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EVALUATION OF DESIGN ANALYSIS PROCEDURES AND ACCEPTANCE CRITERIA FOR ROADSIDE HARDWARE

Volume III: Evaluating Pre-*Report 230* Crash Tests

DEPARTMENT OF TRANSPORTATION ★ UNITED STATES OF AMERICA ★

August 1987
Final Report

Prepared for
Safety Design Division
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16. Abstract

This research was conducted to identify and investigate aspects of NCHRP Report 230 which require additional technical research. This report deals with five broad areas of concern: (1) the importance and effect of soil conditions on the dynamic performance of barriers, (2) methods for re-evaluating pre-Report 230 test results in light of the current Report 230 criteria, (3) linking the occupant risk factor to "real-world" accident cases, (4) assessing the potential hazards of the redirected vehicle, and (5) replacement of the 4500-lb test car.

This is the third of a six-volume report dealing with specific technical topics in NCHRP Report 230. The others in the series are:

Vol. No.	FHWA No.	Title
I	RD-87/096	Executive Summary
II	RD-87/097	The Effect of Soil Strength on Longitudinal Barrier Performance
III	RD-87/098	Evaluating Pre-Report 230 Crash Tests
IV	RD-87/099	The Importance of the Occupant Risk Criteria
V	RD-87/100	Hazards of the Redirected Car
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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in²	square inches	645.2	millimetres squared	mm²
ft²	square feet	0.0929	metres squared	m²
yd²	square yards	0.836	metres squared	m²
mi²	square miles	2.59	kilometres squared	km²
ac	acres	0.395	hectares	ha

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft³	cubic feet	0.0328	metres cubed	m³
yd³	cubic yards	0.0765	metres cubed	m³

NOTE: Volumes greater than 1000 L shall be shown in m³.

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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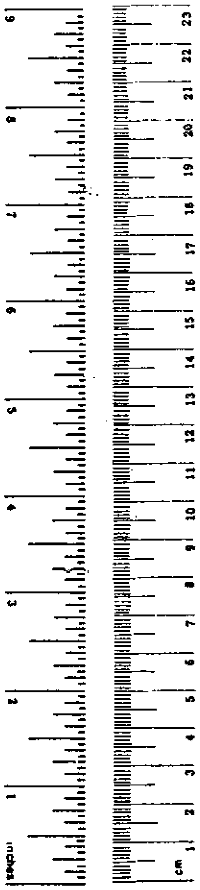
* SI is the symbol for the International System of Measurements



APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
km²	kilometres squared	0.39	square miles	mi²
ha	hectores (10 000 m²)	2.53	acres	ac

MASS (weight)

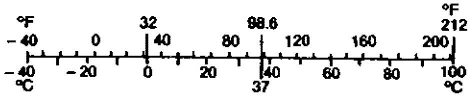
Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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Objective

Within the past twenty years, several hundred vehicle crash tests of highway safety appurtenances have been performed. Nearly all existing roadside hardware has been subjected to one or more crash tests to evaluate collision performance. During this same period, there have been major changes in crash test procedures. With the changes, it is often difficult to compare and correlate findings from tests conducted at different periods of time on the same appurtenance. Techniques for re-evaluating or enhancing findings from historical tests are needed.

The impact speeds and angles for passenger sedan crash tests have remained standardized at 60 and 20 mph (97 and 32 kph) and 15 and 25 degrees, respectively; the vehicle, however, has changed. Two important changes have occurred: (a) mass of test vehicles has been modified, principally the downsizing of the 2250-lb (1020-kg) car to 1800 lb (816 lb) and (b) the more rigorous definition of inertial mass. Other evolutionary changes in vehicle structure such as bumper design, unitized body, and crush stiffness may make the direct comparison of the historical vehicle to today's vehicle fleet meaningless. On the other hand, these differences may not be important under certain conditions and the crash test data can be converted, at least in an approximate manner, to the NCHRP Report 230(1) format.

In addition to changes in the vehicle, the type and quality of data required for appurtenance assessment have become more specific with each new evaluation criteria. This has been done to permit comparison of findings between testing agencies and to insure that tests are performed at known standard reference conditions; tests performed and reported under less restricted conditions may not be comparable to more recent experiments.

The following sections describe methods for converting nonstandard data acquisition procedures to Report 230 guidelines, calculating the occupant risk factor when vehicle accelerations are known, and estimating the occupant risk factor when only the gross barrier and vehicle behavior is known. Each of these sections will provide means for assessing previous crash tests in light of Report 230 standards.

