Supplement: Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems - II

By

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Supplemental Executive Summary

In the SNPRM on advanced air bags, NHTSA proposed a comprehensive set of injury criteria for evaluating the potential for injury to the head, neck, chest and lower extremities for the various dummy sizes, ranging from the 1-year-old child to the 50th percentile male. The comments received and the agency's responses are summarized below and the various performance limits implemented in the final rule are shown in Table SES-1.

Head Injury Criterion (HIC)

In the SNPRM, NHTSA proposed to change the maximum critical time interval used in the calculation of HIC from 36 to 15 milliseconds and proposed specific performance limits for HIC_{15} for each of the various dummy sizes to be used in the regulation. In their response, the Alliance of Automotive Manufacturers (AAM) and the Association of International Automobile Manufacturers (AIAM) endorsed the proposal to change the maximum time duration to 15 milliseconds and agreed with the majority of the proposed performance limits. However, the AAM-AIAM proposed alternative limits for the 6 year old child (723 rather than 700) and the 5th percentile female (779 rather than 700). DaimlerChrysler and Takata also recommended that the agency adopt the HIC_{15} limits proposed by AAM-AIAM. Other commenters such as the Insurance Institute for Highway Safety and Advocates for Highway Safety supported the HIC_{15} criteria and they did not offer further comment on changing any of the performance limits.

NHTSA is adopting a HIC_{15} limit of 700 for the small female dummy based on the fact that the experimental population from which the HIC relationship was derived is representative of adult dummy head sizes ranging from that of the small female dummy to that of the large male dummy. In addition for the six-year-old child dummy, the agency is adopting a HIC_{15} performance limit of 700 because there is currently no biomechanical data that justifies a higher tolerance for young children than for adults. The HIC_{15} limits implemented in the final rule are shown in Table SES-1.

Neck Injury Criteria

In the SNPRM, NHTSA revised its previously proposed neck injury criteria, N_{ij} (a linear combination of tension/compression and flexion/extension moments), by adjusting the critical limit values. In addition, the agency noted that in some of its own testing of air bag systems, the 5th female dummy had on occasion generated rapid and high neck moments (>100 N-m) before the head experienced any significant rotation or the neck experienced any significant bending. Concerned that this phenomenon was a result of the mechanical design characteristics of the dummy's neck and not a true biomechanical characteristic of a human neck, the agency posed the question of whether other organizations have also experienced this loading condition and whether they believe or have data to suggest that this is either biomechanically realistic or an artifact of the dummy's design.

The most detailed response to this proposal came from AAM-AIAM which endorsed the N_{ij} construct but recommended the inclusion of additional, more stringent tension/compression limits to independently control this potentially injurious loading mode. AAM-AIAM also recommended further, minor adjustments to NHTSA's proposed critical limits to consider whether they are being utilized for in- or out-of-position situations. While it has been NHTSA's experience that the SNPRM's proposed N_{ij} formulation and critical limits appear to be sufficient to monitor and prevent injurious neck loads, the AAM-AIAM, the Institute for Highway Safety, and the National Transportation Safety Board stated that they were concerned that the peak tension and peak compression allowed by the N_{ij} criteria when the moment value is zero are too great. NHTSA believes that there is merit in incorporating the AAM-AIAM's proposed additional axial force (tension and compression) limits and adjustments to NHTSA's original N_{ij} proposals because they either track our originally proposed requirements very closely or add additional requirements that more stringently control the potentially injurious axial loading mode. In addition, the agency will accept the AAM-AIAM argument that tensed neck muscles mitigate the effects of measured neck loads by adopting the AAM-AIAM proposal for slightly higher neck limits for in-position testing for the adult dummies. The critical limits implemented in the final rule are shown in Table SES-1.

Although the vast majority of the members of AAM-AIAM, including BMW, Fiat, Ford, General Motors, Isuzu, Mazda, Nissan, Volkswagen, and Volvo, support the use of a modified N_{ij} neck injury criterion, DaimlerChrysler supported the use of tension as the only neck injury criterion because they believe that the Hybrid III neck may be inadequate for accurately assessing the potential for flexion/extension neck injury due to air bag loading. Toyota also recommended delaying the use of any neck injury criteria which contain extension. Although the available data suggests that tension is the best predictor of out-of-position neck injuries, the primary loading mode in this series of tests was limited to tension-extension. Although this is the predominant mode of neck injury seen in field data for out-of-position occupants, current and future vehicle designs may produce other modes of neck loading. The agency believes that tension by itself is not a robust injury criteria for all the possible loading modes experienced in either the out-of-position or the vehicle crash test environments. Consequently, with the vast majority of the members of AAM-AIAM silent on the appropriateness of the Hybrid III neck for evaluating flexion/extension injuries due to air bag loading, the agency supports the use of the modified N_{ij} with the current Hybrid III dummies (and neck) in the final rule as the best criteria to use over the range of loading modes experienced in the crash environment.

Chest Injury Criteria

In the SNPRM, NHTSA proposed using the individual limits of chest deflection and chest acceleration as recommended by AAMA for assessing the risk of thoracic injury, instead of the Combined Thoracic Index (CTI), as originally proposed in the NPRM. In their response, AAM-AIAM endorsed the SNPRM proposal but argued that the chest acceleration limit for the 5th percentile female dummy should be 73 g's rather than the 60 g's proposed in the SNPRM This was reiterated by some other commenters as well. AAM-AIAM requested that the small difference in chest deflection limits for the 3-year old and 5^{th} percentile female dummies be eliminated and the deflection limits proposed by AAM-AIAM be used in the regulation. Furthermore, AAM-AIAM proposed the use of rate of sternal deflection to assess risk of serious thoracic organ injuries in out-of-position tests. Toyota recommended using rate of sternal deflection in place of chest acceleration for assessing thoracic injury risk. DaimlerChrysler also supported the AAM-AIAM proposal and presented a method using Kalman filters which it contended would yield a more reliable rate of deflection measures.

NHTSA has decided to adopt its proposed 60 g's chest acceleration limit for the 5^{th} percentile female dummy. The AAM-AIAM's recommended chest acceleration limit of 73 g's for the 5^{th} percentile female dummy was obtained by using scaling procedures that only considered the effects of the geometric differences between the 50^{th} male and the 5^{th} female. The agency, on the other hand, continues to believe that the additional effect of the decrease in bone strength for the more elderly female population at risk in OOP situations must also be taken into account.

Scaling factors used by NHTSA to scale chest deflection are the same as those used by AAM-AIAM. AAM-AIAM recommended chest deflection limit of 64 mm for the 50^{th} percentile male. In order to harmonize with the chest deflection limits used by Transport Canada, the agency adopted 63 mm for chest deflection limit for the 50^{th} percentile male. This change in the 50^{th} percentile male threshold value resulted in small differences (< 2 mm) between the AAM-AIAM and SNPRM scaled deflection limits for some of the other dummies. NHTSA believes these differences are negligible and will adopt the limits proposed in the SNPRM.

The agency's preliminary research suggests that the chest deflection and chest acceleration threshold limits would be sufficient to distinguish the conditions producing soft tissue thoracic injury from the benign conditions in out-of-position tests. Even if deflection rate were not found to be redundant, there is no standardized, widely accepted method for determining it. Currently, deflection rate is computed by either differentiating chest deflection measurements or by integrating the difference of the sternal and spinal accelerometer measurements. Both of these methods are subject to interpretation and measurement noise, and neither has gained any widespread use or endorsement. At present there are no direct measurement velocity transducers used in standard vehicle crash applications and no reliable method of computing velocity from related measurements. The Kalman filter approach recommended by DaimlerChrysler appears interesting, but it needs further evaluation and acceptance before being implemented. Therefore, until adequate instrumentation and computation techniques to obtain reliable rate of deflection at high rates of loading (as in the case of air bag loading to the out-of-position occupant) are developed, the agency could not utilize chest deflection rate as an objective performance metric. However, the agency encourages automobile manufacturers and restraint suppliers to continue investigating and evaluating additional injury criteria such as rate of deflection to assess the potential for soft tissue thoracic injuries.

Lower Extremity Injury Criterion

In the SNPRM, NHTSA proposed lower extremity injury criteria to limit the axial loads in the femur for the adult dummies (10 kN for 50^{th} percentile male and 6.8 kN for the 5^{th} percentile female). AAM-AIAM and DaimlerChrysler stated that they support axial femur limits of 9.1 kN for the 50^{th} percentile male and 6.2 kN for the 5^{th} percentile female.

NHTSA continues to endorse its position on the axial femur limits for the adult dummies. The current limit of 10kN specified for the 50^{th} percentile male has been used in Federal Motor Vehicle Safety Standard No. 208 for over twenty-three years. The AAM-AIAM has not presented information demonstrating that this value is not adequate. Furthermore, AAM-AIAM has not provided data or an explanation of the method used to arrive at its recommended femur force limit of 9070 N for the 50^{th} percentile male. To date, the most comprehensive analysis of femur impact test data is by Morgan et al. (1989), who examined 126 knee impact tests from various sources. Morgan suggested that internal femur force was a very good predictor of patella-femur-pelvis injury and that a femur force of 10 kN corresponded to a 35% probability of fracture.

The differences between the limits proposed in the SNPRM and that proposed by the AAM-AIAM are small, and the agency believes that adopting the slightly lower value proposed by the AAM-AIAM would have no effect on the overall safety benefits. The agency also believes that the slightly higher axial force limits proposed by the agency will provide some additional design flexibility for manufacturers to optimize head, neck and chest protection in the crash environment.

