect after August 15, 1975, is not addressed by this notice and will be the subject of future rulemaking action.

The test dummy regulation (49 CFR Part 572) and the accompanying amendment to Standard No. 208 were proposed in a notice published April 2, 1973 (38 FR 8455). The dummy described in the regulation is to be used to evaluate vehicles manufactured under sections S4.1.2.1 and S4.1.2.2, (the first and second options in the period from August 15, 1973, to August 15, 1975), and the section incorporating the dummy is accordingly limited to those sections. The dummy has not been specified for use with any protection systems after August 15, 1975, nor with active belt systems under the third restraint option (S4.1.2.3). The recent decision in Ford v. NHTSA, 473 F.2d 1241 (6th Cir. 1973), removed the injury criteria from such systems. To make the dummy applicable to belts under the third option, the agency would have to provide additional notice and opportunity to comment.

. . .

The immediate purpose of this rulemaking is to reconstitute those portions of the standard that will enable manufacturers to build passive restraint vehicles during the period when they are optional. The test dummy selected by the agency "GM Hybrid II", a composite developed by General Motors largely from commercially available components. GM had requested NHTSA to adopt the Hybrid II on the grounds that it had been successfully used in vehicle tests with passive restraint systems, and was as good as, or better than, any other immediately available dummy system. On consideration of all available evidence, the NHTSA concurs in this judgement.

. . .

The Hybrid II dummy has been found by NHTSA to be a satisfactory test instrument. In sled and barrier tests conducted by GM with the GM restraint systems and in sled tests conducted by Calspan Corp. on behalf of NHTSA, the Hybrid II has produced results that are consistent and repeatable. This is not to say that each test at the same nominal speed and deceleration has produced identical values.

In testing with impact sleds, and to an even greater extent with crash-tested vehicles, the test environment itself is complex and necessarily subject to variations that affect the results. The test data show, however, that the variance from dummy to dummy in these tests is sufficiently small that a manufacturer would have no difficulty in deciding whether his vehicle would be likely to fail if tested by NHTSA.

The provisions of the dummy regulation have been modified somewhat from those proposed in the notice of proposed rulemaking, largely as a result of comments from GM. Minor corrections have been made in the drawings and materials specifications as a result of comments by GM and the principal dummy suppliers. The dummy specification, as . . . finally adopted, reproduces the Hybrid II in each detail of its design and provides, as a calibration check, a series of performance criteria based on the observed performance criteria of normally functioning Hybrid II components. The performance criteria are wholly derivative and are intended to filter out dummy aberrations that escape detection in the manufacturing process or that occur as a result of impact damage. The revisions in the performance criteria, as discussed hereafter, are intended to eliminate potential variances in the test procedures and to hold the performance of the Hybrid II within the narrowest possible range.

. . .

The head performance criteria are adopted as proposed.

. . .

The neck performance criteria are revised in several respects, in keeping with GM's recommendations.

. . .

572.6 Head.

. . .

(b) When the head is dropped from a height of 10 inches in accordance with paragraph (c) of this section, the peak resultant accelerations at the head's center of gravity shall not be less than 210g, and not more than 260g. The acceleration/time curve for the test shall be unimodal and shall lie at or above the 100g level for an interval not less than 0.9 milliseconds and not more than 1.5 milliseconds.

[24] 38 FR 22390, August 20, 1973.
FMVSS 218, rule; Docket 72-6, Notice 2.
Motorcycle Helmets

The purpose of this amendment to Part 571 of Title 49, Code of Federal Regulations, is to add a new Motor Vehicle Safety Standard No. 218, Motorcycle Helmets, 49 CFR 571.218, that establishes minimum requirements for motorcycle helmets manufactured for use by motorcyclists and other motor vehicle users.

. . .

In the previous notice, the NHTSA proposed that, effective September 1, 1974, the performance levels for the impact attenuation requirements be upgraded to that of the Head Injury Criterion (HIC) required by Motor Vehicle Safety Standard No. 208. A number of comments on this subject sought to defer a final determination until further research and additional tests could be conducted. The agency has carefully reviewed the issues raised by these comments and has determined that technical data presently being generated on this matter by several investigations should be considered in upgrading the impact attenuation requirements. Accordingly, a decision on the upgrading will be deferred until after this research has been completed and the results evaluated, and after any appropriate data have been reviewed.

Comments to the docket on the initial impact attenuation requirement ranged from abolishing the time duration critieria of 2.0 milliseconds and 4.0 milliseconds at the 200g and 150g levels, respectively, to increasing these criteria to 2.8 milliseconds at the 200g level and 5.6 milliseconds at the 150g level. One approach taken in regard to this requirement contends that the available test data are insufficient for quantifying time limits for the relatively short duration accelerations which are involved in helmet testing. Several comments questioned the validity of the proposed time duration limits, since these limits were based on the optional swing-away (as opposed to fixed anvil) test of the American National Standards Institute (ANSI) Standard Z90.1-1966, which was omitted from the most recent issues of the Z90.1 Standard (1971 and 1973) and was not contained in the proposed motorcycle helmet standard. An additional comment points out that the helmets designed to meet higher energy impacts than the initial attenuation requirement occasionally have difficulty meeting a 2.0 millisecond requirement at the 200g level.

A review of available biomechanical data indicates that the head impact exposure allowed by the 2.0 and 4.0 millisecond limits at the 200g and 150g levels, respectively, is greater than that allowed by other measures of head injury potential. It is the agency's view, moreover, that the best evidence indicates that an increase in the time duration criteria would permit a substantial reduction in the protection provided to the helmet wearer. Since the comments to the docket did not provide any new data or sufficiently compelling arguments which would justify relaxing the proposed limits for tolerable head impact exposure, the 2.0 and 4.0 millisecond criteria are retained as part of the initial impact attenuation criteria.

[25] 39 FR 27585, July 30, 1974.
FMVSS 222, proposal; Docket 73-3, Notice 2.
School Bus Passenger Crash Proctection

This notice proposes a new motor vehicle safety standard <u>School bus passenger seating and crash protection</u>, that would specify seating, restraining barrier, and impact zone requirements for school buses and other buses sold for the primary purpose of carrying children to and from school.

. . .

This proposal again specifies two zones in which impact by a head form must conform to specified force distribution and certain force or acceleration levels.

. . .

S5.3.1 Head protection zone. Any contactable surface of the vehicle within any zone specified in S5.3.1.1 shall meet the requirements of S5.3.1.2 and S5.3.1.3. However, a surface area that has been contacted pursuant to an impact test need not meet further requirements contained in S5.3.

S5.3.1.1 The head protection zones in each vehicle are the spaces in front of each school bus passenger seat which, in relation to that seat and its seating reference point, are enclosed by the following planes:

(a) Horizontal planes 12 inches and 40 inches above the seating reference point;

(b) A vertical longitudinal plane tangent to the inboard (aisle side) edge of the seat;

(c) A vertical longitudinal plane 3.25 inches inboard of the outboard edge of the seat, and

(d) Vertical transverse planes through and 30 inches forward of the seating reference point.

S5.3.1.2 Head form impact requirement. When any contactable surface of the vehicle within the zones specified in S5.3.1.1 is impacted from any direction at 15 miles per hour by the head form described in S6.6, the resultant acceleration at the center of gravity of the head form shall be such that the expression

$$\left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a \, dt\right]^{2.5} (t_2 - t_1)$$

shall not exceed 1,000 where "a" is the resultant acceleration expressed as a multiple of "g" (the acceleration due to gravity), and "t_1" and "t_2" are any two points in time during the impact.

S5.3.1.3 Head form force distribution. When any contactable surface of the vehicle within the zones specified in S5.3.1.1 is impacted from any direction at 15 miles per hour by the head form described in S6.6, the energy necessary to deflect the impacted material shall be not less than 40 inch-pounds before the force level on the head form exceeds 150 pounds. When any contactable surface within such zones is impacted by the head form from any direction at 5 feet per second, the contact area on the head form surface shall not be less than 3 square inches.

. . .

S6.6 Head form. The head form for the measurement of acceleration is a rigid surface comprised of two hemispherical shapes, with total equivalent weight of 11.5 pounds. The first of the two hemispherical shapes has a diameter of 6.5 inches. The second of the two hemispherical shapes has a two-inch diameter and is centered as shown in Figure 3 to protrude from the outer surface of the first hemispherical shape.

S6.6.1 The direction of travel of the head form is coincidental with the straight line connecting the centerpoints of the two spherical outer surfaces which constitute the head-form shape.