Data Processing

In recent years, crash test procedures have become more standardized and more exacting in order to facilitate replication of test results within and among testing agencies. In the course of these changes, data collection and processing techniques have been enhanced and specifically delineated in NCHRP Report 230.(1) Questions have arisen as to the usefulness of crash test data that were acquired prior to Report 230 and processed using different standards. In particular, analog data from vehicle accelerometers were previously filtered to SAE J211b class 60 in the processing stage; in Report 230 the filter class was changed to class 180 to more closely correspond to requirements described in SAE J211b.(2)

A study was made of the significance of data processing on test findings. In essence, the study consisted of processing accelerometer signals from two representative vehicle/appurtenance crash tests that had been recorded in broadband analog format according to both pre and post Report 230 procedures and then comparing the results.

Two crash tests were selected as representative of the typical range of vehicle kinematic and dynamic behavior. Test GR1 is an 1800-lb (816-kg) car impact of a flexible guardrail system at 60 mph (97 kph) and 15 degrees; the vehicle was smoothly redirected. In contrast, test ST-10 is an end-on test of a guardrail terminal in which the vehicle impacts at 60 mph (97 kph) and a 0-degree angle; the terminal performed as a crash cushion, rapidly decelerating the vehicle.

In both tests, the data were acquired and recorded in broad band analog format on magnetic tape. The analog data signals were subsequently replayed through one of four filters (i.e., SAE J211b class 60, 180, 600 or 1000), digitized at a sampling frequency of 4000 Hz and then procesed by computer. An analog signal with a frequency content of 0 to 800 Hz can generally be reproduced from the 4000 Hz digital format.

Typically, each data channel is calibrated at time of test in the positive and negative sense by a known voltage deviation, and these offset voltages represent a known transducer response. Also, a baseline or zero condition for each data channel is arbitrarily established just prior to the vehicle being accelerated to test speed. The data baseline may exhibit some gradual drift due to temperature variation of instrumentation at the test site and subsequent digital processing of the data may show variation depending on the time selected for sampling the baseline signal.

Effects of the SAE J211b filters on the calibration offset and test baselines are shown in table 1 for test GR1 (vehicle redirected by longitudinal barrier) and in table 2 for test ST-10 (vehicle end-on impact into terminal nose). For the accelerometers, the maximum differences for the full range of filter is less than 11 counts out of 1000 to 1700 count shifts, and the variation appears to be more random than a function of a filter class. It appears that the filters have little effect on the calibration signal. With regard to the baseline, there is a variation that could introduce as much as 1.0-g error into the data set. Again, this baseline variation is judged to be associated with timing of the digital processing technician rather than a function of the filter selection. The rate gyro exhibits a somewhat larger variation, but there does not appear to be a pattern associated with the filter selection.

Visual effects of filtering are illustrated in figure 1 for test GR1 and figure 2 for test ST-10. Vehicle longitudinal (R) and lateral (S) accelerations are plotted against time and for two filter conditions: classes 60 and 1000, the two extreme conditions under consideration. Although the purpose of the low pass filter (class 60) is to screen out the higher frequency content of a signal wave, it has the tendency to

Table 1. Variation in digital counts due to filter class, test GR1.

Transducer Calibration	Calibration Equivalent	SAE J211b Filter Class 60	180	600	1000	Max Diff
Accelerometer						
Longitudinal (R)						
Deflection +	28.4 g	1734.4	1727.2	1727.8	1725.5	8.9
Deflection −	28.4 g	−1727.3	−1720.6	−1720.3	−1717.0	10.3
Test Baseline	0 g	18.4	17.0	18.1	67.6	60.1 = 1.0 g
Lateral (S)						
Deflection +	22.8 g	1776.2	1776.0	1776.8	1774.8	2.0
Deflection −	23.1 g	−1779.3	−1780.6	−1779.6	−1779.5	1.3
Test Baseline	0 g	−25.1	−25.5	−22.6	−7.6	17.9 = 0.22 g
Rate Gyro						
Deflection +	290.9 deg/sec	1149.0	1155.6	1143.2	1136.1	19.5
Deflection −	322.9 deg/sec	−1236.7	−1245.9	−1229.4	−1222.4	23.5
Test Baseline	0 deg	100.8	86.0	88.4	92.0	14.8 = 3.74°/s

Table 2. Variation in digital counts due to filter class, test ST-10.

