SURFACE VEHICLE RECOMMENDED PRACTICE	J1727	FEB2015
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(R) Calculation Guidelines for Impact Testing

RATIONALE

The committee reviewed this Recommended Practice to determine what changes were necessary to include the set of calculations, methods, and indexes that are typically calculated by labs performing impact tests. The major changes are outlined below.

ECE R94 was added to the list of references.

FIA Procedure for the Approval of Safety Structures was added to the list of references.

Resultant
The resultant calculation was added to provide a method for combining sensor signals collected at a single location, where the signals provide measurement along mutually orthogonal axes.

Delta V
The delta V calculation was added to provide a method for calculating the total change in velocity of a point location on an object during an impact test. Verbiage was added to explicitly state that delta V is a point measurement relative to the earth fixed coordinate system. Delta V is not a measurement relative to a vehicle or dummy coordinate system.

Maximum Average Acceleration
The maximum average acceleration calculation was added to provide a method for calculating the acceptance criteria for the energy absorbing structures of a motorsport vehicle during a frontal and a rear crash test.

Impactor Load
Impactor load calculation was added to provide a method for calculating the force on the leading face of an impactor when load cells are installed internal to the impactor.

Impactor G-force
Impactor G-force calculation was added to provide a method for calculating the force on the leading face of an impactor when an impactor is instrumented with an accelerometer.

V*C

The viscous criteria section was modified to allow filtering of the chest compression data using a CFC 180 filter. ECE R94 and other organizations specify a CFC 180 filter for dummy chest deflection in lieu of the SAE J211-1 specified CFC 600 filter. Due to the sensitivity of the derivative calculation to signal noise, using the CFC 180 filter for V*C has become popular among several organizations and is in common use.

CWVP

The chest wall velocity predictor was added to provide a method for calculating the chest compressive velocity during impulsive and percussive events such as a mine blast.

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1. SCOPE

This SAE Recommended Practice presents a series of standard calculations and numerical methods for processing safety test instrumentation data that has been acquired during impact tests with instruments installed in ATD's (crash test dummies), vehicle structures, and laboratory fixtures. The output data from performing these calculations may have applications that include energy analysis, biomechanical analysis, regulation compliance, or other purposes. However, application of the output data from these calculations is outside the scope of this document. It is the intent of this document to present a basic set of calculations that are applicable to test labs that follow the practices set forth by SAE J211-1, SAE J211-2, SAE J2570, and SAE J1733. For the calculations that are described in other sources, the relevant documents are referenced.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

2.1.1 SAE Publications

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

SAE J211-1 Instrumentation for Impact Test - Part 1: Electronic Instrumentation

SAE J211-2 Instrumentation for Impact Test - Part 2: Photographic Instrumentation

SAE J1733 Sign Convention for Vehicle Crash Testing

SAE J2570 Performance Specifications for Anthropomorphic Test Device Transducers

SAE #880656 A Review and Evaluation of Various HIC Algorithms, by Chou, Howell, and Chang

SAE #930100 An Evaluation of Various Viscous Criterion Computational Algorithms, by Chou, Lin, and Lim

2.1.2 Federal Publications

Available from the Superintendent of Documents, U.S. Government Printing Office, Mail Stop: SSOP, Washington, DC 20402-9320.

FMVSS 201 Code of Federal Regulations, Title 49, Section 571.201 - Occupant Protection in Interior Impact

FMVSS 203 Code of Federal Regulations, Title 49, Section 571.203 - Impact Protection for the Driver from the Steering Control System

FMVSS 208 Code of Federal Regulations, Title 49, Section 571.208 - Occupant Crash Protection

FMVSS 214 Code of Federal Regulations, Title 49, Section 571.214 - Side Impact Protection

FMVSS 202a Code of Federal Regulations, Title 49, Section 571.202 - Head Restraints

2.1.3 Other Publications

Accidental Injury, Biomechanics and Prevention, 2nd Ed. Alan Nahum and John Melvin, Springer 2002, Chapter 4 "Anthropomorphic Test Devices", by Harold J. Mertz.

Crash Analysis Criteria, Measured Data Processing Vehicle Safety Workgroup, Algorithm Group.

Sign Convention for Load Cells (SAE-J211), Robert A. Denton Inc.

AEP-55, Procedure for Evaluating the Protection Level of Logistic and Light Armoured Vehicles - Mine Threat, A NATO/PIP Unclassified Publication.

An Evaluation of Existing and Proposed Injury Criteria with Various Dummies to Determine Their Ability to Predict the Levels of Soft Tissue Neck Injury Seen in Real World Accidents; Frank Heitplatz et all, ESV Conference 2003.

A Sled Test Procedure Proposal to Evaluate the Risk of Neck Injury in Low Speed Rear Impacts Using a New Neck Injury Criterion (NIC); Paper No. 98-S7-O-07; Ola Bostrom, Yngve Haland, Rikard Frediksson, Autoliv Research Sweden, Mats Y Svensoson Hugo Mellander, Chalmers University of Technology Sweden, 16th ESV Conference; June 1-4, 1998 Windsor Canada.

Biomechanical and Scaling Bases for Frontal and Side Impact Injury Assessment Reference Values; Harold J. Mertz, Annete L. Irwin, Priya Prasad, Stapp Car Crash Journal 2003-22-0009, October 2003.

ECE R94, Uniform Provisions Concerning the Approval of Vehicles with Regards to the Protection of the Occupants in the Event of a Frontal Collision.

Federation Internationale de l'Automobile, Procedure for the Approval of Safety Structures.

3. PRE-CALCULATION CORRECTIONS AND CONVERSIONS

3.1 Scale Correction/Conversion to Engineering Units

Data must be scale corrected to convert the acquired data from bit counts, the standard output unit of an analog to digital (A/D) converter, to physical engineering units. Modern data acquisition systems (DAS) perform this scale correction/conversion automatically by accounting for the transducer sensitivity, channel excitation, channel gain, A/D conversion factor, A/D range, channel full scale physical engineering unit range and any required scale correction factors determined prior to the acquisition of test data.