S6.6.2 The head form is instrumented with an acceleration sensing device whose output is recorded in a data channel that conforms to the requirements for a 1,000 Hz channel class as specified in SAE Recommended Practice J211, October 1970. The head form exhibits no resonant frequency below 3,000 hz. The axis of the acceleration sensing device coincides with the straight line connecting the centerpoints of the two hemispherical outer surfaces which constitute the head form shape.

S6.6.3 The head form is guided by a stroking device so that the direction of travel of the head form is not affected by impact with the surface being tested at the levels called for in the standard.

. . .

[26] 39 FR 38380, October 31, 1974.
FMVSS 208, rule; Docket 74-39, Notice 1.
Seat Belt Interlock Option

This notice amends Standard No. 208, Occupant crash protection, 49 CFR 571.208, by eliminating the ignition interlock. Parallel changes are made to the passive seat belt assembly requirements (S7.) of the standard.

[27] 40 FR 17855, April 23, 1975.
FMVSS 222, proposal; Docket 73-3, Notice 3.
School Bus Passenger Seating and Crash Protection

This notice proposes a new motor vehicle safety standard for school bus seating and crash protection, modified in several respects from the July 30, 1974, proposal (39 FR 27585).

. . .

The major features of this proposal differ little from those of Notice 2.

. . .

S5.3.1.2 Head form impact requirement. When any contactable surface of the vehicle within the zones specified in S5.3.1.1 is impacted from any direction at 22 feet per second by the head form described in S6.6, the axial acceleration at the center of gravity of the head form shall be such that the expression:

$$\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a\,dt\right]^{2.5}(t_2 - t_1)$$

shall not exceed 1,000, where "a" is the axial acceleration expressed as a multiple of "g" (the acceleration due to gravity), and "t_1" and "t_2" are any two points in time during the impact.

[28] 40 FR 33462, August 8, 1975.
Part 572, proposal; Docket 73-8, Notice 3.
Anthropomorphic Test Dummy.*

. . .

Several vehicle manufacturers questioned the adequacy of the head to measure lateral impact forces. The specifications provide a triaxial accelerometer so that the lateral vector is registered in the same way as fore-and-aft forces. Further, NHTSA contract experience with dummies installed at front and rear seating positions of vehicles undergoing side impact by other vehicles demonstrates no artificially-high readings (Contract DOT-HS-4-00922, 5th & 6th progress reports).

. . .

Several manufacturers questioned the objectivity of the dummy as a whole because Part 572 does not include a "whole systems" calibration of the assembled dummy. The NHTSA has considered the advisability of such a test and has decided against it for several reasons. Foremost is the difficulty of devising a calibration procedure which introduces no significant variability into the test. It is clear that Standard No. 208 dynamic deceleration of the dummy introduces many complex variables into the test, such as restraint design and vehicle design. In the description of sled testing of the GM50X dummy (ref. Reports: SAE #740590, DOT-HS-299-3-569), General Motors pointed out that their results demonstrate the complexity of the problem.

Another reason for not introducing a "whole systems" calibration is that the experience to date with well-controlled hard seat sled tests of the dummy show good measurement stability of the dummy as a whole system as long as the dummy meets Part 572 specifications. The most recent presentation of such information appears in an SAE paper by General Motors engineers, comparing an advanced dummy with the Part 572 dummy (Proceedings of Third International Conference on Occupant Protection, pg. 369). Table 10 of that paper shows the coefficient of variation of a Hybrid II dummy to be only 4.5 percent in a measure of Head Injury Criteria and 3.3 percent in a measure of Chest Severity Index. Variation of these criteria between dummies is 3.5 percent and 6 percent respectively. Similar conclusions were reached by J. Versace and R. J. Berton of the Ford Motor Company in SAE paper 750395, "Determination of Restraint Effectiveness", pg. 5. Based on experience of this nature, and in view of the extensive specification in Part 572, the NHTSA concludes that a "whole systems" calibration is not required to establish the dummy as an objective measuring device.

*This notice is unusual in that it refers to and comments on specific technical papers.

[29] 41 FR 4016, January 28, 1976.

FMVSS 222, rule; Docket 73-3, Notice 5.
School Bus Passenger Seating and Crash Protection

This notice establishes a new motor vehicle safety Standard No. 222, School Bus Seating and Crash Protection, that specifies seating, restraining barrier, and impact zone requirements for school buses.

. . .

Effective date: October 26, 1976.

. . .

S5.3.1.2 Head form impact requirement. When any contactable surface of the vehicle within the zones specified in S5.3.1.1 is impacted from any direction at 22 feet per second by the head form described in S6.6, the axial acceleration at the center of gravity of the head form shall be such that the expression

$$\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a\, dt\right]^{2.5} (t_2 - t_1)$$

shall not exceed 1,000 where "a" is the axial acceleration expressed as a multiple of "g" (the acceleration due to gravity), and "t_1" and "t_2" are any two points in time during the impact.

S5.3.1.3 Head form force distribution. When any contactable surface of the vehicle within the zones specified in S.5.3.1.1 is impacted from any direction at 22 feet per second by the head form described in S6.6, the energy necessary to deflect the impacted material shall be not less than 30 inch-pounds before the force level on the head form exceeds 150 pounds. When any contactable surface within such zones is impacted by the head form from any direction at 5 feet per second, the contact area on the head form surface shall be not less than 3 square inches.

[30] 41 FR 54961, December 16, 1976.
FMVSS 208, notice; Docket 74-14, Notice 7.
Advance Notice Concerning Improvements of Seat Belt Assemblies

. . .

Would the establishment of injury criteria and dynamic tests for seat belt assemblies installed in vehicles be an appropriate means to improve seat belt effectiveness?

. . .

The NHTSA, as it stated in April 1973 (38 FR, April 20, 1973), believes that a structural integrity requirement does not contribute substantially to the performance of belt systems, which are required by Standard No. 209 to have higher breaking strength than they would be subjected to during a 30-m.p.h. barrier impact. The agency considers that a more appropriate assessment of a belt system's protective performance capability lies in its ability to properly restrain a Part 572 test dummy in a simulated crash environment. The agency is contemplating a requirement for a dynamic test for belt systems. The test would be a frontal and frontal oblique test at 30 m.p.h. into a fixed flat barrier. A number of alternatives exist to evaluate the belt systems protective performance. First, the head and chest accelerations and femur force levels measured on the dummy could be limited to some levels, although these may not necessarily be the existing levels specified in S5 of FMVSS 208.

[31] 43 FR 21470, May 18, 1978.
FMVSS 213, proposal; Docket 74-9, Notice 4.
Child Restraint Systems

. . .

This notice is being issued in response to public requests. It would amend the existing child restraint standard by extending its applicability to all types of child restraints designed for use in motor vehicles. It would also upgrade existing child restraint performance requirements by improving the performance criteria and by replacing static tests with dynamic tests using anthropomorphic child dummies. The amendments are intended to reduce the number of children under 5 years of age that are killed or injured in motor vehicle accidents.

. . .

SUMMARY OF PROPOSED AMENDMENTS

The most significant amendments proposed by this notice are set forth below:

(1) Dynamic tests would be used to evaluate the performance of the child seating system in a manner which simulated an actual vehicle crash. The simulated crash would be straight forward (0 degree frontal) at 30 m.p.h.

. . .

(3) Injury criteria would be specified for both the head and chest of the dummy for child restraints recommended by their manufacturers for children over 20 pounds. Padding requirements would have to be met by restraints to be used by children weighing not more than 20 pounds.

. . .

TEST DUMMIES

A six-month old dummy and a three-year old dummy have been tentatively selected for testing child restraint systems under the proposed standard. The six-month old dummy was specified in the 1974 proposal as being of "sailcloth construction filled with plastic pellets and lead shot for correct weight distribution." The dummy has since been dynamically tested, modified, and retested in infant carriers of three different manufacturers. The new dummy represents an advance in the state-of-the-art and is vastly superior to the former dummy. Very precise definitions of the new dummy are contained in a set of five blueprints and an engineering description which are available in docket 74-9 to all interested persons.

The tentatively selected three-year old dummy is the NHTSA test dummy SA103C, a slightly modified version of the Alderson Model VIP-3C dummy.

. . .

Injury criteria (expressed in terms of limits on resultant acceleration) are proposed for both the head and chest of the thee-year-old test dummy to allow a quantitative evaluation of the dynamic performance of the child restraints to be made. This approach permits the measurement of padding effectiveness during the dynamic test, thus eliminating any need for a separate test for that purpose and the costs associated with such a test. Since the construction of the six-month-old dummy prevents installing accelerometers so that they will stay in place within the dummy during a test and give accurate measurements, the injury criteria would apply only to restraints recommended by their manufacturers for use by children weighing over 20 pounds.

. . .

