BENEFITS OF THE INFLATABLE TUBULAR STRUCTURE
AN INVESTIGATION ON THE CASUALTY ABATEMENT CAPABILITY OF THE BMW HEAD PROTECTION SYSTEM HPS

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ABSTRACT

Beginning in model year 1997, BMW introduced an innovative head protection system HPS called the Inflatable Tubular Structure (HPS). Tests indicate that the system dramatically reduces the severity of head impacts in side crashes.

This investigation is an evaluation of casualty abatement benefits that are derived from applying injury measures based on the HPS test results to the population in US National Accident Sampling System (NASS/CDS). The results of component and vehicle crash tests are summarized. The procedures for estimating benefits are described along with the benefits in terms of injuries mitigated, maximum injuries to occupants mitigated, and fatalities prevented.

The calculated benefits of the *HPS* in reducing fatalities and the most serious injuries to front seat occupants of passenger cars are:

Casualty Reduction for HPS

Casualty Class	Reductions
Fatalities	*1,344*
AIS 2-5 Injured	*2,598*

The impact mitigation benefits were derived from reducing injuries from head impacts to the following components: A & B pillars, side rails, window frames & glass, and window-pillar interfaces. Approximately 51% of the reductions in fatalities were attributable to the mitigation of head impacts with these components. The remaining 49% of the fatality reductions were associated with mitigation of exterior contacts and prevention of ejection through side windows.

According to the US National Accident Sampling System, the population injured in tow-away motor vehicle crashes suffers an average of about 3 injuries per person. The accounting system used in the tables above does not give credit for injury reduction when the injury is not the most severe of all injuries suffered by an injured person. If the less severe injuries are considered, there is a much larger opportunity for injury reduction. When considering all injuries, the injury reductions for the HPS system are:

HPS Injury Reductions for Front Seat Occupants, All Injuries Considered

Casualty Class	Reductions
AIS 3-6 Injuries	*3,902*
AIS 2-6 Injuries	*8,501*

The benefits cited are over and above the benefits offered by other safety systems. These systems include: frontal air bags, side air bags, FMVSS 214 side impact protection, and FMVSS 201 head protection for the vehicle roof and headers.

THE BMW HEAD PROTECTION SYSTEM HPS

In the opinion of accident researchers, in side-impact collisions top priority should be given to protecting the occupants head. Yet there was no sufficient protection device available so far.

In 1997 BMW started to equip their cars with the so called Head Protection System HPS, also known as ITS, Inflatable Tubular Structure. This device offers the opportunity of deploying a gas filled tubular cushion of about 130 mm in diameter to increase the protection of the head and face. It is offered as standard equipment for the 5 and 7 series and will also be standard fit for the new 3 series car when it is launched in a couple of weeks from now.

The HPS is a unique technology and BMW is the only company to offer an additional protection device for the occupants head and neck. The first ideas were presented at the 14th International Technical Conference on the Enhanced Safety of vehicles ESV in Munich, Germany in 1994. Its function and test results were shown in a presantation at the 15th ESV Conference two years later in Melbourne, Australia.

Since then a lot of improvement has been done and a lot of positive experience has been gained, either from tests but also from statistical analysis and accident researchers are even aware of some real life accidents in which the HPS has performed perfectly in reducing injuries.

The HPS consists of the following components:

- **Inflator** - For the production of the filling medium a pyrotechnical gas generator is installed underneath the instrument panel
- **Flexhose** - a flexible hose leads the gas flow from the inflator to the restraining cushion
- **Bladder** - a gas sealed bladder is filled with the medium and expands its diameter
- **Braid** - surrounding the bladder a braiding texture ensures the tension to contract the system

The undeployed HPS is packaged behind the interior trim parts of the A-pillar and the roof liner of each side of the vehicle. On both ends the system is fixed to the body in white. In case of a side collision with sufficient severity the inflator is activated and the system is filled with gas. During this increase of the tubular structure element, a remarkable tensioning force is created which contracts the tube.

Since the length of the stored system is longer than the shortest distance between the two anchorage points, while contacting the tubular structure is pulled out of the trim and placed in position right beneath the occupants head.

The remarkable tension provided through the effect of a change in the orientation of the fibres in the braiding material restraints the occupant's head without significant neck bending moments.