Table SES-1: Summary of Recommended Injury Criteria for the Final Rule

Recommended Criteria	Large Sized Male§	Mid-Sized Male	Small Sized Female	6 YO Child	3 YO Child	1 YO Infant
Head Criteria: HIC (15 msec)	700	700	700	700	570	390
Neck Criteria: Nij	1.0	1.0	1.0	N/A	N/A	N/A
In- Position Critical Intercept Values						
Tension (N)	8216	6806	4287			
Compression (N)	7440	6160	3880			
Flexion (Nm)	415	310	155			
Extension (Nm)	179	135	67			
Peak Tension (N)	5030	4170	2620			
Peak Compression (N)	4830	4000	2520			
Neck Criteria: Nij	N/A	N/A	1.0	1.0	1.0	1.0
Out-of-Position Critical Intercept Values						
Tension (N)			3880	2800	2120	1460
Compression (N)			3880	2800	2120	1460
Flexion (Nm)			155	93	68	43
Extension (Nm)			61	37	27	17
Peak Tension (N)			2070	1490	1130	780
Peak Compression (N)			2520	1820	1380	960
Thoracic Criteria						
1. Chest Acceleration (g)	55	60	60	60	55	50
2. Chest Deflection (mm)	70 (2.8 in)	63 (2.5 in)	52 (2.0 in)	40 (1.6 in)	34 (1.4 in)	30* (1.2 in)
Lower Ext. Criteria: Femur Load (kN)	12.7	10.0	6.8	NA	NA	NA

§ The Large Male (95th percentile Hybrid III) is not included in the final rule, but the performance limits are listed here for informational purposes.

* The CRABI 12 month old dummy is not currently capable of measuring chest deflection.

Chapter S1
Head Injury Criterion

In the SNPRM, NHTSA proposed to change the maximum critical time used in the calculation of HIC from 36 to 15 milliseconds and proposed specific performance limits for HIC_{15} for each of the various dummy sizes to be used in the regulation (Table S1-1). In their response, the Alliance of Automotive Manufacturers and the Association of International Automoblile Manufacturers, AAM-AIAM, endorsed the proposal to change the maximum time duration to 15 milliseconds and agreed with the majority of the proposed performance limits. However, they proposed alternative limits for the 6-year-old child, (723 rather than 700) and the 5th percentile female, (779 rather than 700). For the two disputed dummy sizes, the AAM-AIAM argued that NHTSA did not apply consistent scaling relationships that consider size differences in arriving at its proposed limits. DaimlerChrysler and Takata also recommended that the agency adopt the HIC_{15} limits proposed by AAM-AIAM. Other commenters such as the Insurance Institute for Highway Safety and Advocates for Highway Safety supported the HIC_{15} criteria but did not offer further comment on changing any of the performance limits.

Table S1-1: Head Injury Criterion for Various Dummy Sizes

Dummy Type	**Large Sized Male***	**Mid-Sized Male**	**Small Sized Female**	**6-Year-Old Child**	**3-Year-Old Child**	**1-Year-Old Infant**
HIC_{15} Limit	700	700	700	700	570	390

* The Large Male (95th percentile Hybrid III) is not included in the final rule, but the performance limits are listed here for informational purposes.

NHTSA is adopting its proposed limits for the disputed occupant sizes. This position is based on the fact that the experimental population from which the HIC relationship was developed included both male and female subjects with head sizes (circumference and weight) which span the range of those of the small female dummy, mid-sized male dummy, and large sized male dummy (Hodgson, 1971; Schneider, 1983; Hubbard, 1973). Consequently, NHTSA believes that the HIC Injury Probability relationship is valid over a range of adult human head sizes between that of a small female to that of a large male. Therefore, NHTSA believes the most appropriate approach would be to assign a HIC_{15} limit of 700 to all sizes that could reasonably represented by existing data set and that the small differences produced by AAM-AIAM's exact size scaling of the 50th percentile male's 700 limit to the other sizes are unjustified.

As discussed in the biomechanics technical report (Eppinger, 1999), in the absence of biomechanics data on the skull fracture and brain injury tolerances for children, the best available and most widely used method for obtaining performance limits for the child dummies is through the scaling process to account for differences in both geometric size and material strength . However after applying the scaling process, engineering judgement must be used to determine if these scaled tolerances are reasonable. For the 1-year-old and 3-year-old dummies, geometric and material scaling yielded a scaled performance limit of 390 and 570, respectively. The limit of 390 for the 1-year-old is consistent with values published by Melvin for a 6-month infant based on a review of the literature and similar scaling techniques (1995). Geometric and material scaling for the 6-year-old dummy lead to a limit of 723, which is greater than that specified for the adult dummies. In the absence of biomechanical data which substantiates a higher tolerance for young children than for adults, the agency believes it is prudent to limit the HIC_{15} value to 700 for the 6-year-old. Furthermore, the agency's testing indicates that a value of 700 is practicable, with 80% and 100% of the vehicles meeting this limit for out-of-position testing (position 1 and position 2, respectively) with the 6-year-old (Eppinger, 1999, Table B.21 and B.24) . Consequently, NHTSA is adopting a performance limit of 700 for HIC_{15} for the 6-year-old dummy.

Chapter S2
Neck Injury Criteria

In the SNPRM, NHTSA revised its previously proposed neck injury criteria, N_{ij}, (a linear combination of tension/compression and flexion/extension moments) and proposed adjusted critical limit values (Table S2-1). In addition, the agency posed two questions to commenters. First, the agency noted that in some of its own testing of airbag systems the 5th female dummy had on occasion generated rapid and high neck moments (>100 N-m) before the neck experienced any significant rotation or bending. Concerned that this phenomenon was a result of the mechanical design characteristics of the dummy's neck and not a true biomechanical characteristic of a human neck, the agency posed the question of whether other organizations also experienced this loading condition and whether they believe or have data to suggest that this is either biomechanically realistic or an artifact of the dummy's design. Second, NHTSA noted that the SAE-recommended filter class for the neck transducers occasionally admits data that has spikes of very short duration that may not be appropriate for evaluating the potential for neck injury to the human . The agency requested comments on an appropriate channel frequency class for evaluating data from neck load cells for injury assessment purposes and whether that channel frequency class should depend on the impact environment (i.e. vehicle crash tests, out-of-position tests, etc.).

Table S2-1. Critical Intercept Values for SNPRM Nij Neck Injury Calculation.

Dummy	Tension (N)	Compression (N)	Flexion (N-m)	Extension (N-m)
CRABI 12 month-old	1465	1465	43	17
Hybrid III 3 year-old	2120	2120	68	27
Hybrid III 6 year-old	2800	2800	93	39
Hybrid III small sized female	3370	3370	155	62
Hybrid III mid-sized male	4500	4500	310	125
Hybrid III large sized male*	5440	5440	415	166

* The Large Male (95th percentile Hybrid III) is not included in the final rule, but the performance limits are listed here for informational purposes.

S2.1 Nij Neck Injury Criteria

The most significant response to this proposal came from the Alliance of Automotive Manufacturers and the Association of International Automobile Manufacturers, AAM-AIAM, in which they endorsed the N_{ij} construct but recommended the inclusion of additional, more stringent tension-compression limits to independently control this potentially injurious axial loading mode. AAM-AIAM also recommended further, minor adjustments to NHTSA's proposed critical limits based on whether the limits are being utilized for in-position(IP) or out-of-position(OOP) situations (Tables S2-2 and S2-3). AAM-AIAM's argued that for in-position testing, because the occupant is most likely anticipating the crash, his or her neck muscles would be tensed, and therefore, some of the load applied to the neck by the head would be borne by the muscles and not contribute to the potential for neck injury. They estimated this load to be equal to 80 percent of the maximum static muscle strength. Thus, for all dummies except the CRABI 12 month-old, an additional load factor was added to the tension and extension limits out-of-position limits to calculate the in-position limits. This translates into approximately a 10 percent increase in the Nij tension and extension intercepts and a 25 percent increase in the peak tension limit.

Table S2-2: AAM-AIAM Proposed Out-of-Position Limits for Nij

	Peak Limits		Nij Intercepts *			
Dummy Size	**Tension (N)**	**Comp (N)**	**Tension (N)**	**Comp (N)**	**Flexion (N-m)**	**Exten (N-m)**
CRABI	780	960	1460	1460	43	17
3 YO	1130	1380	2120	2120	68	27
6 YO	1490	1820	2800	2800	93	37
5F	2070	2520	3880	3880	155	61
50M	3290	4000	6160	6160	310	122
95M	3970	4830	7440	7440	415	162

* Intercepts were rounded to the nearest whole number.

Table S2-3: AAM-AIAM Proposed In-Position Limits for Nij

	Peak Limits		Nij Intercepts *			
Dummy Size	**Tension (N)**	**Comp (N)**	**Tension (N)**	**Comp (N)**	**Flexion (N-m)**	**Exten (N-m)**
CRABI	780	960	1460	1460	43	17
3 YO	1430	1380	2340	2120	68	30
6 YO	1890	1820	3096	2800	93	42
5F	2620	2520	4287	3880	155	67
50M	4170	4000	6806	6160	310	135
95M	5030	4830	8216	7440	415	179

* Intercepts were rounded to the nearest whole number.

The agency acknowledges that the contribution of active muscle force for in-position occupants who are aware of an impending crash may increase the tension and extension tolerances of the neck. However, there is currently no biomechanical data to quantify the amount of this increase. Mertz (1997) suggested that perhaps a minimal amount of muscle tension could be used for the children while 80 percent of the maximum static muscle force could be used for the adult. The AAM-AIAM proposed adding 80 percent of the estimated maximum static human neck muscle capability to the adult, 6 year-old, and 3 year-old dummies as the additional tension and extension load factors for in-position testing. As part of its continuing comprehensive neck injury research program, the agency is directing efforts to quantify the contribution of muscle forces to the tolerance of the neck in various loading modes. Until this research effort is complete, the agency will accept the AAM-AIAM's proposal to use 80 percent of the maximum static muscle force as an additional load factor for in-position testing for the adult dummies. The consequence of this increase results in approximately a 10 percent increase in the Nij tension and extension intercepts and a 25 percent increase in the peak tension limit. However, the agency believes that it is not prudent to apply an additional load factor of 80 percent muscle forces for children because they may not tense their muscles as much in anticipation of an impending crash or not at all. Since only out-of-position tests are required in the final rule for the 3 and 6 year old dummies, the issue of the contribution of muscles to the neck injury tolerance for children need not be resolved in this rulemaking.