Transducer Calibration	Calibration Equivalent	60	180	600	1000	Max Diff
Accelerometer						
Longitudinal (R)						
Deflection +	28.6 g	1262.2	1259.6	1265.2	1261.1	5.6
Deflection -	28.6 g	-1246.7	-1245.9	-1241.5	-1238.5	8.2
Test Baseline	0 g	-27.0	-32.2	-37.0	-32.2	10.0 = 0.22 g's
Lateral (S)						
Deflection +	23.0 g	1063.0	1058.6	1060.8	1062.9	4.4
Deflection -	23.2 g	1089.9	-1087.0	-1083.8	-1080.6	9.3
Test Baseline	0 g	-43.4	-0.2	-9.0	-13.2	43.2 = 0.93 g's
Rate Gyro						
Deflection +	291.6 deg/sec	1332.8	1238.0	1238.7	1240.6	7.8
Deflection -	294.1 deg/sec	-1357.7	-1366.1	-1361.7	-1368.0	12.3
Test Baseline	0 deg	23.9	114.4	104.0	62.4	90.5 = 19.8 deg/sec

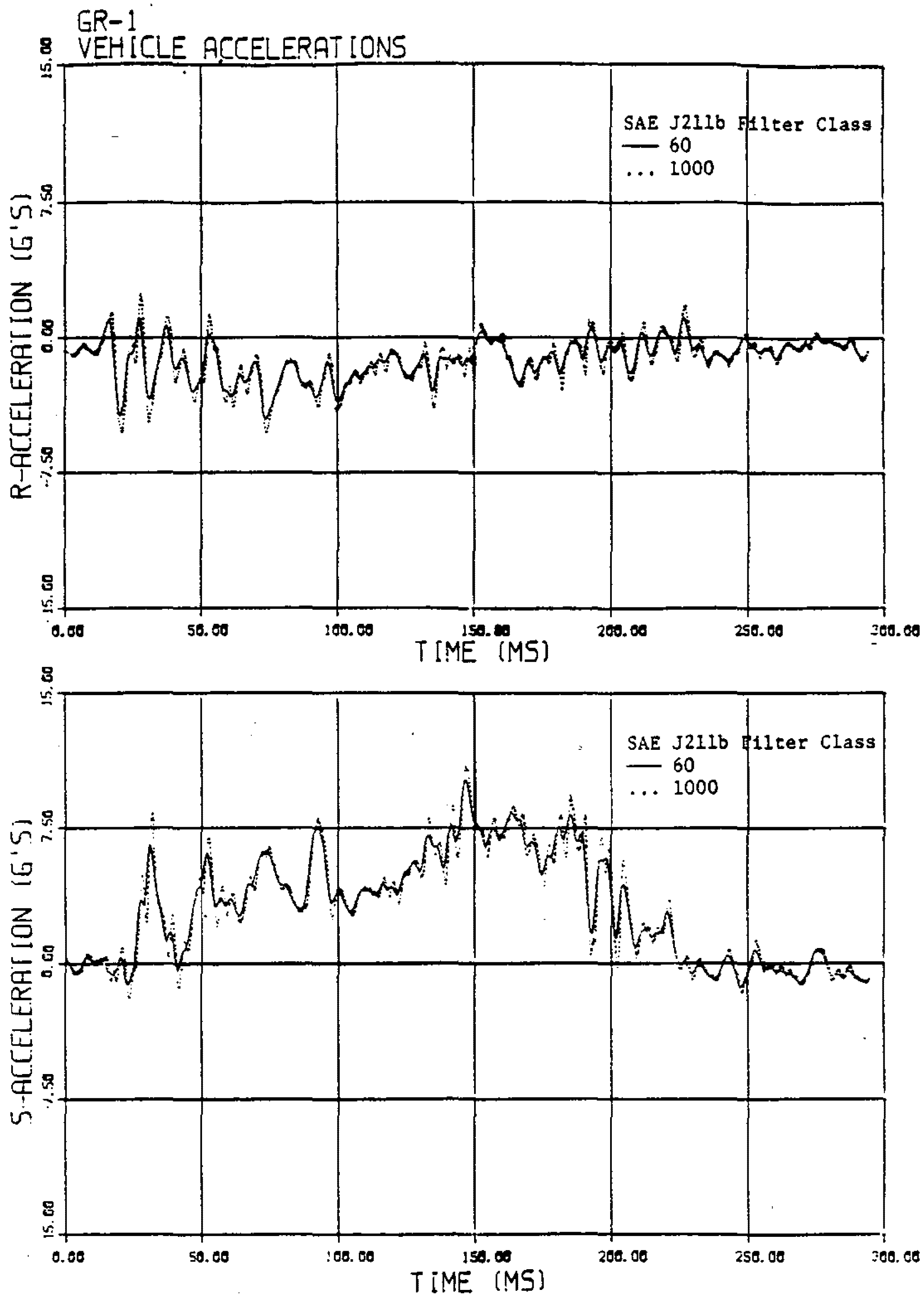


Figure 1. Visual effects of filtering on typical vehicle accelerations produced during redirected impact.