TESTING FOR EFFECTIVENESS ESTIMATES

BMW conducted a variety of tests to assess the reduction in HIC offered by the HPS. These tests included sled tests with dummies, tests with the Free Motion Headform (FMH) specified in FMVSS 201, and vehicle side impacts with moving barriers and poles. A list of test result samples is shown in Table 1.

Table 1
Test Results Tests With and Without HPS

Test Type	Configuration	Delta-V kph	HIC w HPS	HIC w/o HPS
Vehicle	ECE R 95 Side	20	90	97
Vehicle	FMVSS 214	17.5	212	193
Vehicle	Rigid Pole	30	277	2495
Vehicle	Rigid Pole	32	620	4720
Vehicle	Moving Pole	40	475	1867

The test data shows large reductions in the head injury criteria (HIC) for tests conducted in accordance with US and European side impact procedures. In addition, tests into rigid and moving poles show dramatic HIC reductions - much larger than could be expected with a practical thickness of conventional padding.

Severe crash tests into a rigid pole at 20 mph have been conducted independently by the Insurance Institute for Highway Safety. Results are included in Table 1 (Rigid Pole 32 kph).

Rollover tests conducted by NHTSA have demonstrated the ejection prevention capability of the HPS.

In static deployment tests the HPS was deployed against a dummies head to evaluate potential risks in Out Of Position situations. A 5th percentile female dummy was leant against the side glazing such that the HPS contacted the top of the head when the deployment speed was on its maximum. In this test the maximum axial neck force was .7 kN. This is well below any dangerous values.

APPROACH TO THE BENEFITS ANALYSIS

When deployed, the HPS provides primarily protection of a front seat occupant's head and face against impacts with a car's: A-Pillar, B-Pillar, Side Rail, Window Frame & Glass, Window Pillar Interfaces, and other upper side interior car components.

In addition to casualty abatement as cited above, the HPS, when deployed, is capable of reducing occupant ejections through front side windows. Consequently, the HPS reduces injuries and casualties associated with all external injuring sources, for the ejected occupants at issue.

The first objective of this investigation is to identify all head and face injuries, and injury outcomes in tow-away car crashes, associated with an occupant's crash contacts for which the HPS has the ability to influence.

The second and most important objective of the investigation is the evaluation of casualty abatement benefits that derive from the HPS. More detailed data on the non-applicable contacts may be found in the final report of the study (Digges, 1997).

DATA SOURCES

Due to the demand for high resolution of car, occupant, and injury attributes in this investigation, the NASS/CDS file is the main source of data. The available nationally representative samples in this file, for 1988-1995, include about: 44,000 towaway cars, 91,000 crash involved occupants, and 188,000 injuries, before projection to national estimates.

The sample volumes cited above are generally adequate for addressing the issues of this investigation with sufficient resolution concerning: crash modes, injury attributes including severity and injuring contact, and occupant outcomes.

CATEGORIZATION OF CAR OCCUPANT INJURIES

The annual incidence of car occupant injuries is classified in this investigation on the basis of several injury and occupant attributes, crash configurations, and HPS applicability domains. Specifically the following classes and subclasses are distinguished and applied in the estimation procedure of injury reduction and outcome abatement.

The injuries at issue are head and face injuries, AIS=1-6, due to contacts with upper interior parts and surfaces of cars, specifically: A Pillars, B Pillars, Other Pillars, Window Frames & Glass, Window-Pillar Interfaces, Side Rail, Front Headers, Rear Headers, and injuries to any body region due to exterior contacts of car occupants ejected or partially ejected through the front windows.

The annual US incidence of the cited injuries is: 182,855. This is about 4.6% of the total 4,040,000 injuries sustained each year by car occupants in the US. The balance of injuries (4,040,000 - 182,855) are not at issue here, since these injuries may not be influenced by HPS application.

The universe of injuries at issue here, about 182,855 per year, is partitioned and analyzed in all possible combinations of relevant crash configurations, injuring contacts, and injury severities. A total of 186 combinations of AIS, Injuring Contacts, and Crash Configurations results.

CRASH CONFIGURATIONS

For accounting convenience, eight crash/occupant configurations were defined. Five were configurations in which the HPS can influence the outcome. These are defined as applicable configurations. The crash configurations applicable to ITS mitigation are: (1) No Rollover, No Ejection; (2) Rollover, No Ejection; (3) No Rollover, Ejection; (4) Rollover, Ejection; and (5) Too Severe (Catastrophic Vehicle Damage). The configurations not applicable to HPS protection ar: Front or Rear Header Contacts and Rear Seat Occupants. HPS effectiveness is based on all injuries in the crash configurations listed above which are applicable to HPS deployment.

