SAE TECHNICAL
PAPER SERIES

960093

Delta-V Thresholds for Cervical Spine Injury

Murray Kornhauser
EM Systems, Inc.

Reprinted from: Technologies for Occupant Protection Assessment
(SP-1174)

The Engineering Society
For Advancing Mobility
Land Sea Air and Space®
INTERNATIONAL

International Congress & Exposition
Detroit, Michigan
February 26-29, 1996

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (412)776-4841 Fax:(412)776-5760

The appearance of the ISSN code at the bottom of this page indicates SAE's consent that copies of the paper may be made for personal or internal use of specific clients. This consent is given on the condition however, that the copier pay a $7.00 per article copy fee through the Copyright Clearance Center, Inc. Operations Center, 222 Rosewood Drive, Danvers, MA 01923 for copying beyond that permitted by Sections 107 or 108 of U.S. Copyright Law. This consent does not extend to other kinds of copying such as copying for general distribution, for advertising or promotional purposes, for creating new collective works, or for resale.

SAE routinely stocks printed papers for a period of three years following date of publication. Direct your orders to SAE Customer Sales and Satisfaction Department.

Quantity reprint rates can be obtained from the Customer Sales and Satisfaction Department.

To request permission to reprint a technical paper or permission to use copyrighted SAE publications in other works, contact the SAE Publications Group.

GLOBAL MOBILITY DATABASE

All SAE papers, standards, and selected books are abstracted and indexed in the Global Mobility Database.

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

ISSN 0148-7191
Copyright 1996 Society of Automotive Engineers, Inc.

Positions and opinions advanced in this paper are those of the author(s) and not necessarily those of SAE. The author is solely responsible for the content of the paper. A process is available by which discussions will be printed with the paper if it is published in SAE Transactions. For permission to publish this paper in full or in part, contact the SAE Publications Group.

Persons wishing to submit papers to be considered for presentation or publication through SAE should send the manuscript or a 300 word abstract of a proposed manuscript to: Secretary, Engineering Meetings Board, SAE.

Printed in USA 96-0049

960093

Delta-V Thresholds for Cervical Spine Injury

Murray Kornhauser
EM Systems, Inc.

ABSTRACT

Delta-V is an input parameter that correlates well with injury thresholds for responses to impulsive loading, and it is also convenient for the accident reconstructionist to calculate the delta-V experienced by the automotive passenger during a crash. The purpose of this paper is, therefore, to convert to delta-V quantities the cervical spine injury data currently expressed in terms of loading corridors of head bending moment versus angle of rotation of the head. 16 km/hr is an order of magnitude of the delta-V threshold for the 50th percentile male, but there are considerable variations due to size, age, gender, and pre-existing spinal problems.

The special case of the rear-ender accident involving vehicles with energy absorbing bumpers is analyzed. It is found entirely possible to produce "whiplash" injuries in cases where there is little or no damage to either of the vehicles involved in the crash.

HISTORY OF THE DELTA-V/INJURY THRESHOLD METHOD

There is a conventional, two-step, method of relating injury to the input conditions that caused the injury. First, calculation is made of the relative dynamic deflection of the body member, in response to the forces or accelerations applied to that member. Second, injury level is determined by comparing the degree of mechanical response, or deflection, with a data base of injuries that have been produced at the same response level. The predictive accuracy of this method depends on knowledge of the input parameters (typically determined by the accident reconstruction specialist), on the adequacy of the input-response calculation methodology, on the accuracy of characterization of the dynamic mechanical properties of the body members of the individual experiencing the accident, and on the adequacy of the data base of injuries versus response levels.

An alternative method exists, using delta-V as the single input parameter. This method has the virtue of bypassing the response calculation, by correlating injuries directly with a delta-V injury data base. Both the input/mechanical response/injury method, and the delta-V injury method have limited predictive accuracy. However, the latter method is much more convenient to use for the accident reconstructionist who also makes biomechanical predictions. It is therefore the purpose of this paper to begin the process of establishing an injury/delta-V data base for "whiplash", or cervical spine injury in the automotive environment.

The delta-V/injury concept

dates back to the 1940's with DeHaven's work (1) correlating survival threshold with height of free fall, with Kornhauser's work (2) in the 1950's relating inanimate structural failures to delta-V, and Kornhauser and Gold (3), who extended the delta-V/failure concept toward definition of whole body injury/delta-V thresholds. Work on delta-V thresholds for whiplash injuries was conducted in the 1950's by Severy and Mathewson (4) by impacting a stationary car with a second car moving at approximately 16 km/hr. Delta-V of the impacted vehicles are shown in Table 1, taken from Mertz and Patrick (5). Note that these old vehicles did not have energy absorbing bumpers, which would have changed the relationship between impact velocity and delta-V of the car being struck. However, it is noteworthy that Mertz and Patrick characterize the first entry in Table 1 as "nonsevere" and the other two entries as "severe" rear-end collisions. Supposedly, therefore, Mertz and Patrick would select a whiplash injury (of some kind) threshold delta-V as somewhere between approximately 15 and 24 km/hr, on the basis of these data.

Table 1 - Pertinent Kinematic Parameters from Car-to-Car Rear-End Collisions, from Mertz and Patrick (5)

STRUCK CAR KINEMATICS

Struck Car	Impact Velocity, mph	Velocity Change, mph	Pulse Time, ms	Peak Accel., g	Mean Accel., g	Accel. Dist, in.
1956 Olds	10	9.1	135	5.9	3.07	10.8
1956 Olds	23	14.8	132	10.0	5.10	17.2
1955 Nash	23	15.2	135	10.3	5.13	18.1

The data base of delta-V related to cervical spine injury is quite sparse. Except for the meager data on hyperextension injury delta-V as shown in Table 1, some data on cervical fractures in the flexion mode (see Figure 1 for the mode of terminology used in this paper) by Roberts and Compton (6), and statistical data by K.H. Digges (7) on overall head and neck injury levels versus delta-V for frontal and side crashes, are the only injury data expressed in terms of delta-V inputs. Fortunately, however, much delta-V data can be derived from the data base on loading corridors for the neck movements shown in Figure 1.