3.2 Polarity Correction

Polarity of channel data must follow the sign conventions established by SAE J211-1 and SAE J1733. Failure to strictly follow the aforementioned polarity conventions will cause incorrect calculation results. Channel data that is acquired with reverse polarity must be inverted prior to performing calculations that include these channels. Inverting of channel polarity is accomplished by multiplying channel data by –1.

$$Ch(A_{SAE}) = -1 \times Ch(A_{NOT(SAE)})$$

where:

$Ch(A_{NOT(SAE)})$ denotes acquired channel data that does <u>not</u> follow SAE polarity convention

$Ch(A_{SAE})$ denotes channel data that follows SAE polarity convention, i.e., the inverse of $Ch(A_{NOT(SAE)})$

3.3 Bias Correction

Channel data must be bias corrected to account for any DC offset in the acquired signals. Simply relying on hardware systems to balance such data prior to a test event is not recommended. In addition to performing a hardware balance, many data acquisition systems include software routines that bias correct channel data. Bias correction may also be done during data post-processing. Typical bias correction methods include, but are not limited to, the following:

3.3.1 Average Data in a Section of the Test Data File

Average data over a time range in the data stream of the test data file, during which the actual physical values are at a known constant reference value (e.g. zero or 1 g acceleration, zero or non-zero load, zero or non-zero displacement). Typically, the time range selected is prior to the event (t0), and is referred to as pre-trigger data. However, there are cases where other time ranges are more appropriate.

3.3.2 Average Data to Account for a Pre-Load

This method is useful when the unit under test must undergo an unknown pre-load. Average data over a time range in the data stream of a pre-test data file, prior to applying any pre-load, and during which the actual physical values are at a known constant reference value, e.g. zero or 1 g acceleration, zero load, zero displacement. The DAS must not be re-balanced after recording this pre-test data file that is used to determine bias correction factors that account for electrical offsets. Acquire a second pre-test data file with the unit under test in the pre-loaded condition. The time between acquiring the first and second pre-test data files should be as close as possible to reduce any temperature drift or other drift phenomena. The DAS may be rebalanced after collecting the second pre-test data file. Process the second pre-test file using the bias correction factors from the first pre-test file and determine the value of the pre-load. The pre-load value determined from this processing is the known constant reference value that is used with the above method in 3.3.1 and the actual test data file. Other similar methods are also acceptable provided that all electrical offsets and all pre-loads are accounted for.

3.3.3 Average Data in Real-Time

Average data over a series of real-time measured data points during which the actual physical values are at a known constant reference value, e.g. zero or 1 g acceleration, zero or non-zero load, zero or non-zero displacement.

The bias correction factor is obtained by subtracting the calculated average value from the known constant reference value. Acquired channel data is then bias corrected by adding the bias correction factor to all acquired data points. In order to calculate the bias correction factor, it is recommended to average a series of measured data points over a time range, compared to measuring one single data point.

$AVG_{i1\text{-}i2}(Ch(A)) = 1/(i2 - i1 + 1) * Sum(A[i_1\text{-}i_2])$
$CF_{BIAS} = CH(A)_{REF} - AVG_{i1\text{-}i2}(Ch(A))$
$CH(A)_{BiasCorrected} = Ch(A) + CF_{BIAS}$

where:

A = single measurement value from channel A
$CH(A)_{BiasCorrected}$ = bias corrected channel data
Ch(A) = channel data, prior to bias correction
CF_{BIAS} = bias correction factor
$CH(A)_{REF}$ = known constant reference value of channel A during the index range i1 to i2
$AVG_{i1\text{-}i2}(Ch(A))$ = average of channel A, over the index range from i1 to i2
$Sum(A[i_1\text{-}i_2])$ = summation of all channel A values, over the index range from i1 to i2
i1 = starting index for calculating the average
i2 = ending index for calculating the average

4. FILTERING

Channel data must be filtered per SAE J211-1 prior to performing any of the following calculations on the channel data. In cases of performing moment calculations that include lever arms and force channel data, the force channel data is to be filtered in accordance with the SAE J211-1 specification for the moment channel data. In cases where filters other than the CFC filters from SAE J211-1 are used, the filtering algorithm may induce a DC offset error. In these cases, additional bias correction should be performed after filtering.

5. GENERAL COMPUTATIONS

5.1 Integration and Differentiation

Many numerical methods are available for integration and differentiation, including simple rectangular and trapezoidal rules to much more sophisticated techniques. Following the aforementioned SAE recommended practices ensures bandwidths are sufficiently wide and properly located along the spectrum scale to ensure accurate results are obtained with the following methods. Shown below are recommended methods for differentiation and integration.

5.1.1 Integration

The trapezoidal method is recommended for integration.

$F[x] = Integral\{Y[x]\,dx\}$, from x_0 to x_f
$F[x_0] = 0, i = 0$
$F[x_i] = F[x_{i-1}] + (Y[x_i] + Y[x_{i-1}])/2 * (x_i - x_{i-1}), i > 0, i <= f$

where:

F[x] = the resulting integral
Y[x] = the channel to integrate
x = the channel to integrate with respect to
i = the index location, the row number in the column/row matrix of channel data
x_0 = the lower limit of integration, provides the first index location for calculating the integral
x_f = the upper limit of integration, provides the last index location for calculating the integral

* NOTE: Any numerical integration routine will compound a DC offset in the data set; signals must be appropriately bias corrected prior to integrating.

5.1.2 Differentiating with Respect to a Channel with Equidistant Samples

It is recommended to use the following method when differentiating with respect to a channel that has equidistant samples. This is often the case when differentiating with respect to time.

$$Y'[x] = dY[x]/dx$$
$$dY[x_i]/dx = (8*(Y[x_i + \Delta x] - Y[x_i - \Delta x]) - (Y[x_i + 2\Delta x] - Y[x_i - 2\Delta x]))/12\Delta x$$

where:

$Y'[x]$ = the resulting derivative
$dY[x_i]/dx$ = the derivative of Y, with respect to x, at index location i
Y = the channel to be differentiated
x = the channel to differentiate with respect to
i = the index location, the row number in the column/row matrix of channel data
Δx = the equidistant step width of the x channel

5.1.3 Differentiating with Respect to a Channel with Non-equidistant Samples

It is recommended to use the following method when differentiating with respect to a channel that does not have equidistant samples. This is often the case when differentiating with respect to any channel other than time.

