Collision Risk Assessment Based on Occupant Flail-Space Model

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A method is presented to evaluate results of vehicle crash tests of highway safety appurtenances in terms of injury risk to the vehicle occupant. The occupant is assumed to be propelled through the vehicle compartment (flail space); to strike the instrument panel, windshield, or side door; and to subsequently ride down the remaining part of the collision event in contact with the vehicle. Injury is assessed in terms of (a) the impact velocity of the occupant and the instrument panel and (b) accelerations of occupant and vehicle that occur during the subsequent ride down. Evolution of present appurtenance safety criteria is reviewed. Dynamic conditions that produce human injury are briefly discussed along with recommended threshold values that will minimize the degree of the injuries. Finally, a typical application of the flail-space model to crash test results is presented.

Highway appurtenances are evaluated for their potential safety performance by full-scale vehicle crash tests and sometimes by pendulum or bogie tests. Since complete safety is an unattainable ideal, safety performance is measured in terms of degree of risk experienced by occupants when the vehicle collides with a roadside appurtenance.

The degree of risk is determined for two phases of a collision as illustrated in Figure 1. In stage 1, the occupant is flung through the compartment (flail space) and strikes the instrument panel, the windshield, or the door with an injury-dependent velocity and, in stage 2, the occupant rides down with the vehicle during the remaining portion of its velocity change (Figure 1b) and is subjected to injury-dependent accelerations.

The concept of this relatively simplified approach is not new; it has been suggested by several researchers. The purpose of this paper is to present the concept, discuss possible limitations, and then describe practical applications.

BACKGROUND

The first attempt to establish a human injury threshold based on vehicle dynamics during guardrail and median-barrier redirections is attributed to Shoemaker (1). He presented threshold vehicle lateral, longitudinal, and total accelerations along with three assumed occupant restraint conditions--no belt, lap belt only, and lap belt and shoulder belt. In addition, Shoemaker presented maximum duration and acceleration onset rates. Even though Shoemaker made a special effort to emphasize that his proposed criteria were tentative and based on very limited experience, his resultant table of values became "etched in stone" because of its uniqueness in the field. The table has subsequently been reproduced and referenced by numerous researchers (2-5). Since 1961, Shoemaker's criteria have been modified (6) by eliminating the 500 g/s acceleration onset rate limit and by using a maximum average vehicle acceleration of 50 ms and by applying the criteria only to tests with vehicle-barrier impact angles of 15° or less. In addition, data acquisition and processing parameters have been better defined (6). Even with these modifications, researchers have not been satisfied with the criteria because they do not adequately reflect the severity of a redirection and are believed to be overly conservative in some cases. Few longitudinal traffic barriers now satisfy the criteria; yet many are known to perform well in service.

In 1969, Edwards used vehicle velocity change as a measure of collision severity in evaluating breakaway luminaire supports (7). He concluded that, when velocity change exceeds 6 mph (10 km/h), there is a possibility of minor passenger injury; also, he stated that velocity change in excess of 12 mph (19 km/h) should be avoided. Edward's criteria were based on the work of Patrick (8) and Blamey (9), which indicated that head and chest injuries occur when the impact velocity of these body components on the compartment interior exceeds 11 mph (18 km/h). He concluded that the occupant and compartment interior impact velocity was approximately the same as the vehicle velocity change during a luminaire impact. By limiting the vehicle velocity change, he would also be limiting the occupant and compartment interior impact velocity and thus the occupant risk. [This relationship was intended for cases in which the vehicle undergoes full velocity change prior to the occupant impact; for other conditions, the 11-mph (18-km/h) criterion can become overly conservative.] In Federal Highway Administration (FHWA) Notice TO-20 (10) the criterion was converted from velocity change to a 1100-lbf/s (4892-N/s) momentum change. This 1100-lbf/s impulse is equivalent to a car that weighs 2000-4000 lb (907-1814 kg) undergoing a change in velocity from 12.1 to 6.0 mph (from 19.7 to 9.7 km/h). In 1975, the American Association of State Highway and Transportation Officials (AASHTO) (11) indicated that the preferred maximum momentum change should be 750 lbf/s (3336 N/s). In addition to luminaire supports, this criterion has been applied to other breakaway devices such as sign supports and devices that bend over on impact (12). Because of the protracted duration of collisions with yielding supports, Edward's criterion was modified in Transportation Research Circular (TRC) 191 (12) to apply only to that portion of the test vehicle or pendulum momentum change that occurred prior to the hypothetical impact of the occupant on the dashboard (stage 1).

A third set of vehicle-dynamics criteria was developed by Tamanini and Viner in 1970 for crash cushions (13). Essentially, vehicles in a weight range of 2000-4500 lb (907-2041 kg) that hit a crash cushion at speeds of up to 60 mph (97 km/h) were to be stopped at an acceleration that averaged less than 12 g. The vehicle average acceleration was computed, when the initial velocity and the total stopping distance were known, by using the equation