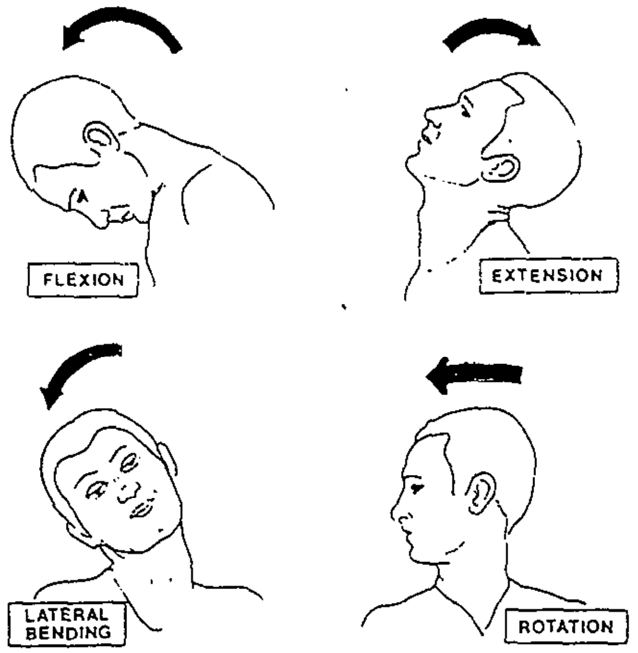

Figure 1. Head & Neck Movements

INJURY DATA FOR INERTIAL LOADING OF THE HEAD-NECK COMPLEX

Mertz and Patrick (5) and (8) and others conducted extensive research on the head-neck complex using human volunteers and cadavers.

Test data were presented in the idealized form of loading corridors, or plots of bending moment about the head-neck junction versus head rotation angle relative to the torso. Only the loading portion of the corridors (omitting the unloading curves) are taken from Nyquist and King in a review report by Melvin and Weber (9), and presented in Figures 2,3, and 4.

Various input levels of applied moment and rotation angle are added to the original versions of Figures 2-4 for purposes of indicating injury levels graphically. In Figure 2 for neck flexion in the forward direction, there were no ligamentous or disc or bone damages even for applied moments as high as 190 Newton-meters. However, the authors indicate the possibility of

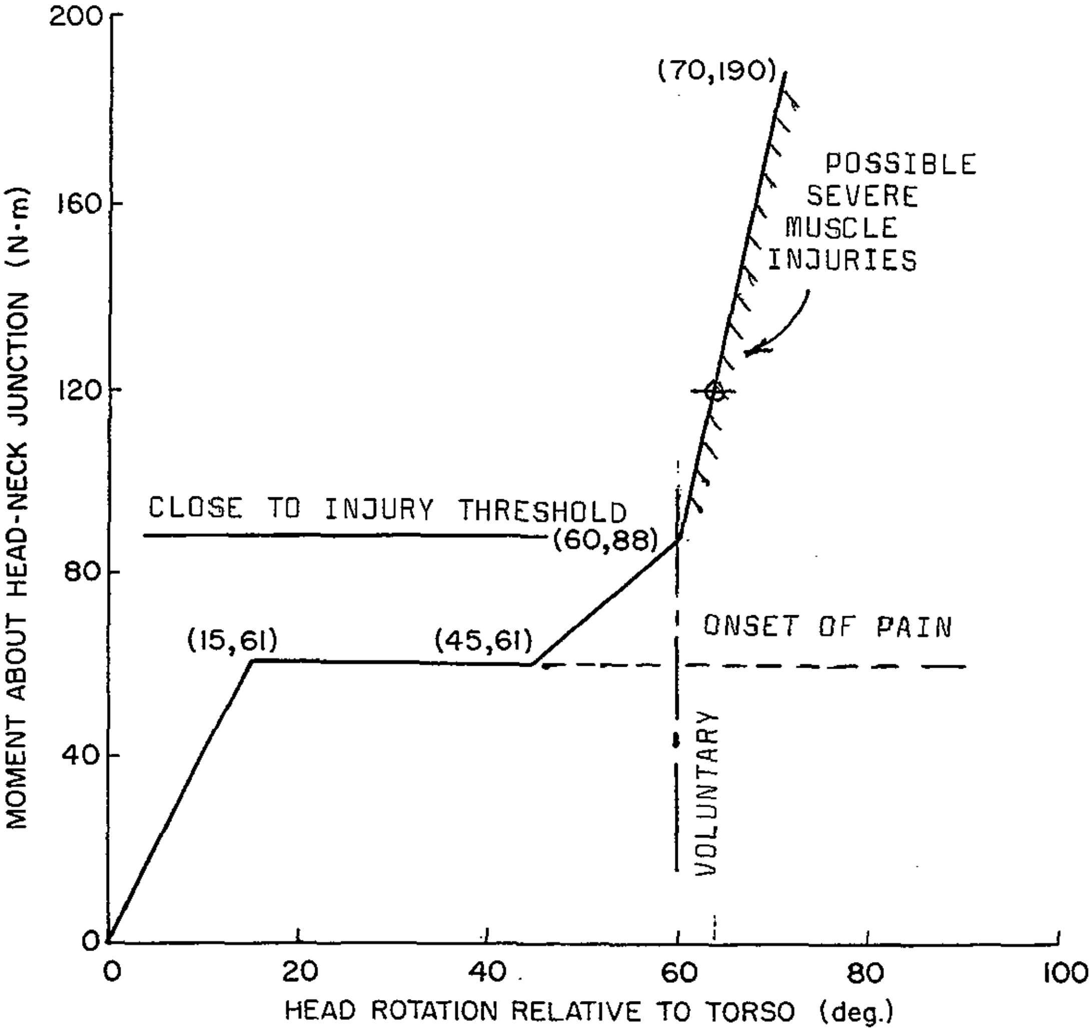

FIGURE 2 Loading corridor for neck flexion (forward bending) based on Mertz et al. 1973.

severe muscle injuries above approximately 88 Newton-meters. Therefore, an injury threshold has been selected arbitrarily at 120 Newton-meters for the flexion mode of the 50th percentile male.

