

**Frontal Offset
Crashworthiness Evaluation**

**Guidelines for Rating
Injury Measures**

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Frontal Offset Crashworthiness Evaluation Guidelines for Rating Injury Measures

Document Revisions: The June 2009 revision of this document clarifies the femur and neck force duration corridors.

Injury measures obtained from an instrumented 50th percentile male Hybrid III dummy in the driver seat are used to determine the likelihood that an occupant would have sustained significant injury to various body regions. Twenty-eight different measures are recorded in each of the Institute's frontal offset crash tests:

- head acceleration (three directions from head's center of gravity)
- axial force, anterior-posterior force, and anterior-posterior bending moment acting at the connection between the dummy's head and neck
- thoracic spine acceleration (three directions)
- sternum compression
- femur axial force (each leg)
- tibia-femur displacement (each leg)
- tibia transverse bending moments (upper and lower, each leg)
- tibia axial force (each leg)
- foot acceleration (two directions, each foot)

The 28 measures are grouped into four body regions: head and neck, chest, left leg and foot, and right leg and foot. Four injury parameters are used to evaluate protection for the head and neck, three parameters for the chest, and six parameters for each leg and foot.

Each body region receives an injury protection rating of good, acceptable, marginal, or poor based on the injury parameters for that region. For any body region to receive a good rating, the scores for all injury parameters in that region must indicate good results. If any parameter indicates an acceptable result, then the rating for that body region is acceptable. If any parameter has a marginal result, then the rating for that body region is marginal. Thus the overall injury rating for any body region is the lowest rating scored for an injury parameter within that region.

Table 1 shows the injury parameter ranges associated with the possible ratings: good, acceptable, marginal, and poor. Injury results that round to the values shown in Table 1 will receive the better of the two ratings they separate. With some exceptions (e.g., chest acceleration), the borders between acceptable and marginal ratings for a given injury parameter correspond to published injury assessment reference values (IARV) for significant injury related to that parameter. Acceptable ratings correspond to measures somewhat below (better than) the IARVs, and good ratings correspond to measures well below the IARVs. Similarly, marginal ratings correspond to measures just above (worse than) the IARVs, and poor ratings correspond to measures well above the IARVs. It is important to remember in reading Table 1 that crashes are complex events. It is not possible for an injury-coding scheme to foresee all the possible combinations of outcomes that could suggest injury risk in a crash. Therefore, the information in Table 1 should be interpreted as providing guidelines for evaluating dummy injury measures, which are always subject to modification based on the circumstances of the particular crash test and on new biomechanical information about injury tolerance. IARVs are based on current biomechanical information about human injury mechanisms and are described in more detail below.

Table 1
Injury Parameter Cutoff Values Associated with Possible Injury Protection Ratings

| Body Region | Parameter | IARV | Good – Acceptable | Acceptable – Marginal | Marginal – Poor |
|------------------------------|--|------|-------------------|-----------------------|-----------------|
| Head and neck | HIC-15 | 700 | 560 | 700 | 840 |
| | N _{ij} | 1.00 | 0.80 | 1.00 | 1.20 |
| | Neck axial tension (kN)* | 3.3 | 2.6 | 3.3 | 4.0 |
| | Neck compression (kN)* | 4.0 | 3.2 | 4.0 | 4.8 |
| Chest | Thoracic spine acceleration (3 ms clip, g) | 60 | 60 | 75 | 90 |
| | Sternum deflection (mm) | -50 | -50 | -60 | -75 |
| | Sternum deflection rate (m/s) | -8.2 | -6.6 | -8.2 | -9.8 |
| | Viscous criterion (m/s) | 1.0 | 0.8 | 1.0 | 1.2 |
| Leg and foot, left and right | Femur axial force (kN)** | -9.1 | -7.3 | -9.1 | -10.9 |
| | Tibia-femur displacement (mm) | -15 | -12 | -15 | -18 |
| | Tibia index (upper, lower) | 1.00 | 0.80 | 1.00 | 1.20 |
| | Tibia axial force (kN) | -8.0 | -4.0 | -6.0 | -8.0 |
| | Foot acceleration (g) | 150 | 150 | 200 | 260 |

* Neck axial force duration corridors are shown in Figures 1 and 2.