$$\bar{a} = V^2/29.9S \qquad (1)$$

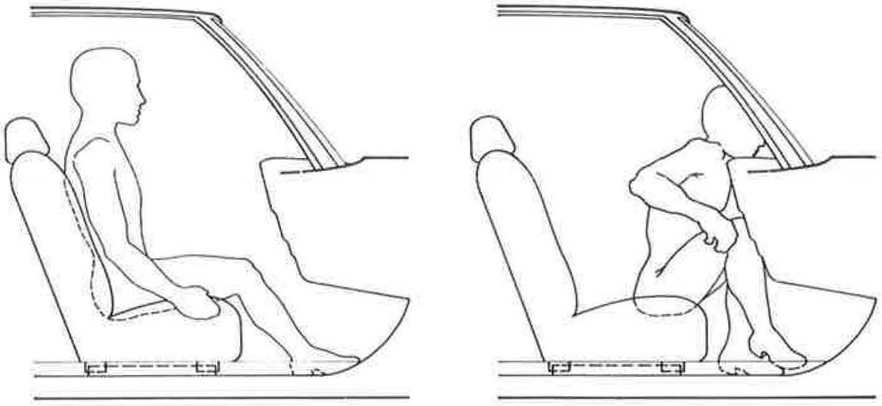
where $\bar{a}$ is average vehicle acceleration in g, V is vehicle impact speed in miles per hour, and S is the stopping distance in feet. A maximum acceleration onset rate of 500 g/s was also stipulated. FHWA collected more than 400 crash-cushion accident records, and the findings convincingly showed that devices that meet these criteria perform well in actual service (14).

A summary of existing occupant risk criteria is shown in Figure 2 [from TRC 191 (12)].

NEED FOR NEW MODEL

The question may be asked whether there is need for

Figure 1. Occupant flail-space kinematics.



(a) Occupant Position at Instant of Vehicle/Barrier Impact

(b) Occupant Poisition at Instant of Impact with Instrument Panel/ Windshield and During Subsequent Vehicle Ridedown

Figure 2. Summary of TRC 191 evaluation criteria.

Evaluation Criteria	Applicable Criteria for Appurtenance			
	Longitudinal Barriers			
	Length-of-Need and Transitions	Terminals	Crash Cushions	Breakaway or Yielding Supports
A. Where test article functions by redirecting vehicle, maximum vehicle acceleration (50 ms 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. For direct-on impacts of test article, vehicle is decelerated to a stop and where lateral accelerations are minimum, the preferred maximum vehicle acceleration average is 6 to 8 g's. The maximum average permissible vehicle deceleration is 12 g, as calculated from vehicle impact speed and passenger compartment stopping distance.		●	●	
C. Maximum momentum change of the vehicle during impact shall be 1100 lb-s (4892 Ns) and preferably less than 750 lb-s (3336 Ns).				●

a new model for occupant risk assessment. The response would be that the three criteria or models now in use are inconsistent, are inadequate measures of occupant risk, and may be overly conservative in some areas.

Even though the ultimate goal of safety performance in the three categories of highway appurtenances (i.e., longitudinal barriers, crash cushions, and breakaway or yielding supports) is to protect the vehicle occupants, the devices are evaluated by different vehicle responses. This inconsistency has caused confusion among researchers, hardware developers, and highway agencies and has unnecessarily added complexity to an existing area of technology.

All present criteria indicate (at least in an overall manner) the degree of occupant risk: The lower the vehicle accelerations and the momentum change are, the less risk is involved in the collision. The momentum-change criterion is probably the best indicator, since it reflects stage 1 occupant impact velocity. The criterion of average accelerations for crash cushions, based on stopping distance, is generally adequate, but there are devices such as lumpy systems that could subject occupants to a more severe ride down than that indicated by the average acceleration value. The criterion of a maximum average vehicle acceleration of 50 ms is probably the least adequate, since this speed may occur prior to the impact between occupant and instrument panel (stage 1) and thus can be irrelevant (except for the velocity change associated with the pulse).

The criterion for longitudinal barriers may be overly conservative to the point at which soon few systems will satisfy the preferred values. The systems that do are characterized as flexible (e.g., cable or weak post devices). These systems are being used by a decreasing number of states. In contrast, the rigid concrete safety shape is one of the more widely used barriers even though the typical crash test severity indicator (e.g., maximum average vehicle acceleration of 50 ms) exceeds the preferred range. In essence, researchers and highway agencies are, to a large degree, ignoring the recommended values and evaluating the crash test performance of a device on a more-subjective basis.

For these reasons, a general and more-indicative model of occupant risk assessment is needed. Such a model, based on the flail-space concept, has been developed and is presented in this paper.

VEHICLE COLLISION ENVIRONMENT

Performance Requirements

Although the main concern of this paper is collision severity as it refers to occupant hazard, appurtenances are evaluated during a series of vehicle crash tests for two other safety performance factors--structural adequacy and vehicle trajectory hazard (12). For structural adequacy, the appurtenance must exhibit certain design strength properties. Based on its design function, the appurtenance must either smoothly redirect or gently stop the impacting test vehicle or must readily break away from it. In other words, the appurtenance must not snag, abruptly decelerate, or upset the test vehicle. Moreover, neither the appurtenance nor any of its components must penetrate or significantly deform the occupant compartment. Until an appurtenance has met these requirements for structural adequacy, it is generally not considered for occupant-risk evaluation. Vehicle trajectory hazard refers to the path the vehicle takes from the collision to the final stopping location. Ideally, the vehicle will be redirected or stopped near the appurtenance without subjecting adjacent traffic to undue hazard.