EXCLUSION OF BENEFITS

Catastrophic crashes are excluded from HPS benefits. These are defined as crashes with either (1) total delta V over 60 mph; or (2) lateral delta V over 40 mph; or (3) extent of damage 4 or higher in CDC scale, when the specific side impact location includes the passenger compartment.

Injuries of rear seat occupants are excluded from HPS benefits, and so are all occupant injuries due to front and rear headers. Such injuries are abated by countermeasures other than the HPS, that may act concurrently. All exterior contact injuries of ejected car occupants benefit from HPS deployment, only if the occupants are ejected via front windows; benefits of qualified ejectees are discounted by 20% in reflection of side effect injuries incurred as a result of retention within the passenger compartment by HPS action.

CONSEQUENCE OF OTHER COUNTERMEASURES

The 1988-1995 NASS data does not adequately reflect the benefits of recently introduced safety improvements. Two of these improvements are: (1) frontal air bags and (2) upper interior head protection. The frontal air bags have been phased in during the past four years, and the upper interior head protection will be phased in during the following four years. Each of these safety systems will reduce the NASS reported level injuries for head and face impacts. Some of the protection provided by these systems supplements the protection provided by the HPS. The presence of the frontal air bag will provide a high level of protection against head and face impact with the A-pillar. The upper interior head protection will reduce the severity head and face impacts with the pillars, side rails and headers. In cases in which it deploys, the

HPS is expected to provide much greater head protection for relevant impacts than that offered by other countermeasures.

A supplemental benefit is applicable in case of no HPS deployment for head and face injuries from contact with the A Pillars. The benefit is achievable by virtue of the main air bag and is applicable for cases of total delta V over 15 mph, i.e. main air bag deployment, irrespective of HPS deployment. The specific benefit is that all head and face injuries due to contact with the A Pillars are reduced to an AIS=1 severity.

Another supplemental benefit is applicable to contacts with A-pillars, B-pillars and side rails in cases of no HPS deployment. Head protective padding on these interior surfaces will limit the HIC to 1000 when tested with the Free Motion Headform (FMH) specified in FMVSS 201, at an impact speeds of 20 km/hr (12 mph).

Adjustments were made to the NASS 1988-95 data to reflect the injury reductions from the two supplemental benefits listed above, under crash conditions in which the HPS does not deploy. The adjustments were made only to contacts which are relevant to HPS protection.

Other safety improvements are likely to enhance the protection offered by HPS. These include improved side impact protection and side air bags for the chest and pelvis. These improvements mitigate the most serious injuries body regions other than the head. The combination of features will further reduce the overall severity of injuries and impairment to the occupant. These improvements do not address head/face injuries and no adjustment for these additional safety features is considered in this analysis.

The increasing use of safety belts in the United States may also reduce injuries in side impacts, irrespective of the HPS. Some of the increases in safety is being offset by the increasing number of light trucks, sport utility vehicles and large cars in US highways. These vehicles increase the severity of side crashes. No adjustment was made for these offsetting factors.

HPS DEPLOYMENT CRITERION

The primary HPS deployment criterion is a lateral delta V of approximately 24 km/hr (15 mph) or higher in planar crashes, irrespective of subsequent rollover. A 30% deployment is applicable for rollovers, based in an analysis of accident data.

HPS Abatement Schedule

Except for the supplemental benefit cited above, the basic mechanism for reduction of head and face injury severities is the large reduction of HIC offered by the HPS when deployed. The HIC associated with a deployed HPS, as a function of lateral delta V, has been determined by test data as shown in the points of Figure 1. The line in this figure represents a best fit to the points, i.e. HIC=18.8*latdv, where latdv is in mph.