Unlike the 1974 proposal, this proposal does not contain requirements for lateral dynamic tests and for limits on lateral excursion.

. . .

571.213

3. A new Federal Motor Vehicle Safety Standard No. 213-80, Child Restraint Systems, would be added to read as set forth below.

571.213-80 Standard No. 213-80; child restraint systems.

. . .

S5.1.2 Injury criteria. When tested in accordance with S6.1, each child restraint system that, in accordance with S5.5.2(f), is recommended for use by children weighing more than 20 pounds, shall--

(a) Limit the resultant acceleration at the location of the accelerometer mounted in the test dummy head as specified in Part 572 such that the expression:

$$\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a\,dt\right]^{2.5}(t_2-t_1)$$

shall not exceed 1,000, where "a" is the resultant acceleration expressed as a multiple of "g" (the acceleration of gravity), and "t_1" and "t_2" are any two moments during the impacts.

[32] 44 FR 72131, December 13, 1979.

FMVSS 213, rule; Docket 74-9, Notice 6.
Child Restraint Systems Seat Belt Assemblies
and Anchorages

. . .

SUMMARY: This rule establishes a new Standard No. 213, Child Restraint Systems, which applies to all types of child restraints used in motor vehicles. It also upgrades existing child restraint performance requirements by setting new performance criteria and by replacing the current static tests with dynamic sled tests that simulate vehicle crashes and use anthropomorphic child test dummies. The new standard would reduce the number of children under 5 years of age killed or injured in motor vehicle accidents.

. . .

Several manufacturers (GM, Ford, Questor, and others) and JPMA objected to the proposed head and chest acceleration limits that must not be exceeded in the dynamic testing. They argued that the acceleration limits are based on biomechanical data for adults and there is no data showing their applicability to children. Because of the lack of biomechanical data on children's tolerance to impact forces, NHTSA has conducted tests of child restraints with live primates to serve as surrogates for three-year-old children. Primates are similar in certain respects to children and have been used by GM, Ford, and others as surrogates in child restraint testing to assess potential injuries to children in crashes. In simulated 30 mph crashes conducted for NHTSA, similar to the test prescribed in the proposed standard, the primates either were not injured or sustained only minor injuries. NHTSA has also conducted child restraint tests using instrumented test dummies representing three-year-old children instead of primates. In the tests, the forces measured on the test dummies, which had not been injurious to the primates, did not exceed the head and chest accelerations criteria proposed in the standard. NHTSA is thus confident that the child restraints which do not exceed these performance criteria in the prescribed tests should prevent or reduce injuries to children in crashes.

Use of instrumented test dummies should not unduly raise the price of child restraints. Since many child restraint systems are already close to compliance, the cost per restraint of any needed design and testing costs should be minimal.

. . .

S5.1.2 Injury criteria. When tested in accordance with S6.1, each child restraint system that, in accordance with S5.5.2(f), is recommended for use by children weighing more than 20 pounds, shall--

(a) Limit the resultant acceleration at the location of the accelerometer mounted in the test dummy head as specified in Part 572 such that the expression:

$$\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a\,dt\right]^{2.5}(t_2-t_1)$$

shall not exceed 1,000, where "a" is the resultant acceleration expressed as a multiple of "g" (the acceleration of gravity), and "t_1" and "t_2" are any two moments during the impacts.

. . .

S5.2.3 Head impact protection.

S5.3.2.1 Each child restraint system, other than a child harness, which is recommended under S5.5.2(f) for children weighing less than 20 pounds shall comply with S5.2.3.2.

S5.2.3.2 Each system surface which is contactable by the dummy head when the system is tested in accordance with S6.1 shall be covered with slow recovery, energy absorbing material with the following characteristics:

(a) A 25 percent compression-deflection resistance of not less than 0.5 and not more than 10 pounds per square inch when tested in accordance with S6.3.

(b) A thickness of not less than 1/2 inch if the material has a 25 percent compression-deflection resistance of not less than 3 and not more than 10 pounds per square inch when tested in accordance with S6.3. If the material has a 25 percent compression-deflection resistance of less than 3 pounds, it shall have a thickness of not than 3/4 inch.

APPENDIX B

Appendix B: Bibliography

Citations are arranged in alphabetical order by author(s) and then in chronological order. The year cited is the date of publication, unless the paper was presented earlier at a conference. In the latter case, the date of presentation of the work is cited, and the date of publication of the proceedings, if different, is given at the end of the reference.

The bibliography was partially compiled by following the references in important papers in the field of head injury biomechanics. Although not exhaustive, some entries include references to papers that cite those particular works. HSRI Library accession numbers are also given to facilitate on-site use of the literature.

Abel, J.M.; Gennarelli, T.A.; Segawa, H. 1978. Incidence and severity of cerebral concussion in the Rhesus monkey following sagittall plane angular acceleration. In _22nd Stapp Car Crash Conference Proceedings, 24-26 October 1978, Ann Arbor, Mich._, pp. 35-53. Warrendale, Pa.: SAE paper no. 780886.

HSRI Library no. 41198 A03

Alderson, S.W. 1967. The development of anthropomorphic test dummies to match specific human responses to accelerations and impacts. In _11th Stapp Car Crash Conference Proceedings, 10-11 October 1967, Anaheim, Calif._, pp. 62-67. New York: SAE paper no. 670908.

Referenced in: McElhaney, Stalnaker, and Roberts, 1972

Aran, F.A. 1844. Recherches sur les fractures de la base du crane. _Archives Generales de Medecine_, 4th Series, T. VI: 180-209, 309-347.

Referenced in: Melvin and Evans, 1971

Baum, W. 1876. Beitrag zur Lehre von den indirecten Schadel Fracturen. _Fuer Klinische Chirurgie_ 19:381-399.

Referenced in: Melvin and Evans, 1971

Becker, E.B. 1972. Measurement of mass distribution parameters of anatomical segments. In 16th Stapp Car Crash Conference Proceedings, 8-10 November 1972, Detroit, pp. 160-185. Warrendale, Pa.: SAE paper no. 720964.

HSRI Library no. 19862 A09
Referenced in: Ewing and Thomas, 1973

Becker, E.B. 1972. Preliminary discussion of an approach to modeling living human head and neck response to $-G_x$ impact acceleration. In Human Impact Response--Measurement and Simulation. Proceedings of the Symposium on Human Impact Response, 2-3 October 1972, Warren, Mich., pp. 321-329. New York: Plenum Press, 1973.

HSRI Library no. 28533 A15
Referenced in: Ewing, Thomas, et al., 1975; Ewing and Thomas, 1973

Becker, E.B.; Willems, G. 1975. An experimentally validated 3-D inertial tracking package for application in biodynamic research. In 19th Stapp Car Crash Conference Proceedings, 17-19 November 1975, San Diego, pp. 899-930. Warrendale, Pa.: SAE paper no. 751173.

HSRI Library no. 33279 A33
Referenced in: Stalnaker, Melvin, et al., 1977; Ewing, Thomas, et al., 1975

Bender, M.; Melvin, J.W.; Stalnaker, R.L. 1976. A high-speed cineradiographic technique for biomechanical impact. In 20th Stapp Car Crash Conference Proceedings, 18-20 October 1976, Dearborn, Mich., pp. 767-781. Warrendale, Pa.: SAE paper no. 760824.

HSRI Library no. 35834
Referenced in: Stalnaker, Melvin, et al., 1977

Brinn, J.; Staffeld, S.E. 1970. Evaluation of impact test accelerations: A damage index for the head and torso. In 14th Stapp Car Crash Conference Proceedings, 17-18 November 1970, Ann Arbor, Mich., pp. 188-220. New York: SAE paper no. 700902.

HSRI Library no. 14855 A08
Referenced in: McElhaney, Stalnaker, and Roberts, 1972; Versace, 1971

Brinn, J.; Staffeld, S.E. 1971. The effective displacement index--an analysis technique for crash impacts of anthropometric dummies. In 15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif., pp. 817-824. New York: Society of Automotive Engineers.

HSRI Library no. 17505 A33

Byars, E.F.; Haynes, D.; Durham, T.; Lilly, H. 1970. Craniometric measurement of human skulls. New York: American Society of Mechanical Engineers.

HSRI Library no. 44577
Referenced in: Nahum and Smith, 1976; Melvin and Evans, 1971

Caveness, W.F.; Walker, A.E., eds. 1966. Head Injury Conference Proceedings, 6-9 February 1966, Chicago. Philadelphia: J.B. Lippincott.

HSRI Library no. 04242
Referenced in: Nahum and Smith, 1976

Chan, H.S. 1974. Mathematical model for closed head impact. In 18th Stapp Car Crash Conference Proceedings, 4-5 December 1974, Dearborn, Mich., pp. 557-578. Warrendale, Pa.: SAE paper no. 741191.