Collision Parameters

Occupant hazard during the collision of a vehicle with a roadside appurtenance is dependent on an extremely complex event that has a large number of variables. The more important of these includes (a) geometry, stiffness, mass, and fracture properties of the appurtenance; (b) mass, crush properties, dynamic stability, inertial properties, and impact speed and attitude of the vehicle; (c) occupant seating position and attitude, size, and physical condition; and (d) vehicle compartment space and stiffness, or energy absorption capacity of interior surfaces.

It may be noted that highway engineers have an influence only on the items in (a) and must attempt to accommodate variation in all other parameters. This has required the highway engineer to be extremely conservative and to design for combinations of worst conditions. Even so, the unforeseen rapid sizing down of the passenger vehicle fleet and the increased safety expectancy of the public have made many appurtenances obsolete well before their anticipated life of 20-30 years.

FLAIL-SPACE MODEL

Injury Mechanisms

It is well known that injury depends on dynamic factors such as duration and magnitude of acceleration, velocity, or momentum change as well as on the constitution of the body or part of the body under consideration. Moreover, these dynamic factors are identified by their duration and intensity: impact, dynamic force, and hydraulic force (15). Impact is characterized by such brisk force application as when the head strikes the windshield and the bone structure is fractured. The load history is much shorter than the natural period of the body element. Before the element response has developed, the impulse has elapsed. As far as the element is concerned, there is only a change of momentum, and neither the deceleration intensity nor the pulse duration is independently important. This injury potential is measured by (16)

$$\int_0^t a\,dt = \Delta V \leqslant (\Delta V)_{\text{limit}} \qquad (2)$$

where a is acceleration (in feet per second squared) on the body element, t is the pulse duration (in seconds), and ΔV is the change in velocity of the body element (in feet per second). Equation 2 indicates the injury potential at the conclusion of stage 1.

Dynamic force had sufficient duration for the body response to be fully developed; the injury potential depends essentially on the amount of force that acts on the body rather than on the momentum. The sustained dynamic force results in deformation and crushing of the body elements and is measured by (16)

$$a \leqslant (a)_{\text{limit}} \qquad (3)$$

where a is acceleration on the body element (in g). Depending on the direction of force application and the body region under consideration, the minimum duration for body response to develop fully varies from 7 to more than 40 ms (17). As the duration of force application decreases from the range of 7-40 ms, the intensity of force required to produce body damage increases (SAE 700398, revised August 1970). Thus, by setting $(a)_{\text{limit}}$ in Equation 3 on the lower bound and using a fully developed response of the body and a duration of interest of, say, 10 ms or more, the dynamic-force injury criterion is defined.

The third injury mechanism is a hydraulic phenomenon in which the dynamic forces act for extremely long periods, e.g., several minutes or more. An example of moderate acceleration for long duration is when body fluids have time to drain away from the brain and cause a blackout. In extreme cases, blood vessels will rupture and vital organs will hemorrhage (15). Because vehicle collisions generally have durations of less than 1 s, the hydraulic-force injury mechanism is not a factor in highway safety.

Flail-Space Hypothesis

The hypothesis divides the collision into two stages. In stage 1, the unrestrained occupant is propelled forward and/or sideways in the compartment space due to vehicle collision acceleration and then hits one or more surfaces and/or the steering wheel with a velocity V. Actually, the vehicle accelerates toward the unrestrained occupant. Thus the occupant experiences no injury-producing forces prior to contact with the compartment surface. In stage 2, the occupant is assumed to remain in contact with the compartment surface and experiences the same accelerations as the vehicle throughout the remainder of the collision. The occupant may sustain injury at the end of stage 1 as measured by Equation 2 and/or during stage 2 as measured by Equation 3.

Simplifications

In order to simplify application of the flail-space hypothesis to full-scale crash testing of highway appurtenances, some assumptions are made:

1. The impact time and velocity of the occupant at initial contact with the compartment surface can be calculated from the vehicle acceleration, compartment geometry, and the consideration that the occupant moves as a free body. (The use of anthropomorphic dummies in a crash test is not required.) Results from sled and vehicle crash tests (18) show that simulated occupants respond as a free body within experimental accuracy. If we consider the wide variation in compartment geometry and flail space in the passenger car fleet, the assumption is judged consistent with the precision of occupant hazard assessment. In the event that an unusually high vehicle acceleration peak occurs just prior to the calculated time of occupant impact, one may wish to include the peak as a part of the stage 2 evalua-

tion to allow for imprecision in calculation of impact time.

2. The occupant does not rebound; therefore, the occupant impact velocity is also the occupant relative velocity change. Moreover, the occupant is assumed to remain in contact with the surface and is directly subject to vehicle accelerations. Movies of dummy kinematics during typical vehicle-appurtenance tests confirm that the dummy remains in contact with the surface at least through the period of high vehicle accelerations (18).

3. The occupant is unrestrained by either a lap or shoulder belt. Less than 20 percent of vehicle occupants use the manual restraint systems at the present time. Although the introduction of compulsory automatic restraints is scheduled for the early 1980s, it will be 7-10 years before a majority of the passenger car fleet is so equipped. Thus this assumption is fairly realistic now but will probably become conservative in time.

4. The occupant is a 50th-percentile male and is considered to be in a normal upright and back-sitting position. This establishes the distances that the occupant can traverse prior to hitting an interior surface. It is noted that a smaller flail space, due either to a small passenger compartment or to the occupant's sitting forward or closer to the impact side, will generally lessen the impact velocity of the occupant on the interior surface.