In the extension mode of rearward bending, which is the so-called "whiplash" mode, the injury threshold has been selected as 57 Newton-meters. In lateral flexion, shown in Figure 4, there appears to be little data on injury levels. Instead, there are test results indicating that volunteers tolerated a maximum 40 degree lateral rotation relative to the torso. Accordingly, in the absence of additional data, the injury threshold is taken as 54 Newton-meters, which is where the 40 degree angle intersects the lateral flexion loading curve.

To summarize, injury threshold moments for the 50th percentile male are selected as 120 N-m in flexion, 57 N-m in extension, and 54 N-m for lateral flexion.

Size, weight, gender, age, and a host of other factors are expected to affect individual injury thresholds. In regard to voluntary range of motion of the head relative to the torso, Mertz and Patrick (8) summarize the data available for females and males in various age groups. Females are approximately 10 percent more flexible than males in extension, and approximately 4 percent more flexible in flexion. Total rotational excursion for males and females decreases from approximately 139 degrees in the 15-24 year old group, to approximately 116 degrees in the 55-64 year old

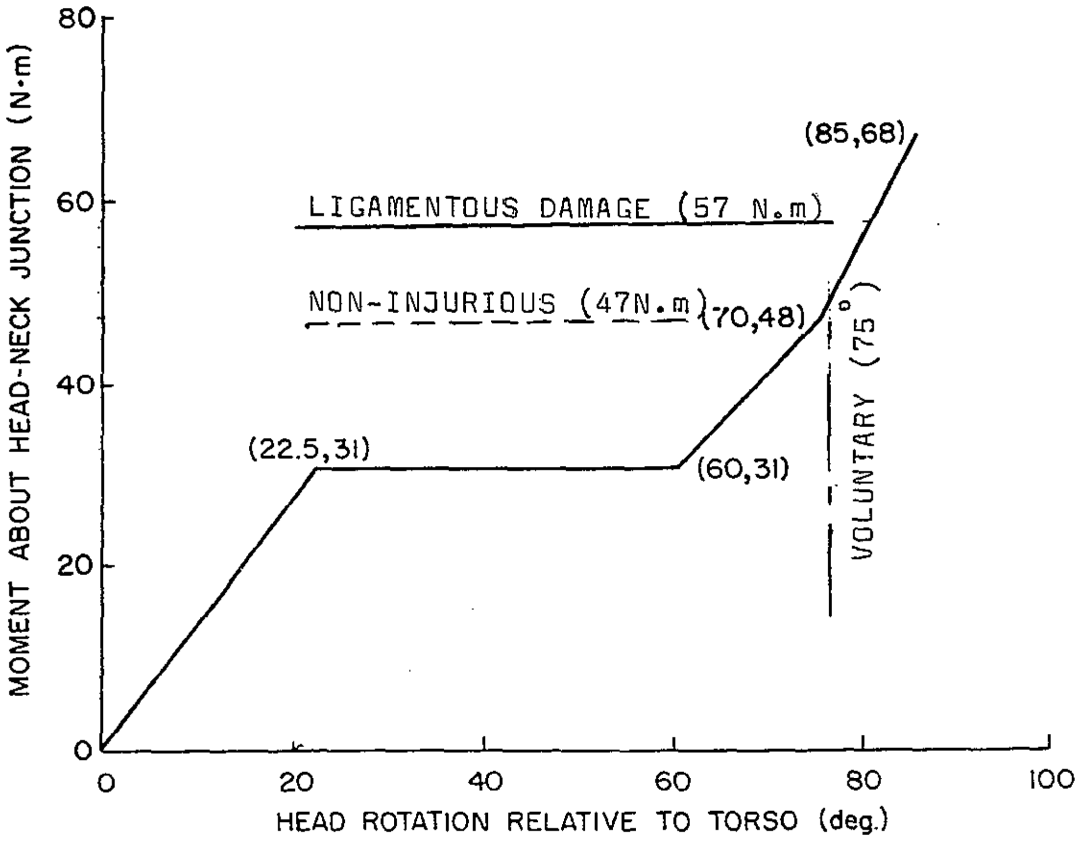

FIGURE 3 Loading corridor for neck extension (rearward bending) based on Mertz et al. 1973.

group, a decrease of approximately 16 percent.

In regard to muscular strength, Nyquist and King (9) report that males are stronger than females by a factor of about 1.5. The ratio between isometric forces exerted by middle-age males (142.8 N) and elderly females (52.5 N), is a factor of 2.72.

Vertebral strength is known to decrease with age, particularly for women with osteoporosis. Nyquist and King (9) cite a decrease in strength of vertebral endplates of over 50 percent between the second and sixth decade of life.