$$Y'[x] = dY[x]/dx$$
$$dY[x_i]/dx = \Delta Y[x_i]/\Delta x_i$$
$$\Delta Y[x_i] = Y[x_{i+1}] - Y[x_i]$$
$$\Delta x_i = x_{i+1} - x_i$$

where:

$Y'[x]$ = the resulting derivative
$dY[x_i]/dx$ = the derivative of Y, with respect to x, at index location i
Y = the channel to be differentiated
x = the channel to differentiate with respect to
i = the index location, the row number in the column/row matrix of channel data
$\Delta Y[x_i]$ = the step width of the Y channel, at index location i
Δx_i = the step width of the x channel, at index location i

5.2 Velocity, Relative Velocity, Displacement, and Relative Displacement for Rectilinear Motion

Velocity, relative velocity, displacement, and relative displacement of objects can be calculated from the acceleration of the objects using numerical integration along with known initial conditions. For the calculations to be valid, the acceleration of each object must return to zero at the end of the test. In addition, the axes of the two objects must remain parallel to each other during the test otherwise the motion is not rectilinear. In general, ATD head X, chest X, and pelvic X channels do not remain parallel to each other or to the vehicle frame during an impact test. In the case of pendulum testing, provided that the stroke of the pendulum during the impact is sufficiently short, approximating the pendulum's tangential motion as rectilinear motion is a valid practice. The methods to calculate the velocity, relative velocity, displacement, and relative displacement of test objects are shown below. Two methods are shown to determine the relative difference in velocity or displacement between two objects whose accelerations have been measured.

5.2.1 Rectilinear Motion Method 1

In order to calculate the relative velocity and relative displacement between two objects, first subtract the two accelerations. Integrate the difference to get the relative velocity. Integrate again to get the relative displacement.

v_{rel} = [Integral{(a_2 – a_1) dt}, from t_0 to t_f] + $v_{rel}(0)$
d_{rel} = [Integral{v_{rel} dt}, from t_0 to t_f] + $d_{rel}(0)$

where:

vrel = relative velocity
vrel(0) = relative velocity at t0
a1 = acceleration of object number 1
a2 = acceleration of object number 2
drel = relative displacement
drel(0) = relative displacement at t0
t0 = time zero, i.e. the time of impact
tf = final time of evaluation

* Although the initial conditions at t0 will often be zero, this should not be assumed.

5.2.2 Rectilinear Motion Method 2

Integrate the acceleration to calculate the velocity of each object. Subtract the velocities to calculate relative velocity. Integrate the velocity to calculate the displacement of each object. Subtract the displacements to calculate relative displacement.

v1 = [Integral{a1 dt}, from t0 to tf] + v1(0)
v2 = [Integral{a2 dt}, from t0 to tf] + v2(0)
vrel = v2 – v1
d1 = [Integral{v1 dt}, from t0 to tf] + d1(0)
d2 = [Integral{v2 dt}, from t0 to tf] + d2(0)
drel = d2 – d1

where:

v_1 = velocity of object 1
$v_1(0)$ = velocity of object 1 at t_0
v_2 = velocity of object 2
$v_2(0)$ = velocity of object 2 at t_0
v_{rel} = relative velocity
d_1 = displacement of object 1
$d_1(0)$ = displacement of object 1 at t_0
d_2 = displacement of object 2
$d_2(0)$ = displacement of object 2 at t_0
d_{rel} = relative displacement
t_0 = time zero, i.e. the time of impact
t_f = final time of evaluation

* Although the initial conditions at t_0 will often be zero, this should not be assumed.

5.3 Resultant

The resultant is a vector calculation that combines scalar quantities that are measured at the same location but along differing directions. For example, a location for a vehicle mounted accelerometer often includes an individual accelerometer in each of the three mutually orthogonal X, Y, and Z directions. The resultant calculation combines the signals from each accelerometer for the purpose of calculating the magnitude of acceleration at the particular vehicle location. The resultant is not limited to 2 or even 3 dimensions as it is merely the square root of the sum of the squares of all mutually orthogonal sensor signals. The resultant is not limited to a particular engineering unit. The resultant can be calculated with force, acceleration, displacement or other sensors as long as the physical parameter is a vector quantity.

NOTE: the input parameters must be mutually orthogonal.

$$a_{res} = (a_x^2 + a_y^2 + a_z^2)^{0.5}$$

where:

a_{res} = resultant acceleration
a_x = acceleration along the x axis
a_y = acceleration along the y axis
a_z = acceleration along the z axis

5.4 Delta V

The delta V is a calculation that provides the total change in velocity at a particular point of a mechanical body. Delta V is in reference to the earth fixed coordinate system; it is not in reference to any rotating coordinate system, such as a rotating vehicle or dummy coordinate system. During impact events such as a vehicle barrier crash, the vehicle rebounds off the wall with some residual negative velocity such that the total change in velocity is larger than the impact speed. In some crashes the vehicle does not completely scrub off all the speed during the crash. For example, if a vehicle rear-ends another vehicle, the bullet vehicle may continue to roll after the impact with some residual velocity. Thus, the delta V is lower than the impact speed. Delta V is typically different than the impact velocity.

5.4.1 Pure Translational Motion Method

In order to calculate delta V, first calculate the change in velocity of the point of interest along each of the three mutually perpendicular earth fixed X, Y, and Z axes. Following, take the resultant of the three mutually orthogonal X, Y, and Z changes in velocity. This is the most common method for full frontal barrier crash tests and other tests where the vehicle does not experience significant yaw rotation.

$$dv_x = v_x - v_x(0)$$
$$dv_y = v_y - v_y(0)$$
$$dv_z = v_z - v_z(0)$$
$$\Delta V = (dv_x^2 + dv_y^2 + dv_z^2)^{0.5}$$

where:

ΔV = Delta V, resultant of the earth fixed X, Y, and Z changes in velocity
dv_x = change in velocity of the point of interest along the earth fixed X axis
v_x = velocity of the point of interest along the earth fixed X axis
$v_x(0)$ = velocity of the point of interest along the earth fixed X axis at time zero
dv_y = change in velocity of the point of interest along the earth fixed Y axis
v_y = velocity of the point of interest along the earth fixed Y axis
$v_y(0)$ = velocity of the point of interest along the earth fixed Y axis at time zero
dv_z = change in velocity of the point of interest along the earth fixed Z axis
v_z = velocity of the point of interest along the earth fixed Z axis
$v_z(0)$ = velocity of the point of interest along the earth fixed Z axis at time zero