HSRI Library no. 30826 A16

Culver, C.C.; Neathery, R.F.; Mertz, H.J. 1972. Mechanical necks with humanlike responses. In 16th Stapp Car Crash Conference, 8-10 November 1972, Detroit, pp. 61-75. New York: SAE paper no. 720959.

HSRI Library no. 19862 A04
Referenced in: McElhaney, Mate, and Roberts, 1973

Eiband, A.M. 1959. Human tolerance to rapidly applied accelerations: A summary of the literature. Cleveland: NASA Lewis Research Center. NASA Memorandum 5-19-59E.

HSRI Library no. 36792

Evans, F.G.; Lissner, H.R. 1957. Tensile and comprehensive strength of human parietal bone. Journal of Applied Physiology 10:493-497.

Referenced in: Melvin and Evans, 1971

Evans, F.G.; Lissner, H.R.; Lebow, M. 1958. The relation of energy, velocity, and acceleration to skull deformation and fracture. Surgery, Gynecology and Obstetrics 107:593-601.

HSRI Library no. 22860
Referenced in: Melvin and Evans, 1971

Ewing, C.L.; Thomas, D.J. 1972. Human head and neck response to impact acceleration. Pensacola, Fla.: Naval Aerospace Medical Research Laboratory Monograph 21. Report no. USAARL 73-1.

HSRI Library no. 19249
Referenced in: Robbins, Melvin, and Stalnaker, 1976; Stalnaker, Melvin, et al., 1977; Ewing, Thomas, et al., 1975; Ewing and Thomas, 1973

Ewing, C.L.; Thomas, D.J. 1973. Torque versus angular displacemnt response of human head to $-G_x$ impact acceleration. In 17th Stapp Car Crash Conference Proceedings, 12-13 November 1973, Oklahoma City, pp. 309-342. New York: SAE paper no. 730976.

HSRI Library no. 28770 A14
Referenced in: Stalnaker, Melvin, et al., 1977; Ewing, Thomas, et al., 1975

Ewing, C.L.; Thomas, D.J.; Beeler, G.W.; Patrick, L.M. 1968. Dynamic response of the head and neck of the living human to $-G_x$ impact acceleration. In 12th Stapp Car Crash Conference Proceedings, 22-23 October 1968, Detroit, pp. 424-439. New York: SAE paper no. 680792.

HSRI Library no. 06742 A22
Referenced in: Mertz and Patrick, 1971; Ewing, Thomas, et al., 1975; Ewing and Thomas, 1973

Ewing, C.L.; Thomas, D.J.; Lustick, L.; Becker, E.B.; Willems, G.; Muzzy, W.H. 1975. The effect of the initial position of the head and neck on the dynamic response of the human head and neck to $-G_x$ impact acceleration. In 19th Stapp Car Crash Conference Proceedings, 17-19 November 1975, San Diego, pp. 487-512. Warrendale, Pa.: SAE paper no. 751157.

HSRI Library no. 33279 A17
Referenced in: Stalnaker, Melvin, et al., 1977

Ewing, C.L.; Thomas, D.J.; Patrick, L.M.; Beeler, G.W.; Smith, M.J. 1969. Living human dynamic response to $-G_x$ impact acceleration II--accelerations measured on the head and neck. In 13th Stapp Car Crash Conference Proceedings, 2-4 December 1969, Boston, pp. 400-415. New York: SAE paper no. 690817.

HSRI Library no. 12067 A23
Referenced in: Mertz and Patrick, 1971; Ewing, Thomas, et al., 1975

Fallenstein, G.T.; Hulce, V.D.; Melvin, J.W. 1969. Dynamic mechanical properties of human brain tissue. Journal of Biomechanics 2(3):217-226.

HSRI Library no. 50277
Referenced in: Nahum and Smith, 1976

Fan, W.R.S. 1971. Internal head injury assessment. In 15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif., pp. 645-665. New York: SAE paper no. 710870.

HSRI Library no. 17505 A22
Referenced in: SAE J885b, 1980

Felicet, G.M. 1873. Researchers anatomiques et experimentals sur les fractures du crane. Paris: A. Delahaye.

Referenced in: Melvin and Evans, 1971

Foster, J.K.; Kortge, J.O.; Wolamin, M.J. 1977. Hybrid III--a biomechanically-based crash test dummy. In 21st Stapp Car Crash Conference Proceedings, 19-21 October 1977, New Orleans, pp. 975-1014. Warrendale, Pa.: SAE paper no. 770938.

HSRI Library no. 38391 A24

Gadd, C.W. 1961. Criteria for injury potential. In Impact Acceleration Stress Symposium, 27-29 November 1961, Brooks AFB, Tex., pp. 141-144. Washington, D.C.: National Academy of Sciences--National Research Council publication no. 977, 1962.

HSRI Library no. 00613 A15

Gadd, C.W. 1966. Use of a weighted impulse criterion for estimating injury hazard. In 10th Stapp Car Crash Conference Proceedings, 8-9 November 1966, Alamogordo, N.M., pp. 164-174. New York: SAE paper no. 660793, 1967.

HSRI Library no. 01812 A08
Referenced in: McElhaney, Stalnaker, and Roberts, 1972; SAE J885b, 1980; Fan, 1971; Versace, 1971

Gadd, C.W. 1971. Tolerable severity index in whole-head, nonmechanical impact. In 15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif., pp. 809-816. New York: Society of Automotive Engineers.

HSRI Library no. 17505 A32
Referenced in: SAE J885b, 1980

Galford, J.E.; McElhaney, J.H. 1969. Some viscoelastic properties of scalp, brain and dura. New York: ASME paper no. 69-BHF-7.

Referenced in: Fan, 1971

Gennarelli, T.A.; Abel, J.M.; Adams, H.; Graham, D. 1979. Differential tolerance of frontal and temporal lobes to contusion induced by angular acceleration. In 23rd Stapp Car Crash Conference, 17-19 October 1979, San Diego, pp. 563-586. Warrendale, Pa.: SAE paper no. 791022.

HSRI Library no. 42984 A20

Gennarelli, T.A.; Ommaya, A.K.; Thibault, L.E. 1971. Comparison of translational and rotational head motions in experimental cerebral concussion. In 15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif., pp. 797-803. New York: Society of Automotive Engineers.

HSRI Library no. 17505 A30
Referenced in: Ewing and Thomas, 1973; SAE J885b, 1980

Gennarelli, T.A.; Thibault, L.E.; Ommaya, A.K. 1972. Pathophysiological responses to rotational and translational accelerations of the head. In _16th Stapp Car Crash Conference Proceedings, 8-10 November 1972, Detroit_, pp. 296-308. New York: SAE paper no. 720970.

HSRI Library no. 19862 A15
Referenced in: Stalnaker, Roberts, and McElhaney, 1973

Got, C.; Patel, A.; Fayon, A.; Tarriere, C.; Walfisch, G. 1978. Results of experimental head impacts on cadavers: The various data obtained and their relations to some measured physical parameters. In _22nd Stapp Car Crash Conference Proceedings, 24-26 October 1978, Ann Arbor, Mich._, pp. 57-99. Warrendale, Pa.: SAE paper no. 780887.

HSRI Library no. 41198 A03

Gross, A.G. 1958. A new theory on the dynamics of brain concussion and brain injury. _Journal of Neurosurgery_ 15:548-561.

HSRI Library no. 22394
Referenced in: McElhaney, Stalnaker, and Roberts, 1972

Grush, E.S.; Henson, S.E.; Ritterling, O.R. 1971. _Restraint system effectiveness_. Dearborn, Mich.: Ford Motor Co. report no. S-71-40.

HSRI Library no. 31861
Referenced in: Versace, 1971

Gurdjian, E.S. 1975. _Impact head injury; mechanistic, clinical and preventive correlations_. Springfield, Ill.: Charles C. Thomas.

HSRI Library no. 34381
Referenced in: Nahum and Smith, 1976

Gurdjian, E.S.; Hodgson, V.R.; Thomas, L.M.; Patrick, L.M. 1968. Significance of relative movements of scalp, skull, and intracranial contents during impact injury of the head. _Journal of Neurosurgery_ 29(1):70-72.

HSRI Library no. 28810
Referenced in: McElhaney, Stalnaker, and Roberts, 1972

Gurdjian, E.S.; Lissner, H.R. 1945. Deformation of the skull in head injury: A study with the "stresscoat" technique. Surgery, Gynecology and Obstetrics 81:679-687.

Referenced in: Melvin and Evans, 1971

Gurdjian, E.S.; Lissner, H.R. 1946. Deformation of the skull in head injury studied by the "stresscoat" technique, quantitative determinations. Surgery, Gynecology and Obstetrics 83:219-233.