In terms of the probablity of injury, Schutt and Dohan (10) reported that women were 4.8 times

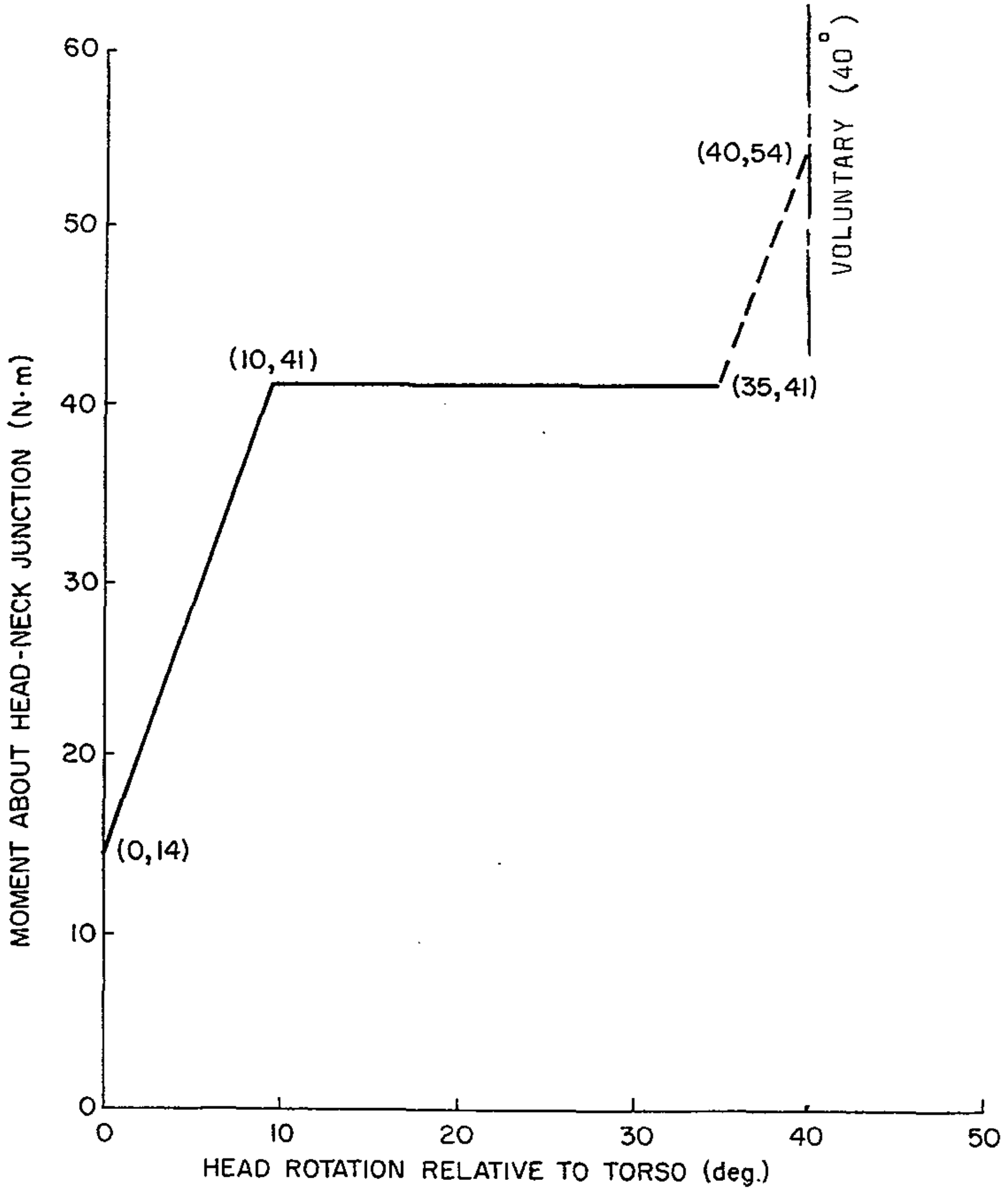

FIGURE 4 Lateral flexion response envelope established by Patrick and Chou (1976).

more likely to receive a whiplash than males in urban areas and 1.7 times more likely in rural areas.

In view of rather large differences in muscular strength, some differences in flexibility, and large differences in vertebral strength, no attempt is made here to define individual delta-V injury differences from the 50th percentile male threshold data. Scaling for size differences and adjusting for age, gender, and physical condition at the time of the crash are all subjects that cannot be treated in this brief paper.

DELTA-V VS. G STRENGTH

The basic concept of delta-V characterization of structural strength, as opposed to the conventional static g-strength characterization, has been developed by Kornhauser (2, 11) in some detail. Without entering into the complexities of that development, one may simplify the overall concept by considering the response and failure of any particular structure in two extreme environments; the short duration, or impulsive loading regime, and the long duration, or static loading regime. In the impulsive regime, it is demonstrated that delta-V is the parameter that best characterizes structural strength. In the static regime, g-strength is the appropriate characterization. Note that "short" or "long" duration of loading is relative to the fundamental natural period of vibration of the structure. As a rule of thumb, short duration loading exists when the loading duration is one-quarter or less of the natural period. By use of delta-V for classifying strength of the head-neck complex, the assumption has been made that the natural period of response of the head-neck complex is at least 4 times as long as the input loading duration. Figures 2-4 provide the empirical data necessary to validate this assumption.

The formula for calculating the natural period of a mass-spring system is as follows:

$$\tau = 2\pi(M/K)^{\frac{1}{2}} \qquad (1)$$

where M is the mass and K is the spring constant. In this case of angular motion, with moment or torque T moving through angle θ, with the mass moving at radius R (taken as 150mm from the occipetal condyles to the center of gravity of the head), the formula for K is as follows:

$$K = T/R^2\theta \qquad (2)$$

Figures 2-4 indicate an initially steep slope of the T-θ curve, but the average slopes, measured up to the injury point, are appropriate for calculating an average period of response. Average periods are given in Table 2.

Loading periods of the order of 50-80 milliseconds or less will qualify as impulsive, while longer duration inputs will tend to make delta-V alone a less rigorous characterization. During auto crashes, the loading times are essentially impulsive, and the delta-V method is good.