** Femur axial force duration corridors are shown in Figure 4.

Head and Neck

Head injury risk is evaluated mainly on the basis of head injury criterion (HIC) with a 15 ms limit on the period over which it is calculated. A value of 700, which is the maximum allowed under the provisions of the U.S. advanced airbag regulation (National Highway Traffic Safety Administration (NHTSA), 2000), marks the border between an Institute rating of acceptable and marginal. A HIC-15 of 700 is estimated to represent a 5 percent risk of a severe injury (Mertz et al., 1997). A “severe” injury is one with a score of 4+ on the Abbreviated Injury Scale (AIS) (Association for the Advancement of Automotive Medicine, 1990).

In addition to HIC-15, the maximum vector resultant acceleration of the head is considered. A maximum head acceleration that exceeds 70 g and is caused by contact between the head and a hard surface of the vehicle interior can result in lowering the head injury rating one level. If the maximum head acceleration occurs during the maximum HIC-15 interval, then only an otherwise good head/neck rating would be downgraded, to acceptable. If the maximum head acceleration occurs outside the maximum HIC-15 interval, then the head/neck rating would be downgraded one level regardless of the rating indicated by other measures on the head and neck. (However, if two distinct events caused head accelerations >70 g, the head/neck rating would be downgraded only one level.) This additional criterion for evaluating protection of the head is based on concern about moderate and serious injuries (AIS 2-3) to the face and weaker parts of the skull than are represented by the biomechanical data underlying the establishment of HIC. This is a particular concern when the high accelerations are caused by head impacts against hard structures with relatively small areas of contact, such as may occur when the back of a dummy’s head hits the B-pillar or the face of the dummy contacts the steering wheel through the deflating airbag. Minimum force levels associated with face and skull fractures caused by blows with a small impactor (6.45 cm² area) range from 670 to 4000 N (Schneider and Nahum, 1972). These forces correspond to head accelerations of 15-90 g for the 4.5 kg head of the Hybrid III dummy used in Institute tests. This additional head evaluation criterion is similar to requirements of the Canadian Motor Vehicle Safety Regulations Standard 208, which limits test dummy head accelerations to less than 80 g in cars not equipped with airbags.

Neck injury risk is evaluated primarily on the basis of N_{ij} , neck tension force, and neck compression force, which are the same parameters used to evaluate compliance with the U.S. advanced airbag rule (NHTSA, 2000). The N_{ij} is a linear combination of neck axial force (F_Z) and the bending moment about a lateral axis passing through the dummy's occipital condyle (M_Y), as shown in Equation 1. The critical values against which the force and moment are compared depend on the direction of the applied loads, as shown in Table 2. An N_{ij} value of 1.0 marks the border between an Institute rating of acceptable and marginal. According to a risk analysis published by NHTSA (Eppinger et al., 1999), an N_{TE} (neck tension-extension) of 1.0 was estimated to represent a 30 percent risk of AIS 2 neck injury, a 22 percent risk of AIS 3 injury, an 18 percent risk of AIS 4 injury, and a 7 percent risk of an AIS 5 injury. Risk assessments for the other load configurations (N_{TF} , N_{CE} , N_{CF}) are not available because the data set on which N_{ij} is based does not include them. Another analysis of the neck injury risk associated with an N_{TE} value of 1.0 suggests a much lower risk of AIS 3+ neck injuries for subjects tensing their neck muscles in anticipation of a crash. According to Mertz and Prasad (2000), this risk would be less than 1 percent. The actual risk of AIS 3+ neck injuries for a human the same shape and size as the Hybrid III dummy used in Institute tests and subjected to similar loads is probably between these estimates.

$$N_{ij} = (F_Z / F_{critical}) + (M_Y / M_{critical}) \quad (1)$$

Table 2
Critical Values for N_{ij} Calculation

| | Tension (+ F_Z) / Flexion (+ M_Y) | Compression (- F_Z) / Extension (- M_Y) |
|-------------------------------------|---|---|
| Neck axial force (F_Z) | 6806 | 6160 |
| Front/back bending moment (M_Y) | 310 | 135 |