Referenced in: Melvin and Evans, 1971

Gurdjian, E.S.; Lissner, H.R.; Evans, F.G.; Patrick, L.M.; Hardy, W.G. 1961. Intracranial pressure and acceleration accompanying head impacts in human cadavers. Surgery, Gynecology, and Obstetrics 113:185-190.

HSRI Library no. 02754
Referenced in: SAE J885b, 1980

Gurdjian, E.S.; Lissner, H.R.; Latimer, F.R.; Haddad, B.F.; Webster, J.E. 1953. Quantitative determination of acceleration and intracranial pressure in experimental head injury; preliminary report. Neurology 3(6):417-423.

HSRI Library no. 22783
Referenced in: SAE J885b, 1980

Gurdjian, E.S.; Lissner, H.R.; Webster, J.E. 1947. The mechanism of production of linear skull fractures. Surgery, Gynecology and Obstetrics 85:195-210.

HSRI Library no. 22201
Referenced in: Melvin and Evans, 1971

Gurdjian, E.S.; Roberts, V.L.; Thomas, L.M. 1966. Tolerance curves of acceleration and intracranial pressure protective index in experimental head injury. Journal of Trauma 6(5):600-604.

HSRI Library no. 23711

Gurdjian, E.S.; Schawan, H.K. 1932. Management of skull fracture involving the frontal sinus. Annals of Surgery, 95:22-32.

Referenced in: SAE J885b, 1980

Gurdjian, E.S.; Webster, J.E. 1953. Recent advances in the knowledge of the mechanism, diagnosis, and treatment of head injury. American Journal of the Medical Sciences 226:214-220.

Gurdjian, E.S.; Webster, J.E.; Lissner, H.R. 1949. Studies on skull fracture with particular references to engineering factors. American Journal of Surgery 78:736-742.

HSRI Library no. 23468
Referenced in: Melvin and Evans, 1971

Gurdjian, E.S.; Webster, J.E.; Lissner, H.R. 1953. Observations on prediction of fracture site in head injury. Radiology 60:226-235.

HSRI Library no. 22447
Referenced in: Melvin and Evans, 1971

Gurdjian, E.S.; Webster, J.E.; Lissner, H.R. 1955. Observations on the mechanism of brain concussion, contusion and laceration. Surgery, Gynecology, and Obstetrics 101:680-690.

HSRI Library no. 22448
Referenced in: SAE J885b, 1980

Hirsch, A.E.; Ommaya, A.K. 1970. Protection from brain injury: The relative significance of translational and rotational motions of the head after impact. In 14th Stapp Car Crash Conference Proceedings, 17-18 November 1970, Ann Arbor, Mich., pp. 299-328. New York: SAE paper no. 700899.

HSRI Library no. 14855 A05
Referenced in: Fan, 1971

Hirsch, A.E.; Ommaya, A.K.; Mahone, R.H. 1970. Tolerance of sub-human primate brain to cerebral concussion. In Impact Injury and Crash Protection, pp. 352-369. Springfield, Ill.: Charles C. Thomas.

HSRI Library no. 12268 A15
Referenced in: SAE J885b, 1980

Hodgson, V.R. 1967. Tolerance of the facial bones to impact. American Journal of Anatomy 120:113-122.

HSRI Library no. 04121
Referenced in: Melvin and Evans, 1971

Hodgson, V.R. 1972. Head model for impact tolerance. In Human Impact Response--Measurement and Simulation. Proceedings of the Symposium on Human Impact Response, 2-3 October 1972, Warren, Mich., pp. 113-128. New York: Plenum Press, 1973.

HSRI Library no. 28533 A06

Hodgson, V.R.; Brinn, J.; Thomas, L.M.; Greenberg, S.W. 1970. Fracture behavior of the skull frontal bone against cylindrical surfaces. In 14th Stapp Car Crash Conference Proceedings, 17-18 November 1970, Ann Arbor, Mich., pp. 341-355. New York: SAE paper no. 700909.

HSRI Library no. 14855 A15
Referenced in: Melvin and Evans, 1971

Hodgson, V.R.; Lange, W.S.; Talwalker, R.K. 1965. Injury to the facial bones. In 9th Stapp Car Crash Conference Proceedings, 20-21 October 1965, Minneapolis, pp. 145-163. Minneapolis: University of Minnesota, Nolte Center for Continuing Education, 1966.

HSRI Library no. 00569 A08
Referenced in: Melvin and Evans, 1971

Hodgson, V.R.; Patrick, L.M. 1968. Dynamic response of the human cadaver head compared to a simple mathematical model. In 12th Stapp Car Crash Conference Proceedings, 22-23 October 1968, Detroit, pp. 280-301. New York: SAE paper no. 680784.

HSRI Library no. 06742 A14
Referenced in: McElhaney, Stalnaker, and Roberts, 1972; Fan, 1971

Hodgson, V.R.; Thomas, L.M. 1971. Comparison of head acceleration injury indices in cadaver skull fracture. In 15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif., pp. 190-206. New York: SAE paper no. 710854.

HSRI Library no. 17505 A08
Referenced in: SAE J885b, 1980

Hodgson, V.R.; Thomas, L.M. 1972. Effect of long-duration impact on head. In 16th Stapp Car Crash Conference Proceedings, 8-10 November 1972, Detroit, pp. 292-295. Warrendale, Pa.: SAE paper no. 720956.

HSRI Library no. 19862 A14
Referenced in: SAE J885b, 1980

Hodgson, V.R.; Thomas, L.M. 1975. Head injury tolerance. In Aircraft Crashworthiness, pp. 175-193. Charlottesville, Va.: University Press of Virginia.

HSRI Library no. 34179 A05

Hodgson, V.R.; Thomas, L.M. 1979. Acceleration induced shear strains on a monkey brain hemisection. In 23rd Stapp Car Crash Conference, 17-19 October 1979, San Diego, Calif., pp. 589-611. Warrendale, Pa.: SAE paper no. 791023.

HSRI Library no. 42984 A21

Hodgson, V.R.; Thomas, L.M.; Brinn, J. 1973. Concussion levels determined by HPR windshield impacts. In 17th Stapp Car Crash Conference Proceedings, 12-13 November 1973, Oklahoma City, pp. 171-190. New York: SAE paper no. 730970.

HSRI Library no. 28770

Hodgson, V.R.; Thomas, L.M.; Gurdjian, E.S.; Fernando, O.U.; Greenberg, S.W.; Chason, J.L. 1969. Advances in understanding of experimental concussion mechanisms. In 13th Stapp Car Crash Conference Proceedings, 2-4 December 1969, Boston, pp. 18-37. New York: SAE paper no. 690796.

HSRI Library no. 12067 A02
Referenced in: Fan, 1971

Hodgson, V.R.; Thomas, L.M.; Prasad, P. 1970. Testing the validity and limitations of the severity index. In 14th Stapp Car Crash Conference Proceedings, 17-18 November 1970, Ann Arbor, Mich., pp. 169-187. New York: SAE paper no. 700901.

HSRI Library no. 14855 A07
Referenced in: McElhaney, Stalnaker, and Roberts, 1972; SAE J885b, 1980

Holbourn, A.H.S. 1943. Mechanics of head injuries. Lancet, 245:438-441.

HSRI Library no. 22184
Referenced in: SAE J885b, 1980

Hubbard, R.P. 1970. Flexure of cranial bone. Urbana: University of Illinois for the National Institute of Neurological Diseases and Stroke.

HSRI Library no. 33042
Referenced in: Melvin and Evans, 1971

Hubbard, R.P.; McLeod, D.G. 1972. A basis for crash dummy skull and head geometry. In Human Impact Response--Measurement and Simulation. Proceedings of the Symposium on Human Impact Response, 2-3 October 1972, Warren, Mich., pp. 129-152. New York: Plenum Press, 1973.

HSRI Library no. 28533 A07
Referenced in: Nahum and Smith, 1976

Huelke, D.F.; Melvin, J.W. 1979. NCSS analysis project literature review. Ann Arbor: University of Michigan Highway Safety Research Institute for the National Highway Traffic Safety Administration. Contract no. DOT-HS-8-01944.

Huelke, D.F.; Melvin, J.W. 1980. Anatomy, injury frequency, biomechanics, and human tolerances. Warrendale, Pa.: SAE paper no. 800098.

HSRI Library no. 43686

Kao, R.; Perrone, N. 1970. Stresses in spherical shells due to local loadings. Washington, D.C.: The Catholic University of America report no. 71-4.