Figure 1:
Vehicle Crash Severity Vs. HIC for HPS

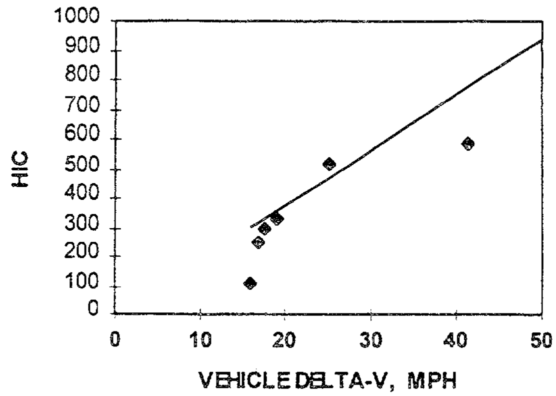
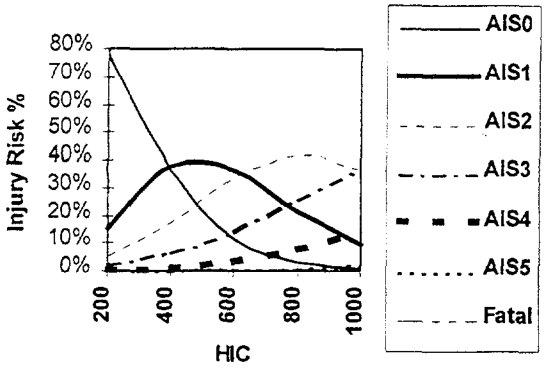


Figure 1 provides the basis for translating the crash severity values for each crash in NASS/CDS to values of HIC experienced by occupants when the HPS is deployed. In turn, the experienced HIC values are translated into sustained head or face injury severities (AIS), as per NHTSA's preferred ways [NHTSA, 1995]. The relationships are:

%AIS1 = 100/[(1+exp(1.54+(200/hic)-.00650*hic))-
(1+exp(2.49+(200/hic)-.00483*hic))];
%AIS2 = 100/[(1+exp(2.49+(200/hic)-.00483*hic))-
(1+exp(3.39+(200/hic)-.00372*hic))];
%AIS3 = 100/[(1+exp(3.39+(200/hic)-.00372*hic))-
(1+exp(4.90+(200/hic)-.00351*hic))];
%AIS4 = 100/[(1+exp(4.90+(200/hic)-.00351*hic))-
(1+exp(7.82+(200/hic)-.00429*hic))];
%AIS5 = 100/[(1+exp(7.82+(200/hic)-.00429*hic))-
(1+exp(12.24+(200/hic)-.00565*hic))];
%AIS6 = 100/[(1+exp(12.24+(200/hic)-.00565*hic))];
%AIS0 = [100-(%AIS1+%AIS2+%AIS3+
%AIS4+%AIS5+%AIS6)]

where %AIS1, 2, 3, etc. are the projected probabilities, in percent, of head or face injury occurrence at shown AIS severities. The graphical representation of these relationships is shown in Figure 2.

Figure 2:
Relationship Between HIC and Injury Risk



In addition to the reduction of head and face injuries originating from interior contacts, injuries to any body region due to exterior contacts are all but eliminated. Earlier studies indicated an 80% reduction in injuries was attributed to occupant containment within the vehicle (Malliaris, 1985). The mechanism in effect in this case is the HPS prevention of ejection for qualified occupants. BMW studies of accident data indicate that 30% of rollovers have a lateral acceleration of sufficient magnitude to deploy the HPS.

INJURY OUTCOME

The principal benefit of the HPS is to mitigate head and facial injuries. In instances where ejection is not involved, the HPS is assumed to have no influence on mitigating injuries to other body regions. However, for occupants with multiple injuries, the reduction of any of the most severe injuries reduces the risk of death and impairment.

The benefits analysis to follow addresses injury outcomes at three categories - Category 1, *Individual Injuries*; Category 2, *Most Severe Injuries*; and Category 3, *Fatalities*.

Most injured occupants suffer multiple injuries. On average, injured occupants in NASS have 3.4 injuries. It should be noted that NHTSA's benefit analysis for FMVSS 201, considers only those injured occupants whose most severe injury is a head or face injury. No benefits are assigned to reducing head and face injuries present. Consequently, many of the head and face injuries reduced by the countermeasure are not considered. The Category 1, *individual injury,* benefits considers all relative injuries, without regard to the outcome of the injured occupant. This approach may over count the benefits, since a sall number of the injured occupants may die from injuries to body regions which are not influenced by the HPS.