In the SNPRM's proposal, N_{ij} formulation and critical limits appeared to be sufficient to monitor and prevent critical neck loads. AAM-AIAM, the Institute for Highway Safety, and the National Transportation Safety Board stated that they were concerned that the peak tension and peak compression allowed by the Nij criteria when the moment value is zero are too great. Available NHTSA test data for in-position and out-of-position testing of the adult and child dummies suggests that situations where high tension or compression forces occur in the absence of a bending moment are very rare. As shown in Figures S2-1 through S2-3, the test data does not typically lie in the upper or lower "corner" (indicated by arrows) of the kite-shaped allowable region defined by Nij, but rather lies off the y-axis closer to a 45 degree diagonal line. However, since the agency's testing was limited, it is possible that there may be situations which generate high peak tension forces with very low moments. Consequently, the agency believes there is merit in adding the more stringent peak tension and compression limits proposed by the AAM-AIAM .

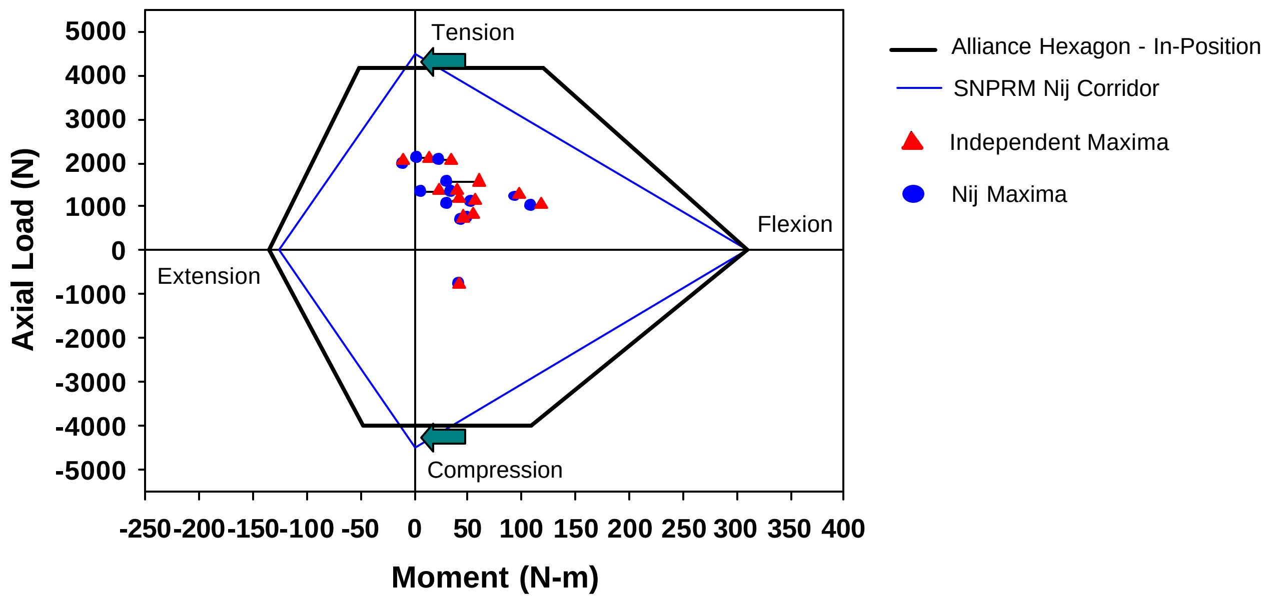

Figure S2-1: Final Rule Nij Criteria for 50th percentile male dummy in the driver's position (30 mph rigid barrier, unbelted)

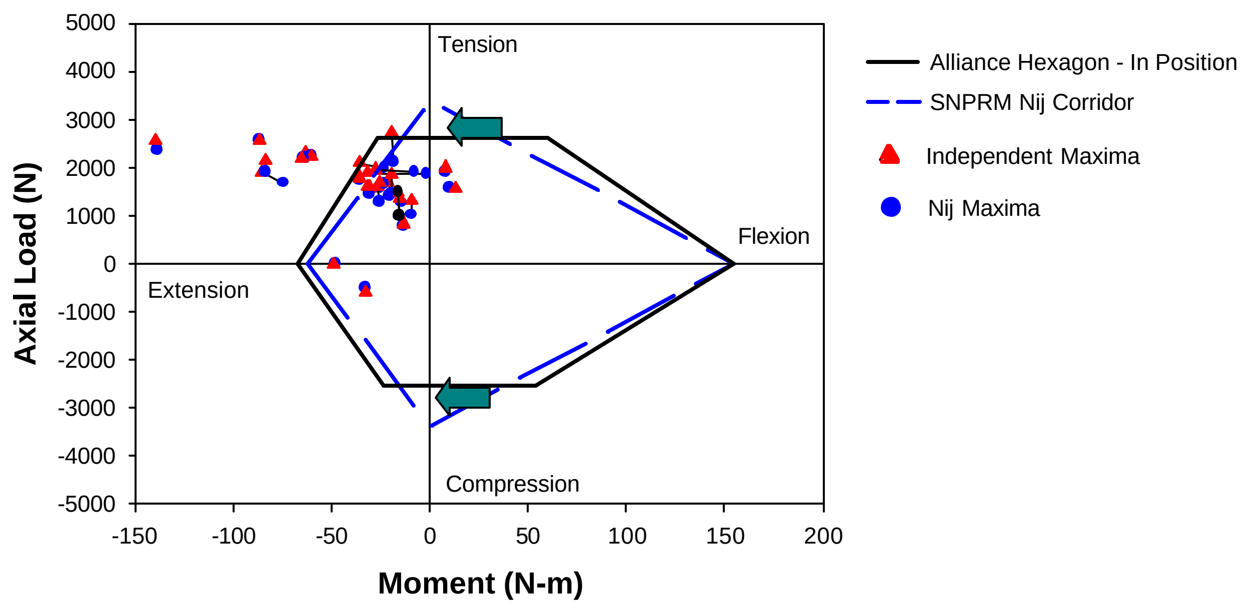

Figure S2-2: Final Rule Nij Criteria for 5th percentile female dummy in the driver's position (30 mph rigid barrier, belted)

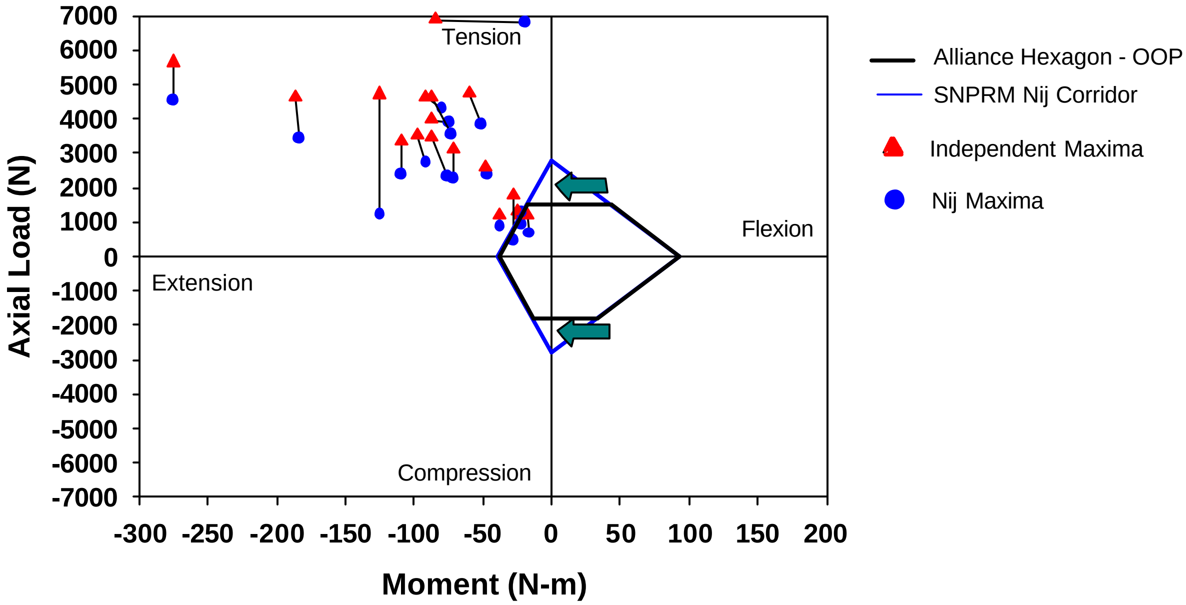

Figure S2-3: Final Rule Nij Criteria for 6 year-old dummy in static out-of-position 1

In summary, NHTSA believes that there is merit in incorporating the AAM-AIAM's proposed additional tension/compression limits and adjustments to NHTSA's N_{ij} proposals because they either track our proposed requirements very closely or add additional requirements that more stringently control the potentially injurious axial loading mode. The agency will accept the AAM-AIAM argument that tensed neck muscles mitigate the effects of measured neck loads by adopting the AAM-AIAM proposal for slightly higher neck limits for in-position testing for the adult dummies. The critical limits implemented in the final rule are shown in Table S2-4.

Table S2-4: Final Rule Nij Intercepts and Independent Axial Force Limits

	Peak Limits		Nij Intercepts			
Dummy Size - Testing Condition	**Tension (N)**	**Comp (N)**	**Tension (N)**	**Comp (N)**	**Flexion (N-m)**	**Exten (N-m)**
CRABI-OOP	780	960	1460	1460	43	17
3 yo - OOP	1130	1380	2120	2120	68	27
6 yo -OOP	1490	1820	2800	2800	93	37
5F - OOP	2070	2520	3880	3880	155	61
5F - IP	2620	2520	4287	3880	155	67
50M - IP	4170	4000	6806	6160	310	135

S2.2 Nij Criteria vs. Tension Only Criteria

DaimlerChrysler argued that the Hybrid III neck may be inadequate for accurately assessing the potential for flexion/extension neck injury due to air bag loading. This issue will be discussed in greater detail in section S2.3. DaimlerChrysler recommended that tension should be used as the only indicator of neck injury.

