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16. Abstract

This report gives a summary of the evolution of present standards for testing roadside barriers in connection with the mitigation of human injuries. After a critical review of pertinent literature, a new set of injury criteria is recommended. These criteria are based on the average deceleration and the velocity change up to the instant of secondary impact. The reasonableness of these criteria is assessed.

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LIST OF SYMBOLS

a = acceleration (deceleration)

dt = time differential

f = frequency

t = time duration

t_1 = corner duration

t_R = rise time

Y = excursion of a vibrating body

T = period of vibration

V = velocity

δ = maximum excursion of a vibrating body

ω = circular frequency

Δ = increment

$+G_x$ = Accelerations in G-units in forward x - direction i.e., longitudinal to the vehicle (or transverse to a seating occupant,) known to aerospace workers as "eyeball-in."

$-G_x$ = ditto in backward x - direction or "eyeball out."

$\pm G_y$ = Accelerations in G-units in y - directions, i.e., lateral or transverse to the vehicle (or the occupants).

$+G_z$ = Acceleration in G-units in downward vertical direction known to aerospace workers as "Head out".

$-G_z$ = ditto in upward vertical direction known as "Head in".

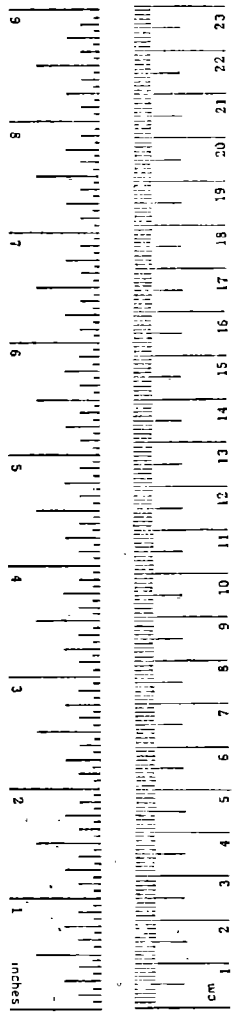
ΔV = Relative velocity of occupant to the occupant compartment at time of impact of occupant with vehicle interior.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

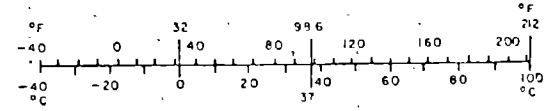
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



INTRODUCTION

Bridge rails, guardrails and median barriers are roadside structures frequently struck by errant vehicles. These structures should be properly engineered so that a striking vehicle will be redirected or brought to stop in a controlled manner, thus increasing the chances of survival of its occupants. This is one of the important goals of the Federal Highway Administration's research efforts.

In evaluating the performance of a barrier, progress has been made in methods of determining the dynamic responses of the barrier, the impacting vehicle and its occupants, both through theoretical and experimental means. Of major importance is the establishment of a set of injury assessment criteria, which can relate dynamic factors to levels of human injury.

This report contains an historical perspective of the evolution of the present criteria, appended with critical comments. Also, a rational approach, using simple mathematical models and experimentally determined parameters, is discussed. Finally, proposed thresholds of fatal and irreversible injuries are presented.

EVOLUTION OF INJURY THRESHOLD CRITERIA

The most frequently referenced criterion of human injury threshold in cases involving vehicle-highway barrier impact is contained in a table, developed by Shoemaker (1)* of the Cornell Aeronautical Laboratory and presented in this Report as Table 1. The data, however, have several shortcomings which limit their usefulness. For example, only two references (Stapp (2) and Severy(3)) are cited, and these studies were based on full-scale tests without any theoretical guidance. Certain factors, such as duration and onset rate are controversial. Although Shoemaker took great pains to emphasize that his proposed criteria were tentative and based on very limited experience, his resultant table has been reproduced and referenced as a standard by numerous researchers, because it is unique in its field. (Graham et al (4), Olson et al (5), Nordlin et al (6), Michie et al (7)).

Graham et al in their study adopted, as the severe injury threshold, a limit deceleration 10G over 50 m. sec. period of "highest average deceleration," in an apparent effort to approximate the pulse by a trapezoidal shape. Olson et al, who made an extensive analysis of other pertinent data which will be discussed later, concluded that the percentage of vehicles which contain injured occupants in any severity equals 10 times the lateral acceleration in G level. They believed that their findings supported not only Shoemaker's criteria but also Graham's 10 G theory as the threshold of fatal injury for unrestrained occupants, provided that the impact is at an angle with a time duration of less than 200 m sec. The discrepancy between this time duration and Graham's assumption (50 m sec time duration) was not addressed by Olson. The latter report also omitted

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* Numbers in parentheses refer to the references at the end of this paper..

the limitation on the onset rate. In Nordlin's article a note was inserted under an abridged Shoemaker's table, stating, "highest 50 m sec average, vehicle passenger compartment," as suggested by Graham et al, but in contradiction to the 200 m sec duration which Shoemaker originally postulated. Michie adopted Nordlin's version of the table, including the highest 50 m sec average clause. In addition, he reinserted the 500 G per second onset rate limit.

NCHRP REPORT 153 (8) in its "Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances" adopted Nordlin's version of the Shoemaker table, with the following exceptions (Table 2):

(1) Figures for unrestrained occupants are noted as "preferred."

(2) Figures for lap-belted occupants are noted as "acceptable."

(3) Figures for lap and shoulder restrained occupants are deleted.

(4) Impact angle is limited to 15 degrees or less.

Another source of data emanated from researchers in the Biodynamics Division, Wright-Patterson AFB. Their findings were officially adopted as Military Specifications for the U.S.A.F. (9), a portion of which were reproduced by Hyde (10). These specifications contain an "Ellipsoidal Envelope for Defining the Multiaxial Acceleration Limits" (Fig. 1) but fail to supply supporting documentation or references. Nevertheless, the Texas Transportation Institute team (TTI) extracted from them the following values (11):

Maximum Plateau Acceleration in G's		
Lateral	Longitudinal	Vertical
15	20	17

According to the Military Specifications, "power-assisted upper torso integrated harness and lower torso lap belt" were required as the restraint system, which was interpreted to be the equivalent of a standard

lap-belt and shoulder harness by the TTI team. From an FHWA document, "Instructional Memorandum 40-5-72," TTI also extracted a tolerance limit of 12G as the upper limit for a lap-belted or lap and shoulder-belted occupant. This subsequently was used to establish the tolerance limit for longitudinal deceleration for lap belt restraint. Comparing this figure of 12G with the corresponding value given in Hyde's diagram (valid for less than 30 m sec rising time), the ratio is exactly 0.6. This figure of 0.6 has come to be considered a universal constant not only for deceleration in other directions, but also for the ratio between the tolerance for unrestrained occupants and for those restrained by lap belts. For instance, the limits for unrestrained occupants were assumed to be 60 percent of 60 percent of the corresponding figures indicated by Ellipsoidal Envelope in Fig. 1. The end result is shown in Table 3. As implied in the foregoing the threshold for a "crash at an angle" is related to the thresholds along the three principal axes by the ellipsoidal relationship:

$$\left(\frac{G_x}{G_x'}\right)^2 + \left(\frac{G_y}{G_y'}\right)^2 + \left(\frac{G_z}{G_z'}\right)^2 = S^2$$

where S = severity index (a term coined by the TTI team), and the prime quantities are the respective threshold limits in similar restraint conditions. The criterion is: "The occupants survive if S is equal to or less than unity."

In order to verify Shoemaker's table, Olson (5) made an extensive study based on Michalski's "Proportion of Injury" vs. "Vehicle Damage Rating" relationship for angle impacts. The "damage rating" was in turn related to the average lateral deceleration through available full-scale test data obtained from sources in New York, Texas and California.

Actual damage ratings were then determined by a consensus of opinion of six engineers on the TTI team, who compared photographs of test results with those of Michalski's seven-step rating scales. Lateral deceleration values were compared using Michalski's simple analytical model and the film data. Without describing the methodology in detail, we remark here that the deceleration used was the average over the total duration of the lateral motion of the vehicle. In other words, the deceleration was obtained by dividing the total change in lateral velocity by the total time interval elapsed during the rise time. Also noteworthy is the fact that, while the average duration for the California tests was 200 m sec, durations of lateral movements for the New York tests, with one exception (a very acute angle impact of 6 degrees), were well above 200 m sec with an average of 396.3 m sec in twenty tests. Although these data appeared in an appendix, they were not discussed in the main text. Using Michalski's scale as a link, Olson correlated the test data with traffic accident data in Oregon. The variation between the deceleration and injury proportion can be described by the following relation:*

$$G = 10P$$

where G = lateral deceleration in G units at c.g. of the vehicle;

P = proportion of vehicles in which injury can be expected.

Hence, a lateral deceleration of 10 G is expected to cause 100 percent injury. It should be emphasized, however, that the type and severity of injury were not specified, but it was known that less than five percent of injuries were fatal. We should also note that only five percent of the passengers in Michalski's study were restrained in any way.

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* In a private communication, Viner pointed out that there were inclusions of head-on impact data in which negligible lateral decelerations were present, in the development of the relationship. Upon removal of these data, the sample size would become too small to draw any statistically meaningful conclusions.

The aforegoing criteria are referenced to the deceleration at the c.g. of the vehicle. An alternative approach is to refer to the deceleration in the part of the human body under consideration. This approach was used in early studies of head injury, e.g., Wayne State Tolerance Curve (WST). Through a graphical fitting of WST, there evolved an empirical relation known as Gadd's Severity Index (GSI), which was subsequently adopted as a criterion of injury by the Society of Automobile Engineers and the American Medical Association. A modified form was adopted in FMVSS208. Details will not be included here since this approach is listed only as an optional alternative in NCHRP Report 153, "Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances." (8)

EVALUATION OF INJURY CRITERIA

The overall categorization of all these criteria is that they are too empirically oriented. It is clear that some theoretical guidance, even if based on extremely simply dynamic models, would be very useful in separating the important parameters from the insignificant. Without this, one can only rely on hunches which can be misleading. The overemphasis on the onset rate is only one of the damaging consequences. Major inconsistencies in the utilization of short vs. long duration loadings is another. Other sources of confusion are caused by imprecise definitions of terms, some examples being maximum or peak deceleration, time history vs. duration, average deceleration with no specification of duration. One other area of confusion is inadequate information transfer from aerospace to highway technology. In an aerospace injury, acceleration

is more steady when a long-duration and constant (plateau) acceleration exists, while in a highway crash this almost never occurs. Also, most aerospace transverse ($\pm Gy$) direction injuries are due to deceleration, while in highway injuries the cause is primarily due to the impact of the occupant with the interior of the vehicle. Further, the direction of acceleration in the automobile industry refers to the axes of the vehicle while in the aerospace industry it refers to the axes of the body. Thus, the longitudinal in the former sense is transverse in the latter sense.