5. The compartment remains intact; there are no inward penetrations or partial collapse that would affect the occupant trajectory. Also, the windows and doors remain closed during the impact.

6. For redirection or side impacts, only the near-side occupant is considered critical. This coincides with accident statistics to be discussed in the next section.

7. Vehicle accelerations are measured at vehicle center of mass. Only forward and lateral accelerations are considered; since the vehicle remains upright, vertical accelerations are limited to subcritical values.

8. Pitching and rolling motions of the vehicle are not explicitly considered. Front-seat occupant positions are near and just aft of the center of mass for both compact and subcompact sedans; thus these motions do not significantly affect the occupant impact velocities.

HUMAN TOLERANCES

Degree of Injury

Occupant risk is ultimately referenced to the degree of injury sustained by the vehicle occupant during collision. Ideally, the roadside appurtenance should perform so that the degree of injury is zero; however, this is technically unattainable, regardless of cost (19).

In recent years, a number of injury scales have been used by highway accident investigators to quantify the degree of injury and collision severity. The Abbreviated Injury Scale (AIS) (20), developed and endorsed by the American Association for Automotive Medicine, has emerged as a national and international standard. The scale is presented below. AIS-80 is used in this report and links laboratory and experimental research with actual highway experience.

Code	Category
0	No injury
1	Minor
2	Moderate
3	Severe (not life threatening)
4	Serious (life threatening, survival probable)
5	Critical (survival uncertain)
6	Maximum (currently untreatable)
9	Unknown
-	Death (recorded or separate element)

In line with current Federal Motor Vehicle Safety Standard (FMVSS) 208, an upper design limit for occupant protection falls between codes 3 and 4. That is, severe injury is accepted as long as it is not life threatening. This seems to be a reasonable upper bound for appurtenance safety performance. Depending on the class of appurtenance, the mechanics involved, and the state of the possible, the developer and the highway agency would, of course, be encouraged to set the acceptable injury level at a lower code. As discussed in the subsequent section, this can be accomplished by dividing the vehicle dynamic response factor that corresponds to the code 3 or 4 limit by the appropriate design margin.

Threshold Values

Human tolerances and injury responses are presented in Table 1 as a function of the abrupt velocity change that occurs when the occupant, dummy, test animal, or cadaver hits a rigid or yielding surface or restraint system. Results have been assembled from sled tests with both human and animal subjects and from automobile and other types of accident data. It is noted that some accident statistics were gathered prior to 1965 and represent the more-hostile environment of the automobile compartment space before the emphasis on safety, e.g., cluttered instrument panel, unyielding windshields, and non-collapsible steering columns.

Longitudinal Velocity Change

Based principally on head impacts into windshields at velocities that range from 44 to 51 fps (13-16 m/s) and a FMVSS 208 head injury criterion less than 1000, a nominal 40 fps (12 m/s) appears to be a reasonable upper impact velocity threshold $[(\Delta V)_{limit}]$ for unrestrained occupants that strike the instrument panel or windshield. It is believed that the 40-fps (12-m/s) value is consistent with the compartment design and padding of most of the current vehicle population. As a frame of reference, it is noted that a crash cushion designed to the current TRC 191 12-*g* criterion could subject the occupants to a 39-fps (12-m/s) impact velocity with the dashboard or windshield. Obviously, an appurtenance developer should strive to achieve a lower occupant impact velocity and thus further reduce the risk to the occupants. The design ΔV can be established by the equation

$$(\Delta V)_{design} = (\Delta V)_{limit}/F \qquad (4)$$

where F is an appropriate factor of safety, governed to a large extent by the state of the possible with the consideration that there are sometimes conflicting requirements of vehicle sizes within the traffic population.

For test purposes, the longitudinal impact velocity of the unrestrained occupant can be experimentally acquired from instrumented dummies, from analysis of high-speed movies of dummy kinematics, or from calculations, if we assume that the occupant moves as a free missile toward the compartment surface, propelled by vehicle accelerations. In the calculations, a 2-ft (0.6-m) travel space may be

Table 1. Summary of expected effects of abrupt velocity change on injury severity.