Although the vast majority of the members of the AAM-AIAM, including BMW, Fiat, Ford, General Motors, Isuzu, Mazda, Nissan, Volkswagen, and Volvo, support the use of a modified neck injury criterion, Nij, DaimlerChrysler supported the use of tension as the only neck injury criterion with the current neck because they believe that the Hybrid III neck may be inadequate for accurately assessing the potential for flexion/extension neck injury due to air bag loading. Furthermore, DaimlerChrysler argued that since tension was found to be a better predictor of neck injury than extension alone or a combination of tension and extension in a series of out-of-position air bag deployments, tension alone should be used to assess the potential for neck injury. Toyota also recommended delaying the use of any neck injury criteria which contains extension.

Although the available data, which was developed in a study using pig necks, suggest that tension is the best predictor of out-of-position neck injuries, the primary loading mode in this series of tests was limited to tension-extension. Although this is the predominant mode of neck injury seen in field data for out-of-position occupants, current and future vehicle designs may produce other modes of neck loading. The agency believes that tension by itself is not a robust injury criterion for all the possible loading modes experienced in the out-of-position and crash environment. For instance, the injury potential of a top-mounted air bag which deploys over an occupants head and compresses and flexes the neck would not be accurately assessed by a tension only criteria. There may also be situations where large flexion or extension moments accompanied by large head rotations occur in the crash event which would be ignored with a tension only criterion. For example, the Nij criteria are capable of assessing the potential for compression-type neck injuries which may occur when the head of an unbelted occupant contacts the vehicle interior. Thus, the Nij criteria which includes tension, compression, flexion and extension, are more robust than a tension only criteria. Since the proposed Nij criteria was formulated for frontal crash testing, Nij does not consider torsional loading or lateral bending of the neck in evaluating the potential for injury. Further research is necessary to determine the tolerances of the neck in these loading modes.

The AAM-AIAM did not comment on the issue of the adequacy of the Hybrid III dummy neck for assessing the potential for flexion/extension neck injury due to air bag loading and said they reserved comment on this issue pending the release of the individual dummy rules. It should be noted that a NPRM for each individual dummy size had been proposed several months prior to the SNPRM for FMVSS No. 208, and interested parties had an opportunity to comment on the design of the neck or other issues. Consequently, with the vast majority of the members of the AAM-AIAM silent on the appropriateness of the Hybrid III neck for evaluating flexion/extension injuries due to air bag loading, the agency is adopting Nij as previously described (Table S2-4) with the current Hybrid III dummies (and neck) in the final rule as the best criteria to use over the range of loading modes experienced in the crash environment.

S2.3 Biofidelity of Hybrid III Neck Design for Air Bag Loading Scenarios

In the SNPRM, NHTSA noted that in some of its own testing of airbag systems the 5th female dummy had on occasion generated rapid and high neck moments (>100 N-m) before the head experienced any significant rotation or the neck experienced any significant bending. After studying the situation, NHTSA staff postulated that this condition was a result of a particular loading condition that opposed bending due to shear loads against bending due to moments. Concerned that this phenomenon was a result of the mechanical design characteristics of the dummy's neck and not a true biomechanical characteristic of a human neck, NHTSA described the situation in the SNPRM and posed the question of whether other organizations also experienced this loading condition and whether they believe or have data to suggest that this is either biomechanically realistic or an artifact of the dummy's design. Several organizations noted that they did observe the high moment/low rotation loading condition and one organization, DaimlerChrysler, offered test data to suggest that the dummy's neck design does not follow established biomechanical response corridors.

DaimlerChrysler presented data from a series of passenger air bag deployments using a 5th percentile female in the full forward seat track position with the dummy leaning forward to increase the likelihood of the air bag interacting under the chin. DaimlerChrysler described what it believed were three typical categories of interactions of the air bag with the dummy head and neck. In the first scenario, the air bag directly loaded the head which produced a flexion moment at the neck, positive shear force, and negligible tension. In the second scenario, the air bag contacted the head under the chin and became trapped under the chin during the deployment, which produced extension moments in the neck, negative shear forces, and tension. In the third scenario described by DaimlerChrysler, the air bag contacted the head below the chin and entrapped the fabric between the neck and the jaw which produced extension moments, large negative shear, and tension. In all three cases, the neck deformed in a S-shaped manner with little angular deformation of the head and high flexion or extension moments. When the neck moments obtained from this series of air bag tests were plotted as a function of head-to-chest relative angular rotations and compared to the corridors developed by Mertz and Patrick to which the Hybrid III dummy is designed, the dummy neck showed much stiffer responses (i.e., higher flexion or extension moments for the same head-to-chest relative angular rotation) than the design corridor for the three loading scenarios. DaimlerChrysler postulated that the significant differences seen in the dummy's head/neck response between the air bag test and the test used in developing the biomechanics corridors could be due to the different neck bending modes that occur in these different test conditions. The Mertz and Patrick neck response corridors were generated based solely on neck loads generated by the inertial effects of the head when the occupant experiences either belted deceleration or seatback loading. In this loading mode, the forces and moments acting on the head are transferred up the neck structure and the neck bends in a uniform manner, in a C-like curve. During air bag loading, significant loads are most frequently applied directly to the head and then transmitted down the neck. This causes the neck to bend in a S-shaped mode. DaimlerChrysler argued that the Mertz and Patrick flexion and extension response corridors of the Hybrid III dummy neck are not applicable to the neck responses in air bag tests and that additional biomechanical data are needed to accurately assess the injury potential to human subjects during air bag loading.

The agency acknowledges that there may be some situations in which direct loading of the dummy's head causes the neck response to fall outside the established moment-angle corridors. Based on a review of agency films of both crash testing and out-of-position testing, the dummy neck sometimes fell outside the established moment-angle corridors and resulted in high neck extension and Nij values. One example of this scenario occurs when the top fold of the expanding air bag loads the head under the chin, as evidenced by chalk transfers on the back side of the air bag. Another example of this scenario that the agency has seen occurs in crash tests when there seemed to be insufficient restraint of the thorax and lower body such that the air bag preferentially loaded the head and face, causing extension of the neck. None of the commenters, including DaimlerChrysler, provided the agency with any additional data to justify or develop alternative dummy neck response requirements that either verify the responses of the current Hybrid III design or provide the basis for improving it. The agency will execute two specific actions: First, because of the need to minimize the risk of air bags producing neck injuries and lack of testing alternatives, it will use the various current Hybrid III neck designs and corresponding AAM-AIAM recommended performance criteria in the final 208 rule. The agency believes that the urgency of the situation justifies this action. As of February 2000, excluding cases which involve rear facing car safety seats, NHTSA's Special Crash Investigations has documented that about 50 percent of air bag related fatalities are believed to be due to neck injury (either exclusively or in conjunction with head and chest injuries) in children and adults. Thus, in order to minimize the number of air bag related fatalities, it is imperative to include a neck injury critiera in the final 208 rule. The agency, as the second action, will also immediately establish new and accelerate existing research and development efforts to further address this issue.

S2.4 Recommended Filtering for Neck Injury Criteria Calculations

In the SNPRM, NHTSA noted that the SAE recommended channel frequency class for the neck transducers occasionally admits data that has spikes of very short duration that may not be appropriate for evaluating the potential for neck injury to the human (Figure S2-4). The agency requested comments on an appropriate channel frequency class for evaluating data from neck load cells for injury assessment purposes and whether that channel frequency class should depend on the impact environment (i.e. vehicle crash tests, out-of-position tests, etc.) The AAM-AIAM and DaimlerChrysler stated that they believe that the filters specified by SAE J211 are appropriate for evaluating neck injury and that sources of the spikes, which may be noise, need to be identified and eliminated. Examples of possible sources of noise offered by the commenters include metal-to-metal contact, poor grounding, and poor solder joints. DaimlerChrysler also suggested that the neck injury criteria component data should be gathered using phaseless filters specified in the SAE Standard J211 for accurate combination.

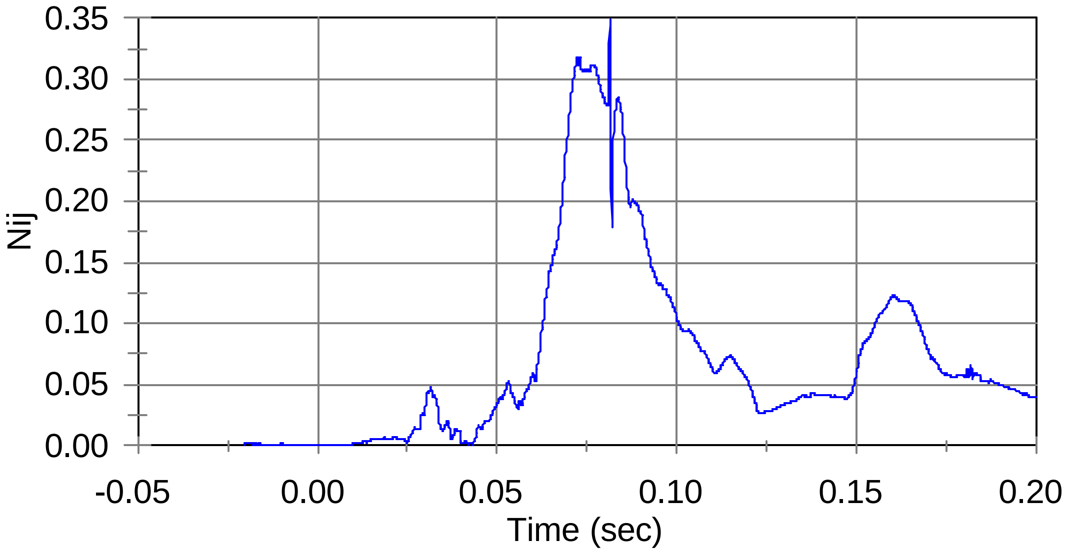

Figure S2-4: Example of Nij with a Noise Spike (CFC 600)

The agency concurs with the commenters' suggestion that the SAE filter specifications for the individual neck loads are sufficient for evaluating neck injury potential. The sources of noise do not appear to be inherent in the dummy neck design, but rather may be caused by incorrect assembly/maintenance of a specific dummy or by procedural issues which need to be corrected at the testing laboratories. However, because Nij combines the neck bending moment and the neck axial force which have different channel frequency classes (CFC 600 for moment, CFC 1000 for axial force), the agency believes it is more appropriate to have a pure channel class frequency of 600 for Nij. Thus, the agency concludes that a CFC 600 should be used for computing the axial force component of Nij, but should remain CFC 1000 for computing the peak axial neck forces.