Table 2 - Calculation of Natural Period of the Head-Neck Complex

Deflection Mode	Slope of T-θ Curve, N-m/Deg.	Period, Msec
Lateral Flexion	1.00	274
Extension	0.71	325
Flexion	1.85	202

CALCULATION OF DELTA-V THRESHOLDS FOR CERVICAL SPINE INJURY

When calculating the dynamic responses of an inanimate structure consisting of a cantilever beam with a concentrated end mass, it may be shown that this system may be treated as a single-degree-of-freedom system with a concentrated mass equal to the end mass plus 0.23 times the mass of the beam. Idealizing the head-neck complex in this manner, the total mass experiencing a delta-V relative to the torso is taken as a 4.54 kg head mass plus 0.23 times a 1.45 kg neck mass, for a total mass of 4.87 kg. The kinetic energy of this mass, moving at velocity V relative to the torso, is equated to the area under the moment-angle loading curve (Figs. 2-4) as follows:

$$\tfrac{1}{2}MV^2 = \int T d\theta \qquad (3)$$

where M is the total mass defined above, T is torque or applied moment, and θ is head rotation angle. Table 3 contains the results of applying Equation 3 to the data in Figures 2-4.

Equation 3 indicates that delta-V varies as the square root of the injury threshold moment, which itself depends on muscular strength and vertebral strength. Therefore, a reduction in vertebral strength to 50 percent will result in a reduction of delta-V to 70.7 percent, and a reduction in isometric strength to 36.8 percent (equal to 1/2.72) will result in a delta-V to 60.6 percent. The delta-V characterization of injury thresholds is therefore much less sensitive than individual variations in strength and mass. It is therefore more generally useful to the accident reconstructionist who attempts to demonstrate the potential of an automotive crash to produce injury.

THE COLLISION DYNAMICS THAT RESULT IN DELTA-V

On frontal impact, the seatbelt system restrains the torso and lower body in the seat, and inertia loading on the head tends to bend the head forward in the flexion mode shown in Figure 1. For a barrier crash of a vehicle without an energy absorbing bumper, delta-V is equal to the vehicle's initial velocity. For a multi-vehicle crash, the accident reconstructionist must analyze the crash dynamics, making use of the principles of momentum exchange and energy conservation as applied to all the evidence available in the form of tire marks, vehicular deformations, etc.

Side impact presents an additional problem, besides inertial motions relative to the seat, since the door may still be deforming and

Table 3 - Calculation of Delta-V for Cervical Spine Injury

Mode of Loading	Injury Threshold, N-m	Area, N-m-Deg.	V,mph	V,km/hr
Flexion	120	3,412	11.1	17.8
Extension	57	2,169	8.83	14.2
Lateral Flexion	54	1,135	7.42	11.9

moving relative to the rest of the struck vehicle when it comes in contact with the inertially moving driver or passenger. Another source of complexity may be rotational accelerations caused by impacts away from the center of gravity of the struck vehicle. In side impacts, the primary response of the driver may be in the lateral bending mode shown in Figure 1.

It is not the primary purpose of this paper to discuss the techniques of accident reconstruction. However, the introduction of energy absorbing bumpers can result in situations that confuse the layman and the accident reconstructionist. Namely, in some instances where a vehicle is rear-ended, individuals in the struck vehicle will experience cervical spine injury, or "whiplash", even when there is very little or no sheet metal damage to the vehicles. It is therefore important to analyze the dyamics of rear-end collisions, to see if injury in the extension mode is consistent with the nominal 14.2 km/hr delta-V threshold shown in Table 3.

Figure 5, taken from States (12), shows head deflections of a driver who has been rear-ended, when there is no head rest on the back of the seat. Injury is produced by motion of the head relative to the torso. Even with a headrest, whiplash can be produced by bending of the cervical spine. First, most people do not drive in the perfectly erect posture that would be required to place the back of the head against the headrest. Observation of the posture of several drivers shows gaps of the order of 18 to 25 cm between the back of the head and the front of the headrest. In a rear end collision, the seat is projected forward and the inertia of the head tends to drive the head back toward the headrest, thus producing backward bending of the spine. To make matters worse, there may be differential rebound from the headrest and seatback. The chest and shoulders may rebound beneath the head, hyperextending the neck. Figure 6, taken from States (12), shows these effects.

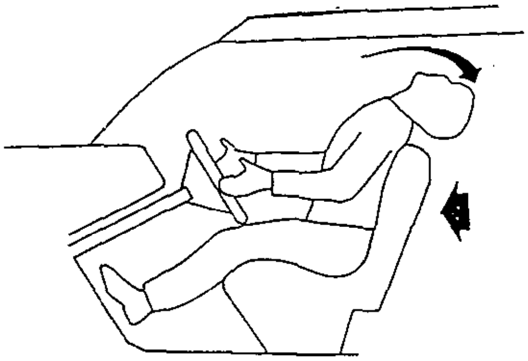

Fig. 5 Hyperextension in the Absence of a Headrest

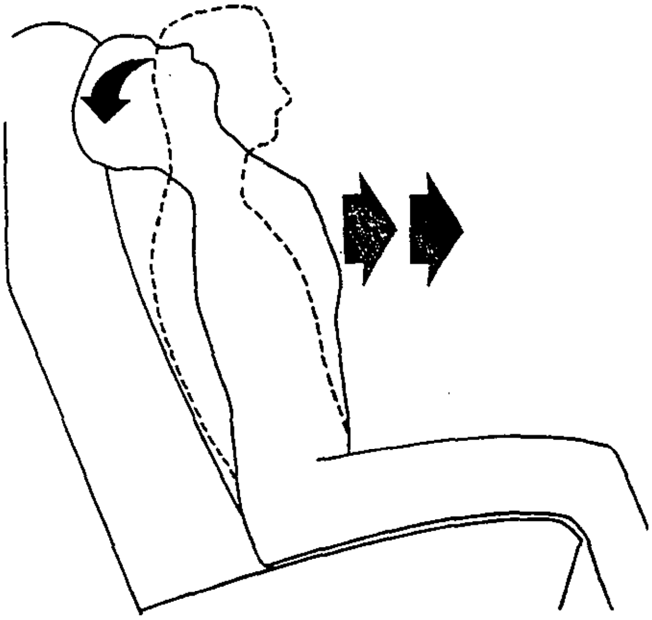

Fig. 6 Hyperextension Caused by Differential Rebound and by Initial Gap Between Head and Headrest