In addition to N_{ij} , neck axial force by itself is compared with the cutoff values shown in Table 1. Axial forces of 4.0 and 3.3 kN mark the borders between Institute ratings of acceptable and marginal for compression and tension, respectively. The compression limit for an acceptable rating is the same as the highest compression forces allowed under the provisions of the U.S. advanced airbag regulation (NHTSA, 2000), but the tension limit for an acceptable rating is somewhat lower than the highest forces allowed by Federal Motor Vehicle Safety Standard (FMVSS) 208. The lower limit for acceptable tension loading was chosen because it is consistent with earlier versions of the injury rating protocol, which were based on evaluation of neck loads by Mertz (1984). The neck tension reference value in that report is based on tests with the Hybrid III dummy that simulated real crashes (Nyquist et al., 1980). This lower limit for an acceptable tension force rating also is consistent with the 3 percent AIS 3+ injury risk for an unaware subject, according to Mertz and Prasad (2000). In contrast, the FMVSS 208 limit assumes the subject is resisting the crash forces by tensing the neck muscles. Although tensing of the neck muscles can effectively increase a subject's tolerance to neck injuries, the amount of tensing present in real-world crash-involved occupants is not known, so the more conservative limit is used here.

Finally, a head/neck rating that is otherwise good will be lowered to acceptable if the neck tension, compression, or shear (X-direction) forces fall outside the force duration corridors specified by Mertz (1984). The force duration corridor limits are shown in Figures 1-3.