Shoemaker's notion of "total deceleration" (at an angle), which is higher than the thresholds in either principal direction, is ill-founded. It is clear that the effects of injuries from all three impacting directions would interact. The result might be the ellipsoidal envelope as indicated by the Military Specifications (9) and would be analogous to the interaction diagram in the theory of plasticity.

At best, however, the deceleration tolerance described in the Military Specifications (9) for short duration impact is misleading. It can be established that tolerance to a short duration impact depends primarily on momentum change and not on peak deceleration. It is plausible that a pulse of extremely short duration can be tolerated in the resultant momentum is sufficiently low, even though the maximum intensity can be very high.

Shoemaker's criteria were based on Stapp's empirical formula:

$$a = 50 - 125\ t$$

which he applied to an average duration of 200 m sec in his tests to obtain the 25G limit longitudinal impact. This is unambiguous for constant

acceleration. However, the average of a time-varying acceleration is sensitive to the duration used in computation. It is obvious that the tolerable acceleration would be much higher if a duration of 50 m sec is used. Graham, in quoting Shoemaker's table, interpreted the 200 m sec as the "upper limit" of duration of tolerance, by stating that "Cornell Aeronautical Laboratory suggested tentative limits of combined lateral and longitudinal decelerations where the duration did not exceed 0.2 sec---." This, of course, implies that an impact lasting longer than 200 m sec is intolerable, while Stapp's formula indicates clearly that there is no upper limit for duration as such. Graham acknowledged Shoemaker's understanding of the tenuous nature of his recommendations by stating, "However, laboratory engineers reported that further work with anthropomorphic dummies subjected to known decelerations are required to better establish these limits." He then continued, "Although there is no relationship between the decelerations of a vehicle and an unrestrained occupant, one can reasonably assume that low decelerations of a vehicle would mean that the probable chances of severe injury to the occupants would be less. During this study a total deceleration of 10 g's for more than 0.05 sec (50 M sec) at the vehicle center of gravity has been considered as probably capable of producing serious injuries and perhaps even fatal injuries. Every effort has been made, therefore, to keep vehicle decelerations below this level during collision with the barriers developed during this study."

No reasons were given as to how this tolerance criterion conclusion was drawn. Olson, in turn, inferred that the tolerance limit should stay constant as long as the duration was more than 50 m sec but did not exceed 200 m sec. He concluded that a 10G deceleration

would result in fatalities in the majority of accidents although the curve which he fitted through the Michalski data for "lateral acceleration" shows 100 percent probability of injury (occupants unrestrained) at this level.

We shall see later that the threshold for the impact load should be the velocity change, not the acceleration. We agree with Payne (12) that,"the very short duration of Handbook of Instructions for Aircraft Designers' allowables were nonsense."

The principle used by Olson (5), incorporating Michalski's work, was a meaningful method to attack a very complicated problem. His method is reminiscent of Sweringen's approach (13) to head injury caused by impact with the instrument dash panel (see later). It would be most beneficial if extensive work like this could be done in the near future, especially if the injury rating (similar to the vehicle damage rating) and the probability of occurrence were incorporated into the study. This is a so-called phenomenological approach to relate the input dynamic parameters to the injury. There is no need to measure the dummy responses during the impact, if this approach is used.

In WST and its related methods, such as GSI and FMVSS 208 (14), some attempts were made to measure the dynamic responses of the human body. This might be called the "response model." In WST, the location of the accelerometer is at a point on the cadaver head directly opposite the point of impact. FMVSS 208 recommends a location at the c.g. of the dummy head. Since, however, response can vary widely between these two locations, this extrapolation of empirical relations can lead to unreliable results. FMVSS 208 (14) modified GSI's weighting factor, but this modified version is only tenuously related to WST and its reliability is questionable. It appears that, considering the present state-of-the-art, it would be premature to attempt to recommend a set of injury criteria on the basis of a

response model. The author of NCHRP Report 153 (8), acted wisely when he listed it as an optional alternative, rather than a recommended approach.

INJURY MECHANISM

It is pertinent to discuss the injury mechanism for vehicle occupants in a barrier crash environment. First we shall summarize the injury mechanism of rigidly restrained humans, i.e., some dynamic factors which cause injuries when applied to the human directly.

It is well-known that an injury depends on dynamic factors such as duration and magnitude of acceleration, velocity or momentum change, as well as the constitution of the human or the part of his body under consideration. Physiologically, there are three zones of injury phenomena -- impact, hydraulic and dynamic force. In impact tolerance, the duration of the load history is much shorter than the natural period of the body element. Before the response is developed, the impulse has elapsed. As far as the body is concerned, there is only a change of momenta, and neither the deceleration nor the pulse is important. The injury itself is measured by:

$$\int_0^{\Delta t} a\,dt = \Delta V < (\Delta V) \text{ limit}$$

In the case of longer-duration loading, however, after the response is fully developed, the injury criterion depends essentially upon the amount of "force" acting on the body rather than on the momentum. It is often measured by the non-dimensional deceleration, the G-unit, which is the deceleration in terms of multiples of gravitational acceleration. In an extremely long period of duration, e.g., several minutes or more, the injury mechanism is a hydraulic phenomenon. The

body fluids, especially blood, have time to overcome the viscosity and drain towards the most forward portion of the body. When the body is undergoing vertical motion, sufficiently long deceleration would cause black-out or red-out. In an extreme case, it could result in rupture of blood vessels and hemorrhaging in vital organs. There is evidence to show that the critical deceleration is somewhat less than 10 G-units for a duration of about a minute, presumably asymptotic to 1 G-unit when the duration is indefinite (Boudurant et al (16)). This phenomenon can be demonstrated in centrifuge tests. Paradoxically, an impact load on the abdomen can cause a surge of pressure which is also a hydraulic phenomenon.

Of greatest interest for injury in a barrier crash environment is the time duration of somewhat less than a second, a range which also happened to be of interest in sled tests and design of airplane ejection seats. This problem was studied by Geertz (17), whose work was summarized by Ruff (18). The data were analyzed by Payne (19) and Kornhauser (20) through the help of some very simple mathematical models. Kornhauser found that the data may be more conveniently plotted as "sensitivity curves" that employ velocity change as the ordinate and the average acceleration as the abscissa (Figure 2). The time duration appears implicitly in the sensitivity diagram as a parameter. As discussed previously, for long and short durations, the sensitivity curve would be asymptotic to the average acceleration and velocity change, respectively. In the intermediate range, the sensitivity curve is in a transition zone. It is simpler and more conservative to ignore this transition, and it is accurate enough for most applications. In this way the sensitivity curve is represented by two straight lines. The "corner" duration was shown by Payne (19) to be:

$$t_1 = \frac{2}{\omega} = \frac{1}{\pi f}$$

The measured natural frequencies of various parts of the body in different positions were given by Stapp (21) as shown in Table 4. Payne (19) gave the following figures:

Viscera (vertical)	2 cps
Spinal (vertical)	45 cps
Torso (transverse)	8 cps

ONSET RATE AND HYPER-ACCELERATION

It is a common but erroneous notion that the onset rate is an important factor in the injury criteria of a barrier crash environment. The onset rate is the time rate change of acceleration, otherwise known as the "jerk" or "jolt." Mathematically, it is the third derivative of displacement. According to Routh, "If the third differential coefficient were required, we should use some such name as the hyper-acceleration, but this extension is not necessary to dynamics." The dynamic response of a mass is sensitive to the change of acceleration. If the change is too fast, the system has very little time to respond fully and must lag behind. Subsequently, the mass would race to catch up, resulting in an overshoot (Figure 3a). The overshooting acceleration may be as much as twice the input acceleration for purely elastic models. However, with damping, the overshoot will be reduced considerably (19, p. 206). On the other hand, for a gradually applied force, the mass would respond in unison to the input and overshoot would thus be negligible (Figure 3b). The problem boils down to what is the measure of "suddenness" of applied force. Theoretically, the measure is the rise time. Frankland (15) showed that, when the rise time is longer than five times the natural period, the overshoot (or dynamic load factor, as he called it) will be

negligible (Figure 3c). When the rise is less than one-tenth of the natural period, the overshoot will be almost equal to that for the impact load. For linearly varying accelerations, the onset rate is equal to the ratio of peak acceleration and rise time. This is true for a ramp-type of input which persists indefinitely. Thus, provided other conditions are equal, the higher the peak acceleration the higher will be the permitted onset rate (Figure 4). It is the ratio of rise time and the natural period of the system, not the onset rate itself, that is the controlling factor of the amount of overshoot. For long-duration input, the onset rate by itself cannot be the controlling factor of the amount of overshoot. For short-duration input, the onset rate by itself is even less important. Let us take a triangular pulse of given duration as an example. To obey the maximum onset rate criterion, the shorter the pulse duration the lower the tolerable peak intensity (Figure 4). This, however, is a wrong conclusion since it has long been established that the opposite is true. As discussed before, for impact loading, the intensity is unimportant and only velocity change matters. This was realized by Geertz, who stated (16), "An acceleration of any magnitude may be safe regardless of the tensile strength of the skeleton, as long as it is of very short duration."

This view has been supported by more recent investigators such as von Gierki, Kornhauser, Latham and Hess, who have been quoted by Payne (12). Paradoxically, the myth of maximum onset rate limitation originated with Geertz. It was invoked by Stapp (2) and Severy (3), undoubtedly because Geertz' work suddently became readily available when the U.S. Government Printing Office published "German Aviation Medicine in World War II" in 1950. The notion has evolved into a binding criterion since the Handbook of Instructions for Aircraft Designers, USAF

adopted an onset rate of 1500 G per sec as a limit of tolerance in 1965 (22). The fallacy was effectively pointed out by Holcomb (23), when he demonstrated that the rate of onset per se is not a relevant parameter in injury studies. Thus, Shoemaker's proposed onset rate of 500 G per sec for all deceleration levels is not supported by available evidence.