For simplicity, the two vehicles involved in the rear-end collision are assumed to have bumpers that are able to protect them in barrier crashed at either 2.5 mph or 5.0 mph, and it is further assumed that the vehicle structures other than the bumpers are rigid bodies that absorb no energy. Figure 7 shows the two

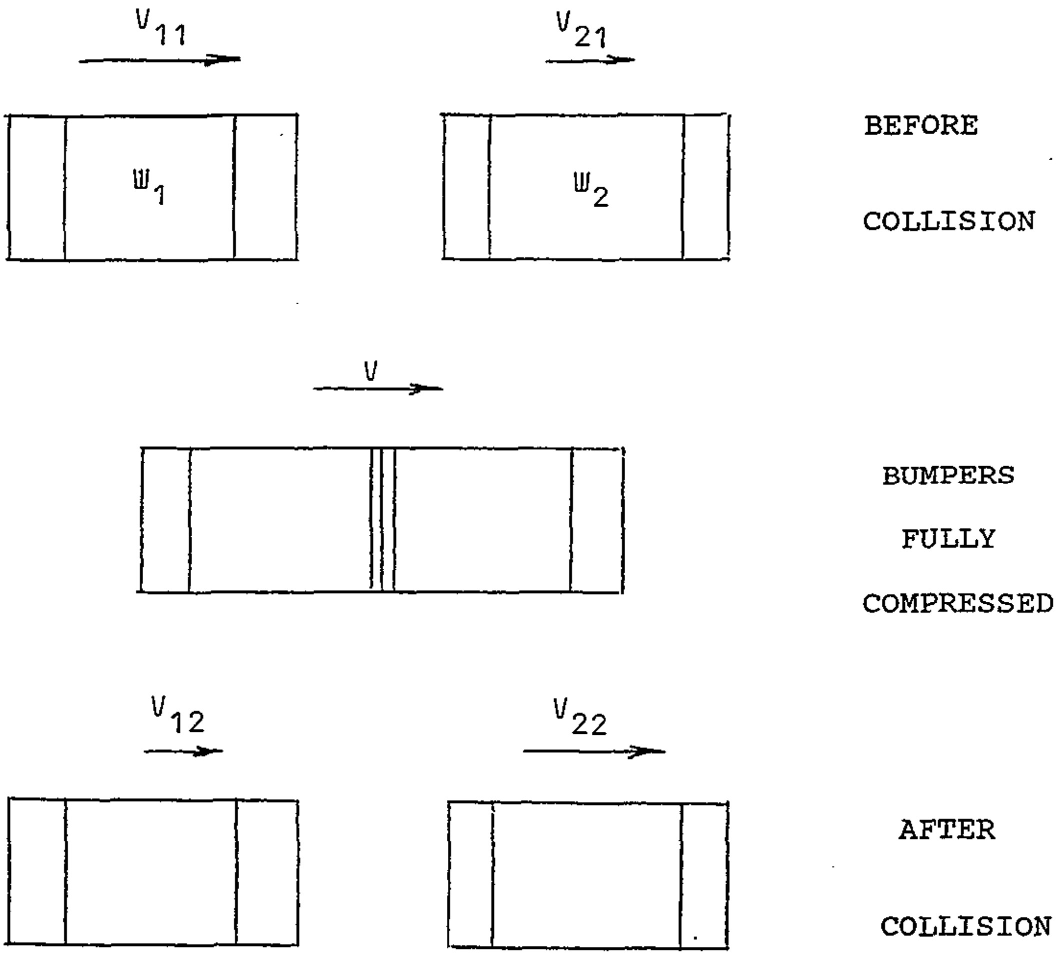

Fig. 7 Collision Mechanics During Rear-End Impact

vehicles just before the collision, at the time when two elastic bumpers are fully compressed to their rated values, and after the collision when the bumpers have restored their energy to their respective vehicles.

When the impacting vehicle's bumper is fully compressed, it has absorbed the vehicle's kinetic energy as though the vehicle had struck a barrier at the bumper's rated velocity of V_{R1}, equal to $\frac{1}{2}W_1V_{R1}^2/g$. Likewise, the rear-ended vehicle's bumper will have absorbed $\frac{1}{2}W_2V_{R2}^2/g$ when it is fully compressed. The kinetic energy equation may be written as follows:

$$W_1V_{11}^2 + W_2V_{21}^2 = W_1V_{R1}^2 + W_2V_{R2}^2 + (W_1 + W_2)V^2 \qquad (4)$$

where subscripts 11 and 12 refer to the impacting vehicle before and after the collision, respectively, and subscripts 21 and 22 refer to the rear-ended vehicle before and after the collision, respectively.

The momentum equation is as follows, when the two bumpers are fully compressed:

$$W_1V_{11} + W_2V_{21} = (W_1 + W_2)V \qquad (5)$$

Solving Equations 4 and 5 simultaneously:

$$(V_{R1}/V_{11})^2[\ (W_1/W_2 + 1) + (W_2/W_1+1)(V_{R2}/V_{R1})^2\ ] = (1 - V_{21}/V_{11})^2 \qquad (6)$$

Equation 6 is solved for V_{11}, the allowable impact velocity that produces full compression of the two bumpers, but no damage to either vehicle. Note that this condition will exist only if the two bumpers are designed to develop approximately the same force when they are fully compressed, which is the case for vehicle frame strengths approximately equal.