The March 1995 revision of SAE J211/1, Instrumentation for Impact Test, specifies that "Any filtering algorithm can be used for CFCs 1000 or 600 as long as the results conform to the data channel performance requirements as given in section 4 ... For CFCs 180 or 60, the digital Butterworth filter (*4-pole phaseless digital filter*) [1] described in Appendix C should be used.". Thus, the standard does not require a phaseless filter for the neck force and moment data which are filtered at CFC 1000 and 600, respectively. To reduce the uncertainty in time shifts when comparing the electronic data to films, the agency recommends also requiring the use of the 4-pole phaseless Butterworth filter specified in the March 1995 revision of SAE J211/1 for all neck load measurements.

[1] Phrase in italics added for clarity

Chapter S3
Thoracic Injury Criteria

In the SNPRM, NHTSA proposed using the individual limits of chest deflection and chest acceleration recommended by AAMA instead of using the Combined Thoracic Index (CTI) as originally proposed in the NPRM for assessing the risk of thoracic injury. Table S3-1 presents the thoracic injury criteria proposed by NHTSA in the SNPRM.

Table S3-1. Thoracic Injury Criteria Proposed by NHTSA in the SNPRM

	12 month old	3-year old	6-year old	5th percentile female	50th percentile male	95th percentile male§
3 ms clip of result. chest accel. (g's)	50	55	60	60	60	55
chest deflection (mm)	30*	34	40	52	63	70

* The CRABI 12 month old is not currently capable of measuring chest deflection.

§ The 95th percentile Hybrid III dummy is not included in the final rule, but the performance limits are listed here for informational purposes.

In its comments to the SNPRM, AAM-AIAM endorsed the SNPRM proposed thoracic injury criteria but argued that the chest acceleration limit for the 5th percentile female dummy should be 73 g's rather than the 60 g's proposed in the SNPRM. This was reiterated by some individual manufacturers as well. The Insurance Institute for Highway Safety supported the suggested injury criteria in the SNPRM with reservations about the use of chest acceleration which they continue to believe to be a non-unique predictor of injury.

AAM-AIAM requested that the small difference in chest deflection limits for the 3-year old and the 5th percentile female dummies be eliminated and the deflection limits previously suggested by the AAMA be used in the regulation.

Furthermore, AAM-AIAM proposed the use of rate of sternal deflection to assess the risk of serious thoracic organ injuries in out-of-position tests. Toyota recommended using rate of sternal deflection in place of chest acceleration for assessing thoracic injury risk. DaimlerChrysler also supported the AAM-AIAM proposal and presented a method using Kalman filters, which it contended would yield a more reliable rate of deflection measure.

Table S3-2 presents the thoracic injury criteria suggested by the AAM-AIAM in their response to the SNPRM.

Table S3-2. Thoracic Injury Criteria Proposed by AAM-AIAM in Response to SNPRM

	12 month old	3-year old	6-year old	5th percentile female	50th percentile male	95th percentile male*
3 ms clip of result. chest accel. (g's)	50	55	60	73	60	54
chest deflection (mm)	--	36	40	53	64	71
rate of sternal deflection (m/s) for OOP tests	7.6	8.0	8.5	8.2	8.2	8.2

* The Large Male (95th percentile Hybrid III) is not included in the final rule, but the performance limits are listed here for informational purposes.

S3.1 Chest Acceleration Limit for the 5th Percentile Female Dummy

The chest deflection (D) and the chest acceleration (A) threshold limits for various dummy sizes were obtained by scaling the chest deflection and acceleration limits, $D_{50\%male}$ and $A_{50\%male}$, for the 50th percentile male dummy according to the formula

$$D = l_{L,depth} D_{50\%\,male}$$

$$A = \frac{l_E}{l_{L,mass}} A_{50\%\,male} \qquad \text{(S3.1)}$$

where

$$l_{L,depth} = \frac{\text{chest depth}}{\text{chest depth of 50\% male}}$$

$$l_{L,mass} = \left(\frac{\text{mass}}{\text{mass of 50\% male}} \right)^{1/3}$$

Using these size only scaling factors outlined in both the NPRM and SNPRM biomechanics papers, the chest acceleration threshold limit for the 5th percentile female dummy would be 70 g's. This scaling assumes that the modulus of elasticity and the failure stress of bone for the 5th percentile female are similar to that for the 50th percentile male. That is, $\lambda_E = \lambda_{\sigma f} = 1$.

NHTSA's Special Crash Investigations suggest that adult female drivers and passengers with serious to fatal injuries due to air bag deployments have an average age of 50 years. By contrast, the average age of mid-size males who are involved in frontal crashes is approximately 34 years. Therefore, to assure that females receives the same level of protection as do the mid-sized males, NHTSA proposed to further adjust the acceleration limit for the 5th percentile female dummy by incorporating the effect of the reduced bone strength of the older female SCI population.

According to Yamada (1970), the average ratio of bone failure stress for a 50 year old (male and female subjects) to a 35 year old is approximately 0.9 (Table S3-3). Riggs (1981) measured the bone mineral density in 105 normal women and 82 normal men and found that there was an overall 47% decrease in bone mineral density in women throughout life while there was minimal decrease in bone mineral density with increase in age among men (Figure S3-1). Jurist (1977) found that the human ulnar bending strength correlated very well with the bone mineral content (correlation coefficient =0.947). Bonfield et al. (1985) noted that due to the decrease in bone mineral density with increasing age, there was a decrease in the fracture toughness of cortical bone with the increase in age.

Due to the greater bone loss with the increase in age among females as compared to males, the ratio of bending strength for different age groups will be smaller in females than that presented in Table S3-3 for the combined male and female population. The ratio of the bending strength between a 50 year old female to a 35 year old female is estimated to be 0.88 rather than 0.9 shown in Table S3-3.

Table S3-3. Average ultimate bending strength (kg/mm^2) of human (male and female) wet long bones in anteroposterior direction for different age groups (Yamada, 1970).

Age (years)	20-39	40-49	50-59	60-69	70-89
bending strength (kg/mm2)	22.1	20.7	20	19.1	17.5
Ratio	1.0	0.94	0.9	0.86	0.79

In order to protect the more vulnerable older 5th percentile female population, NHTSA continues to believe that the acceleration threshold limit of 70 g's should be scaled by $\lambda_{\sigma f} = 0.88$ to account for the age effects. The resulting scaled acceleration threshold limit is then 61.6 g's. Taking into consideration some uncertainty in the age scaling factor, the acceleration threshold limit was maintained at 60 g's which is the same as that of the 50th percentile male.

NHTSA conducted nine 30 mph full frontal rigid barrier crash tests with the 5th percentile female dummy in the driver and front passenger seats. Three out of the nine vehicles exceeded the chest G criteria (maximum was 68.6 G). If the AAM-AIAM 73G criteria were adopted by the agency, then all nine vehicles would pass the injury limits for the driver and passenger. Film analysis suggested that the 5th percentile female dummy passenger hit the instrument panel in at least two of the tests where the passenger failed the 60 g chest acceleration limit. However, the maximum chest deflection recorded was less than 15 mm in these two tests. Therefore, the chest acceleration limit of 60 g's was able to distinguish the potentially injurious impact event which the chest acceleration limit of 73 g's or the chest deflection limit of 52 mm failed to detect. These observations suggest that limiting chest acceleration to 60 g's to protect the vulnerable older 5th percentile female is prudent. Therefore, NHTSA has decided to adopt the proposed 60 g's acceleration limit for the 5th percentile female dummy.

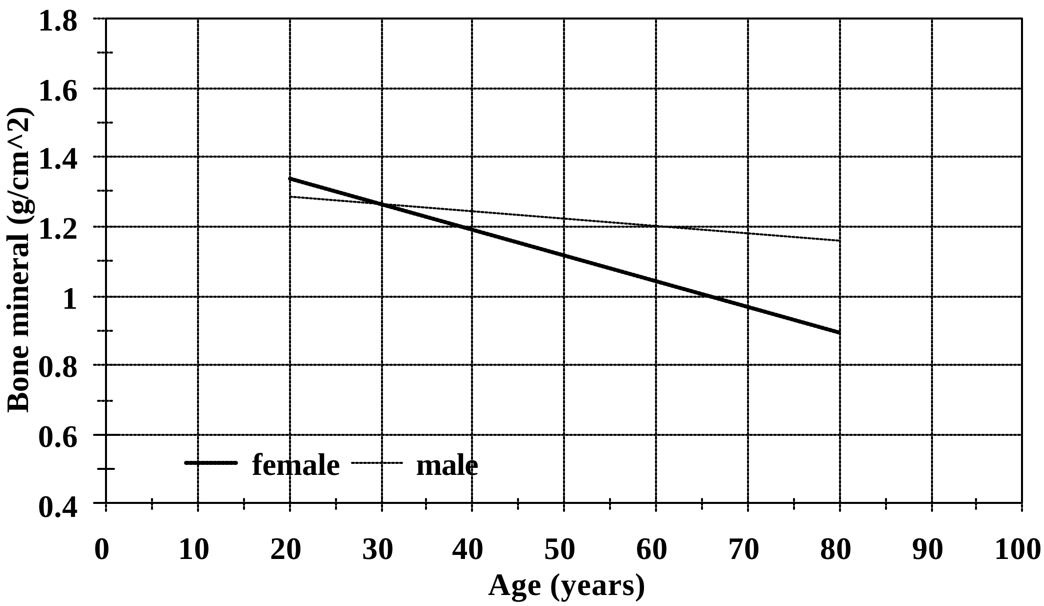

Figure S3-1. Regression of BMD of lumbar spine on age in 105 normal women and 82 normal men.