5.4.2 2D Translational plus Yaw Motion Method

If a vehicle rotates as a result of impact, the calculation of delta V can still be performed. This calculation provides the delta V method for a vehicle experiencing 2D planar motion in the X and Y axes and yaw rotation about the Z axis. Angular rotation data of the vehicle is needed to perform the coordinate transformation when calculating delta V for a rotating vehicle. Angular rotation data can be obtained with the use of angular rate sensors. Angular rotation data can also be obtained with the use of accelerometers located at different points on the vehicle but this method is not recommended and the calculation for this method is not included here. Note that two relevant coordinate systems are included. The vehicle fixed coordinate system utilizes lower-case characters l, k, and m, where l, k, and m correlate to the forward, right, and downward directions fixed to the vehicle. It is typical to use lowercase x, y, and z to represent the vehicle coordinate system. However, to eliminate any misinterpretation the characters l, k, and m are used for this calculation. The earth fixed coordinate system utilizes upper-case characters X, Y, and Z. The vehicle fixed m axis and the earth fixed Z axis are parallel. The vehicle acceleration is measured at the point of interest in reference to the vehicle coordinate system. This delta-V calculation requires transforming, at each time step in the data stream, the measured acceleration to an acceleration in reference to the earth fixed coordinate system. Following, the accelerations are integrated to calculate velocities in reference to the earth fixed coordinate system. The delta V is then calculated in same manner as shown in the abovementioned method.

$Q_Z[t_i] = Q_Z[t_{i-1}] + 0.5*(W_m[t_i] + W_m[t_{i-1}])/(t_i - t_{i-1})$
$a_X[t_i] = a_l[t_i] * \cos(Q_z[t_i]) – a_k[t_i] * \sin(Q_z[t_i])$
$a_Y[t_i] = a_k[t_i] * \cos(Q_z[t_i]) + a_l[t_i] * \sin(Q_z[t_i])$
$v_X[t] = [\text{Integral}\{a_X[t]\ dt\}, \text{ from } t_0 \text{ to } t_f] + v_X[t_0]$
$v_Y[t] = [\text{Integral}\{a_Y[t]\ dt\}, \text{ from } t_0 \text{ to } t_f] + v_Y[t_0]$
$dv_X = v_X[t] – v_X[0]$
$dv_Y = v_Y[t] – v_Y[0]$
$\Delta V = (dv_x^2 + dv_y^2)^{0.5}$

where:

Q_Z = angular position of the vehicle, in reference to the earth fixed Z axis
W_m = angular rate of the vehicle, in reference to the vehicle fixed m axis
a_l = input channel acceleration signal, measured in reference to the vehicle fixed l axis
a_k = input channel acceleration signal, measured in reference to the vehicle fixed k axis
a_X = transformed acceleration signal, in reference to the earth fixed X axis
a_Y = transformed acceleration signal, in reference to the earth fixed Y axis
v_X = velocity, in reference to the earth fixed X axis
v_Y = velocity, in reference to the earth fixed Y axis
dv_x = change in velocity of the point of interest along the earth fixed X axis
$v_x(0)$ = velocity of the point of interest along the earth fixed X axis at time zero
dv_y = change in velocity of the point of interest along the earth fixed Y axis
$v_y(0)$ = velocity of the point of interest along the earth fixed Y axis at time zero
ΔV = Delta V, resultant of the earth fixed X, and Y changes in velocity

As a supplement, the equations below are provided in the case that the vehicle acceleration measurement is not performed with an accelerometer in the location of interest. Oftentimes the delta V is desired to be known at the location where a vehicle occupant is seated, but the vehicle accelerometer is not mounted at this location. The equations below show the method to calculate the acceleration at the location of interest (point A) based on accelerometer measurements at an arbitrary location (Point P). Angular rate data is needed for this calculation. The vehicle axes are labelled l, k, and m to be consistent with the above delta V calculations. The calculated acceleration at point A are used as inputs to the above delta V calculation for 2D motion plus yaw.

$a_{l\text{-}A} = a_{l\text{-}P} – R_m * (l_A – l_P) – W_m^2 * (l_A – l_P)$
$a_{k\text{-}A} = a_{k\text{-}P} + R_m * (k_A – k_P) – W_m^2 * (k_A – k_P)$
$R_m = dW[m]/dm$

where:

$a_{l\text{-}P}$ = measured acceleration of point P along the vehicle l axis
$a_{l\text{-}A}$ = calculated acceleration of point A along the vehicle l axis
$a_{k\text{-}P}$ = measured acceleration of point P along the vehicle k axis
$a_{k\text{-}A}$ = calculated acceleration of point A along the vehicle k axis
l_P = vehicle location of point P in the direction of the l axis
l_A = vehicle location of point A in the direction of the l axis
$l_A - l_P$ = distance from point P to point A in the direction of the l axis
k_P = vehicle location of point P in the direction of the k axis
k_A = vehicle location of point A in the direction of the k axis
$k_A - k_P$ = distance from point P to point A in the direction of the k axis
W_m = angular rate of the vehicle, in reference to the vehicle fixed m axis
R_m = angular acceleration of the vehicle, in reference to the vehicle fixed m axis
dW[m]/dm = the derivative of the angular rate, with respect to the vehicle m axis

5.5 Maximum Average Acceleration

When performing tests to evaluate the performance of energy attenuating structures on the forward and trailing edge of motorsports vehicles, often the acceptance criteria is based on the maximum average acceleration experienced by the vehicle during the impact test. This calculation is performed on the unfiltered acceleration data, not the acceleration data filtered per SAE J211-1. The calculation is a running average of all the discrete measured acceleration data points, calculated from the instant of impact, event t0, until the first instant the test vehicle speed is less than zero. In many cases the acceleration input to this calculation is the average of signals from two symmetrically located left/right accelerometers.