For bumpers that are elastic, returning their full energy of compression to the vehicle after being compressed, the kinetic energy equation after the collision is as follows:

$$W_1V_{11}^2 + W_2V_{21}^2 = W_1V_{12}^2 + W_2V_{22}^2 \quad (7)$$

The momentum equation, before and after the collision, is as follows:

$$W_1V_{11} + W_2V_{21} = W_1V_{12} + W_2V_{22} \quad (8)$$

Equations 7 and 8 may be solved for the velocity change of the rear-ended vehicle, as follows:

$$(V_{22}-V_{21})/V_{11} = 2(1-V_{21}/V_{11})/(W_2/W_1+1) \quad (9)$$

Equations 6 and 9 may be solved simultaneously for the velocity change of the rear-ended vehicle impacted at the maximum velocity that fully compresses the two bumpers but does not produce vehicular damage. Note that this velocity change is independent of the initial velocity of the rear-ended vehicle; in other words, it does not matter whether it is initially at rest or moving. Figure 8 contains plots of the velocity change, delta-V, for fully elastic bumpers.

Delta-V depends on the weight ratio of the two vehicles and on the energy absorbing ratings of the two bumpers. In addition, it may be shown that the use of bumpers that absorb all collision energy, and do not return their compressed energy to the vehicle, will reduce the delta-V numbers in Figure 8 by a factor of two. For fully elastic bumpers, Figure 8 indicates that non-damaging (to the vehicles, but not necessarily to the occupants) rear-enders of equal mass vehicles can generate delta-V's of the impacted vehicle between 5 and 10 mph (between 8.0 km/hr and 16.1 km/hr), depending on the energy absorbing ratings on the bumpers of both vehicles.

It is not in doubt that the occupants of the struck vehicle will eventually experience whole-body delta-V's equal to the delta-V of the vehicle itself. However, the delta-V's that produced the head-neck responses shown in Figures 2-4 were transient delta-V differences between head and torso, which will vary dynamically as the occupant's entire body is being brought up to the post-impact velocity change of the struck vehicle. Consider, for example, the dashed outline in Figure 6. At the time consistent with this outline, the vehicle's seatback may be projected forward with the struck vehicle's delta-V, but the occupant's head and torso are still moving at the struck vehicle's initial velocity. Since the occupant's torso is initially in contact with the seatback, it will be projected forward as shown in the solid outline, with a velocity equal to the seatback's delta-V <u>plus</u> the rebound velocity caused by the coefficient of restitution of the seatback's cushions. In the extreme, if the seatback has 100 percent bounce, the torso could move forward at twice the delta-V of the seatback. At the same time, because of the initial gap between the back of the occupant's head and the headrest, the head may experience <u>no</u> delta-V until it strikes the headrest. Therefore, it is conceivable that the upper limit on delta-V between head and torso could be double the struck vehicle's delta-V.

If the struck vehicle's delta-V of 10 mph or 16.1 km/hr for no vehicular damage to equal mass vehicles each having 5 mph bumpers, is doubled to account for a seatback