S3.2 Chest Deflection Limits for Different Size Dummies

The AAM-AIAM recommended chest deflection limits (Table S3-2) are very similar to those proposed in the SNPRM (Table S3-1). The chest deflections were scaled according to Equation S3.1 using scaling factors that were outlined in the SNPRM and Mertz et al. (1997). The chest deflection limits initially proposed by Mertz et al. (1997) and endorsed by AAM-AIAM address heart and aortic rupture injuries. According to Mertz, the ratio of stress in the heart between different size subjects is equal to the corresponding ratio of sternal deflection to chest depth ratio of the subjects. Therefore, assuming the failure stress of the heart tissue is the same for all size subjects, the chest deflection limits were scaled using only the chest depth for different size dummies. AAM-AIAM recommended chest deflection limit of 64 mm for the 50th percentile male, which, it contended correspond to a 5% probability of AIS$4 heart/aortic injury. In order to harmonize with the threshold limits used by Transport Canada, the agency adopted 63 mm for chest deflection threshold limit instead of the 64 mm limit recommended by AAM-AIAM. This change in the 50th percentile male threshold value resulted in small differences (< 2mm) between AAM-AIAM and SNPRM recommended scaled threshold limits for some of the other dummies. NHTSA believes these differences are negligible and is adopting the limits proposed in the SNPRM.

S3.3 Rate of Sternal Deflection Limit

In its comments to the SNPRM, AAM-AIAM suggested the use of rate of sternal deflection to assess the risk of AIS$4 thoracic organ injuries due to air bag "punch-out" forces in out-of-position conditions.

As noted in the SNPRM, in ISO-2 out-of-position tests using 5th percentile female cadaveric subjects, (Crandall, et al., 1997) chest deflection was found to correlate better with thoracic injury (r=0.82) than rate of sternal deflection (r=0.49). In ISO-1 and ISO-2 out-of-position tests using the 6 year old dummy, the rate of deflection limit of 8.5 m/s was exceeded in almost all the cases where the chest deflection or chest acceleration limit was exceeded (Figure S3-2). This suggests that the chest deflection and chest acceleration threshold limits would be sufficient to distinguish the conditions producing soft tissue thoracic injury from the benign conditions in out-of-position tests.

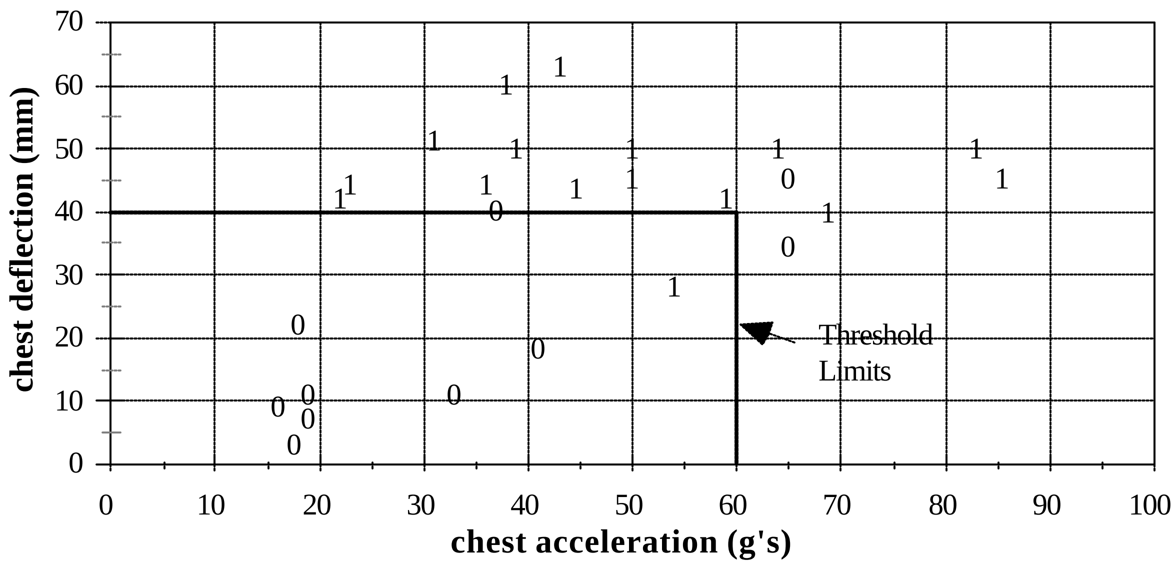

Figure S3-2. Plot of maximum chest deflection and chest acceleration measured in ISO-1 and ISO-2 out-of-position tests using the six year old dummy. The 0 indicates tests where maximum chest velocity was below 8.5 m/s and the 1 are tests where the rate of chest deflection exceed 8.5 m/s.

Even if deflection rate was not found to be redundant, there is no standardized, widely accepted method for determining it. Currently, deflection rate is computed by either differentiating chest deflection measurements or by integrating the difference of the sternal and spinal accelerometer measurements. Both of these methods are subject to interpretation and measurement noise and neither has gained any wide spread use or endorsement. Numerical differentiation of displacement data is inherently noisy and may result in inaccurate rate of deflection measures. Numerical integration of accelerometer data is subject to drift and time shifting and emphasizes any steady state errors that may exist in the system. At present there are no direct measurement velocity transducers used in standard vehicle crash applications and no reliable method of computing velocity from related measurements. The Kalman filter approach recommended by DaimlerChrysler appears interesting, but it needs further evaluation and acceptance before being implemented.

Until adequate instrumentation and computation techniques to obtain reliable rate of deflection at high rates of loading (as in the case of air bag loading to the out-of-position occupant) are developed, the agency could not utilize chest deflection rate as an objective performance metric. However, the agency encourages automobile manufacturers and restraint suppliers to continue investigating and evaluating additional injury criteria such as rate of deflection to assess the potential for soft tissue thoracic injuries.

Chapter S4
Lower Extremity Injury Criteria

In the SNPRM, NHTSA proposed lower extremity injury criteria to limit the axial loads in the femur for the adult dummies (10 kN for 50th percentile male and 6.8 kN for the 5th percentile female). Table S4-1 presents the femur injury criteria proposed by NHTSA in the SNPRM.

Table S4-1. Femur Injury Criteria Proposed by NHTSA in the SNPRM

	5th percentile female	50th percentile male	95th percentile male *
Femur Force (N)	6800	10,000	12,700

* The 95th percentile Hybrid III dummy is not included in the final rule, but the performance limits are listed here for informational purposes.

Furthermore, in the context of possibly adding a 48 to 56 km/h (30 to 35 mph) unbelted offset deformable barrier crash test, the agency requested comments on how it should proceed in upgrading the 5th percentile adult female and 50th percentile adult male dummies (Hybrid III and/or Thor-Lx) so that they are capable of measuring tibia and foot/ankle injury potential, and in selecting/developing appropriate injury criteria.

In their response to the SNPRM, AAM-AIAM and DaimlerChrysler stated that they support axial femur force limits of 9070 N for the 50th percentile male and 6190 N for the 5th percentile female rather than the limits proposed in the SNPRM. Table S4-2 presents the femur injury criteria proposed by AAM-AIAM in response to the SNPRM.

Table S4-2. Femur Injury Criteria Proposed by AAM-AIAM in response to the SNPRM

	5th percentile female	50th percentile male	95th percentile male
Femur Force (N)	6190	9070	11,540

The AAM-AIAM stated that they reserve comments on the various tibia and foot/ankle injury criteria, such as the tibia index with a limit of 1.3 currently used by the EEVC, until such time that their members have developed and assessed performance data for the dummies under the crash conditions proposed by NHTSA and the Alliance. The AAM-AIAM and Daimler Chrysler stated that they do not support the use of the Thor-Lx until it has been fully evaluated. Autoliv supported the use of the Thor-Lx in future regulation, since the biofidelity of Thor-Lx is much better than the Hybrid III instrumented leg. Autoliv further supported the implementation of new injury criteria for the tibia and ankle.

S4.1 Femur Axial Force Limits

NHTSA maintains its position on the axial femur force limits for the adult dummies. The current limit of 10 kN specified for the 50th percentile male has been used in Federal Motor Vehicle Safety Standard No. 208 for over twenty three years. AAM-AIAM has not presented information demonstrating that this value is not adequate. Further, AAM-AIAM has not provided data or an explanation of the method used to arrive at their recommended femur force limit of 9070 N for the 50th percentile male. AAM-AIAM provides a reference of a paper by Mertz (1984) as the basis for their recommendation. The paper by Mertz (1984) also does not provide an explanation but merely lists more references (Patrick et al. 1967, King et al. 1973, Melvin et al. 1975, Powell et al. 1975). Further examination of these references do not suggest that 9070 N is the femur force injury threshold limit. On the contrary, based on four unrestrained cadaver sled test data, Patrick et al. (1967) noted that it was not unreasonable to have femur force of 8700 N without any fractures. Similarly, King et al. (1973) suggested that a femur force limit of 7560 N was a conservative estimate of femur fracture tolerance since it was based on data from embalmed cadaver tests. Melvin et al. (1975) and Powell et al. (1975) examined data from longitudinal pendulum impacts to the knee of unembalmed cadavers and found the femur fracture tolerance to be in excess of 10 kN.

To date, the most comprehensive analysis of femur impact test data is by Morgan et al. (1989) who examined 126 knee impact tests from various sources (including Melvin, (1975) and Powell, (1975)). Morgan suggested that internal femur force was a very good predictor of patella-femur injury ($p=0.0001$) and that a femur force of 10 kN corresponded to a 35% probability of femur/patella fracture.