It can be shown that an onset rate of these magnitudes would cause an overshoot not much lower than a similar load applied so suddenly that the rise time would be negligible. For example, let the plateau acceleration and natural frequency be 25 G and 2 cps, respectively. For an onset rate of 500 G per sec, the rise time, t_R, will be 0.05 sec. We can calculate ωt_R to be $\pi/5$. With this abscissa we can obtain, from Frankland's diagram (Figure 3c), the overshoot to be almost 2, which is the value for the impact load in elastic conditions. Furthermore, the onset and offset rates (rate of decrease of acceleration level per unit of time) have some significance only if a plateau duration of constant acceleration exists. Rapidly varying acceleration at any time would cause transient responses to the system. By minimizing the initial part of the input through limiting the onset rate, the overshoot would not be eliminated, since any subsequent change of acceleration at the middle course would have overshoot effects. As long as the constant flat plateau cannot be realized in the center of gravity of the vehicle, it is useless just to limit the onset rates.

Viner has kindly pointed out to the author that onset rates in excess of 500 G/sec, as measured in the vehicle occupant compartment, have not been reported for practical highway barrier designs. It is expected that designs developed under current criteria would likely satisfy 500 G/sec onset rate easily. It is noted also that the onset rate limitations were not included in the current recommendations of NCHRP

Report 153 (8).

The dynamic effect of rapid variation of acceleration on humans can often throw them off balance. A man can learn to brace himself against a constant rate of acceleration, though this is a reaction which cannot be adequately simulated by dummies, cadavers or anesthetized mammals. Against rapidly changing acceleration, however, an occupant will be off-balance and will move freely in relation to the vehicle. How well the victim can restore his balance depends largely on his reflexes and agility. It is conservative to assume that he would travel as a free missile, starting from the rest position and accelerating with the same magnitude as the vehicle decelerates until he strikes the restraining straps or other parts of the vehicle interior. Actual behavior must await a more detailed study of vehicle-barrier-occupant interaction. Such a study will shortly be undertaken under the sponsorship of the FHWA.

EFFECT OF RESTRAINT AND PHYSICAL CONSTITUTION

According to current practice, the governing acceleration is measured at the center of gravity of the vehicle. The acceleration of the occupant is presumably quite different from that of the vehicle unless the former is rigidly restrained by a contour-type encasement. The aerospace-type harness comes close to being a total constraint for low loads, with the exception of the head, which is not restrained for forward movements. In forward and upward accelerations, there is evidence to show that, for higher loads, the harness would be stretched and the body would move a few inches before rebounding back against the seat. The size and material composition of the harness can change many characteristics of the acceleration pulse, especially the onset rate and sometimes even the peak value. For downward and backward accelerations,

the dominating factor is the seat cushion which, although beneficial at low loads, will "bottom" at high loads and will produce a very sharp acceleration pulse. For lateral acceleration, even the aerospace-type harness is of questionable value. The automobile-type lap belt and shoulder harness are much simpler and should be considered as partial restraints. They are designed to minimize, rather than to prevent, the relative motion between the occupant and the vehicle. Figure 5 shows the relative motion due to a forward acceleration, namely that considerable forward motion can and does occur. For side impact, the effectiveness of automobile restraints would be significantly reduced.

At present, we do not have any very detailed studies on the effects of restraints and cushions on the relative responses of the occupant and the vehicle. A further complication is the fact that the vehicle usually assumes a curvilinear trajectory upon impacting a roadside barrier. This is not in accord with test conditions of most injury studies which were based on rectilinear motions.

In any case, it is clear that in real life the injury caused by a loosely worn restraint system is caused not so much by the deceleration of the vehicle per se, but by the occupant "striking" the restraint system. This energy load against the lap belt would probably cause very little damage due to the presence of massive pelvic bones unless it was worn so loosely that the sudden pressure on the abdomen would cause internal damage. Williams (24) reported intestinal and spinal damage due to the latter cause. On the other hand, when a shoulder harness is wrapped around a relatively fragile rib cage, there is evidence that the ribs may break along the edge of the strap (Aldman (25)). This sort of impact

can also cause injuries to internal organs by direct pressure, and the force can produce a surge of pressure in the blood stream which can cause the vessels to rupture at some remote location (Evans and Patrick (26)). Occupants restrained by a lap belt alone (without a shoulder harness) would jackknife in a forward motion (Fig. 6). It is likely that the driver would strike against the steering column and that the front passenger would strike his head against the dashboard or other structures in the vehicle interior. In the case of unrestrained occupants, the driver would impact the windshield and steering post while the front passenger would impact the windshield with his head and the instrument panel with his chest (Fig. 6). All of these are short-duration impact situations. A properly designed ("long-stretch" type) restraint would not greatly change the duration and peak value of the pulse. They would decrease the onset rate but increase the offset rate, with the end effect being that they would probably compensate for each other (Fig. 7).

The design and material composition of restraints vary from manufacturer to manufacturer. Other uncertainties are variations in size, strength and age of crash victims. All these factors greatly affect the chance of injury. As was borne out by Michalski's study, quoted by Olson (5), some occupants would be injured to some degree even in a minor accident and, of course, the proportion of cars in which injuries occur increases with the increase of severity of the accidents. Some degree of injury must, therefore, be accepted since it is impossible to prevent all injuries to all occupants in the present environment. What, then, is a reasonable limit for acceptable injury levels?

INJURY THRESHOLDS

Human injury is a very complicated phenomenon. A detailed

study would probably take a team of physiologists and engineers several decades at least. In a barrier crash situation, the causes may be confined to extrernal dynamic factors such as deceleration, impact with interior structures of the vehicle, mechanical pressure from restraining straps and impact with foreign objects. In a severe frontal crash, it is possible to have injuries caused by the intrusion of the engine into the passenger compartment. This rarely happens in crashes with roadside barriers; rather, the instrusion of foreign objects such as sign posts piercing the windshield may be a very real threat. The relative importance of these factors depends on the restraint conditions, the physical constitution of the subjects and the size and trimming of the vehicle interior. Most of these variations must be accepted as uncontrollable and treated as uncertainties in an analysis.

What is the meaning of uncertainty? It means that we must accept the fact that there might be some injuries in any mishap, no matter how slight. We would have to accept the possibility of minor injuries in all cases. It is plausible, however, that tolerance to serious injuries, such as fatalities and irreversible disablement, would be similar for all conditions and could be used as a norm. For any conservative criteria, an additional factor of safety can be employed.

For the injury tolerance criterion, the sensitivity curve approach by Kornhauser (20) appears to be the best. It has a sound rational basis and it covers a wide range of duration. It degenerates properly to extreme cases. With Payne's modification (19), it is very convenient to use; i.e.,

$$\Delta V \leq (\Delta V) \text{ limit}$$

or

$$a \leq (a) \text{ limit}$$

where ΔV = velocity change and a = deceleration as computed by ΔV divided by the total duration. In the original Kornhauser-Payne version, it is an either-or proposition. At least one condition must be satisfied but a violation of both would produce disastrous consequences. The basis of this criterion is the consideration of the aerospace environment in which long, steady, ramp-type deceleration pulses and full restraints are in effect. In automobile crashes, there are two effects: the deceleration and the secondary impact against the vehicle interior. The limit on deceleration is similar to the requirement in aerospace studies and, in addition, the limit on velocity change is intended to take care of the secondary impact, which is usually of short duration. Thus, these two conditions must be used to take care of two distinctly different accident phenomena. In contrast to Kornhauser's criteria that constitute an either-or proposition, the present criteria require the satisfaction of both inequalities shown above. We remark in passing that there are conditions for which the presently proposed criterion could conceivably rule out otherwise acceptable conditions and become unduly conservative. An example may be a pulse of high intensity and of very short duration by itself. However, since this occurrence is rare for most practical barriers, we will not deal with this possibility.

If we accept the criterion, we must seek to specify two values for each mode of injury cause. For fairly long duration deceleration there is an abundance of data, mostly from aerospace research (Fig. 8). Due to the high elasticity of the elaborate harness used in these tests, the deceleration at the sternum was found to be as much as twice as high as that on the seat, apparently due to the overshooting effect. In what follows, unless otherwise noted, the term "tolerance limits" will mean the maximum acceleration or velocity change which will not cause

fatal or irreversible damage. The generally agreed tolerance limit is about 40G plateau acceleration of the vehicle. From the Handbook of Instruction for Aircraft Designers (22), the tolerance limit is a plateau deceleration of 35G for a minimum peak duration of 23 m sec, with an onset rate limitation of 1500G per sec in backward deceleration. An average deceleration on the basis of total duration (rather than a plateau duration) will be in the neighborhood of 20-25G. This figure is said to be valid up to a total duration of 300 m sec. Payne (19) quoted test data by Douglas Aircraft, Kornhauser, Hegenwald and his own results and put an injury limit against a rectangular pulse at around 30G. Severy's conclusions (3), as quoted by Shoemaker, appear to be subjective and as such must be given a much lesser weight than conclusions reached from quantitative data.*

It would appear that 25G is a reasonable limit to longitudinal deceleration, provided that the duration is based on the total duration of the pulse. The tolerance limit to velocity change was placed at 24.4 m/s by Kornhauser after a survey of studies on air crashes, suicide attempts and his own drop tests(20). He estimated a velocity of 6.4m/s as the non-injury threshold. Hyde showed that the limiting velocity change is 15.2 m/s for a triangular pulse. Payne calculated the limit and concluded it to be in the neighborhood of 15.2m/s for whole body impact with cushions under the head. If head impact is involved, the threshold against a rigid surface is reduced to 6.1m/s. For sheet metal surfaces such as parts of the vehicle interior, which is far from a flat rigid surface, we can rely on Swearingen's data (13) which were obtained by striking dash panels

* Severy stated that, "High speed photographs of motion of a dummy in both driver and front-seat passenger locations indicated probable fatality for the unrestrained occupant and the occupant restrained only by a lap-belt, etc." No details were given.

with an instrumented dummy head form. The dents which matched the size and depth of those in actual accidents were used as evidence that a duplication of the original event was in fact obtained. From this, he gave a tolerance limit of 12.2m/s with a duration of 40 m sec, which is equivalent to average deceleration of 30G approximately. The results of impacting window glass show that an impact of 6.1m/s was also a reasonable threshold for serious head injuries (Patrick and Daniel (27)).

Another well-studied area, traced back to Geertz, is the effect of vertical acceleration. Payne established a tolerance limit of 22G and quoted the Douglas and Hegenwald test data which scattered over an area ranging from 5G to 25G. Air Force data in the Military Specifications (9), also reproduced by Hyde (10), give a limit of 17G for downward accelerations and 12G for upward ones. For an extremely short duration impact, Payne (19) gives a tolerance limit for velocity change at about 3.0 m/s.