Body Element	Impact Surface	Impact Velocity (ft/s)	Severity	Acquisition Method	Ref.
Longitudinal Direction					
Whole	Contoured couch	80	Survival limit	Accident cases; human in supine position	16, p. 335
	Couch/head pad	53.6	Gross injury limit	Empirical and general testing	17, p. 211
	Aviator restraint	48	AIS 3	Sled test of human (Capt. Beeding)	16, p. 341
	Unspecified	34	AIS $\geq$ 5	Automobile statistics prior to 1960	16, p. 342
	Three-point restraint	47	OAIS $\leq$ 3	Accident data from Germany	21, p. 217
Head	Windshield (several types)	44	HIC < 1000	Wham III sled tests with dummy	22, p. 560
	Windshield (type 10-20)	51	HIC < 700	Wham III sled tests with dummy	23, p. 155
Whole	Lap and/or shoulder belt	39	Fatality threshold	Literature review	15, p. 34
	Unspecified	39[a]	Acceptable (crash cushion)	Occupant/vehicle impact based on constant 12 *g* and 2-ft distance	12, p. 10
	Unspecified	32[a]	Preferred (crash cushion)	Occupant/vehicle impact based on constant 8 *g* and 2-ft distance	12, p. 10
	Unspecified	36[a]	Acceptable (redirectional barrier)	Occupant/vehicle impact based on constant 10 *g* and 2-ft distance	12, p. 10
	Unspecified	25[a]	Preferred (redirectional barrier)	Occupant/vehicle impact based on constant 5 *g* and 2-ft distance	12, p. 10
	Unspecified	11[a]	Preferred (breakaway support)	Occupant/vehicle impact based on 2250-lb car and 750 lbf/s	12, p. 10
	Unspecified	16	Acceptable (breakaway support)	Occupant/vehicle impact based on 2250-lb car and 1100 lbf/s	12, p. 10
Lateral Direction					
Whole	Vehicle interior	30-37	10 percent AIS $\geq$ 4	MDAI accident files	24, p. 8
	Vehicle interior	58	100 percent AIS $\geq$ 4	MDAI accident files	25, p. 8
Chest	Vehicle interior	30	AIS $\leq$ 3	FMVSS 214 Advance Notice	25
Whole	Vehicle interior	32	0 percent AIS $\geq$ 3	Car-to-car accident statistics (France) (near-side occupant, no intrusion)	26, p. 202
	Vehicle interior	23	22 percent AIS $\geq$ 3	Car-to-car accident statistics (France) (near-side occupant, with intrusion)	26, p. 202
	Vehicle interior	31	50 percent $\geq$ 3	Car-to-fixed-object statistics (France)[b]	26, p. 209
	Vehicle interior	19	10 percent $\geq$ 3	Car-to-fixed-object statistics (France)[b]	26, p. 209
	Lap and shoulder belt	39	Fatality threshold	Literature review	15, p. 34
	Lap belt or unrestrained	20	Fatality threshold	Literature review	15, p. 34
	Unspecified	18[a]	Acceptable (redirectional barrier)	Occupant/vehicle impact based on constant 5 *g* and 1-ft distance	12, p. 10
	Unspecified	14[a]	Preferred (redirectional barrier)	Occupant/vehicle impact based on constant 3 *g* and 1-ft distance	12, p. 10

Notes: Force = ΔV. 1 ft/s = 0.3 m/s; 1 lb = 0.45 kg. OAIS = Occupant Abbreviated Injury Scale. HIC = head injury criteria. MDAI = Multidisciplinary Accident Investigation.

[a] Calculated from TRC 191 criterion. [b] Generally with compartment intrusion.

assumed when actual values are unknown.

Lateral Velocity Change

Most human tolerance data for lateral impact have been acquired from automobile accident data files. The following factors complicate analysis of accident statistics:

1. The occupant next to the affected side sustains a higher level of injury than does the far-side occupant (26,27),
2. The injury to the near-side occupant is greater when there is intrusion to the compartment space (26),
3. Collisions between the side of a car and a fixed object are generally more severe than car-to-car impacts (26,27), and
4. Restraint systems provide little benefit other than ejection prevention for the near-side occupant (26).

The human being may exhibit similar longitudinal and lateral velocity change tolerances; however, this fact cannot be concluded from automobile accident data. This is probably due to compartment-space intrusion, which is typical of car-to-car and car-to-fixed-object collisions. When the compartment space is not intruded, an upper lateral occupant impact velocity of 30 fps (9 m/s) appears to be a reasonable limit that is consistent with the FMVSS 214 Advance Notice proposal and with accident statistics from France (Table 1). It is noted that compartment-space intrusion rarely, if ever, occurs during vehicle redirectional crash tests. On the other hand, accident records show that side intrusion frequently occurs when the vehicle skids sideways into a rigid narrow fixed object or even into a breakaway support. Breakaway performance for side-impact conditions is not specified or evaluated by crash testing at present. If such a requirement is deemed necessary in the future, performance of a breakaway device should first be assessed for the lack of compartment intrusion and then for occupant collision risk.

To be noted in Table 2 are the lateral velocity changes that can be inferred by TRC 191 (12) severity criteria. As with the threshold level of the longitudinal velocity change, this value is divided by an appropriate factor F to establish a less-severe design limit.

Accelerations

For the unrestrained conditions, the occupant experiences essentially no absolute accelerations prior to hitting some part of the compartment surface; that is, the vehicle is accelerating relative to the occupant. At impact, the degree of injury sustained by the occupant is indicated by the occupant and compartment impact velocity. Subsequent to this impact, the occupant is assumed to remain in contact with the surface hit and then to directly experience the vehicle accelerations. The occupant may or may not sustain further injuries, depending on the magnitude of these accelerations.

Typical long-term acceleration values are presented in Table 2 for both longitudinal and lateral directions. For both directions it appears that an upper limiting value of 20 g is survivable, even for pulses of long duration. Even discounting the lower threshold record for smoothed 50-ms accelerations, current values from TRC 191 are probably unnecessarily conservative in order to minimize the unconsidered stage 1 occupant and compartment impact. As with the velocity change, it is suggested that the

Table 2. Summary of expected effects of average acceleration on injury severity.