Referenced in: Melvin and Evans, 1971

Khalil, T.B.; Hubbard, R.P. 1977. Parametric study of head response by finite element modeling. Journal of Biomechanics 10(2):119-131.

HSRI Library no. 53427

King, A.I. 1975. Survey of the state of the art of human biodynamic response. In Aircraft Crashworthiness, pp. 83-120. Charlottesville, Va.: University Press of Virginia.

HSRI Library no. 34179 A01
Referenced in: SAE J885b, 1980

King, A.I.; Padganokar, A.J.; Krieger, K.W. 1974. Measurement of angular acceleration of a rigid body using linear accelerations. In 2nd Human Subjects for Biomechanical Research Meeting, Committee Reports and Technical Session Papers, 6 December 1974, Ann Arbor, Mich., pp. 48-59. International Ad Hoc Committee on Human Subjects for Biomechanical Research.

HSRI Library no. 31829 A02
Referenced in: Stalnaker, Melvin, et al., 1977

LeCount, E.R.; Appelnach, C.W. 1920. Pathologic anatomy of traumatic fractures of cranial bones and concomitant brain injuries. Journal of the American Medical Association 74:501-511.

Lindenberg, R.; Freytag, E. 1969. The mechanism of cerebral contusions. AMA Archives of Pathology 69:440-469.

Referenced in: Nahum and Smith, 1976

Lissner, H.R.; Lebow, M.; Evans, F.G. 1960. Experimental studies on the relation between acceleration and intracranial pressure changes in man. Surgery, Gynecology, and Obstetrics 111:329-338.

HSRI Library no. 21365
Referenced in: SAE J885b, 1980

McAdams, H.T. 1972. The repeatability of dummy performance. In Human Impact Response--Measurement and Simulation. Proceedings of the Symposium on Human Impact Response, 2-3 October 1972, Warren, Mich., pp. 35-67. New York: Plenum Press, 1973.

HSRI Library no. 28533 A03

McElhaney, J.H.; Fogle, J.L.; Melvin, J.W.; Haynes, R.R.; Roberts, V.L.; Alem, N.M. 1970. Mechanical properties of cranial bone. Journal of Biomechanics 3(5):495-511.

HSRI Library no. 50140
Referenced in: Stalnaker, Roberts, and McElhaney, 1973

McElhaney, J.H.; Mate, P.I.; Roberts, V.L. 1973. A new crash test device--"Repeatable Pete". In 17th Stapp Car Crash Conference Proceedings, 12-13 November 1973, Oklahoma City, pp. 467-507. New York: SAE paper no. 730983.

HSRI Library no. 28770

McElhaney, J.H.; Melvin, J.W.; Roberts, V.L.; Portnoy, H.D. 1972. Dynamic characteristics of the tissues of the head. In Perspectives in Biomedical Engineering, pp. 215-222. Symposium on Perspectives in Biomedical Engineering, June 1972, Glasgow. London: Macmillan Press, 1973.

HSRI Library no. 29567 A03
Referenced in: McElhaney, Mate, and Roberts, 1973; Stalnaker, Melvin, et al., 1977

McElhaney, J.H.; Roberts, V.L.; Melvin, J.W.; Skelton, W.; Hammond, A.J. 1972. Biomechanics of seat belt design. In 16th Stapp Car Crash Conference Proceedings, 8-10 November 1972, Detroit, pp. 321-344. New York: SAE paper no. 720972.

HSRI Library no. 19862 A17
Referenced in: McElhaney, Stalnaker, and Roberts, 1972

McElhaney, J.H.; Stalnaker, R.L.; Roberts, V.L. 1972. Biomechanical aspects of head injury. In Human Impact Response--Measurement and Simulation. Proceedings of the Symposium on Human Impact Response, 2-3 October 1972, Warren, Mich., pp. 85-110. New York: Plenum Press, 1973.

HSRI Library no. 28533 A05
Referenced in: McElhaney, Mate, and Roberts, 1973; SAE J885b, 1980

McElhaney, J.H.; Stalnaker, R.L.; Roberts, V.L.; Snyder, R.G. 1971. Door crashworthiness criteria. In _15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif._, pp. 489-517. New York: SAE paper no. 710864.

HSRI Library no. 16364
Referenced in: McElhaney, Stalnaker, and Roberts, 1972; Stalnaker, Roberts, and McElhaney, 1973

McLeod, D.G.; Gadd, C.W. 1972. An anatomical skull for impact testing. In _Human Impact Response--Measurement and Simulation. Proceedings of the Symposium on Human Impact Response, 2-3 October 1972, Warren, Mich._, pp. 153-163. New York: Plenum Press, 1973.

HSRI Library no. 28533 A08

Melvin, J.W.; Evans, F.G. 1971. A strain energy approach to the mechanics of skull fracture. In _15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif._, pp. 666-685. New York: SAE paper no. 710871.

HSRI Library no. 17505 A23

Melvin, J.W.; Fuller, P.M.; Barodawala, I.T. 1970. _The mechanical properties of the diploe layer in the human skull_. Society for Experimental Stress Analysis Spring Meeting, 19-22 May 1970, Huntsville, Ala.

Referenced in: Melvin and Evans, 1971

Melvin, J.W.; Fuller, P.M.; Daniel, R.P.; Pavliscak, G.M. 1969. Human head and knee tolerance to localized impacts. _Society of Automotive Engineers Mid-Year Meeting, 19-23 May 1969, Chicago_. New York: SAE paper no. 690477.

HSRI Library no. 09982
Referenced in: Melvin and Evans, 1971

Melvin, J.W.; McElhaney, J.H.; Roberts, V.L. 1970. Development of a mechanical model of the human head--determination of tissue properties and synthetic substitute materials. In _14th Stapp Car Crash Conference Proceedings, 17-18 November 1970, Ann Arbor, Mich._, pp. 221-240. New York: SAE paper no. 700903.

HSRI Library no. 14855 A09
Referenced in: McElhaney, Mate, and Roberts, 1973

Melvin, J.W.; McElhaney, J.H.; Roberts, V.L. 1972. Improved neck simulation for anthropometric dummies. In 16th Stapp Car Crash Conference Proceedings, 8-10 November 1972, Detroit, pp. 45-60. New York: SAE paper no. 720958.

HSRI Library no. 19862 A03
Referenced in: McElhaney, Mate, and Roberts, 1973

Melvin, J.W.; McElhaney, J.H.; Roberts, V.L. 1972. Evaluation of dummy neck performance. In Human Impact Response--Measurement and Simulation, Proceedings of the Symposium on Human Impact Response, 2-3 October 1972, Warren, Mich., pp. 247-261. New York: Plenum Press, 1973.

HSRI Library no. 28533 A12

Mertz, H.J.; Patrick, L.M. 1967. Investigation of the kinematics and kinetics of whiplash. In 11th Stapp Car Crash Conference Proceedings, 10-11 October 1967, Anaheim, Calif., pp. 175-206. New York: SAE paper no. 670919.

HSRI Library no. 04293 A16
Referenced in: Mertz and Patrick, 1971

Mertz, H.J.; Patrick, L.M. 1971. Strength and response of the human neck. In 15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif., pp. 207-255. New York: SAE paper no. 710855.

HSRI Library no. 17505 A09
Referenced in: McElhaney, Mate, and Roberts, 1973; Patrick and Levine, 1975; Ewing and Thomas, 1973

Messerer, O. 1880. Uber Elastiticat und Festigkeit der Menschlichen Knochen. Stuttgart: J.G. Cotta.

Referenced in: Melvin and Evans, 1971

Metz, H.; McElhaney, J.H.; Ommaya, A.K. 1970. A comparison of the elasticity of live, dead, and fixed brain tissue. Journal of Biomechanics 3(4):453-458.

HSRI Library no. 50138
Referenced in: Nahum and Smith, 1976

Mucciardi, A.N.; Sanders, J.D.; Eppinger, R.H. 1977. Prediction of brain injury measures from head motion parameters. In 21st Stapp Car Crash Conference Proceedings, 19-21 October 1977, New Orleans, pp. 369-415. Warrendale, Pa.: SAE paper no. 770923.

HSRI Library no. 38391 A09

Nahum, A.M.; Gatts, J.D.; Gadd, C.W.; Danforth, J. 1968. Impact tolerance of the skull and face. In 12th Stapp Car Crash Conference Proceedings, 22-23 October 1968, Detroit, pp. 302-316. New York: SAE paper no. 680785.

HSRI Library no. 06742 A15
Referenced in: Melvin and Evans, 1971

Nahum, A.M.; Smith, R.; Raasch, F.; Ward, C.C. 1979. Intracranial pressure relationships in the protected and unprotected head. In 23rd Stapp Car Crash Conference Proceedings, 17-19 October 1979, San Diego, Calif., pp. 615-636. Warrendale, Pa.: SAE paper no. 791024.