There are few data available for lateral acceleration tolerance. The Air Force Military Specifications call for a 15G limit, decreasing to 10G at 400 m sec peak duration, but most other sources suggest the use of the same values as in longitudinal acceleration. Zabrowski (28) reported that an average deceleration of 9G units would produce only discomfort such as soreness and stiffness in the neck for occupants restrained by either lap-belts alone or lap-shoulder harnesses. Weiss et al (29) reported that volunteers in sled tests restrained by a foam couch and semi-rigid microballoon couch have been subjected to a peak lateral acceleration in excess of 21G with no complaint other than having the "wind knocked out" of them.

The only known source of injury data concerning the torso impacting the restraining straps is found in Stapp (21), who quotes two types of test runs: in one, weighted "harness assemblies" were dropped on human

volunteers lying supine on a table and, in the other, human volunteers were thrown forward with their torsos hitting against restraining straps. The tolerance limit was determined to be at least 40G at 331G per second onset for 320 m sec duration, which was equivalent to an average deceleration of 30G.

The recently released NCHRP Report 153, "Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances," (8) retained the 12G figure for longtiudinal impact. As for angle impacts in barrier crashes, it retained the first two lines of Shoemaker's Table. Instead of the terms "unrestrained" and "lap-belt only," it used "preferred" and "acceptable," respectively and it retained reference to the "maximum 50 m sec average" phase. It deleted the requirement for limiting the duration and onset rates, and this is definitely an improvement. However, the report again failed to recognize the importance of assessing the secondary impact (to the vehicle interior), except for the breakaway supports and yielding signs which are required to be designed on the basis of momentum change. The definition of the "duration of event" for yielding signs is the lesser of the following:

(1) time between incipient contact and loss of contact between the vehicle and the yielding support;

(2) the time for a free missile to travel a distance of 0.6 m starting from rest with the same magnitude as the vehicle deceleration.

Item (2) above is unmistakably intended for secondary impacts. This is definitely an improvement over the criterion based on deceleration alone. We believe that the time has come to apply a similar provision to the criteria which govern other barrier tests.

After this paper was completed, Melvin *et al* (30) gave very detailed data of a response model type including many internal organ tolerance levels. However, the authors also admitted that, "appropriate levels for tolerable impact forces, accelerations or deflections have not yet been established and the criteria being used are sometimes uncertain and disputable."

CONCLUSIONS AND RECOMMENDATIONS

Based on all available information, the tolerance limits for barrier tests as shown in Table 5 for irreversible or disabling injuries are recommended. A suitable factor of safety can be applied to these figures for a conservative design. In the longitudinal direction the magnitudes of velocity changes were taken from Swearingen's result on dash impacts, and relatively conservative results were obtained from Hyde, Kornhauser, Payne and others. The limiting value for lap and shoulder belts is based on Stapp's and Aldman's discussions of rib damage caused by strap pressure, which is assumed to compensate for any benefitical effects of the harness. The unrestrained passenger is assumed to impact the windshield, and the limiting value was taken from results by Patrick and Daniel. The deceleration figure is obtained from the average deceleration range of 20 to 25G in the last section, with some favor given to lap-shoulder belt conditions in which the upper limit is used. For lack of information, the tolerance limits in the lateral direction are assumed to be the same as their longitudinal counterparts, with the exception of the ΔV for a lap belt, for which the restraining effect to lateral motion is neglected. The thresholds for vertical motions are based on Geertz', Payne's and the HIAD (22) results. These are minor considerations for a barrier crash and very conservative figures are recommended.

The use of the present criteria shown in Table 5 requires a detailed knowledge of the displacement history of the occupants during the crash into the barrier and their terminal velocities. This knowledge can be obtained through a simulation study of the barrier, the vehicle and its occupants. The Federal Highway Administration, through its Fairbank Highway Research Station, has included this study in its research program. A successful com-

pletion of this study will provide useful knowledge in this area and yield a reliable injury assessment. During the interim period, one has to resort to simplifying assumptions. These will be discussed presently.

We have concluded that it is more conservative to ignore muscle resistance to sudden motion and regard the occupants as free missiles moving relative to the vehicle interior with the same magnitude of acceleration as the vehicle's deceleration. This is precisely the assumption used in NCHRP Report 153's recommendations for yielding sign posts (8). The same assumption should also be used for longitudinal barriers. The next step is to determine what is the free space between the occupants and the vehicle interior. This is easily done except that some exercise of judgment is required. NCHRP Report 153 (8) recommends a distance of 0.6 m. (2 ft.). Using this assumption, we can easily convert an average deceleration of a vehicle to the terminal velocity of a free missile, as shown in the following table: (Note that the vehicle deceleration is equal to occupant acceleration.)

a(G)	3	5	6	10	12	20	25
V(m/sec)	5.9	7.7	8.4	10.8	11.9	15.4	17.2

Using the above table we can change any average deceleration limits into the velocity limits. Suppose we assume for a moment that the decelerations in Table 2 were the average accelerations, then the comparison for the tolerance limits for <u>velocity changes</u> (secondary impacts) are as follows:

	Lateral		Longitudinal	
	Table 2	Table 5	Table 2	Table 5
Unrestrained	5.9	6	7.7	6
Restrained by lap belt	7.7	6	10.8	12

The agreement is striking. Of course, the NCHRP decelerations were the "highest 50 m sec average" and not the average over the duration.

As we have already discussed, Graham (4) acknowledged that this is an arbitrary interpretation without a known relationship to injury causation. In its commentary, the NCHRP Panel explains that its reason for the acceptance of this interpretation was because it was more conservative. It may be worthwhile to reopen the issue since the interpretation might be too conservative. It appears that we now have a more rational basis to evaluate this dispute.

In the course of this study, the following observations were made and are recorded here as recommendations:

(1) Clarification of terminology:

Terms such as peak acceleration, maximum acceleration, onset rate, etc. are controversial and not pertinent to barrier crash studies. Worse still, they have caused confusion and led experts to wrong conclusions. They should either be abandoned or standardized with precise meanings.

(2) Concerted effort toward practical knowledge:

An interdisciplinary team should be assembled to conduct extensive studies, following the principles established by Swearingen and Michalski, and make simulation runs in laboratories to correlate field injury data.

(3) Basic research:

Most of the detailed simulation studies and full-scale tests have been conducted prematurely without fundamental investigation. An effort should be made to make a simple or even a crude mathematical model analysis along the lines established by Payne and Kornhauser. Without the guiding light of fundamental studies, we would not know how to interpret simulation results even if we obtained them.

(4) Simplification of test procedures:

Based on fundamental studies, a rational injury criterion should be established. In this approach (Table 5), we need only to know the velocity

change and the duration of the event. The accelerometer trace need not be recorded, and the controversial filtering procedure can be eliminated. Rather, the data are fed through an integrator to obtain the velocity traces. We can thus concentrate on the duplicating runs to test the reproducibility of the velocity traces. The acceleration traces are obviously non-repeatable.

In closing, it should be remarked that too conservative an approach would require a set of tolerance limits much lower than necessary. Even though many existing designs can satisfy these limits, their adoption might have a tendency to disqualify a perfectly safe barrier of rigid type design, such as the concrete barrier. From the economic point of view, one can argue that such a barrier is cheaper in the long run since it requires infrequent maintenance. This economic factor may justify a lower safety factor to be applied to the values in Table 5. However, there is very good ground to be conservative in barrier crash studies, especially when the vehicle is redirected. In the latter case, the vehicle may be travelling at 75 percent of the impact speed or higher. Even a brief loss of consciousness on the part of the driver could cause very grave consequences.

REFERENCES

1. Shoemaker, N. E., "Summary Report of Highway Barrier Analysis and Test Program", Cornell Aeronautical Laboratory Report No. VJ-1472-V-3, 1961.

2. Stapp, J. P., "Human Tolerance to Dynamic Forces", U.S.A.F. Aeromedical Field Laboratory, Holloman Air Force Development Center, 1955.

3. Severy, D. M. and Mathewson, T. H., "Technical Findings from Automobile Impact Studies", SAE Transactions, 65, pp. 70-83, 1957.

4. Graham, M. D., Burnett, W. C., Gibson, J. L. and Freer, R. H., "New Highway Barriers, The Practical Application of Theoretical Design", Highway Research Record No. 174, 1969.

5. Olson, R. M., Post, E. R. and McFarland, W. F., "Tentative Service Requirements for Bridge Rail Systems", NCHRP Report 86, 1970.

6. Nordlin, E. F., Woodstrom, J. H., Hackett, R. P. and Folsom, J. J., "Dynamic Tests of the California Type 20 Bridge Barrier Rail", Highway Research Record No. 343, 1971.

7. Michie, J. D. and Bronstad, M. E., "Location, Selection and Maintenance of Highway Traffic Barriers", NCHRP Report 118, 1971.

8. Bronstad, M. E. and Michie, J. D., "Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances." NCHRP Report 153, 1974.

9. Military Specification - General Specification for Seat System: Upward Ejection, Aircraft, MIL-S-9479A (USAF), June 16, 1967.

10. Hyde, A. S., "Biodynamics and Crashworthiness of Vehicle Structures", Wyle Laboratories Report WR68-3, Vol. III, March 1968.

11. Weaver, G. D. and Marquis, H. L., "The Safety Aspects of Roadside Slope Combinations", Paper presented at 53rd Annual Meeting of Highway Research Board, January 1974.

12. Payne, P. R., "Injury Potential of Ejection Seat Cushions", Journal of Aircraft, 6, 3, pp. 273-278, May-June 1969.

13. Swearingen, J. J., 7th Stapp Conference, 1965.

14. "Occupant Crash Protection in Passenger Cars, Multipurpose Passenger Vehicles, Trucks and Buses", Motor Vehicle Safety Standard No. 208, Rev. May 1972.

15. Frankland, J. M., "Effects of Impact on Simple Elastic Structures", Proc. Soc. Exp. Stress Analysis, VI 2, 1948.

16. Boundurant, S., Clarke, N. P. and Blanbard, W. G., "Human Tolerance to Some of the Accelerations Anticipated in Space Flight", WADC TR58-156, 1958.

17. Geertz, A., "Limits and Special Problems in the Use of Seat Catapults", AAF Aero Medical Center ATI No. 56946 (Translated August 1946), 1914.

18. Ruff, S., "Brief Acceleration: Less Than One Second", German Aviation Medicine in WWII, Vol. 1, pp. 584-597, US Government Printing Office, 1950.

19. Payne, P. R., "The Dynamics of Human Restraint Systems", Impact Acceleration Stress, NAS National Research Council Publication 977, pp. 195-258, 1961.