Body Element	Impact Surface	Acceleration (g)	Severity	Acquistion Method	Ref.
Longitudinal Direction, Acceleration Force					
Whole	Contoured couch	20	Survival limit	Sled tests; human in supine position	16, p. 335
	Contoured couch	40	Critical long term	Empirical	17, p. 211
	Aviator restraint	40	Survival limit	Sled tests; human in sitting position	27, p. 739
	Lap and shoulder belts	25[a]	Reasonable limit	Literature review	15, p. 34
	Lap belt only or no belt	20[a]	Reasonable limit	Literature review	15, p. 34
	Unspecified	12	Maximum acceptable (crash cushion)	Average test vehicle acceleration calculated from stopping distance	12, p. 10
	Unspecified	8	Preferred (crash cushion)	Average test vehicle acceleration calculated from stopping distance	12, p. 10
	Unspecified	10	Maximum acceptable (redirectional barrier)	Maximum vehicle acceleration (50-ms avg)	12, p. 10
	Unspecified	5	Preferred (redirectional barrier)	Maximum vehicle acceleration (50-ms avg)	12, p. 10
Lateral Direction, Acceleration Force					
Whole	Aviator restraint	33.6	Fainting shock	Sled tests; human in sitting position	SAE 700 398, p. 740
	Aviator restraint	25	Reversible injury	Sled tests; human seated facing forward	SAE 700 398, p. 742
Chest	Unspecified	60	Survival limit	FMVSS 214 performance criteria (proposed)	24, p. 24
Whole	Lap and shoulder belts	25[a]	Reasonable limit	Literature review	15, p. 34
	Lap only or no belt	20[a]	Reasonable limit	Literature review	15, p. 34
	Unspecified	5	Maximum acceptable (redirectional barrier)	Maximum vehicle acceleration (50-ms avg)	12, p. 10
	Unspecified	3	Preferred (redirectional barrier)	Maximum vehicle acceleration (50-ms avg)	12, p. 10

[a] Average over duration of event.

20-g upper limit be divided by an appropriate factor to obtain an appropriate design acceleration level.

The vehicle acceleration values to be compared with the design levels are the highest 10-ms averages that occur during the pulse duration that begins at, or just prior to, the calculated time of occupant impact. It is noted that, when compared to the highest 50-ms averages, test data processed to the 10-ms average requirement will generally result in higher acceleration indices.

Recommended threshold and design values for both occupant impact velocity and accelerations are presented in Table 3.

APPLICATION

Test Conditions

Highway appurtenances are evaluated by occupant risk under selected test conditions (12). Generally excluded are tests to evaluate the structural adequacy of a system or device. Because of its low mass, the small-car tests of length of need and terminals of longitudinal barriers, crash cushions, and breakaway or yielding supports are critical, since velocity changes and acceleration levels are greater than they are for heavier vehicles. The larger passenger sedan end-on impact into the guardrail terminal and crash cushion is also evaluated for occupant risk.

Data Acquisition and Processing

Vehicle accleration data are acquired according to SAE J211b, Channel Class 180, for processing and integration for free-missile velocity and displacements (28). Typical test data results are shown as a function of time in Table 4.

To determine the occupant impact velocity, the longitudinal and lateral accelerations of the vehicle are integrated to acquire occupant relative velocity and relative displacement as a function of time after initial vehicle impact. At the instant the occupant has traveled, say, 2 ft (0.6 m) in the longitudinal direction and/or, say, 1 ft (0.3 m) in the lateral direction, the occupant relative velocity is calculated or read, which yields the hypothetical occupant impact velocity.

The vehicle 10-ms average accelerations are scanned (Table 4) from the instant of occupant impact to the end of the pulse or impact event. The highest value is identified. Since the time of occupant impact is an approximation, one may wish to expand the time of interest from 20 to 40 ms before impact on through the pulse duration. It is noted in Table 4, for example, that very little occupant movement occurs in the first half of the 155-ms flail duration.

Critical values from Table 4 are as follows (1 fps = 0.3 m/s):

Impact Direction	Occupant Impact Velocity (fps)	Acceleration (g)
Longitudinal	Not critical	Not critical
Lateral	17.0	9.7

These values are then compared with those in Table 3.

For redirectional barrier impacts, the occupant impact velocity is sensitive to the actual vehicle impact conditions; that is, occupant lateral impact velocity will be higher when either the actual vehicle impact velocity or the approach speed (or both) exceeds the target test conditions. Accordingly, when the actual vehicle impact conditions vary from the target conditions, the occupant impact velocity should be normalized to the target conditions by the following equation:

$$(\Delta V)^* = [(V \sin\phi)_{\text{target}}/(V \sin\phi)_{\text{actual}}]\,(\Delta V) \quad (5)$$

where $(\Delta V)^*$ is normalized occupant impact velocity (in feet per second), (ΔV) is occupant impact velocity for actual test conditions (in feet per second) and $[(V \sin\phi)_{\text{target}}/(V \sin\phi)_{\text{actual}}]$ is

Table 3. Occupant risk values.

	Occupant/Dashboard Impact Velocity[b] (fps)			Occupant Ride-Down Acceleration[e] (g)		
	Flail-Space Recommendation			Flail-Space Recommendation		
Appurtenance Type	$(\Delta V)_{\text{limit}}/F$[c]	$(\Delta V)_{\text{design}}$	TRC 191[d]	$(a)_{\text{limit}}/F$	$(a)_{\text{design}}$	TRC 191[f]
Longitudinal (X) Direction[a]						
Breakaway/yielding support						
Sign and luminaire	40/2.67	15	11-16	20/1.33	15	
Timber utility pole	40/1.33	30		20/1.33	15	
Vehicle deceleration device						
Crash cushion and barrier terminal	40/1.33	30	32-39	20/1.33	15	
Redirectional barrier						
Longitudinal, transition, and crash cushion side impact	40/1.33	30	25-36	20/1.33	15	
Lateral (Y) Direction[a]						
Redirectional barrier						
Longitudinal, transition, and crash cushion side impact	30/1.50	20	14-18	20/1.33	15	

[a] With respect to vehicle axis.
[b] Occupant to windshield, dashboard, or door impact velocity; occupant propelled by vehicle deceleration pulse through 2-ft forward or 1-ft lateral flail space.
[c] F is design factor.
[d] Values calculated from Transportation Research Circular 191 criteria assuming most severe interpretation.
[e] Flail-space accelerations are highest 10-ms averages from occupant impact to completion of pulse.
[f] TRC 191 accelerations are less severe, highest 50-ms averages or those averaged over vehicle stopping distance and are not directly comparable.