$a_{max(avg)} = Max(a_{avg})$
$a_{avg} = AVG_{i1\text{-}i2}(Ch(a))$
$AVG_{i1\text{-}i2}(Ch(a)) = 1/(i2 - i1 + 1) * Sum(a[i_1\text{-}i_2])$

where:

a = input channel acceleration signal
$AVG_{i1\text{-}i2}(Ch(a))$ = average of channel a, over the index range from i1 to i2
$Sum(a[i_1\text{-}i_2])$ = summation of all channel a values, over the index range from i1 to i2
i1 = starting index for calculating the average, correlates to event t0
i2 = ending index for calculating the average, correlates to first occurrence where speed < 0

5.6 Impactor Load

An impactor such as a dummy calibration probe or a rigid moving barrier is often instrumented with a load cell or an array of load cells internal to the impactor. The load data of interest however is on the leading face of the impactor, not at the intermediate location where the load cells are positioned. Using the law of equal and opposite forces, this impactor face load is the blunt force imposed on the object under test. In order to calculate the impactor load/ blunt force, the mass forward and aft of the neutral axis of the load cells must be taken into account and a correction factor applied to the signals measured by the load cells.

$F_{impact} = L_{measured} * (1 + m_{fwd}/m_{aft})$

where:

F_{impact} = the impact load/ blunt force between the impactor and the object under test.
$L_{measured}$ = the load measured by load cells
m_{fwd} = the mass of the impactor forward of the load cells + the mass of the load cells forward of their neutral axes
m_{aft} = the mass of the impactor aft of the load cells + the mass of the load cells aft of their neutral axes

5.7 Impactor G-force

An impactor such as a dummy calibration probe or a moving barrier is often instrumented with an accelerometer. The data of interest is the force at the leading face of the impactor. Using the law of force equals mass time acceleration, the impactor g-force may be calculated. Caution must be exercised as this calculation requires the impactor to undergo only translation motion during the time of interest. Any rotational motion will cause this calculation to provide erroneous results.

$$F_{impact} = m_{impactor} * a_{impactor}$$

where:

F_{impact} = the impact load/ blunt force between the impactor and the object under test.
$m_{impactor}$ = the mass of the impactor
$a_{impactor}$ = the acceleration of the impactor

5.8 Time Limited Amplitude Determination (Xms)

Two methods exist to compute the time limited amplitude determination, the single peak and the cumulative peak methods.

5.8.1 Single Peak Method

Measurement of amplitudes not exceeding a given time duration, such as the 3-ms "clip" limits of FMVSS 201, 203, and 208, shall be determined on a continuous basis. This means that you must find the greatest amplitude level of the channel for which the amplitude is continuously above the level for at least the specified time duration. In other words, if the amplitude drops below the given level during an observed time interval, this shall be considered as two separate time periods, not added together. Calculation of amplitude and time duration shall be based on straight-line interpolated values between data sample points.

5.8.1.1 Perform a running window search, where the window width is equal to the time duration. Linear interpolations shall be applied when the sample rate is not a multiple of the window width.

5.8.1.2 Determine the lowest amplitude value found in each search window. Linear interpolations shall be applied when the beginning and ending samples do not have the same value.

5.8.1.3 Determine the largest amplitude value of all the values found in 5.3.1.2.

5.8.2 Cumulative peak method

The cumulative method does not require the signal amplitude to be continuously above the threshold level. If the sampling rate is not a multiple of the time duration, calculation of amplitude and time duration shall be based on straight-line interpolated values between data sample points.

5.8.2.1 Sort the channel data in ascending order.

5.8.2.2 Determine the index location in the sorted data, correlating to the window width. If the sample rate is not a multiple of the window width, linearly interpolate between values as mentioned above.

5.8.2.3 Determine the channel amplitude value at the index location found in 5.3.2.2.

6. ATD CALCULATIONS

6.1 Head Injury Criterion (HIC)

The HIC is calculated using an optimized function that multiplies the average head resultant acceleration raised to the power of 2.5 by the time interval of averaging (SAE #880656). The start and end times are selected to maximize the HIC. The time interval is constrained to not be larger than a specified value, e.g. 15 or 36 milliseconds, but the time interval may be smaller such that the HIC is maximized.

$$HIC = (t_2 - t_1) * \{(t_2 - t_1)^{-1} * [\text{Integral}\{a\ dt\}, \text{ from } t_1 \text{ to } t_2]\}^{2.5}$$

where:

HIC = head injury criterion
a = resultant of head X, Y, Z acceleration channels, in units of G's
t_1 = start time, in units of seconds
t_2 = end time, in units of seconds

6.2 Performance Criterion (HIC(d))

The HIC(d) is the weighted HIC value, where the specified time interval is 36 ms.

$$HIC(d) = 0.75446 * HIC_{36} + 166.4$$

6.3 Head Angular Acceleration Y axis

Head angular acceleration about the lateral Y axis can be calculated when using an ATD that has a Z axis accelerometer installed in the skullcap on the head in addition to the Z axis accelerometer at the head cg. The center of mass of the second accelerometer is located a known horizontal distance (D) rearward from the center of mass of the Z axis accelerometer mounted at the center of gravity of the head. The vertical and lateral distances between these accelerometers must be zero.

$$A_{ANGY} = (A_{REARZ} - A_{CGZ})/D$$

where:

A_{ANGY} = angular acceleration about the Y axis
A_{CGZ} = Z axis acceleration at the head CG
A_{REARZ} = Z axis acceleration at the skull cap
D = horizontal distance between skull cap and head cg Z axis accelerometers

6.4 Head to Torso Rotation Analysis

The change in angle between the head and torso as measured from the head cg to the spine may be calculated using data acquired from angular rate transducers installed in the ATD's head and spine. The acquired angular velocity data is to be filtered in accordance with CFC180 per SAE J211-1. Note that the polarity must follow SAE J1733 as mentioned above. Each angular velocity channel is integrated to calculate a channel with a physical dimension of rotation angle. It is important to realize that this integral does not represent an absolute angle as off-axis correction is needed. The head to torso angles are calculated as shown below.

$$Q_n = [\text{Integral}\{W_n\ dt\}, \text{ from } t_0 \text{ to } t_f] + Q_n(0)$$