20. Kornhauser, M. and Gold, Armand, "Application of Impact Sensitivity Method to Animate Structures", Impact Acceleration Stress, NAS National Research Council Publication 977, pp. 333-344, 1961.

21. Stapp, John P., "Jolt Effects of Impact on Man", Impact Acceleration Stress, NAS National Research Council Publication 977, pp. 123-130, 1961.

22. Handbook of Instructions for Aircraft Designers, ARDCM 80-1, April 1960.

23. Holcomb, G. A., "Impact Studies of the U. S. Aero-Space Industry", Impact Acceleration Stress, NAS National Research Council Publication 977, pp. 83-120, 1961.

24. Williams, J. S., "The Nature of Seat Belt Injuries", 14th Stapp Conference, pp. 44-65, 1970.

25. Aldman, Bertil, "Investigation on Long-Stretching Body Restraints", Impact Acceleration Stress, NAS National Research Council Publication 977, pp. 355-362, 1961.

26. Evans, F. G. and Patrick, L. M., "Impact Damage to Internal Organs", Impact Acceleration Stress, NAS National Research Council Publication 977, pp. 159-172, 1961.

27. Patrick, L. M. and Daniel, R. P., "Comparison of Standard and Experimental Windshields", 8th Stapp Conference, pp. 147-166, 1966.

28. Zaborowski, A. V., "Human Tolerance to Lateral Impact with Lap Belt Only", 8th Stapp Conference, 1966.

29. Weiss, E. B., von Gierke, H. E. and Clark, N. P., "Mechanical Impedance as a Tool in Biomechanics", ASME-63-WA-280, Winter Annual Meeting, Nov. 1963.

30. Melvin, John W., Mohan, D. and Stalnaker, R. L., "Human Injury Mechanisms and Impact Tolerance", Paper presented at the 54th Annual Meeting of the Transportation Research Board, Jan. 16, 1975.

TABLE I

LIMITS OF TOLERABLE DECELERATION (Ref. (1))

(TENTATIVE)

RESTRAINT	LATERAL			LONGITUDINAL			TOTAL		
	Max. Dec. (G)	Duration Sec	Rate-of Onset G/Sec	Max. Dec. (G)	Duration Sec	Rate-of Onset G/Sec	Max. Dec. (G)	Duration Sec	Rate-of Onset G/Sec
Unrestrained Occupant	3	0.200	500	5	0.200	500	6	0.200	500
Occupant Restrained by Lap Belt	5	0.200	500	10	0.200	500	12	0.200	500
Occupant Restrained by Lap Belt and Shoulder Harness	15	0.200	500	25	0.200	500	25	0.200	500

TABLE 2

SAFETY EVALUATION GUIDELINES

Dynamic Performance Factors	Evaluation Criteria	Applicable Criteria for Appurtenance			
		Longitudinal Barriers		Crash Cushions	Breakaway or Yielding Supports
		Length-of-Need and Transitions	Terminals		
I. Structural Adequacy	A. The test article shall redirect the vehicle; hence, the vehicle shall not penetrate or vault over the installation.	●			
	B. The test article shall not pocket or snag the vehicle causing abrupt deceleration or spinout or shall not cause the vehicle to rollover. The vehicle shall remain upright during and after impact although moderate roll and pitching is acceptable. There shall be no loose elements, fragments or other debris that could penetrate the passenger compartment or present undue hazard to other traffic.	●	●	●	●
	C. Acceptable test article performance may be by redirection, containment, or controlled penetration by the vehicle.		●	●	
	D. The terminal shall develop tensile and/or flexural strength of the length-of-need.		●		
II. Impact Severity (See Section VII of Commentary for discussion and limitation of guideline values)	A. Where test article functions by *redirecting* vehicle, maximum vehicle acceleration (50 msec avg) measured near the center of mass should be less than the following values: Maximum Vehicle Accelerations (g's) Lateral / Longitudinal / Total / Remarks 3 / 5 / 6 / Preferred 5 / 10 / 12 / Acceptable These rigid body accelerations apply to impact tests at 15 deg or less.	●	●	●	
	B. (Optional). Anthropometric dummy responses should be less than those specified by FMVSS 208 (e.g., resultant chest acceleration of 60 g, Head Injury Criterion of 1000, 1800 lb (8 kN) shoulder harness and 5000 lb (22.2 kN) total lap belt).	○	○	○	○
	C. For direct-on impacts of test article, where vehicle is decelerated to a stop and where lateral accelerations are minimum, the maximum average permissible vehicle deceleration is 12 g as calculated from vehicle impact speed and passenger compartment stopping distance.		●	●	
	D. Maximum momentum change of the vehicle during impact shall be 1100 lb-s (4892 Ns). This is required for Test 1 only; preferably it is applicable to both Tests 1 and 2.				●
III. Vehicle Trajectory Hazard	A. After impact, the vehicle trajectory and final stopping position shall intrude a minimum distance into adjacent traffic lanes.	●	●	●	●
	B. Vehicle trajectory behind the terminal is acceptable.		●		

TABLE 3 (Ref. (11))

TOLERABLE ACCELERATION LIMITS ESTABLISHED FOR DITCH TRAVERSAL STUDY (TENTATIVE)

Restraint	Maximum Acceleration (G's)		
	Lateral (G_y)	Longitudinal (G_x)	Vertical (G_z)
Unrestrained Occupant	5[e]	7[e]	6[d]
Lap Belt Restraint	9[c]	12[b]	10[c]
Lap Belt and Shoulder Harness[a]	15[a]	20[a]	17[a]

Notes:

a. Maximum limits established by Hyde (See Figure 5).

b. Commonly accepted limit for lap belt restraint in crash cushion and breakaway studies. (Represents 60 percent of Hyde's lap belt and shoulder harness acceleration limits).

c. Established as 60 percent of lap belt and shoulder harness restraint limits.

d. Lower limit established by Hyde for safety and substantiated by TVI research team field tests. (Represents 60 percent of established lap belt restraint vertical acceleration limit).

e. Established as 60 percent of lap belt restraint limits.

Table 4 Resonance Frequency of Parts of Human Body (21)

	Peak Resonance cps	Period T Seconds T/4	Jolt G per second at T/4 for peak G of 20	30	40	50	100	200
Transverse, supine	1	.25	80	120	160	200	400	800
Whole body, unit mass	2	.125	160	240	320	400	800	1,600
Longitudinal, supine	3-3,5	.082	240	360	480	600	1,200	2,400
Vertical, sitting	4	.0625	320	480	640	800	1,600	3,200
Vertical, standing	5	.05	400	600	800	1,000	2,000	4,000
Longitudinal, abdomen	6	.041	480	720	960	1,200	2,400	4,800
Longitudinal, anterior chest	7	.035	560	840	1,120	1,400	2,800	5,600
Longitudinal, abdomen	8	.031	640	960	1,280	1,600	3,200	6,400
Longitudinal, anterior chest	9	.027	720	1,080	1,440	1,800	3,600	7,200
Longitudinal, anterior chest	10	.025	800	1,200	1,600	2,000	4,000	8,000
Longitudinal, anterior chest	11	.0225	880	1,320	1,760	2,200	4,400	8,800
Vertical, standing	12	.0207	960	1,440	1,920	2,400	4,800	9,600
Vertical, seated, head	18	.014	1,440	2,160	2,880	3,600	7,200	14,400
Vertical, standing, head	20	.0125	1,600	2,400	3,200	4,000	8,000	16,000
Vertical, standing, head	30	.081	2,400	3,600	4,800	6,000	12,000	24,000
Vertical, seated, eyeballs	60	.0041	4,800	7,200	9,600	12,000	24,000	48,000
Vertical, seated, eyeballs	90	.0027	7,200	10,800	14,400	18,000	36,000	72,000
Jaw versus head	100	.0025	8,000	12,000	16,000	20,000	40,000	80,000
Skull	300	.0008	24,000	36,000	48,000	60,000	120,000	240,000
Skull	400	.0006	32,000	48,000	64,000	80,000	160,000	320,000
Skull	600	.0004	48,000	72,000	96,000	120,000	240,000	480,000
Skull	900	.00027	72,000	108,000	144,000	180,000	360,000	720,000

TABLE 5

CRITERIA FOR RECOMMENDED TOLERANCE LIMITS FOR FATAL OR IRREVERSIBLY DISABLING INJURIES

	Longitudinal ($\pm G_x$)		Lateral ($\pm Gy$)		Vertical ($\pm G_z$)	
	ΔV	a	ΔV	a	ΔV	a
Lap and Shoulder belts	12[c]	25[a]	12[d]	25[d]	3[f]	12[f]
Lap belts only	12[c]	20[b]	6[e]	20[d]	3[f]	12[f]
Unrestrained	6[c]	20[b]	6[d]	20[d]	3[f]	10[f]

where ΔV = Velocity change due to the occupant impacting the vehicle interior in meters/sec (usually the terminal velocity before impact.)

a = Average deceleration in G - units over the duration of impact.

Superscripts:

a. Based on tests by Douglas Aircraft, Kornhauser and Hegenwald quoted by Payne (18), and HIAD (22) -- Upper limits.

b. Ditto -- Lower limits.

c. Based on Swearingen's (13) results.

d. Assumed same as longitudinal counterparts.

e. Restraining effect to lateral motion neglected.

f. Based on results of Geertz (17), HIAD (22) and Payne (12).

Note: These values are recommended for the tolerance thresholds for fatal or irreversibly disabling injuries. For a conservative design of barriers a suitable factor of safety, say in the range of two or three, should be used.