Figure 1
Force Duration Corridor for Neck Tension Force

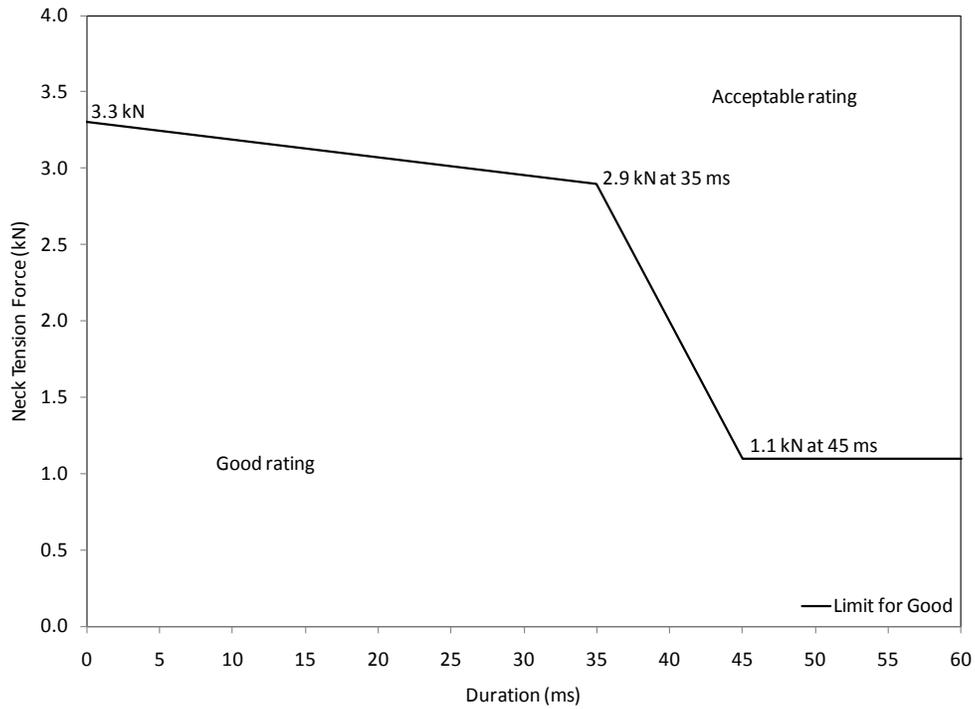


Figure 2
Force Duration Corridor for Neck Compression Force

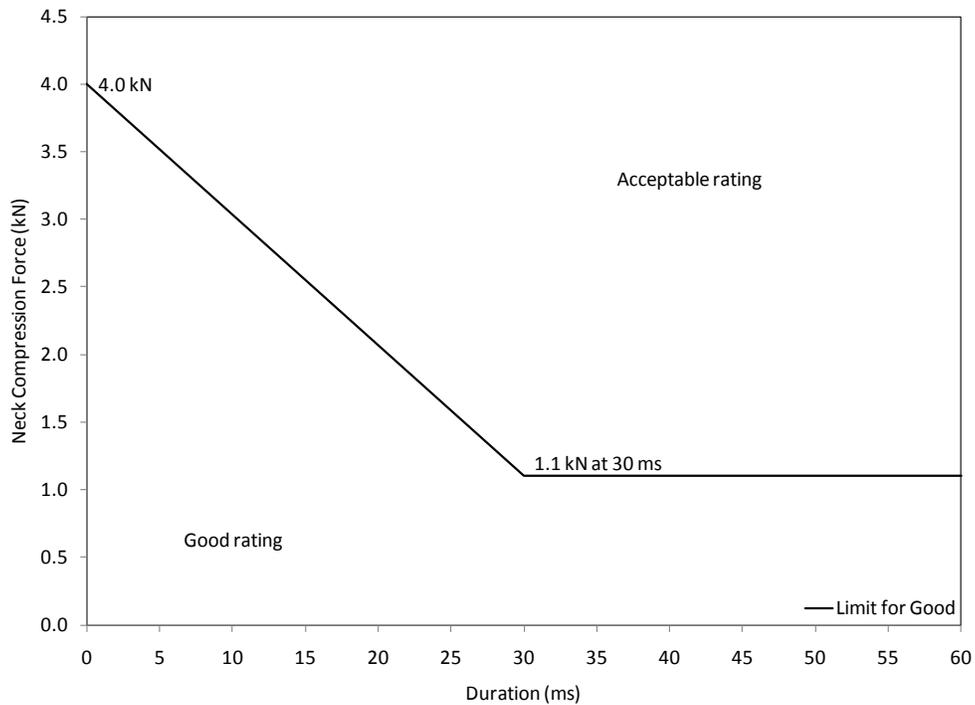
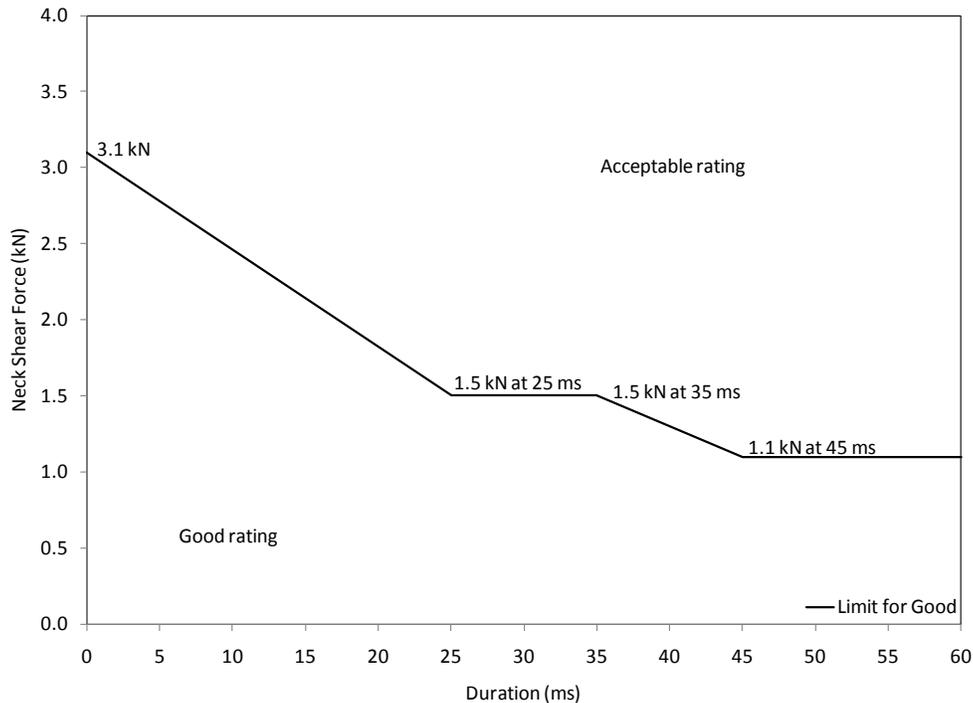