HSRI Library no. 42984 A22

Nahum, A.M.; Smith, R.; Ward, C.C. 1977. Intracranial pressure dynamics during head impact. In 21st Stapp Car Crash Conference Proceedings, 19-21 October 1977, New Orleans, pp. 339-366. Warrendale, Pa.: SAE paper no. 770922.

HSRI Library no. 38391 A08

Nahum, A.M.; Smith, R.W. 1976. An experimental model for closed head impact injury. In 20th Stapp Car Crash Conference Proceedings, 18-20 October 1976, Dearborn, Mich., pp. 783-814. Warrendale, Pa.: SAE paper no. 760825.

HSRI Library no. 35834 A25
Referenced in: Stalnaker, Melvin, et al., 1977

Neathery, R.F.; Mertz, H.J.; Hubbard, R.P.; Henderson, M.R. 1974. The Highway Safety Research Institute dummy compared with General Motors biofidelity recommendations and the Hybrid II dummy. In Proceedings of the 3rd International Conference on Occupant Protection, 10-12 July 1974, Troy, Mich., pp. 357-383. New York: SAE paper no. 740588.

HSRI Library no. 30029 A24

Nusholtz, G.S.; Axelrod, J.B.; Melvin, J.W.; Ward, C.C. 1979. Comparison of epidural pressure in live anesthetized and postmortem primates. In _7th International Workshop on Human Subjects for Biomechanical Research Proceedings, 16 October 1979, Coronado, Calif._, pp. 175-200. Washington, D.C.: Distributed by National Highway Traffic Safety Administration.

HSRI Library no. 43820 A06

Nusholtz, G.S.; Melvin, J.W.; Alem, N.M. 1979. Head impact response comparisons of human surrogates. In _23rd Stapp Car Crash Conference Proceedings, 17-19 October 1979, San Diego, Calif._, pp. 499-541. Warrendale, Pa.: SAE paper no. 791020.

HSRI Library no. 42984 A18

Ommaya, A.K.; Fisch, F.J.; Mahone, R.M.; Corrao, P.; Letcher, F. 1970. Comparative tolerances for cerebral concussion by head impact and whiplash injury in primates. In _1970 International Automobile Safety Conference Compendium, 13-15 May 1970, Detroit; 8-11 June 1970, Brussels_, pp. 808-817. New York: SAE paper no. 700401.

HSRI Library no. 13115 A53
Referenced in: SAE J885b, 1980

Ommaya, A.K.; Hirsch, A.E. 1971. Protection of the brain from injury during impact: Experimental studies in the biomechanics of head injury. In _Linear Acceleration of Impact Type_, pp.7-1--7-19. Aerospace Medical Panel Specialist Meeting, 23-26 June 1971, Oporto, Portugal. Paris: AGARD conference proceedings no. 88.

HSRI Library no. 17905 A06
Referenced in: McElhaney, Stalnaker, and Roberts, 1972

Ommaya, A.K.; Hirsch, A.E.; Martinez, J.L. 1966. The role of whiplash in cerebral concussion. In _10th Stapp Car Crash Conference Proceedings, 8-9 November 1966, Alamogordo, N.M._, pp. 314-324. New York: SAE paper no. 660804.

HSRI Library no. 01812 A19

Patrick, L.M. 1972. Comparison of dynamic response of humans and test devices (dummies). In Human Impact Response--Measurement and Simulation. Proceedings of the Symposium on Human Impact Response, 2-3 October 1972, Warren, Mich., pp. 17-34. New York: Plenum Press, 1973.

HSRI Library no. 28533 A02

Patrick, L.M.; Levine, R.S. 1975. Injury to unembalmed belted cadavers in simulated collisions. In 19th Stapp Car Crash Conference Proceedings, 17-19 November 1975, San Diego, pp. 79-115. Warrendale, Pa.: SAE paper no. 751144.

HSRI Library no. 33279 A04

Patrick, L.M.; Lissner, H.R.; Gurdjian, E.S. 1963. Survival by design-head protection. In 7th Stapp Car Crash Conference Proceedings, 11-13 November 1963, Los Angeles, pp. 483-499. Springfield, Ill.: Charles C. Thomas, 1965.

HSRI Library no. 00566 A36
Referenced in: SAE J885b, 1980

Patrick, L.M.; Mertz, H.J.; Kroell, C.K. 1967. Cadaver knee, chest, and head impact loads. In 11th Stapp Car Crash Conference Proceedings, 10-11 October 1967, Anaheim, Calif., pp. 106-117. New York: SAE paper no. 670913.

HSRI Library no. 04293 A16
Referenced in: Stalnaker, McElhaney, et al., 1972; Neathery, 1974; Neathery, Kroell, and Mertz, 1975

Piekarski, K. 1970. Fracture of bone. Journal of Applied Physics 41:215-223.

Referenced in: Melvin and Evans, 1971

Rawling, L.B. 1904. Fractures of the skull. Lancet 1:973-979, 1034-1039, 1097-1102.

Referenced in: Melvin and Evans, 1971

Robbins, D.H. 1980. Impact head injury data base. Ann Arbor: University of Michigan Highway Safety Research Institute for the National Institute for Occupational Safety and Health.

Robbins, D.H.; Roberts, V.L. 1971. Michigan injury criteria hypothesis and restraint system effectiveness index. In 15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif., pp. 686-709. New York: SAE paper no. 710872.

HSRI Library no. 17505 A24

Roberts, V.L.; Hodgson, V.R.; Thomas, L.M. 1967. Fluid pressure gradients caused by impact to the human skull. In Biomechanics Monograph, pp. 223-235. New York: American Society of Mechanical Engineers.

HSRI Library no. 01819 A17
Referenced in: McElhaney, Stalnaker, and Roberts, 1972

Rowbotham, G.F. 1942. Acute injuries of the head. Baltimore: Williams and Wilkins Co.

Referenced in: Melvin and Evans, 1971

Schneider, D.C.; Nahum, A.M. 1972. Impact studies of facial bones and skull. In 16th Stapp Car Crash Conference Proceedings, 8-10 November 1972, Detroit, pp. 186-203. New York: SAE paper no. 720965.

HSRI Library no. 19862 A10

Shugar, T.A. 1975. Transient structural response of the linear skull-brain system. In 19th Stapp Car Crash Conference Proceedings, 17-19 November 1975, San Diego, Calif., pp. 581-614. Warrendale, Pa.: SAE paper no. 751161.

HSRI Library no. 33279 A21

Slattenschek, A.; Tauffkirchen, W. 1970. Critical evaluation of assessment methods for head impact applied in appraisal of brain injury hazard, in particular in head impact on windshields. In 1970 International Automobile Safety Conference Compendium, 13-15 May 1970, Detroit; 8-11 June 1970, Brussels, pp. 1084-1112. New York: SAE paper no. 700426.

HSRI Library no. 13115 A74
Referenced in: McElhaney, Stalnaker, and Roberts, 1972; Fan, 1971; Versace, 1971

Slattenschek, A.; Tauffkirchen, W.; Benedikter, G. 1971. The quantification of internal head injury by means of the phantom head and the impact assessment methods. In 15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif., pp. 742-766. New York: SAE paper no. 710879.

HSRI Library no. 17505 A27

Smith, G.R.; Hurite, S.S.; Yanik, A.J.; Greer, C.R. 1972. Human volunteer testing of GM air cushions. 2nd International Conference on Passive Restraints, 22-25 May 1972, Detroit. New York: SAE paper no. 720443.

HSRI Library no. 19900
Referenced in: McElhaney, Stalnaker, and Roberts, 1972

Society of Automotive Engineers. 1965. Instrument panel laboratory impact test procedures. In SAE Handbook 1966, pp. 862-865. New York: SAE J921.

Society of Automotive Engineers. 1966. Human tolerance to impact conditions as related to motor vehicle design. SAE Handbook 1968, pp. 911-913. New York: SAE J885a.

Society of Automotive Engineers. 1968. Anthropomorphic test device for dynamic testing. SAE Handbook 1969, pp. 977-980. New York: SAE J963.

Society of Automotive Engineers. 1969. Motor vehicle driver's eye range. SAE Handbook 1970, pp. 942-945. New York: SAE J941b.

Referenced in: McElhaney, Mate, and Roberts, 1973

Society of Automotive Engineers. 1980. Human tolerance to impact conditions as related to motor vehicle design. New York: SAE Handbook Supplement J885 APR80.

Stalnaker, R.L.; Alem, N.M.; Benson, J.B. 1977. Validation studies for head impact injury model. Ann Arbor: University of Michigan Highway Safety Research Institute for the National Highway Traffic Safety Administration. Report no. DOT/HS-802 566.