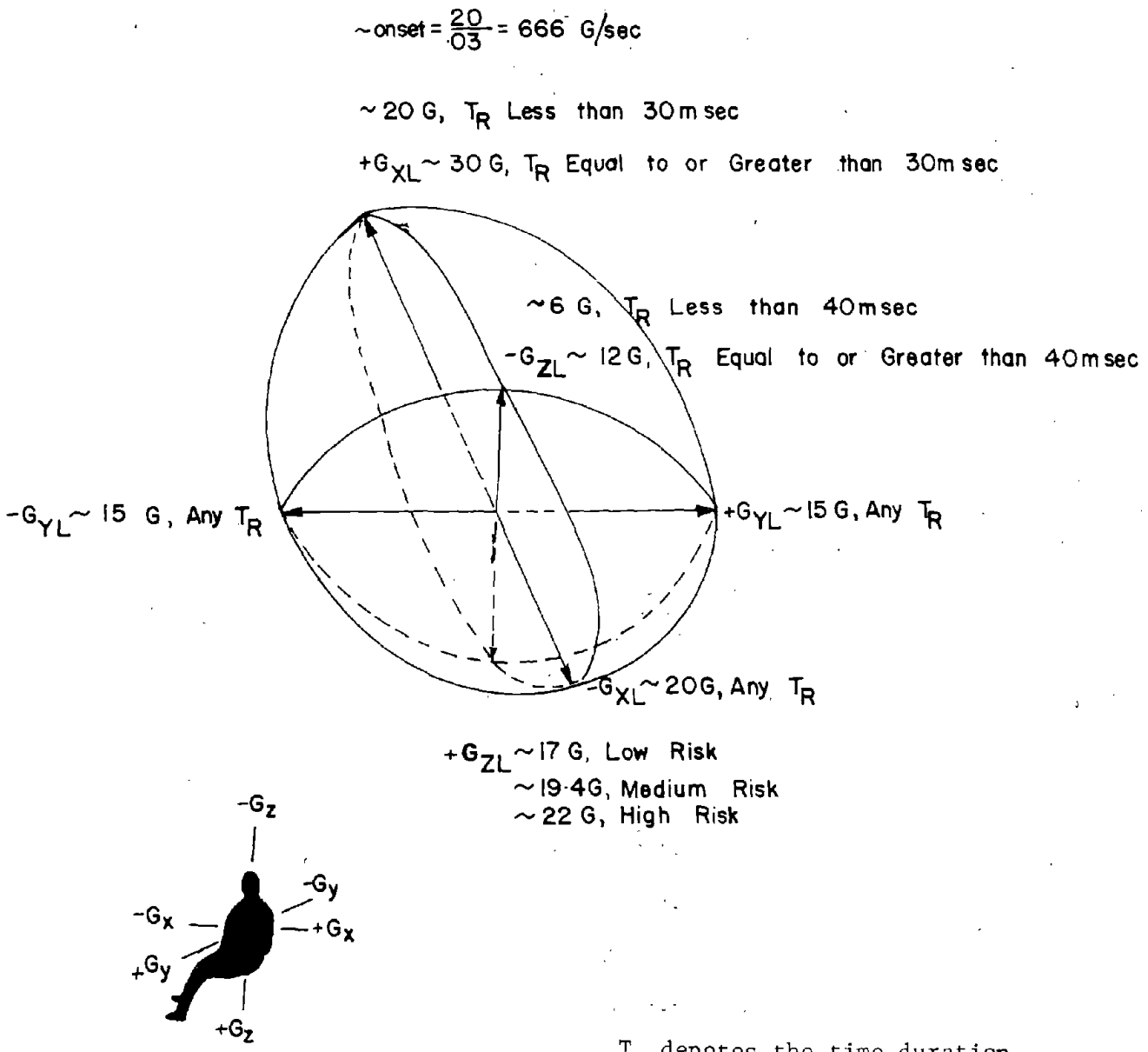


Figure 1 Ellipsoidal Envelope for Defining the Multiaxial Acceleration Limits (Ref. 10)

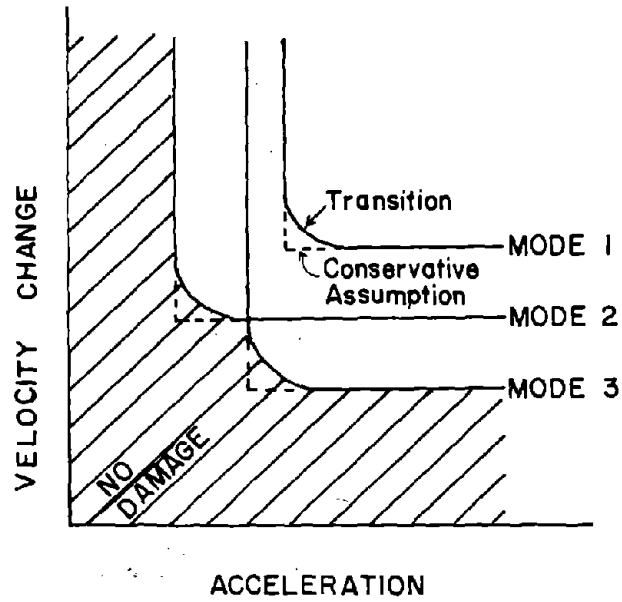


Figure 2 Kornhauser's Sensitivity Curves (Ref. 20)

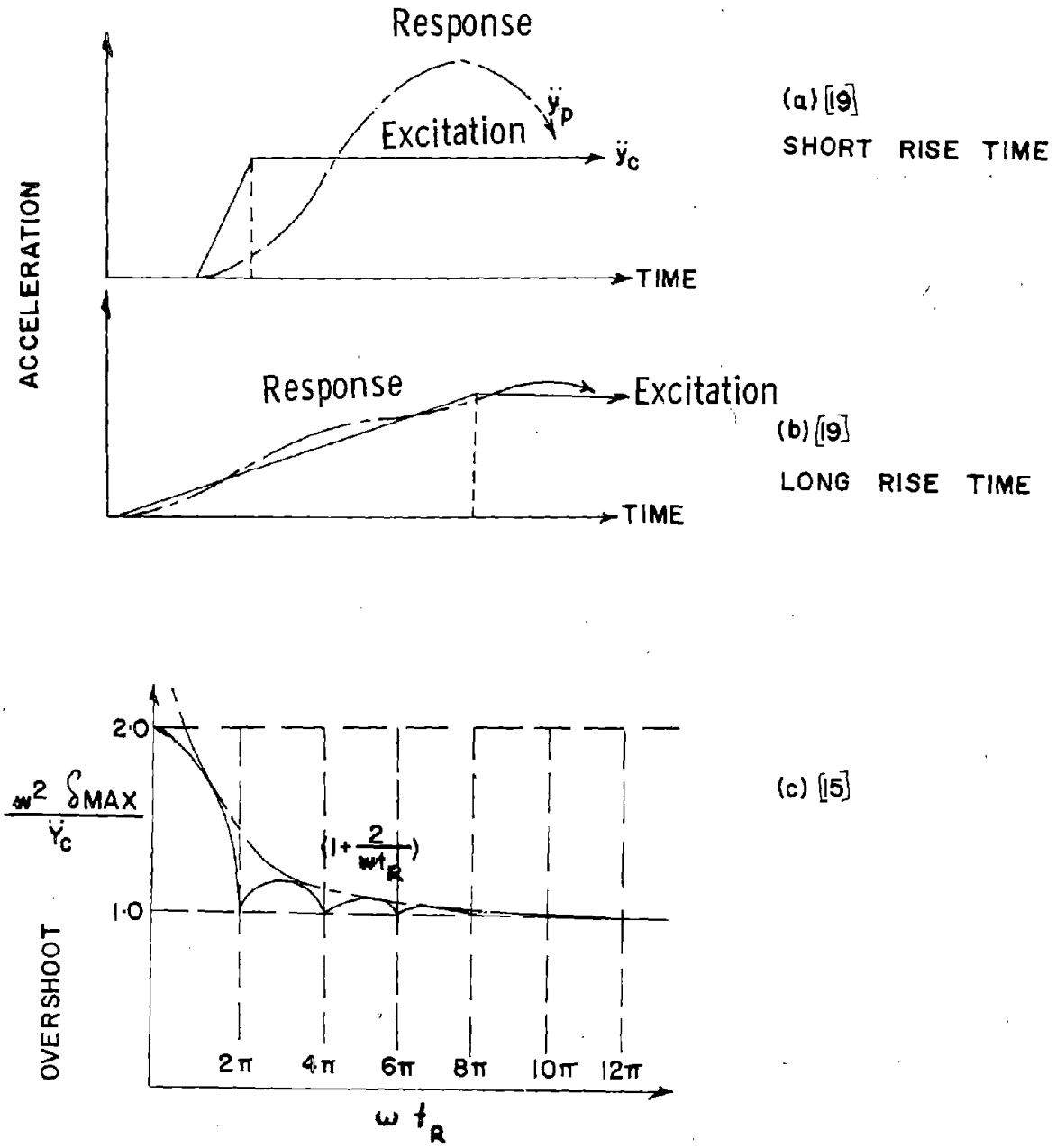


Figure 3 Theoretical Effect of Rise Time (Ref. 15 and 19)

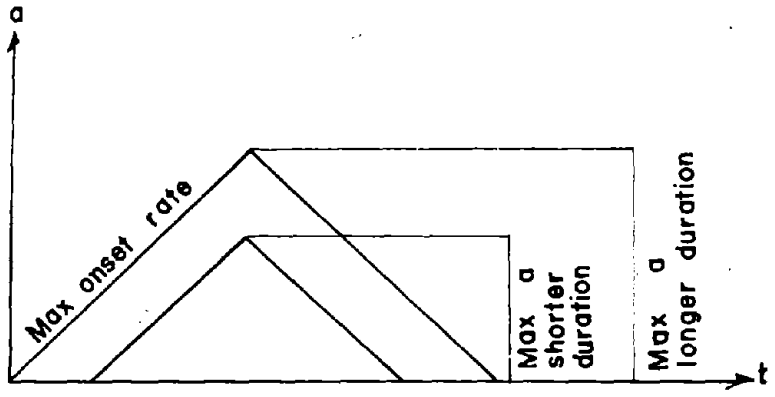
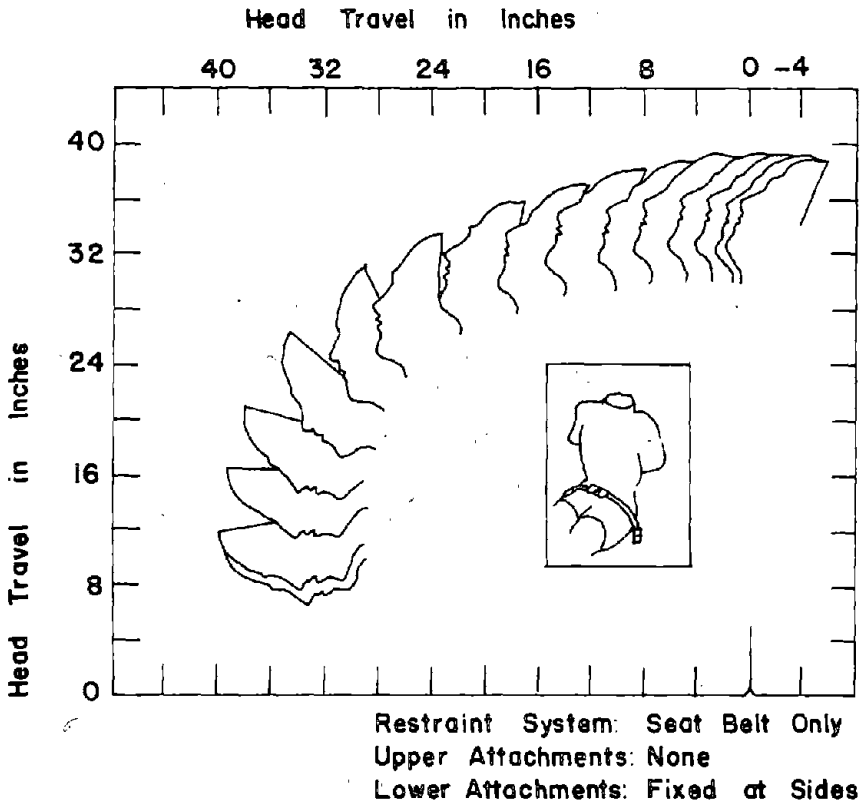