For Category 1, *individual injury,* benefits the appropriate NASS records of crash exposed car occupants are addressed for each injury as implied by configuration, injuring contact, and injury severity. A computer algorithm is applied which incorporates the abatement schedule containing categorical information about: (a) the HPS effectiveness in reducing injury severity based on HIC reduction; (b) applicability limits; and (c) side effects. The first pass is made assuming no HPS action. Subsequently, a second pass is made assuming full HPS action under the conditions and exceptions discussed earlier. Thus are obtained the projected injury reduction benefits offered by an HPS application, and the percent effectiveness of this application, defined as: (before-after)/before.

The Category 2, *most severe injury,* benefits examines the outcomes of injured survivors, by the AIS level of their most severe injury (MAIS). Injury reduction is applied only if the mitigated injury is the most severe injury. This approach under counts the benefits, because reductions in impairment from head injury may not be counted when the head injury is not the most severe injury.

The relatively simple procedure described for evaluating the reduction of individual injuries is not applicable in the evaluation of outcomes, as an occupant's outcome is not the result of a single injury. Rather, it is the collective effect of all injuries incurred by this occupant.

For each injured survivor, the entire set of an occupant's up to 45 injuries is addressed. Each occupant's maximum injury severity and the corresponding classification attributes (injuring contact, injured body region etc.) are determined before, as well as after an abatement schedule has been applied.

An occupant's classification by most severe injury is subject to a further control, namely: no abatement of an applicable injury, e.g. head or face injury by upper interior car component, is registered when there is one or more non-applicable injuries of equal severity for the same occupant.

Thus, counts of occupants by most severe injury, (both before and after abatement application) in conjunction with other injury attributes become the basis for the most straightforward evaluation of outcomes for injured survivors.

The Category 3, *fatality,* benefits are based on fatality risk reductions associated with reducing individual head and face injuries. The procedure followed in the estimation of fatalities, either before or after the application of an abatement schedule, is based on the assignment of a fatality probability for each occupant in the crash records, based on the severities of the three most severe injuries of this occupant, and the occupant's age, irrespective of any other injury attributes.

The fatality probability in question is obtained from and calibrated by all available crash involved car occupant records. For this purpose a logistic regression is applied that models successfully the probability of fatality as a function of the injury severities of an occupant's three most severe injuries, and the occupant's age. With the help of this information a fatality probability is assigned to each and every occupant in the pertinent crash records. The fatality risk is assessed first before and then after application of the instructions provided by the abatement schedule under consideration.

Occupants that have none of their three most severe injuries eliminated or abated, show up with the same fatality probability both before and after application of the abatement schedule. Occupants with injuries that qualify for abatement, show up in the after abatement records with a fatality probability that is reduced with respect to that before abatement.

The sum of all occupants on record, either before or after abatement, with each occupant weighted by the corresponding probability of fatality, is the number of projected fatalities, either before or after abatement. Note that the fatality probability as a weighing factor is applied over and above the familiar inflationary weight, used to derive national estimates from the NASS samples.

This accounting method offers, among other advantages, estimation of fatality reduction, and automated accounting of injuries and injured occupants. At the same time the applied approach prevents double counting of potential benefits, irrespective of abatement schedule complexity.

SUMMARY OF RESULTS

The results of the Category 1, *individual injury* benefits analysis are summarized in Table 2. The annual reduction of AIS 2+ head and face injuries is 6502, with an effectiveness of relevant contacts equal to 34%. The annual reduction of AIS 3+ injuries is 3015, with an effectiveness of relevant contacts equal to 49%.

Table 2
Annual Incidence of Head and Facial Injuries Before and After HPS - Occupants not Ejected

AIS	Before HPS	After HPS	HPS Benefit	% Reduction
6	70	30	40	57%
5	1148	567	581	51%
4	1597	886	711	45%
3	3381	1698	1683	50%
2	12941	9454	3487	27%
2+	19137	12635	6502	34%
3+	6196	3181	3015	49%

In addition, to the head injury reduction, there are injury reductions to all body regions for occupants who are prevented from ejection through side windows by the deployed HPS. The results are summarized in Table 3. The AIS 2+ injury reduction is 1999, with an effectiveness of 32%. For AIS 3+ injuries, the reduction is 887 for an effectiveness of 35%.