The agency used the same scaling factors as that used by AAM-AIAM to scale from the femur axial force limit of 10000 N for the 50th percentile male to that of the 5th percentile female. The agency continues to accept this scaled axial force limit for the 5th percentile female of 6800 N which differs from the AAM-AIAM recommended 6190 N.

The differences between the limits proposed in the SNPRM and that proposed by AAM-AIAM are small, and the agency believes that adopting the slightly lower value proposed by the AAM-AIAM would have no effect on the overall benefits. The agency also believes that the slightly higher axial force limits proposed by the agency will provide some additional design flexibility to optimize protection for the 50th percentile male and the 5th percentile female by allowing more energy to be dissipated through the lower extremities.

S4.2 Tibia and Foot-Ankle Injury Criteria

Based on the comments received, the agency will not be including a high speed unbelted offset deformable barrier crash test in the final rule. Consequently, the issue of tibia and foot/ankle injury criteria and instrumentation will not be addressed in this rulemaking effort.

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Supplemental Appendix
Final Rule Nij Program

```
//---------------------------------------------------------------
//			FMVSS No. 208 Final Rule Nij (Version 10) Reference Implementation
//
//		This code is a reference implementation of the Final Rule Nij injury criteria
//			this was written for purposes of clarity and no consideration has been made
//			for speed, style, or efficiency.  The Standard C++ library was used to avoid
//			any confusion due to c-style memory allocation.
//
//		Program Input:
//			This program requires input of three ascii x-y files, where each line of the
//			input file contains two floating point values, one for the time and one
//			for the y value
//
//			*** All three files must have the same number of points and the same time data **
//
//			*** All input data must be unfiltered and will be filtered within this program
//			*** Fx and Fz files are filtered at CFC 1000 for reporting maxima.
//				Fx, My, and Fz files are filtered at CFC600 for Nij calculations.
//
//			Additionally, the program queries for the dummy size and whether the condyle
//			correction factor is to be applied
//
//		Program Output:
//			The Nij injury criteria, the time of Peak injury
//---------------------------------------------------------------
#include <iostream>
#include <fstream>
#include <vector>
#include <ctype.h>

using namespace std;
typedef vector <double> DBLVECTOR;

#include "bwfilt.h"								// bwfilt implementation

// declarations
bool ReadAsciiFile ( char *filename, DBLVECTOR &x, DBLVECTOR &y);
void VectorMax( float &Max, float &MaxTime, DBLVECTOR &time, DBLVECTOR &fVector);
void VectorMin( float &Min, float &MinTime, DBLVECTOR &time, DBLVECTOR &fVector);
double FindTimeStep( DBLVECTOR &time );


int main( int argv, char *argc[])
{
	DBLVECTOR tx, ty, tz, xForce, yMoment, zForce;		//CFC 600 for Nij use
	DBLVECTOR xForce1000, zForce1000;					//CFC 1000 for force maxima use
	char szbuf[255];
```

```
// read in the filename for the x axis
cout << "Enter file Name for X axis Force Data: "<< endl;
cin >> szbuf;
if ( !ReadAsciiFile(szbuf, tx, xForce) )
{
        cout << "Error X axis data File" << endl;
        exit (0);
}

// read in the filename for the y axis
cout << "Enter file Name for Y axis Moment Data: "<< endl;
cin >> szbuf;
if ( !ReadAsciiFile(szbuf, ty, yMoment) )
{
        cout << "Error Y axis data File" << endl;
        exit (0);
}

// read in the filename for the x axis
cout << "Enter file Name for Z axis Force Data: "<< endl;
cin >> szbuf;
if ( !ReadAsciiFile(szbuf, tz, zForce) )
{
        cout << "Error Z axis data File" << endl;
        exit (0);
}

// make sure all three files have identical time data
if ( (tx.size() != ty.size()) || (tx.size() != tz.size()) )
{
        cout << "Time data does not match between Axes" << endl;
        exit (0);
}
int i;
for (i=0; i<tx.size(); i++)
{
        if ( (tx[i]!=ty[i]) || (tx[i]!=tz[i]) )
        {
                cout << "Time data does not match between Axes" << endl;
                exit (0);
        }
}

// clear two of the time arrays - not needed any longer
ty.erase(ty.begin(), ty.end() );
tz.erase( tz.begin(), tz.end() );

// find the time step, and make sure that it is constant (within 1%)
double del = FindTimeStep( tx );
if (del<=0.0)
{
        cout << "Could not find a constant time step for the data" << endl;
```

```
        exit(0);
}

// copy x and z data into xForce1000 & zForce1000
xForce1000=xForce;
zForce1000=zForce;

// Filter the data - assume unfiltered data
bwfilt( xForce, del, 600);
bwfilt( zForce, del, 600);
bwfilt( yMoment, del, 600);
bwfilt( xForce1000, del, 1000);
bwfilt( zForce1000, del, 1000);

// Select the dummy type
int nDummyType=0;
cout << "1 - CRABI 12 month old Dummy" << endl;
cout << "2 - Hybrid III - 3 Year old Dummy - Out of Position" << endl;
cout << "3 - Hybrid III - 6 Year old Dummy - Out of Position" << endl;
cout << "4 - Hybrid III - 5th % female Dummy - Out of Position" << endl;
cout << "5 - Hybrid III - 5th % female Dummy" << endl;
cout << "6 - Hybrid III - 50th % male Dummy" << endl;
cout << endl << "Enter Dummy Type :";
cin >> nDummyType;
if ( (nDummyType <=0) || (nDummyType > 6) )
{
        exit( 0 );
}

// set the critical values based on the dummy type
double CVt, CVc, mCVf, mCVe, fCondyle;
switch (nDummyType)
{
case 1:                                 // CRABI 12 month old Dummy OOP
        CVt = 1460.0;
        CVc = 1460.0;
        mCVf =  43.0;
        mCVe =  17.0;
        fCondyle = 0.0058;
        break;
case 2:                                 // Hybrid III - 3 Year old Dummy OOP
        CVt = 2120.0;
        CVc = 2120.0;
        mCVf = 68.0;
        mCVe =  27.0;
        fCondyle = 0.0;
        break;
case 3:                                 // Hybrid III - 6 Year old Dummy OOP
        CVt = 2800.0;
        CVc = 2800.0;
        mCVf = 93.0;
        mCVe =  37.0;
```

```
		fCondyle = 0.01778;
		break;
	case 4:					// Hybrid III - 5th % female Dummy OOP
		CVt = 3880.0;
		CVc = 3880.0;
		mCVf = 155.0;
		mCVe =  61.0;
		fCondyle = 0.01778;
		break;
	case 5:					// Hybrid III - 5th % female Dummy
		CVt = 4287.0;
		CVc = 3880.0;
		mCVf = 155.0;
		mCVe =  67.0;
		fCondyle = 0.01778;
		break;
	case 6:					// Hybrid III - 50th % male Dummy
		CVt = 6806.0;
		CVc = 6160.0;
		mCVf = 310.0;
		mCVe = 135.0;
		fCondyle = 0.01778;
		break;
	}

	// prompt for Condyle Correction
	cout << "Correct for Occipital Condyle Offset (" << fCondyle << ") Y / N ?" << endl;
	char yesNo;
	cin >> yesNo;
	yesNo = toupper( yesNo );

	// compute the normalized data
	DBLVECTOR Tension, Compression, Flexion, Extension;
	for (i=0; i<tx.size(); i++)
	{
		if (zForce[i] > 0 )
		{
			Tension.push_back( zForce[i] / CVt );			// Tension
			Compression.push_back( 0.0f );
		}
		else
		{
			Compression.push_back( -zForce[i] / CVc );	// Compression
			Tension.push_back( 0.0f );
		}

		// Condyle Correction
		if (yesNo == 'Y')
		{
			yMoment[i] -= xForce[i] * fCondyle;
		}
```

```
        if (yMoment[i] > 0 )
        {
                Flexion.push_back( yMoment[i] / mCVf );                 // Flexion
                Extension.push_back( 0.0f );
        }
        else
        {
                Extension.push_back( -yMoment[i] / mCVe );              // Extension
                Flexion.push_back( 0.0f );
        }
}



// find the maximums and the time of the maximum
float maxTension, maxCompression, maxShear, minShear;
float maxFlexion, maxExtension;
float tTension, tCompression, tShearmax, tShearmin;
float tFlexion, tExtension;
VectorMax( maxTension, tTension, tx, zForce1000);
VectorMin( maxCompression, tCompression, tx, zForce1000);
VectorMax( maxShear, tShearmax, tx, xForce1000);
VectorMin( minShear, tShearmin, tx, xForce1000);
VectorMax( maxFlexion, tFlexion, tx, Flexion);
VectorMax( maxExtension, tExtension, tx, Extension);

// Output the Maximums
cout << "Maximum Shear      \t" << maxShear << "\tat " << tShearmax << " ms" << endl;
cout << "Minimum Shear      \t" << minShear << "\tat " << tShearmin << " ms" << endl;
cout << "Maximum Tension    \t" << maxTension << "\tat " << tTension << " ms" << endl;
cout << "Maximum Compression\t" << maxCompression << "\tat " << tCompression << " ms" << endl;
cout << "Maximum Flexion    \t" << maxFlexion*mCVf << "\tat " << tFlexion << " ms" << endl;
cout << "Maximum Extension  \t" << maxExtension*mCVe<< "\tat " << tExtension << " ms" << endl;
cout << endl;

// Compute the Nij Values
DBLVECTOR Ntf, Nte, Ncf, Nce;
for (i=0; i<tx.size(); i++)
{
        if ( (Tension[i] > 0.0) && (Flexion[i]>0.0) )