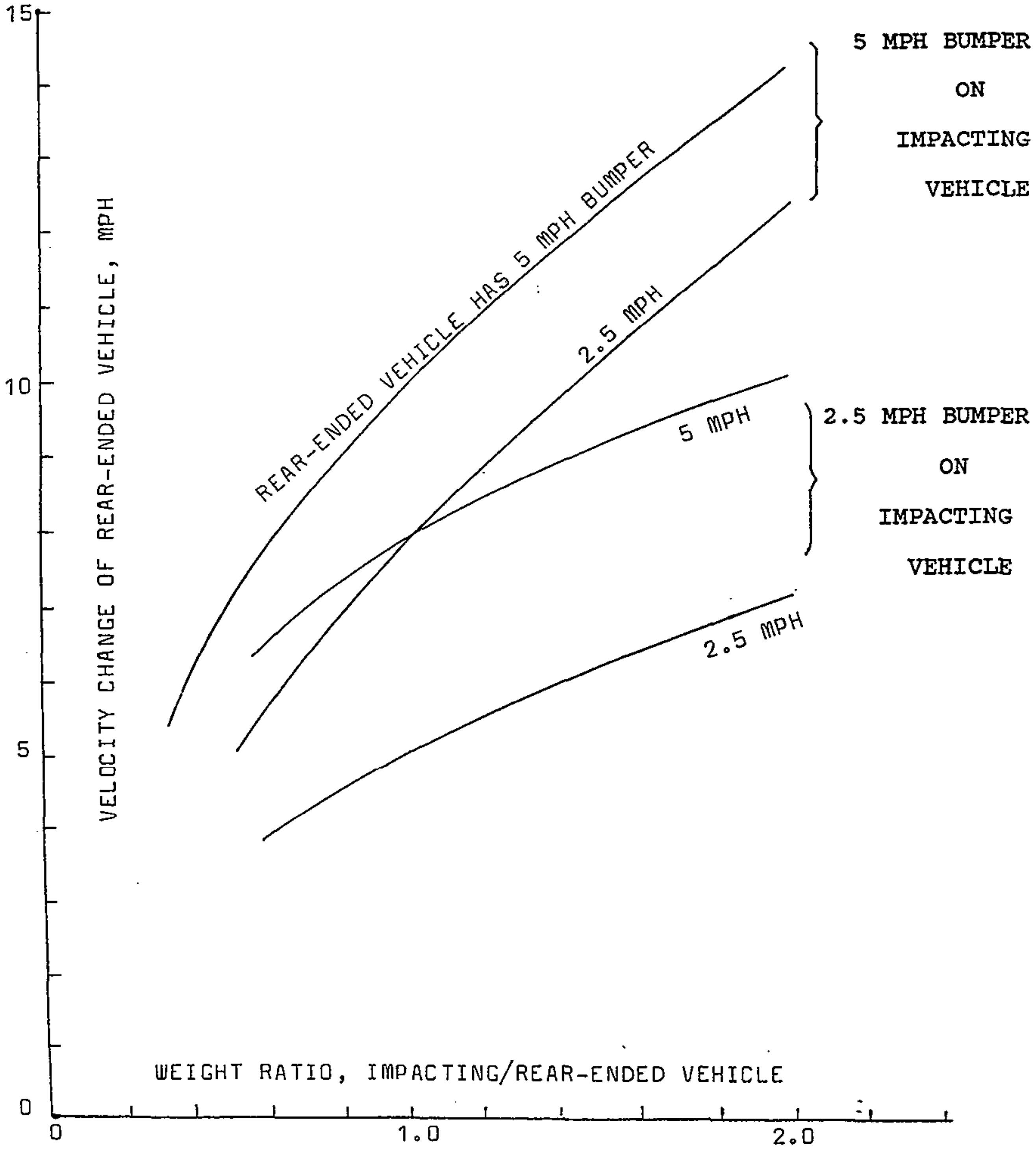

Fig. 8 - Velocity Change of Rear-Ended Vehicle, Elastic Bumpers

with 100 percent bounce, the torso's delta-V relative to the head could be 32.2 km/hr. This is more than twice the 14.2 km/hr injury threshold for the 50th percentile male in the hyperextension mode of response of the head-neck complex. Even without seatback bounce, it is entirely possible for the accident reconstructionist to be faced with a no-vehicular-damage rear-end accident that resulted in severe cervical spine injury.

CONCLUSIONS

The accident reconstruction specialist can acquire the information required to determine what delta-V was actually delivered to the struck vehicle's occupants. Besides bumper characteristics and seatback characteristics and data on vehicular crushup, there may be additional useful data on stopping distance of the struck vehicle. The reconstructed delta-V may provide compelling evidence that the accident was severe enough to have been the cause of the injuries reported by the vehicle's occupants.

However, for calculated delta-V's below the 50th percentile injury thresholds given in Table 3, the reconstruction specialist must rely on the biomechanics community to provide data on divergences from these threshold data. Size, weight, pre-crash physical condition, gender, and age have been shown to influence injury thresholds considerably, but quantitative data are very sparse in terms of delta-V thresholds.

Even the orientation of the head at the time of crash is important. In Reference 13 it is noted that the neck will be more susceptible to injury if the head is turned to one side at the onset of a rear-end collision. For all these reasons, and because whiplash is a most common cause of long-term suffering, biomechanics researchers are urged to generate more quantitative empirical data on the delta-V's leading to cervical spine injury.

APPENDIX - INJURIES WITH VOLUNTEERS AT 8 KM/HR

Recent work has been conducted with human volunteers in rear-end collisions wherein the struck vehicles attained a delta-V of 8 km/hr. In McConnell et al (14), four healthy male volunteer test subjects ranging in age from 45 to 66 years received only mild discomfort. In Szabo et al (15), the human volunteers were male and female, ages 27 to 58 years, with various degrees of cervical and lumbar spine degeneration. Again, no injuries. It is apparent that the injury threshold is above 8 km/hr, even for subjects with mild pre-existing spinal degeneration. It is also noteworthy that little cushion or bumper rebounds were obtained at these low impact velocities.

REFERENCES

1. DeHaven, H., "Mechanical Analysis of Survival in Falls from Heights of Fifty to One Hundred and Fifty Feet", War Medicine, 2, 586, 1942.

2. Kornhauser, M., "Prediction and Evaluation of Sensitivity to Transient Accelerations", J. Appl. Mech., 21, 371, 1954.

3. Kornhauser, M. and A. Gold, "Application of the Impact Sensitivity Method to Animate Structures", Nat. Acad. Sci., Nat. Res. Council Pub. 977, 333, 1962.

4. Severy, D.M. and J.H. Mathewson, "Automobile Barrier and Rear-End Collision Performance", Paper 62C, SAE Summer Mtg., Atlantic City, NJ, June 1958.

5. Mertz, H.J., Jr. and L.M. Patrick, "Investigation of the Kinematics and Kinetics of Whiplash", SAE Paper 670919, 43-71 in SAE PT-43, "Biomechanics of Impact Injury and Injury Tolerances of the Head-Neck Complex", Ed. by S.H. Backaitis, 1993.

6. Roberts, V.L. and C.P. Compton, "The Relationship Between Delta V and Injury", SAE Paper 933111, 37th Stapp Car Crash Conf. Proc., SAE P-269, November 1993.

7. Digges, K.H., "The Prevention of Head and Neck Injuries in Motor Vehicle Crashes", 241-255 in SAE P-276, Head and Neck Injury, Ed. by R.S. Levine, 1994.

8. Mertz, H.J. and L.M. Patrick, "Strength and Response of the Human Neck", SAE Paper 710855, 821-846 in SAE PT-43, "Biomechanics of Impact Injury and Injury Tolerances of the Head-Neck Complex", Ed. by S.H. Backaitis, 1993.

9. Melvin, J.W. and K. Weber, Eds., "Review of Biomechanical Impact Response and Injury in the Automotive Environment", DOT HS 807 042, Chap. 2, "Spine" by G.W. Nyquist and A.I. King, March 1985.

10. Schutt, C.H. and C.F. Dohan, "Neck Injury to Women in Auto Accidents", Journal AMA, 206, 2689-2692, 1968.

11. Kornhauser, M., "Theoretical Prediction of the Effect of Rate-of-Onset on Man's G-Tolerance", Aerospace Medicine, 32, 5, 1961.

12. States, J.D., "Soft Tissue Injuries of the Neck", 37-43 in "The Human Neck - Anatomy, Injury Mechanisms and Biomechanics", SP-438, SAE Mtg. Feb.26-March 2, 1979.

13. SAE Information Report, "Human Tolerances to Impact Conditions as Related to Motor Vehicle Design", p. 19, SAE J885, Revised July 1986.

14. McConnell, W.E. et al, "Analysis of Human Test Subject Kinematic Responses to Low Velocity Rear End Impacts", SAE Paper 930889, SAE Congress and Exposition, March 1993.

15. Szabo, T.J., "Human Occupant Kinematic Response to Low Speed Rear-End Impacts", SAE Paper 940532, 1994.