Figure 4 Onset Rate Paradox



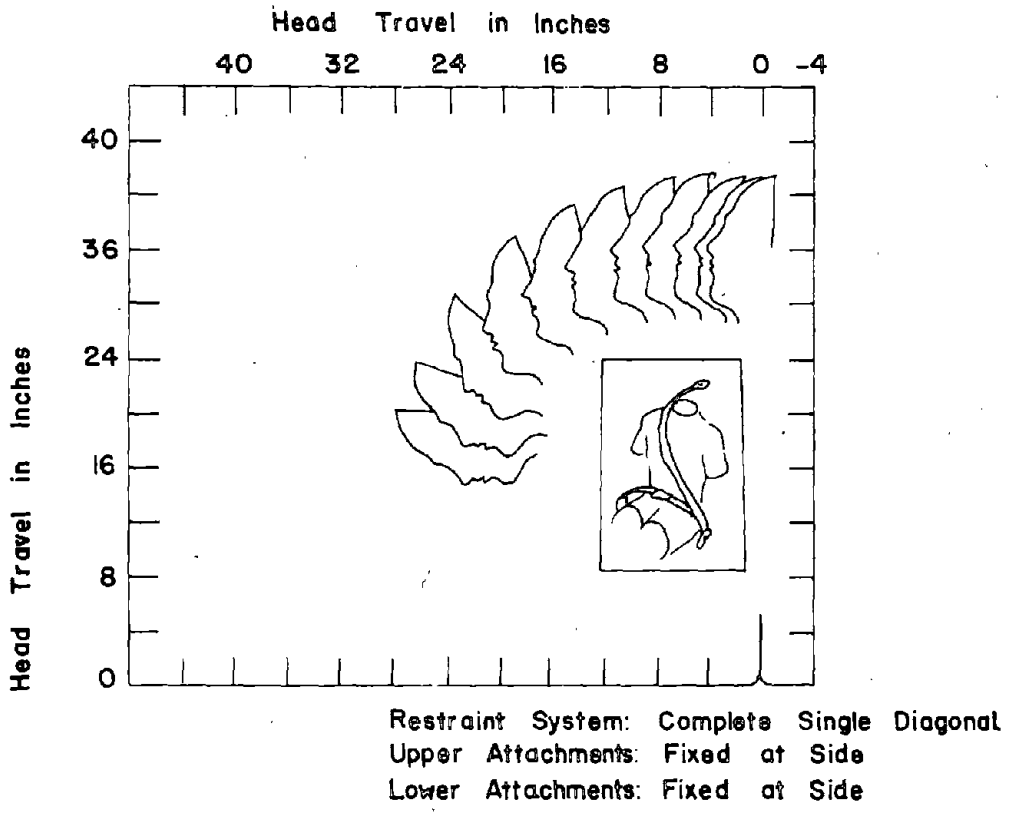
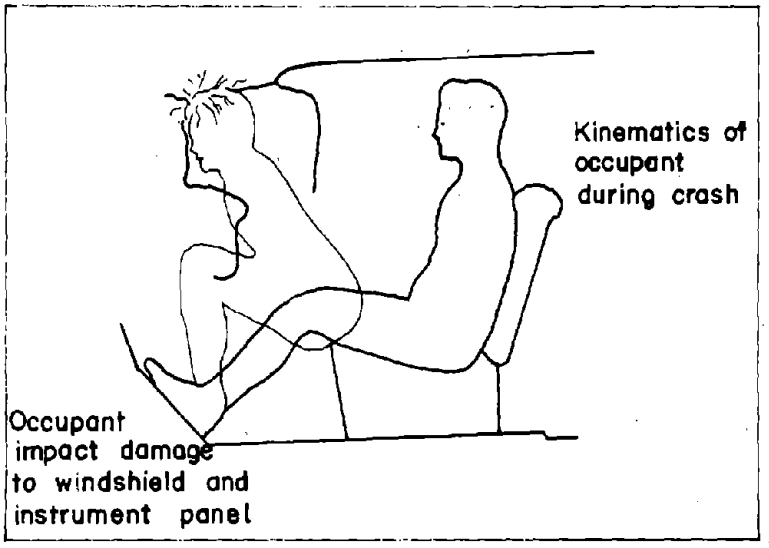


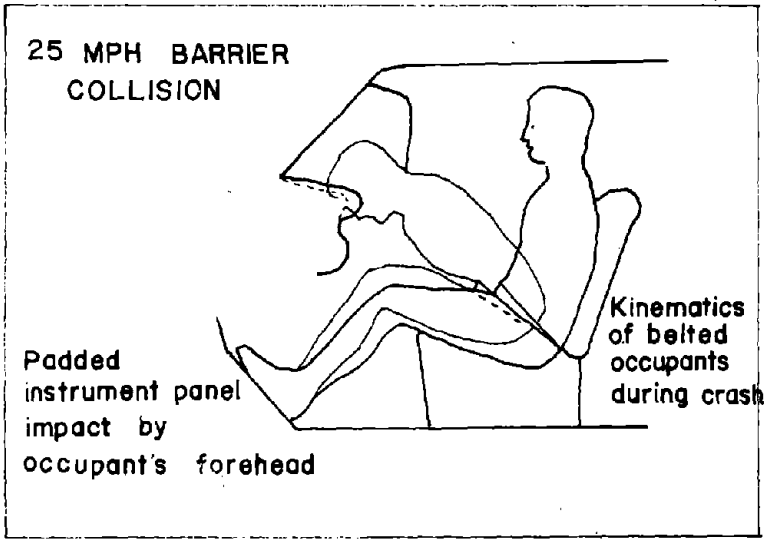
Figure 5 Effect of Restraints on Body Motion (Ref. 10)

Fig. 6a



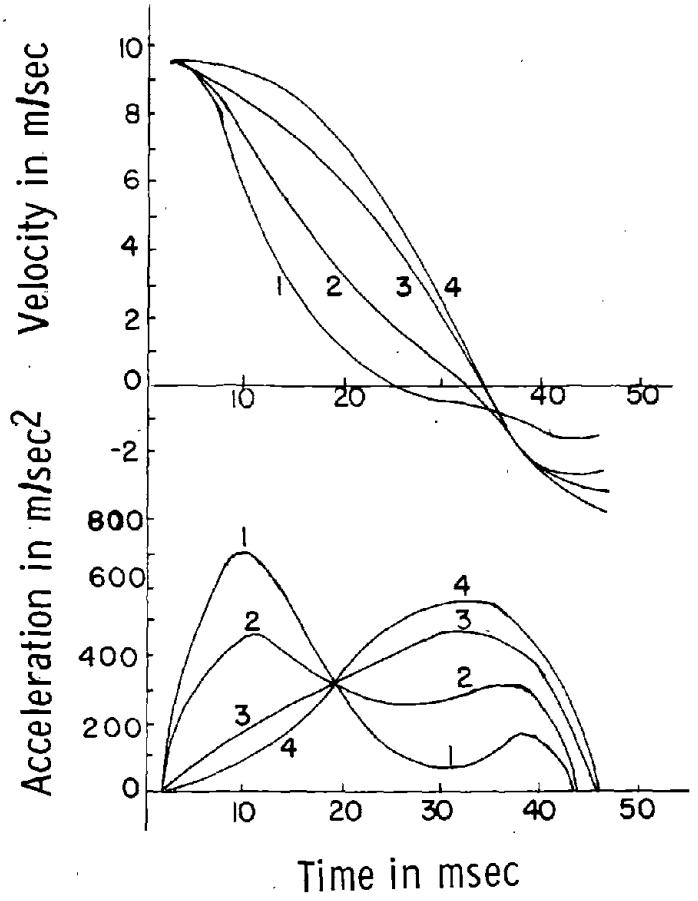
OCCUPANT WITHOUT SEAT BELT IN BARRIER CRASH