                Ntf.push_back( Tension[i] + Flexion[i] );
        else
                Ntf.push_back( 0.0 );

        if ( (Tension[i] > 0.0) && (Extension[i]>0.0) )
                Nte.push_back( Tension[i] + Extension[i] );
        else
                Nte.push_back( 0.0 );

        if ( (Compression[i] > 0.0) && (Flexion[i]>0.0) )
                Ncf.push_back( Compression[i] + Flexion[i] );
        else
```

```
                Ncf.push_back( 0.0 );

            if ( (Compression[i] > 0.0) && (Extension[i]>0.0) )
                Nce.push_back( Compression[i] + Extension[i] );
            else
                Nce.push_back( 0.0 );
        }

        // save the Max Value and the Time of the Max Value
        float maxNtf, maxNte, maxNcf, maxNce;
        float tNtf, tNte, tNcf, tNce;
        VectorMax( maxNtf, tNtf, tx, Ntf );
        VectorMax( maxNte, tNte, tx, Nte );
        VectorMax( maxNcf, tNcf, tx, Ncf );
        VectorMax( maxNce, tNce, tx, Nce );

        // Output the results
        cout << "Maximum Ntf\t" << maxNtf << "\tat " << tNtf << " ms" << endl;
        cout << "Maximum Nte\t" << maxNte << "\tat " << tNte << " ms" << endl;
        cout << "Maximum Ncf\t" << maxNcf << "\tat " << tNcf << " ms" << endl;
        cout << "Maximum Nce\t" << maxNce << "\tat " << tNce << " ms" << endl;
        cout << endl;

        return 0;
}

bool ReadAsciiFile ( char *szFilename, DBLVECTOR &x, DBLVECTOR &y)
{
        ifstream inFile;

        inFile.open( szFilename );
        if (inFile.fail() )
        {
            return false;
        }

        double xTemp, yTemp;
        while ( !inFile.eof() )
        {
            inFile >> xTemp >> yTemp;
            // check for errors
            if (inFile.fail() )
            {
                // input failed - save the data we already have and return;
                if (x.size() > 0)
                    break;
                // no data was read - return an error
                return false;
            }
            x.push_back( xTemp );
            y.push_back( yTemp );
        }
```

```
	// close the file
	inFile.close();
	return true;
}

void VectorMax( float &Max, float &timeMax, DBLVECTOR &time, DBLVECTOR &fVector)
{
	Max = timeMax = 0.0f;
	for (int i=0; i<fVector.size(); i++)
	{
		if (fVector[i] > Max)
		{
			Max = fVector[i];
			timeMax = time[i]*1000.0f;
		}
	}
}

void VectorMin( float &Min, float &timeMin, DBLVECTOR &time, DBLVECTOR &fVector)
{
	Min = timeMin = 0.0f;
	for (int i=0; i<fVector.size(); i++)
	{
		if (fVector[i] < Min)
		{
			Min = fVector[i];
			timeMin = time[i]*1000.0f;
		}
	}
}

double FindTimeStep( DBLVECTOR &time )
{
	// make sure there is data
	if ( time.size()<=2)
		return 0.0;

	double del = time[1]-time[0];
	double test;
	double tError = 0.01*del;			// allow a 1% deviation in time step
	for (int i=2; i<time.size(); ++i)
	{
		test = time[i] - time[i-1];
		if ( test<=0)
			// check for errors - time must be monotonically increasing
			return 0.0;
		else if ( abs(test-del) > tError)
			return 0.0;
	}
	return del;
}
```

```
// bwfilt.h
// butterworth filtering function prototypes
//
int bwfilt( DBLVECTOR &y, float del, float fCut);        // cutoff frequency
int bwfilt( DBLVECTOR &y, float del, int nClass);        // channel class
int bwfilt( DBLVECTOR &y, DBLVECTOR &yf, float del, float fCut);      // no overwrite

// bwfilt.cpp
#include <math.h>
#include <vector>
#include <iostream>
typedef std::vector <double> DBLVECTOR;

template< class T >
inline
T const &
min( T const & x, T const & y ) { return ( ( x < y ) ? x : y ); }

//==============================================================================
//          In-Place Second-Order Butterworth Filter of Time Series
//
//          Function:
//                    Filters data forward and backward with a second order
//                    Butterworth algorithm, giving zero phase shift and according to the
//                    SAE J211.  This algorthim operates on the -3db cutoff frequency, which is
//                    indicated as Fn in the J211 s[ecification.  There is an overloaded entry
//                    point which allows specifying one of the J211 Channel Frequency Classes.
//                    This routine implements  the algorithm outlined in J211 and uses a reversed
//     mirror pre-start treatment for both the forward and reverse passes.
//
//          Authors: Stuart G. Mentzer, Stephen Summers
//
//          Fortran version - 5/95, C version 9/96, C++ standard library version 3/98
//
//          input:
//                    y - pointer to data array (float)
//                    del - time increment between points in y (float)
//                    fCut - Cutoff Frequency, -3db, indicated as Fn in SAE J211
//          return:
//                    0 on success
//                    1 on failure
//==============================================================================

int bwfilt( DBLVECTOR &y, float del, float fCut)
{
  int nTailPoints, nHalfTailPoints, i;
  double f6db, wd, wa, a0, a1, a2;
  double b1, b2, x0, x1, x2, y0, y1, y2, ynfp2;

  int nPoints = y.size();
  // Check for a positive number of points
  if (nPoints <= 0 )
```

```
{
        std::cout << " BWFILT Error - Nonpositive number of Data Points";
        return(0);
}
// Check positive time step
if (del <= 0 )
{
        std::cout << " BWFILT Error - Nonpositive time step";
  return(0);
}
// Check positive cutoff frequency
if (fCut <= 0 )
{
        std::cout << " BWFILT Error - Nonpositive Cutoff Frequency";
  return(0);
}
if ( fCut > (0.5f/del*0.775) )
{
        // sampling rate is lower than the cutoff frequency - return true
        //      BwFilt goes unstable as fCut approaches 0.5/del
        return 1;
}

// Set 6dB attenuation frequency
f6db = fCut * 1.2465;

// Compute filter coefficients per J211
wd = 6.2831853L * f6db;
wa = sin(wd * del * 0.5) / cos(wd * del * 0.5);
a0 = wa*wa / (1. + sqrt(2.0)*wa + wa*wa);
a1 = 2 * a0;
a2 = a0;
b1 = -2.0*(wa*wa - 1.0) / (1.0 + sqrt(2.0)*wa + wa*wa);
b2 = (-1.0 + sqrt(2.0)*wa - wa*wa) / (1.0 + sqrt(2.0)*wa + wa*wa);

// Set the number of tail points to use
nTailPoints = (int)(0.01 / ( min(fCut*0.01, 1.0) * del) + 0.5);

//SAE J211 reccomends at least 10 ms, increase if necessary
i = (int) (0.01 / del + 0.5);
if (nTailPoints < i)
        nTailPoints = i;

// regardless of time step and Frequency spec, use at least one point
if (nTailPoints < 1)
  nTailPoints = 1;

// Make sure that enough data points exist for the tail, else cut back tail
if (nTailPoints > nPoints)
{
        //cout << "BWFILT tail length < 10 ms, does not satisfy SAE J211 reccomendation";
        nTailPoints = nPoints;
```

```
}

// Set up pre-start array - Inverted mirror
ynfp2 = 2 * y[0];
x1 = ynfp2 - y[nTailPoints];
x0 = ynfp2 - y[nTailPoints-1];
y1 = 0.0;
nHalfTailPoints = ( nTailPoints / 2 ) + 1;
for (i=nHalfTailPoints; i<=nTailPoints; i++)
{
  y1 = y1 + y[i];
}
y1 = ynfp2 - ( y1 / ( nTailPoints - nHalfTailPoints + 1 ) );
y0 = y1;
for (i=-nTailPoints+2; i<=-1; i++)
{
  x2 = x1;
  x1 = x0;
  x0 = ynfp2 - y[-i];
  y2 = y1;
  y1 = y0;
  y0 = a0*x0 + a1*x1 + a2*x2 + b1*y1 + b2*y2;
}

// Filter forward
for (i=0; i<nPoints; i++)
{
  x2 = x1;
  x1 = x0;
  x0 = y[i];
  y2 = y1;
  y1 = y0;
  y0 = a0*x0 + a1*x1 + a2*x2 + b1*y1 + b2*y2;
  y[i] = (float) y0;
}

// setup the pre-start array for the backward filter
ynfp2 = 2 * y[nPoints-1];
x1 = ynfp2 - y[nPoints -1 -nTailPoints];
x0 = ynfp2 - y[nPoints -2 -nTailPoints];
y1 = 0.0;
for (i=nHalfTailPoints; i<=nTailPoints; i++)
{
  y1 = y1 + y[nPoints -1 -i];
}
y1 = ynfp2 - ( y1 / ( nTailPoints - nHalfTailPoints + 1 ) );
y0 = y1;
for (i=nPoints-nTailPoints+3; i<=nPoints-2; i++)
{
  x2 = x1;
  x1 = x0;
  x0 = ynfp2 - y[i];
```

```
    y2 = y1;
    y1 = y0;
    y0 = a0*x0 + a1*x1 + a2*x2 + b1*y1 + b2*y2;
  }

  // Filter backwards
  for (i=nPoints-1; i>=0; i--)
  {
    x2 = x1;
    x1 = x0;
    x0 = y[i];
    y2 = y1;
    y1 = y0;
    y0 = a0*x0 + a1*x1 + a2*x2 + b1*y1 + b2*y2;
    y[i] = (float) y0;
  }

  return(1);
}

//
//    optional entry routine to BWFILT using a channel frequency class.
//    This routines translates the J211 Channel Frequency Class into
//    specified cutoff frequency (Fn).
//
int bwfilt( DBLVECTOR &y, float del, int nClass)
{
        if ( (nClass!= 60) && (nClass!=180) && (nClass!=600) && (nClass!=1000) )
                std::cout << "Frequency Channel Class is not specified in SAE J211";

        return(bwfilt( y, del, (float)(nClass*1.666667) ));
}

//
//          overloaded function definition to allow calling with separate array
//          pointers so that the original displacement data is not overwritten
//
int bwfilt( DBLVECTOR &y, DBLVECTOR &yf, float del, float fCut)
{
        for (int i=0; i<y.size(); i++)
                yf[i] = y[i];

        return(bwfilt( yf, del, fCut ));
}
```