Table 4. Evaluation of typical redirecting barrier for occupant risk.

SwRI Test—SRB-4 | Vehicle Type—Mini-Auto | Vehicle Wt.—2083 lbs
Test Date—10/24/1979 | Nominal Impact Vel.—60.0 mph | Nominal Impact Angle—15.0 degrees

Time-Sec.	Vehicle Acceleration-G's*		Occupant Velocity-ft/sec		Occupant Displacement-inches	
	AX	AY	VX	VY	DX	DY
.000	-1.7	.7	.0	.0	.0	.0
.005	.3	.6	.1	.1	.0	.0
.010	.6	-.2	-.0	.1	.0	.0
.015	.1	.1	-.1	.1	.0	.0
.020	.2	-.0	-.1	.1	-.0	.0
.025	-.5	.0	-.0	.1	-.0	.0
.030	-.3	.4	.1	.1	-.0	.0
.035	-1.9	5.1	.4	.9	.0	.1
.040	-.0	3.0	.3	1.4	.0	.1
.045	-2.1	3.5	.7	2.0	.1	.2
.050	-3.0	2.3	1.1	2.4	.1	.4
.055	-2.7	4.1	1.5	2.9	.2	.5
.060	2.2	3.2	1.3	3.6	.3	.7
.065	-1.9	5.2	1.6	4.4	.4	.9
.070	-1.2	1.5	1.8	4.6	.5	1.2
.075	-1.7	1.5	2.1	4.9	.6	1.5
.080	-2.7	3.2	2.5	5.3	.7	1.8
.085	-1.8	3.0	2.7	5.9	.9	2.2
.090	.2	3.2	2.7	6.3	1.0	2.5
.095	-2.2	3.3	3.0	6.9	1.2	2.9
.100	.5	4.4	3.0	7.6	1.4	3.3
.105	-1.0	4.5	3.2	8.3	1.6	3.8
.110	-.9	7.0	3.3	9.4	1.8	4.4
.115	-1.6	7.7	3.5	10.6	2.0	5.0
.120	-2.9	6.4	4.0	11.7	2.2	5.6
.125	-1.2	6.0	4.2	12.6	2.5	6.4
.130	-2.1	8.6	4.5	14.0	2.7	7.1
.135	1.0	.6	4.3	14.1	3.0	8.0
.140	-1.4	5.5	4.6	15.1	3.2	8.9
.145	-.1	4.7	4.6	15.8	3.5	9.8
.150	.4	3.8	4.6	16.4	3.8	10.8
.155	.1	4.4	4.6	17.0	4.1	11.8
.160	-1.1	5.7	4.8	18.0	4.4	12.8
.165	-1.8	9.7 ←	5.0	19.5	4.7	13.9
.170	-.4	7.8	5.1	20.7	5.0	15.1
.175	-1.5	8.4	5.3	22.2	5.3	16.4
.180	-.7	8.1	5.4	23.4	5.6	17.8
.185	-1.9	5.6	5.7	24.4	5.9	19.2
.190	.5	5.1	5.7	25.2	6.3	20.7
.195	.2	4.6	5.7	26.0	6.6	22.3
.200	.4	3.3	5.6	26.5	7.0	23.8
.205	-.3	1.4	5.7	26.8	7.3	25.4
.210	-.5	1.1	5.8	27.0	.7	27.1
.215	.2	.7	5.8	27.1	8.0	28.7
.220	.6	.7	5.7	27.2	8.3	30.3
.225	-1.2	.5	5.8	27.3	8.7	31.9
.230	.5	-.2	5.7	27.3	9.0	33.6
.235	.2	-1.8	5.8	27.0	9.4	35.2
.240	-.6	-1.1	5.8	26.9	9.7	36.8
.245	-.4	.6	5.9	26.9	10.1	38.4
.250	-.4	-.5	6.0	26.8	10.4	40.0

Summary
Vy = 17.0 fps
Ay = 9.7 g
V_x, A_x Non-critical as occupant moves less than 24 in.

*10 ms moving average; analog signal sampled at minimum rate of 1000 per second.

Note: 1 mph = 0.45 m/s; 1 lb = 0.45 kg; 1 fps = 0.3 m/s; 1 in = 25 mm.

Table 5. Typical longitudinal barrier severity tests.