RXA = HX*cos(HZ)*cos(HY) – HY*sin(HZ) + HZ*sin(HY) – TX*cos(TZ)*cos(TY) + TY*sin(TZ) – TZ*sin(TY)
RYA = HY*cos(HZ)*cos(HX) + HX*sin(HZ) – HZ*sin(HX) – TY*cos(TZ)*cos(TX) – TX*sin(TZ) + TZ*sin(TX)
RZA = HZ*cos(HX)*cos(HY) – HX*sin(HY) + HY*sin(HX) – TZ*cos(TX)*cos(TY) + TX*sin(TY) – TY*sin(TX)

where:

RXA = the head-to-torso angle about the X axis, corrected for off axis rotation
RYA = the head-to-torso angle about the Y axis, corrected for off axis rotation
RZA = the head-to-torso angle about the Z axis, corrected for off axis rotation
W_n = measured angular velocity about axis n
Q_n = integrated angular velocity, resulting channel is a vector of angles, referenced to the initial condition
$Q_n(0)$ = initial condition, angle at t_0
HX = head X angular velocity converted to a vector of angles, referenced to its position at event (t_0)
HY = head Y angular velocity converted to a vector of angles, referenced to its position at event (t_0)
HZ = head Z angular velocity converted to a vector of angles, referenced to its position at event (t_0)
TX = torso X angular velocity converted to a vector of angles, referenced to its position at event (t_0)
TY = torso Y angular velocity converted to a vector of angles, referenced to its position at event (t_0)
TZ = torso Z angular velocity converted to a vector of angles, referenced to its position at event (t_0)
t_0 = time zero, i.e. the time of impact
t_f = final time of evaluation

6.5 Moment About the Occipital Condyle (Moc)

ATD neck load cells measure moments about X, Y, and Z axes. The X and Y axes of the upper neck load cell are typically displaced from the axes of the occipital condyle. Note that the filter class of the force data used in the Moc calculations must be consistent with the filter class of the moment data as specified by SAE J211-1.

$M_{ocx} = M_x + (D * F_y)$
$M_{ocy} = M_y – (D * F_x)$

where:

M_{ocx} = moment X about the occipital condyle
M_{ocy} = moment Y about the occipital condyle
F_x = load cell force output in the X direction
F_y = load cell force output in the Y direction
M_x = load cell moment output about the X axis
M_y = load cell moment output about the Y axis
D = the vertical distance between the load cell neutral axis and the occipital condyle

Table 1 provides the offset distance, D, in meters and also in inches.

Table 1 - Upper neck load cell, neutral axis to occipital condyle - offset distances

Upper Neck Load Cell	ATD	D [m] (in)
1716, 2896, 3454, 3933, 2564, 4037, IF-2564, IF-205, IF-207, 555B/6UN	HIII95M, HIII50M, HIII5F, HIII10C, HIII6C, SID-IIs	0.01778 (0.700)
3454	THOR	0.00 (0.00)
2062	HIII50M	0.00876 (0.345)
3303, IF-234	HIII3C	0.00 (0.00)
2554, IF-954, 560G/6ULN	CRABI12, CRABI18	0.0058 (0.23)
2554, IF-954, 560G/6ULN	CRABI6, P1-1/2	0.0102 (0.40)
2331, 2587, IF-212, IF-235, 5583G/3ULN	P3/4, P3	0.00 (0.00)
4085, IF-240, 5552G/6UN	ES-2re	0.0200 (0.787)
3715, IF-217, 5563G/6LN	Q series	0.00 (0.00)
4949, 4985	BioRID	0.01778 (0.700)
W50-71000, W50-71005	WorldSID	0.0195 (0.768)

6.6 Total Moment about the Base of the Neck (Mto)

ATD neck load cells measure moments about X, Y, and Z axes. The axes of the lower neck load cell are typically displaced from the axes of the base of the neck (C7/T1). Note that the filter class of the force data used in the Mto calculations must be consistent with the filter class of the moment data as specified by SAE J211-1. The equations below provide the corrected moments at the base of the neck when using a fixed lower neck load cell.

$M_{tox} = M_x – (F_y * D_z)$
$M_{toy} = M_y + (F_x * D_z) + (F_z * D_x)$
$M_{toz} = M_z – (F_y * D_x)$

where:

M_{tox} = total moment X about the base of the neck
M_{toy} = total moment Y about the base of the neck
M_{toz} = total moment Z about the base of the neck
M_x = load cell moment output about the X axis
M_y = load cell moment output about the Y axis
M_z = load cell moment output about the Z axis
F_x = load cell force output in the X direction
F_y = load cell force output in the Y direction
F_z = load cell force output in the Z direction
D_x = the fore/aft distance between the load cell neutral axis and the center point at the base of the neck
D_z = the vertical distance between the load cell neutral axis and the center point at the base of the neck

Table 2 provides the fixed lower neck load cell distances, D_x and D_z, for use with the M_{to} equations.

Table 2 - Fixed lower neck load cell, neutral axis to base of neck - offset distances

Fixed Lower Neck Load Cell	ATD	D_x [m] (in)	D_z [m] (in)
1794, IF-242, IF-210	HIII95M, HIII50M	0.0508 (2.00)	0.0286 (1.125)
1794, IF-242, IF-210	BioSID	0.0508 (2.00)	0.0254 (1.00)
2150, 3251, 4541	HIII5F	0.0445 (1.75)	0.0286 (1.125)
3166	SID-IIs	0.0445 (1.75)	0.0254 (1.00)
2430	HIII6C	0.0318 (1.25)	0.0237 (0.934)
5294	SID-H3	0.00 (0.00)	0.0127 (0.50)
4366	THOR 50th	0.00 (0.00)	0.0254 (1.00)
5575	THOR 5th	0.00 (0.00)	0.0191 (0.75)
W50-71000	WorldSID	0.00 (0.00)	0.0145 (0.571)
3300, 4365	EuroSID-1, ES-2re	0.00 (0.00)	0.022 (0.87)
3303	HIII3C	0.00 (0.00)	0.0168 (0.66)
3304	HIII3C	0.00 (0.00)	0.0168 (0.66)
3715	Q-Series	0.00 (0.00)	0.00 (0.00)
2554	CRABI 6/12/18	0.00 (0.00)	0.0127 (0.50)

If an adjustable lower neck load cell is used, the direction of the X and Z load cell axes may not be parallel to the axes at the base of the neck. In addition to correcting for the displaced axes, transformations must be incorporated into the equations to calculate the equivalent forces Fx and Fz, and moments Mx and Mz parallel to the axes of the base of the neck. Note that the filter class of the force data used in the Mto calculations must be consistent with the filter class of the moment data as specified by SAE J211-1. The equations below provide the corrected forces and moments at the base of the neck when using an adjustable lower neck load cell.