Figure 3
Force Duration Corridor for Neck Shear Force



Chest

Chest injury risk is evaluated on the basis of sternum deflection, sternum deflection rate, viscous criterion, and thoracic spine acceleration. A sternum deflection of 60 mm marks the border between an Institute rating of acceptable and marginal. This is near the same limit used to evaluate compliance with the U.S. advanced airbag rule (NHTSA, 2000). According to Mertz et al. (1997), it represents either a 45 or 70 percent risk of an AIS 3+ chest injury depending on whether the airbag or seat belt causes the chest deformation. The higher injury risk for seat belt loading is in approximate agreement with earlier risk estimates based on re-creations of real-world crashes using a Hybrid III dummy (Mertz et al., 1991).

A sternum deflection rate of 8.2 m/s marks the border between an Institute rating of acceptable and marginal. The Alliance of Automobile Manufacturers (1999) recommended to NHTSA that this limit be used to evaluate compliance with the U.S. advanced airbag rule (NHTSA, 2000), but NHTSA rejected the recommendation pending the availability of more biomechanical data to justify it. According to Mertz et al. (1997), this level of sternum deflection rate is estimated to represent a 65 percent risk of AIS 3+ chest injury or about a 15 percent risk of AIS 4+ chest injury.

Another rate-dependant injury criterion, viscous criterion, also is calculated from sternum deflection measurements. Viscous criterion is the product of sternum deflection, normalized by chest depth, and the sternum deflection rate. According to Lau and Viano (1986), a viscous criterion value of 1 m/s represents a 25 percent risk of AIS 4+ thoracic injury.

A thoracic spine acceleration of 60 g (3 ms) marks the border between an Institute rating of good and acceptable. This value also is used to evaluate compliance with the U.S. advanced airbag rule (NHTSA, 2000). According to NHTSA (2001), this represents a 20 percent risk of AIS 4+

chest injury. However, the value of whole-body thorax acceleration as a predictor of injury was highly debated through the development of the advanced airbag rule because the injuries observed among crash-involved occupants generally are associated with rib cage deformation. Mertz and Gadd (1971) reviewed the biomechanics literature and conducted experiments with a volunteer to better ascertain the survivable levels of whole-body acceleration. They noted cases of people surviving falls from as high as 30 m (100 ft) and estimated average chest accelerations of 20-200 g for such falls. One experiment involved a chest deceleration with a duration of 90 ms and a peak of 83 g, which was described as the definite limit of tolerance and caused minor injuries. Their own experiments consisted of measurements made on the body of a stunt performer who dove from heights of 8-17 m (27-57 ft) onto cushions of low-density polyurethane foam. The highest dive, which caused no discomfort to the performer, produced a chest deceleration with a duration of 100 ms and a peak of 49 g. They recommended a tolerance level of 60 g for pulse durations lasting about 100 ms on the basis of this work. These arguments suggest that the meaningfulness of chest acceleration is limited, especially given the presence of other measures that were directly related to the injury mechanism. Nevertheless, including chest acceleration in the evaluation of chest injury risk does not pose an unreasonable hurdle to achieving a good chest rating with the cutoff values shown in Table 1.

Legs and Feet

Leg and foot injury risk is evaluated on the basis of femur axial force, tibia-knee displacement, tibia indices measured at the upper and lower portions of the tibia, tibia axial force measured at the distal end of the tibia, and foot acceleration. The femur axial force cutoff value for an acceptable rating is somewhat lower than the limit allowed by FMVSS 208 but is the same as proposed by Mertz (1984). In addition to comparing the maximum femur axial force with the cutoff values in Table 1, force duration is compared with the corridors described by Mertz. The force duration corridor limits are shown in Figure 4.