Table 3
Annual Incidence of Ejection Injuries With and Without HPS

AIS	Before HPS	After HPS	HPS Benefit	% Reduction
6	129	90	39	30%
5	272	121	151	56%
4	469	302	167	36%
3	1630	1100	530	33%
2	3754	2642	1112	30%
2+	6254	4255	1999	32%
3+	2500	1613	887	35%

The results of the Category 2, *most severe injury*, benefits analysis for non-ejected occupants is summarized in Table 4. This analysis applies the Category 1 injury reductions to each injured survivor in the NASS file, and reduces the maximum AIS (MAIS) for the survivor only when the mitigated injury is their most severe injury.

Table 4
Annual Incidence of Injured Survivors by Max. Injury Severity (MAIS) With and Without HPS for Target Population -Occupants not Ejected

MAIS	Before HPS	After HPS	HPS Benefit	% Reduction
5	432	251	181	42%
4	151	95	56	37%
3	1295	1054	241	19%
2	9812	7855	1957	20%
2+	11690	9255	2435	21%
3+	1878	1400	478	25%

The reductions Category 2, *most severe injury*, by HPS ejection prevention are shown in Table 5.

Table 5
Annual Incidence of Injured Survivors by Max. Injury Severity (MAIS) With and Without HPS for Ejected Population

MAIS	Before HPS	After HPS	HPS Benefit	% Reduction
5	51	12	39	76%
4	56	46	10	18%
3	271	238	33	12%
2	990	909	81	8%
2+	1368	1205	163	12%
3+	378	296	82	22%

The results of the Category 3 (fatality) benefits analysis is summarized in Table 6. This analysis applies the Category 1 injury reductions to each fatally injured occupant in the NASS file, and reduces the fatality risk for those injuries mitigated by the HPS.

Table 6
Annual Incidence of Fatalities With and Without HPS by Shown Target Population

Fatalities	Before HPS	After HPS	HPS Benefit	% Reduction
Non Ejection	1858	1166	692	37%
Ejection	1695	1043	652	38%
Total	3553	2209	1344	38%

A summary table of the total benefits of HPS is shown in Table 7.

Table 7
Summary of Injury and Fatality Reductions by HPS

Totals	Before HPS	After HPS	HPS Benefit	% Reduction
AIS 3+ Injuries	8696	4794	3902	45%
AIS 2+ Injuries	25391	16890	8501	33%
MAIS 3+ Injuries	2256	1696	560	25%
MAIS 2+ Injuries	13058	10460	2598	33%
Fatalities	3553	2209	1344	38%

When examined by crash mode, 23% of the fatality reductions were in crashes which included rollovers. The resulting casualty reductions in rollover crashes are shown in Table 8.

Table 8
Casualty Reduction for HPS in Rollover Crashes

Casualty Class	Reductions
Fatalities	306
AIS 2-5 Injured	382

CONCLUSIONS

The test results of the HPS show dramatic reductions of head injury criteria in very severe crashes. Independent vehicle testing by IIHS demonstrated that injury measures could be drastically reduced in a pole crash which was previously considered unsurvivable. In addition, ejection prevention of the HPS in rollovers has been demonstrated by NHTSA.

Based on the available test data, and the exposure to injuries predicted by NASS/CDS 1988-96, the HPS is estimated to prevent 1,344 fatalities annually if applied to the entire passenger car fleet. In addition, 8,500 AIS 2+ injuries would be mitigated, and 2,500 AIS 2+ injured survivors would have reduced head and face injuries.

The effectiveness of the HPS is estimated at 33% in fatality reduction, 45% for AIS 3+ injuries, and 33% for AIS 2+ injuries.

The estimated HPS casualty reduction is as large as that of the recent US standards in side impact protection and upper interior head protection.

REFERENCES

Digges, K., and Malliaris, A., "Benefits Analysis of the *Inflatable Tubular Structure* (HPS), *Report to* BMW, August, 1997.

Malliaris, A., and Digges, K., "Crash Protection Offered by Safety Belts", Proceedings of the Eleventh International Conference on Experimental Safety Vehicles, p.242-252, May 1987.

Kompass K., Haberl J. and Messner G., „Field study on the potential benefit of different side airbag systems", The 15th International Technical Conference on the Enhanced safety of vehicles, Melbourne, Australia, 1996

NHTSA, 1995, "Final Economic Assessment; FMVSS No. 201, Upper Interior Head Protection", NHTSA Plans and Policy, June 1995