$F_x = F_{xm}*\cos(q) + F_{zm}*\sin(q)$
$F_y = F_{ym}$
$F_z = F_{zm}*\cos(q) – F_{xm}*\sin(q)$
$M_{tox} = M_{xm}*\cos(q) + M_{zm}*\sin(q) – F_y*D_z*\cos(q) – F_y*D_x*\sin(q)$
$M_{toy} = M_{ym} + F_{xm}*D_z + F_{zm}*D_x$
$M_{toz} = M_{zm}*\cos(q) – M_{xm}*\sin(q) – F_y*D_x*\cos(q) + F_y*D_z*\sin(q)$

where:

F_x = force X at the base of neck
F_y = force Y at the base of neck
F_z = force Z at the base of neck
M_{tox} = total moment X about the base of the neck
M_{toy} = total moment Y about the base of the neck
M_{toz} = total moment Z about the base of the neck
F_{xm} = load cell force output in the X direction
F_{ym} = load cell force output in the Y direction
F_{zm} = load cell force output in the Z direction
M_{xm} = load cell moment output about the X axis
M_{ym} = load cell moment output about the Y axis
M_{zm} = load cell moment output about the Z axis
D_x = relative to the coordinate system fixed to the load cell, the fore/aft distance between the load cell neutral axis and the center point at the base of the neck
D_z = relative to the coordinate system fixed to the load cell, the vertical distance between the load cell neutral axis and the center point at the base of the neck
q = The angle between the base of the neck X axis and the load cell X axis, determined by the setting location of the adjustable load cell. This acute angle is entered as a positive value in the equations above.

Table 3 provides the adjustable lower neck load cell distances, Dx and Dz, for use with the Mto equations.

Table 3 - Adjustable lower neck load cell, neutral axis to base of neck - offset distances

Adjustable Lower Neck Load Cell	ATD	D_x [m] (in)	D_z [m] (in)
2992, 4092	HIII95M, HIII50M, FAA-HIII-50th	0.0635 (2.50)	0.0437 (1.72)
IF-219	HIII95M, HIII50M,	0.0641 (2.525)	0.0447 (1.758)
3716, 3471	HIII95M, HIII50M	0.0589 (2.32)	0.0991 (3.90)
5045	HIII5F	0.0523 (2.06)	0.0371 (1.46)
3717	HIII5F	0.0508 (2.00)	0.0904 (3.56)
5686	SID-IIs	0.0516 (2.03)	0.0340 (1.34)
5124	HIII10C	0.00 (0.00)	0.0188 (0.74)

6.7 Neck Injury Index (Nij)

The neck tension/compression force and flexion/extension moment are used to calculate four combined neck injury indices, collectively referred to as Nij. The Nij may be calculated using upper neck or lower neck load cell data. In the case of the upper neck the force and moment is referenced to the occipital condyle, and in the case of the lower neck the force and moment is referenced to the base of the neck. Note that the filter class of the force data used in the Nij calculations must be consistent with the filter class of the moment data as specified by SAE J211-1.

$$N_{ij} = F_z/F_{zc} + M_y/M_{yc}$$

where:

N_{ij} = neck injury index
F_z = tension/compression force, at the occipital condyle or the base of the lower neck
F_{zc} = force critical value
M_y = flexion/extension moment, about the occipital condyle (M_{ocy}) or the base of the lower neck (M_{toy})
M_{yc} = moment critical value

Four Nij channels are to be created, each one correlating to one of four permutations of the Fz and My polarities. When the polarity condition of the specific permutation under consideration is true, the correlating Nij channel is calculated per the above equation. When the polarity condition of the specific permutation under consideration is false, the correlating Nij channel is zero. Table 4 shows the permutations and polarity conditions for each Nij channel.

Table 4 - N_{ij} permutations

N_{ij} Channel	Force Polarity Condition	Moment Polarity Condition
N_{tf}	$F_z>0$, Tension	$M_y>0$, Flexion
N_{te}	$F_z>0$, Tension	$M_y<0$, Extension
N_{cf}	$F_z<0$, Compression	$M_y>0$, Flexion
N_{ce}	$F_z<0$, Compression	$M_y<0$, Extension

Note that the Nij is a combined neck injury index, characterized by a combination of tension/compression force and flexion/extension moment. If the combination ceases to exist, i.e. either the tension/compression force or the flexion/extension moment is zero; a combined injury mode is not possible.

The critical values are permutation dependent, specific to the model of ATD, dependent on location (upper or lower neck), and dependent on the type of test, i.e. whether the ATD is in-position or out-of-position. Tables 5 and 6 show the upper neck N_{ij} force and moment critical values. These upper neck critical values are referenced from FMVSS 208 as available, with the remaining values referenced from Stapp Car Crash Journal 2003-22-0009, as indicated by the asterisk.

Table 5 - Upper neck N_{ij} critical values for in-position tests

ATD	F_{ZC} [N] ($F_Z>0$, Tension)	F_{zc} [N] ($F_z<0$, Compression)	M_{yc} [N-m] ($M_{ocy}>0$, Flexion)	M_{yc} [N-m] ($M_{ocy}<0$, Extension)
* HIII95M	8180	-7480	405	-177
HIII50M	6806	-6160	310	-135
HIII5F	4287	-3880	155	-67
* HIII10C	3710	-3390	125	-54.8
* HIII6C	3080	-2820	96	-42
* HIII3C	2330	-2130	67	-29.3
* CRABI18	1760	-1610	46.8	-20.4
* CRABI12	1610	-1470	42.5	-18.6
* CRABI6	1510	-1380	39.5	-17.3

Table 6 - Upper neck N_{ij} critical values for out-of-position tests

ATD	F_{zc} [N] ($F_z>0$, Tension)	F_{zc} [N] ($F_z<0$, Compression)	M_{yc} [N-m] ($M_{OCY}>0$, FLEXION)	M_{yc} [N-m] ($M_{ocy}<0$, Extension)
* HIII95M	7480	-7480	405	-162
* HIII50M	6200	-6200	305	-122
HIII5F	3880	-3880	155	-61
* HIII10C	3390	-3390	125	-50.1
HIII6C	2800	-2800	93	-37
HIII3C	2120	-2120	68	-27
* CRABI18	1610	-1610	46.8	-18.7
CRABI12	1460	-1460	43	-17
* CRABI6	1380	-1380	39.5	-15.8

Tables 7 and 8 show the lower neck Nij force and moment critical values, referenced from Stapp Car Crash Journal 2003-22-0009.