A tibia-femur displacement of 15 mm marks the border between an Institute rating of acceptable and marginal. This is the reference value recommended by Mertz (1984) and based on work by Viano et al. (1978). Similarly, a tibia index of 1.0 is the cutoff value between an acceptable and marginal rating. Tibia indices are calculated using adjusted bending moments as shown in Equations 2 and 3 to account for the fact that the shape of the Hybrid III dummy's legs causes unhumanlike bending under the influence of pure axial forces. The details of the rationale for this adjustment are described by Zuby et al. (2001) and Welbourne and Schewchenko (1998).

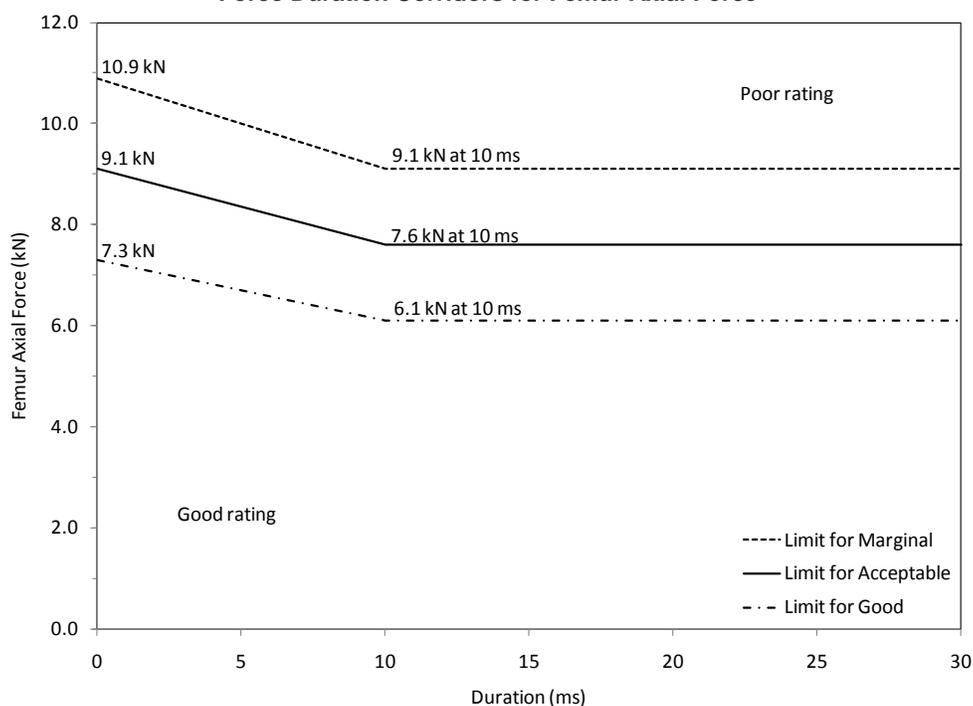
$$M_{Y \text{ upper } adj} = M_{Y \text{ upper } meas} - [(F_{Z \text{ tib}})(0.02832)], \text{ moment in Nm, force in N} \quad (2)$$

$$M_{Y \text{ lower } adj} = M_{Y \text{ lower } meas} + [(F_{Z \text{ tib}})(0.006398)], \text{ moment in Nm, force in N} \quad (3)$$

The acceptable-marginal cutoff value for tibia axial force is somewhat lower than the reference value recommended by Mertz (1984) because Crandall et al. (1998) have shown that heel fractures (AIS 2, but associated with high degree of impairment) occur at considerably lower forces.

Zeidler (1984) suggested the conservative limit of 150 g for foot acceleration based on tests with volunteers and dummies. This level of acceleration is associated with jumps from a height beyond which injury was feared. Consequently, it marks the limit allowed for a good rating, whereas only much higher accelerations result in marginal or poor leg/foot ratings.

Figure 4
Force Duration Corridors for Femur Axial Force



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