Item	Southwest Research Institute Crash Test[a]				
	RF-22	CMB-7	CMB-9	CMB-13	SRB-4
	Barrier Type				
	Vertical Concrete Wall	GM Safety Shape	NJ Safety Shape	F Safety Shape	Self-Restoring Thrie Beam
Test condition					
Vehicle mass (lb)	2140	2250	2250	2250	2083
Impact speed (mph)	61.9	57.1	58.9	56.4	54.7
Approach angle (°)	18.3	16.5	15.5	14.3	17.1
TRC 191 evaluation					
Vehicle acceleration (highest 50-ms avg, *g*)					
Lateral/maximum limit	16.1/5	4.6/5	6.0/5	7.3/5	9.7/5
Longitudinal/maximum limit	8.2/10	3.4/10	0.9/10	3.8/10	3.0/10
TRC 191 appraisal	Poor (lateral acceleration)	Good	Marginal	Marginal	Poor
Flail-space evaluation					
Occupant lateral impact velocity (fps)					
Test	28.0	22.4	17.7	16.2	17.0
Normalized[a]	22.4	21.4	17.5	17.8	16.4
Design limit[b]	20.0	20.0	20.0	20.0	20.0
Occupant ride-down lateral acceleration (highest 10-ms avg, *g*)					
Test	8.6	4.8	4.9	4.6	9.7
Design limit[b]	15.0	15.0	15.0	15.0	15.0
Flail-space appraisal	Poor	Marginal	Good	Good	Good

[a] Occupant impact velocities normalized by the factor $[(V \sin\phi)_{target}/(V \sin\phi)_{actual}]$.

[b] As suggested in Table 3.

the ratio of target to actual vehicle impact conditions.

Results from five occupant-risk tests of longitudinal barriers are shown in Table 5. Test RF-22 is on a vertical rigid concrete wall. Tests CMB-7, CMB-9, and CMB-13 are on concrete safety shapes. Test SRB-4 is on a semiflexible metal beam barrier.

SUMMARY

A new criterion of highway-appurtenance crash-test evaluation is presented. The criterion evaluates all appurtenances regardless of function to the same flail-space approach and thus presents a more-consistent evaluation yardstick. The new criteria should simplify data acquisition and processing. Finally, the criteria and the suggested threshold values are not believed to be significantly more stringent or liberal than current evaluation standards.

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Publication of this paper sponsored by Committee on Safety Appurtenances.

Heavy-Vehicle Tests of Tubular Thrie-Beam Retrofit Bridge Railing

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A retrofit modification has been developed for a current concrete parapet design that has a narrow walkway configuration to improve its safety performance with impacting vehicles. The retrofit was originally developed for and tested with subcompact and standard-sized automobiles; the successful results indicated that the design might also perform with heavier vehicles that weigh up to 40 000 lb (18 144 kg). An earlier paper covered the automobile tests performed with the original retrofit system. Reported here are findings from six vehicle crash tests performed with the retrofit system—four tests with the original design and two tests with a modified design necessitated when vehicle rollovers occurred during the test series. The modified retrofit system successfully redirected a 40 000-lb intercity bus that impacted at 56.3 mph (90.6 km/h) and a 14.5° angle. In addition, it redirected a minicompact automobile that impacted at 58.1 mph (93.5 km/h) and an 18.8° angle; the vehicle exhibited no tendency to wedge under the higher rail design. Tests were documented by using both vehicle accelerometers and high-speed photography.

In a 1976 Federal Highway Administration report (1), existing bridge-rail designs used along the nation's highways are reviewed in terms of current safety performance criteria. Since the majority of these designs were found to be deficient in performance and their replacement to be cost-prohibitive, a methodology for upgrading their performance by retrofitting was developed. One existing design common to many states was a concrete parapet that has a curb and a narrow walkway. Although aluminum and concrete retrofits were developed for this particular bridge rail, the most promising retrofit system appeared to be a steel system that used a back-to-back triple-corrugated beam rail or tubular Thrie beam. Impact tests that used subcompact and standard-sized automobiles were successful, and it appeared that this system might be capable of performance with a heavier vehicle such as a school bus or an intercity bus. This paper presents the results of the continuation program that used heavy vehicles.

ORIGINAL DESIGN

As shown in Figure 1, the original concrete parapet was 25 in (635 mm) high and was located behind a walkway 18 in (457 mm) wide that had a curb 10 in (254 mm) high. This configuration was retrofitted with a tubular Thrie beam 20 in (508 mm) wide attached to the concrete by means of TS6x6x0.1875 box-beam posts spaced at 8.33-ft (2.54-m) intervals and with intermediate collapsing-tube elements 6 in (152 mm) in diameter. The front of the tubular Thrie beam was located in line with the curb face. Rail height was 32 in (813 mm).

The original test installation design was 125 ft (38 m) long and each end was transitioned off the simulated bridge deck into a single Thrie beam 25 ft (7.6 m) long on soil-mounted W6x8.5 steel posts. Each end of the rail was anchored by using a standard 0.75-in (19-mm) cable attached to a concrete footing 24 in (610 mm) in diameter.

MODIFIED DESIGN

Modification to the original retrofit design was deemed desirable when the large vehicle rolled on its side after redirection in the third and fourth tests of the series. These rollovers were attributed to two factors--insufficient rail height and the yield of the collapsing tubes that allowed rail deflection and corresponding vehicle body roll while the nonyielding curb face kept the vehicle wheels along a fixed trajectory. As shown in Figure 2, significant changes to the barrier system were that the beam rail height was increased to 38 in (965 mm) and the 6-in (152-mm) diameter collapsing tube on each post was replaced by a 3-in (76-mm) diameter tube and a TS6x6x0.1875 box-beam spacer. This latter modification projected the beam rail 3 in in