Fig. 6b



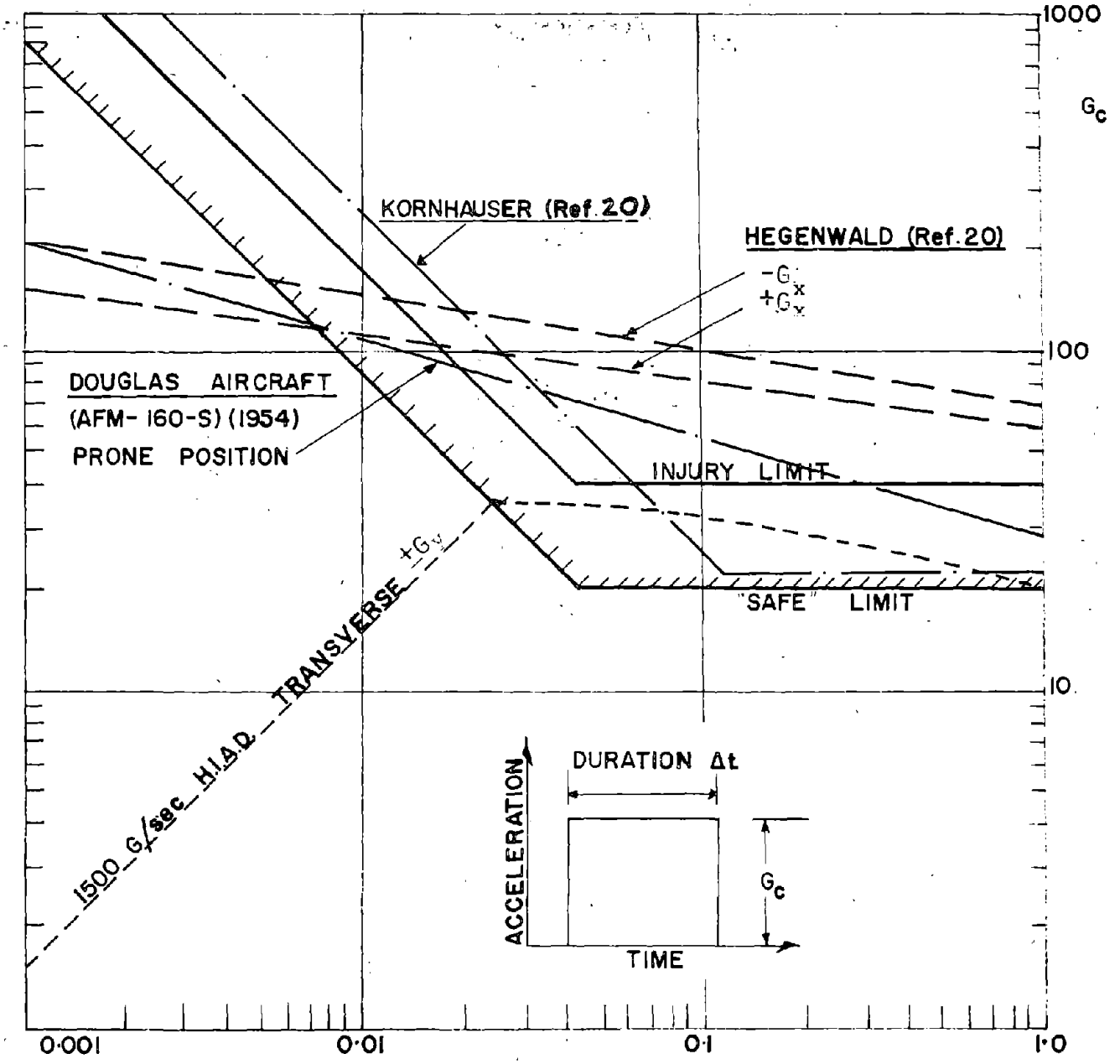
OCCUPANT WEARING SEAT BELT IN BARRIER CRASH

Figure 6 Kinematics of Occupants During Crash



1. Near the anchoring point in test vehicle
2. In the middle of the strap
3. Near the loading weight
4. At the loading weight

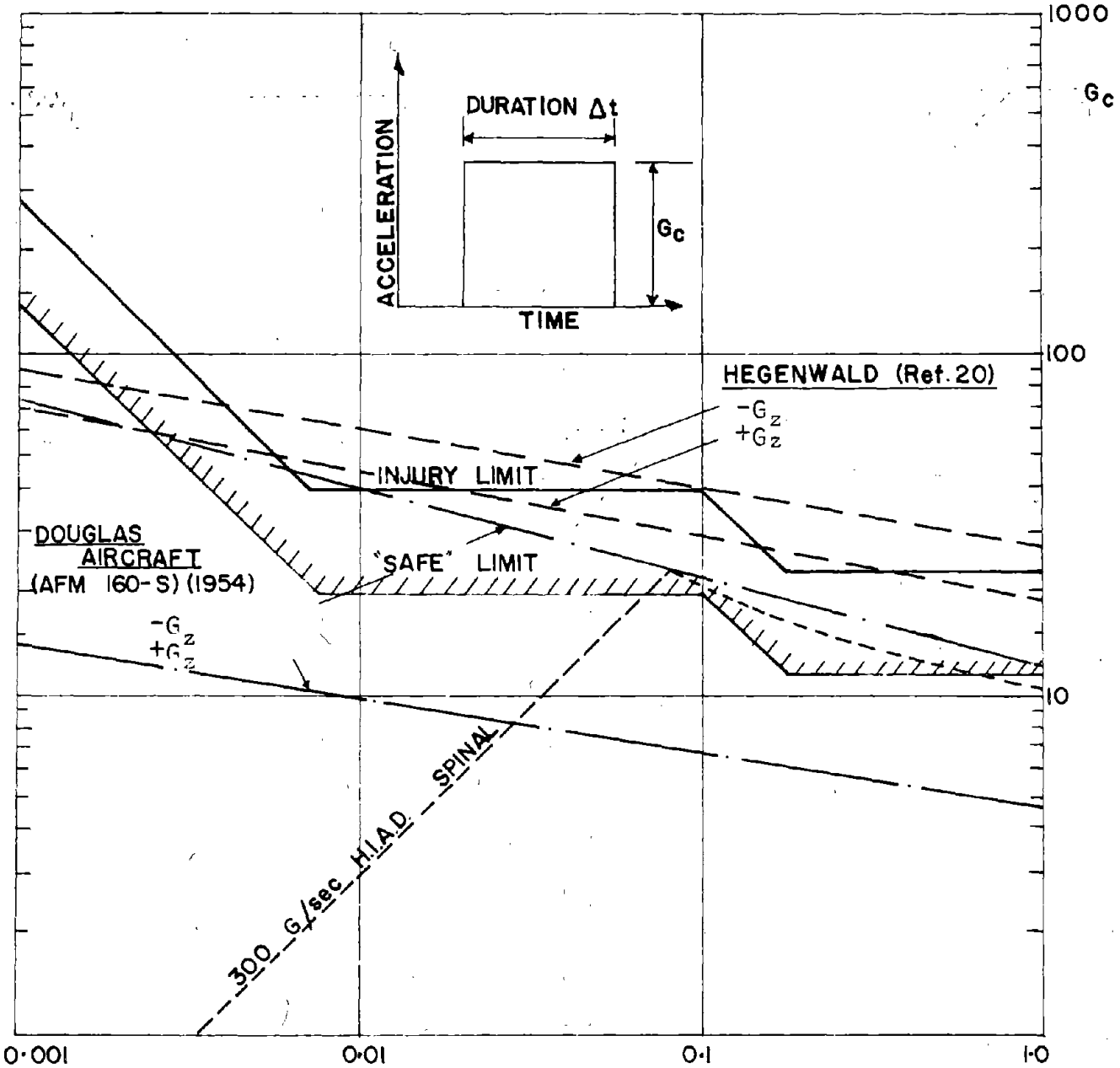
Figure 7 Dynamic Stretching of Single Strap-Velocity and Deceleration



DURATION OF ACCELERATION PULSE IN SECONDS – Δt

Note that the HAID curve is based upon a trapezoidal definition, and is therefore more severe than appears from this plot.

Figure 8 Human Tolerance to Deceleration (a) Transverse with Soft Head Restraint (19)



DURATION OF ACCELERATION IN SECONDS – Δ t

Note that the H.I.A.D. curve is based upon a trapezoidal definition, and therefore is more severe than appears from this plot.

Figure 8 Human Tolerance to Deceleration (b) Spinal (19)

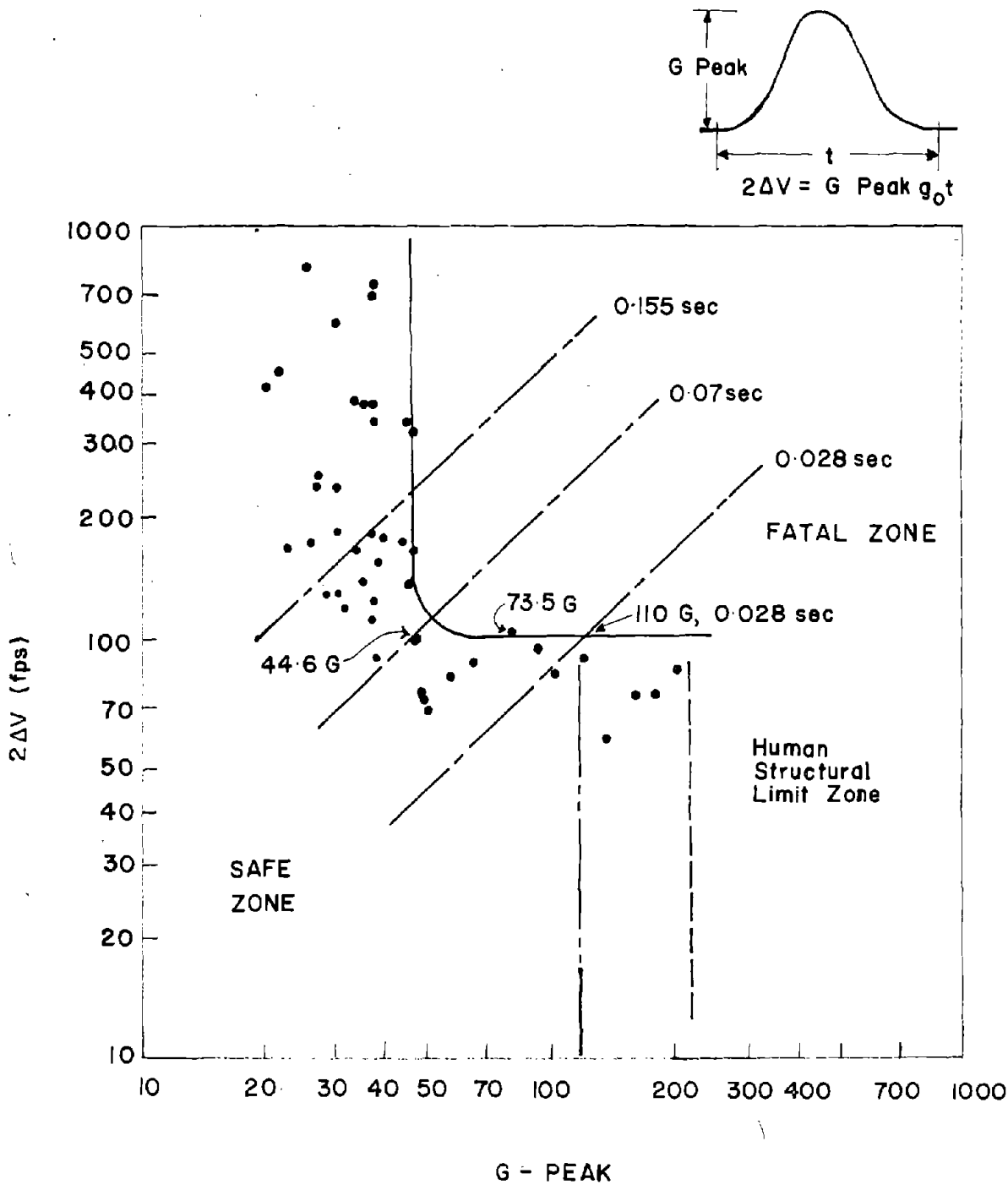


Figure 8 Human Tolerance to Deceleration (c) Impact, Transverse (Ref. 10)

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