HSRI Library no. 37960

Stalnaker, R.L.; Fogle, J.L.; McElhaney, J.H. 1970. Driving point impedance characteristics of the head. American Society of Mechanical Engineers Biochemical and Human Factors Conference, 31 May - 3 June 1970, Washington, D.C. New York: ASME paper no. 70-BHF-14.

HSRI Library no. 13415
Referenced in: Stalnaker, Roberts, and McElhaney, 1973

Stalnaker, R.L.; Fogle, J.L.; McElhaney, J.H. 1971. Driving point impedance chacteristics of the head. Journal of Biomechanics 4(2):127-139.

HSRI Library no. 50255
Referenced in: McElhaney, Stalnaker, and Roberts, 1972; Stalnaker, Roberts, and McElhaney, 1973

Stalnaker, R.L.; McElhaney, J.H. 1970. Head injury tolerance for linear impacts by mechanical impedance methods. American Society of Mechanical Engineers Winter Annual Meeting, 29 November - 3 December 1970, New York. New York: ASME paper no. 70-WA/BHF-4.

HSRI Library no. 19043
Referenced in: Fan, 1971

Stalnaker, R.L.; McElhaney, J.H.; Roberts, V.L. 1971. MSC tolerance curve for head impacts. New York: ASME paper no. 71-WA/BHF-10.

HSRI Library no. 16266
Referenced in: Versace, 1971

Stalnaker, R.L.; McElhaney, J.H.; Roberts, V.L.; Snyder, R.G. 1971. Door crashworthiness criteria. In 15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif., pp. 489-517. New York: SAE paper no. 710864.

HSRI Library no. 17505
Referenced in: Stalnaker, McElhaney, et al., 1972

Stalnaker, R.L.; Melvin, J.W.; Nusholtz, G.S.; Alem, N.M.; Benson, J.B. 1977. Head impact response. In 21st Stapp Car Crash Conference Proceedings, 19-21 October 1977, New Orleans, pp. 303-335. Warrendale, Pa.: SAE paper no. 770921.

HSRI Library no. 38391 A07

Stalnaker, R.L.; Mohan, D.; Melvin, J.W. 1975. Head injury evaluation: Criteria for assessment of field, clinical and laboratory data. In 19th Conference of the American Association for Automotive Medicine Proceedings, 20-22 November 1975, San Diego, pp. 168-178. Morton Grove, Ill.: AAAM.

HSRI Library no. 33203 A15
Referenced in: Stalnaker, Melvin, et al., 1977

Stalnaker, R.L.; Roberts, V.L.; McElhaney, J.H. 1973. Side impact tolerance to blunt trauma. In 17th Stapp Car Crash Conference Proceedings, 12-13 November 1973, Oklahoma City, pp. 377-408. New York: SAE paper no. 730979.

HSRI Library no. 28770 A17

Stapp, J.P. 1955. Tolerance to abrupt deceleration. AGARDograph 6:122-169

HSRI Library no. 23637
Referenced in: SAE J885b, 1980

Stapp, J.P. 1961. Human tolerance to severe, abrupt deceleration. In Gravitational Stress in Aerospace Medicine, pp. 165-188. Boston: Little Brown.

Referenced in: SAE J885b, 1980

Swearingen, J.J. 1965. Tolerances of the human face to crash impact. Oklahoma City: Civil Aeromedical Research Institute.

HSRI Library no. 02959

Tarriere, C.; Sapin, C. 1969. Biokinetic study of the head to thorax linkage. In 13th Stapp Car Crash Conference Proceedings, 2-4 December 1969, Boston, pp. 365-380. New York: SAE paper no. 690815.

HSRI Library no. 12067 A21
Referenced in: Mertz and Patrick, 1971; Clemens and Burow, 1972

Tennant, J.A.; Jensen, R.H.; Potter, R.A. 1974. GM-ATD 502 anthropomorphic dummy--development and evaluation. In Proceedings of the 3rd International Conference on Occupant Protection, 10-12 July 1974, Troy, Mich., pp. 394-420. New York: SAE paper no. 740590.

HSRI Library no. 30029 A26
Referenced in: Neathery, 1974; Neathery, Kroell, and Mertz, 1975

Thomas, A.M. 1972. Dummy performance in crash simulations environments. In Human Impact Response--Measurement and Simulation. Proceedings of the Symposium on Human Impact Response, 2-3 October 1972, Warren, Mich., pp. 69-82. New York: Plenum Press.

HSRI Library no. 28533 A04

Thomas, D.J. 1972. Specialized anthropometry requirements for protective equipment evaluation. In Current Status in Aerospace Medicine, pp. C9-1--C9-8. Aerospace Medical Panel Specialist Meeting, 7-8 September 1972, Glasgow, Scotland. Paris: AGARD conference proceedings no. 110, 1973.

HSRI Library no. 43796
Referenced in: Stalnaker, Melvin, et al., 1977; Ewing, Thomas, et al., 1975; Ewing and Thomas, 1973

Thomas, D.J.; Ewing, C.L. 1971. Theoretical mechanics for expressing impact accelerative response of human beings. In Linear Acceleration of Impact Type, pp. 12-1--12-7. Aerospace Medical Panel Specialist Meeting, 23-26 June 1971, Oporto, Portugal. Paris: AGARD conference proceedings no. 88.

HSRI Library no. 17905 A11
Referenced in: Robbins, Melvin, and Stalnaker, 1976

U.S. National Center for Health Statistics. 1970. Skinfolds, body girths, bio-cromial diameter, and selected anthrometric indices of adults: United States, 1960-1962. Washington, D.C.: NCHS series 11, no. 35.

HSRI Library no. 13662
Referenced in: McElhaney, Mate, and Roberts, 1973

U.S. National Highway Traffic Safety Administration. 1972. Head injury criterion for Federal Motor Vehicle Safety Standard no. 208. Washington, D.C: NHTSA. Supplement to 37 FR 5507.

Referenced in: SAE J885b, 1980

U.S. National Transportation Safety Board. 1979. Safety effectiveness evaluation of the National Highway Traffic Safety Administration's rulemaking process. Vol. II: Case history of Federal Motor Vehicle Safety Standard 208: Occupant crash protection. Washington, D.C. NTSB-SEE-79-5.

HSRI Library no. 43180

Unterharnscheidt, F.J. 1971. Translational versus rotational acceleration: Animal experiments with measured input. In 15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif., pp. 767-770. New York: SAE paper no. 710880.

HSRI Library no. 17505 A28

Versace, J. 1971. A review of the severity index. In 15th Stapp Car Crash Conference Proceedings, 17-19 November 1971, Coronado, Calif., pp. 771-796. New York: SAE paper no. 710881.

HSRI Library no. 17505 A29
Referenced in: McElhaney, Stalnaker, and Roberts, 1972; SAE J885b, 1980

Viano, D.C. 1978. Thoracic injury potential. In 3rd International Meeting on the Simulation and Reconstruction of Impacts in Collisions Proceedings, 12-13 September 1978, Lyon, France, pp. 142-156. Bron, France: International Research Committee on the Biokinetics of Impacts.

HSRI Library no. 41734 A13

Viano, D.C.; Gadd, C.W. 1975. Significance of rate of onset in impact injury evaluation. In 19th Stapp Car Crash Conference Proceedings, 17-19 November 1975, San Diego, pp. 807-819. Warrendale, Pa.: SAE paper no. 751169.

HSRI Library no. 33279

Walker, L.B.; Harris, E.H.; Pontius, U.R. 1973. Mass, volume, center of mass, and mass moment of inertia of head and head and neck of human body. In _17th Stapp Car Crash Conference Proceedings, 12-13 November 1973, Oklahoma City_, pp. 525-537. New York: SAE paper no. 730985.

HSRI Library no. 28770 A23
Referenced in: Ewing and Thomas, 1973

Ward, C.C. 1977. Analytical brain models for head impact. In _3rd International Conference on Impact Trauma Proceedings, 7-9 September 1977, Berlin_, pp. 389-398. Bron, France: International Research Committee on the Biokinetics of Impacts.

HSRI Library no. 38068 A21

Ward, C.C.; Thompson, R.B. 1975. The development of a detailed finite element brain model. In _19th Stapp Car Crash Conference Proceedings, 17-19 November 1975, San Diego_, pp. 641-674. Warrendale, Pa.: SAE paper no. 751163.

HSRI Library no. 33279 A23

Wood, J.L. 1971. Dynamic response of human cranial bone. _Journal of Biomechanics_ 4:1-12.

Referenced in: Melvin and Evans, 1971