Table 7 - Lower neck N_{ij} critical values for in-position tests

ATD	F_{zc} [N] (F_z>0, Tension)	F_{zc} [N] (F_z<0, Compression)	M_{yc} [N-m] (M_{toy}>0, Flexion)	M_{yc} [N-m] (M_{toy}<0, Extension)
HIII95M	8180	-7480	810	-354
HIII50M	6780	-6200	610	-266
HIII5F	4260	-3900	306	-134
HIII10C	3710	-3390	250	-110
HIII6C	3080	-2820	192	-84
HIII3C	2330	-2130	134	-58.6
CRABI18	1760	-1610	93.6	-40.8
CRABI12	1610	-1470	85	-37.2
CRABI6	1510	-1380	79	-34.6

Table 8 - Lower neck N_{IJ} critical values for out-of-position tests

ATD	F_{zc} [N] (F_z>0, Tension)	F_{zc} [N] (F_z<0, Compression)	M_{yc} [N-m] (M_{toy}>0, Flexion)	M_{yc} [N-m] (M_{toy}<0, Extension)
HIII95M	7480	-7480	810	-324
HIII50M	6200	-6200	610	-244
HIII5F	3900	-3900	306	-122
HIII10C	3390	-3390	250	-100
HIII6C	2820	-2820	192	-76.8
HIII3C	2130	-2130	134	-53.6
CRABI18	1610	-1610	93.6	-37.4
CRABI12	1470	-1470	85	-34
CRABI6	1380	-1380	79	-31.6

6.8 Rear Impact Neck Injury Criteria (NIC)

The rear impact NIC requires upper neck (C1) and lower neck (T1) longitudinal accelerations. The head cg acceleration may be used in place of C1. Note that the filter class of the acceleration data used in the rear impact NIC calculations must be consistent with the filter class of spine acceleration data as specified by SAE J211-1.

$$NIC = 0.2 * a_{rel} + v_{rel}^2$$
$$a_{rel} = a_{T1x} - a_{headx}$$
$$v_{rel} = [\text{Integral}\{a_{rel}\ dt\}, \text{ from } t_0 \text{ to } t_f] + v_{rel}(0)$$

where:

NIC = rear impact neck injury criteria
a_{T1x} = longitudinal acceleration at lower neck (T1), in units of m/s^2
a_{headx} = longitudinal acceleration at head cg (C1), in units of m/s^2
a_{rel} = relative longitudinal acceleration between head cg and lower neck
v_{rel} = relative longitudinal velocity between head cg and lower neck
v_{rel} (0) = relative longitudinal velocity between head cg and lower neck at t_0. This must be 0 for a valid test.
t_0 = time zero, i.e. the time of impact, in units of seconds
t_f = final time of evaluation, in units of seconds

The NIC shall be evaluated during a time interval not exceeding 150 milliseconds after the time of impact or after the ATD's head is no longer in contact with the head restraint, whichever occurs first.

6.9 Lower Neck Load Index (LNL)

The LNL requires lower neck force and moment data. Note that the filter class of the force data must be consistent with the moment data as specified by SAE J211-1.

$$LNL = ABS(M_{toy})/C_{moment} + ABS(F_x)/C_{shear} + ABS(F_z)/C_{tension}$$

where:

LNL = lower neck load index
M_{toy} = total moment Y about the base of the neck. ABS indicates absolute value.
F_x = force X at the base of the neck. ABS indicates absolute value.
F_z = force Z at the base of the neck. ABS indicates absolute value.
C_{moment} = moment critical value
C_{shear} = shear force critical value
$C_{tension}$ = tension force critical value

Table 9 shows the moment, shear force, and tension force LNL critical values, referenced from Frank Heitplatz et all, ESV Conference 2003.

Table 9 - LNL critical values

ATD	C_{moment} [N-m]	C_{shear} [N]	$C_{tension}$ [N]
BioRID	15	250	900

6.10 Time-Dependent Loading Criteria

Time-dependent loading criteria have been proposed for neck tension, neck compression, neck shear, and femur compression for measurements made with the Hybrid III family of dummies. Injury assessment reference boundaries are presented in the publications shown in 2.1.3. An example graph is included as Figure 1. The ordinate of these graphs is the load level and the abscissa is the maximum continuous time duration that the load exceeds this level.

The method used to determine and plot the corresponding measured load-and-duration data points is as follows:

a. Determine the maximum value of the measured load. Divide this maximum value by 100.

b. Create a matrix of 2 columns and 101 rows. In the first column store the load values starting with the maximum value in row 1. For each subsequent row, the load value will be equal to the previous load value minus 1/100 of the maximum value. The load value in the last row will be zero.

c. In the second column store the duration values starting with a value of 0 in row 1. For each subsequent row, determine the maximum continuous time interval that the measured load exceeds the load value in the first column. Use the method shown in 5.3.1 to determine the time interval and round to the nearest millisecond.

d. Each row of the matrix now defines a measured load-and-duration point. Plot these points and the reference boundary on the same graph. Plot only those points with durations less than 60 ms.

e. For each row in the data matrix with a duration value less than 60 ms, compute the ratio of the measured load value divided by the reference boundary load value and multiply by 100. The greatest value of these calculations is the percent of the Injury Assessment Reference Value (IARV) for the loading curve.

f. Add a marker or arrow on the graph to indicate the location on the loading curve corresponding to the percent IARV calculated in (e). Also, add a note to display the percent IARV and its duration on the graph.