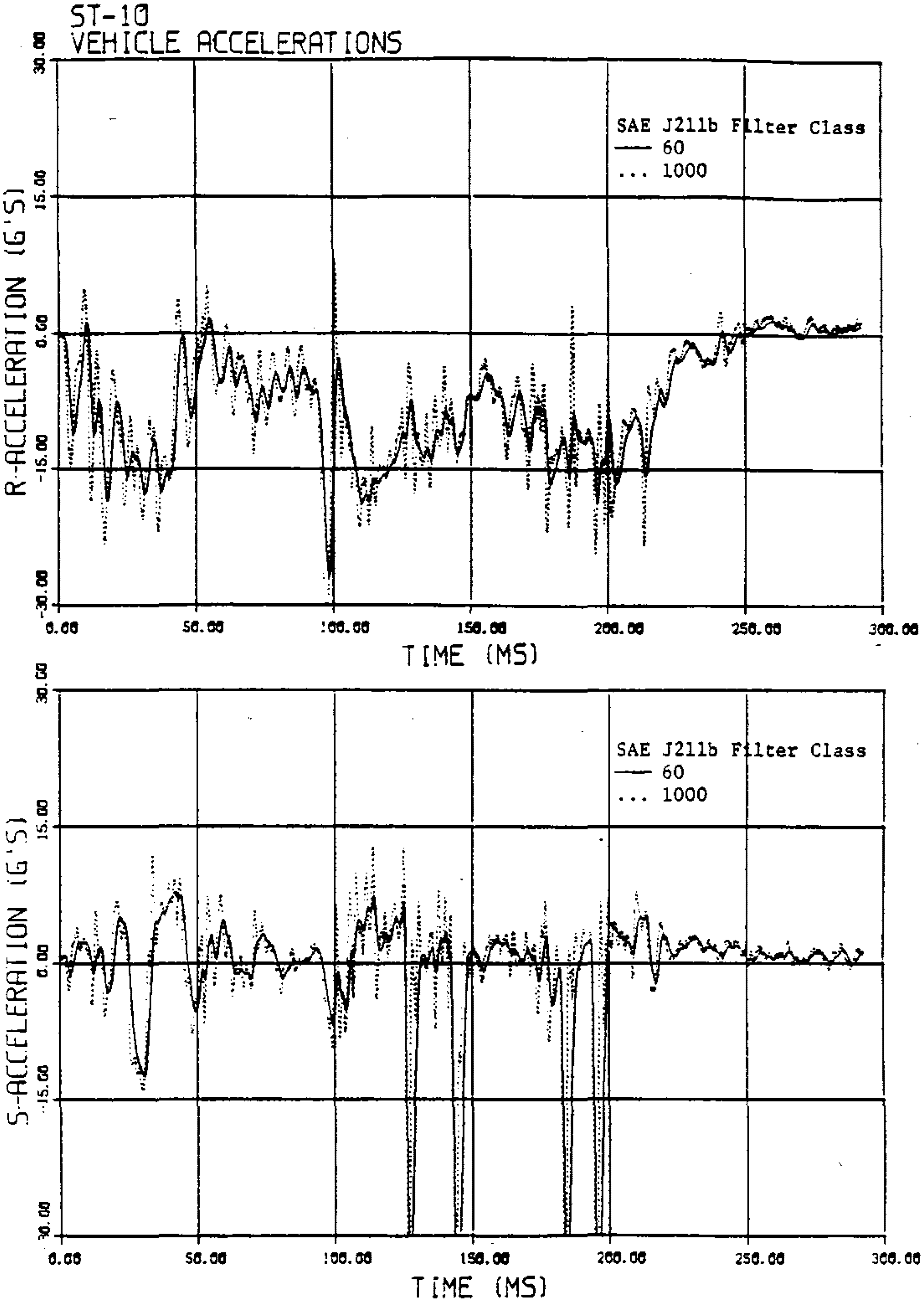


Figure 2. Visual effects of filtering on typical vehicle accelerations produced during end-on collision with terminal.

distort the wave, mainly by (1) attenuating the magnitude of the excursions and (2) delaying the wave events. For these cases, the basic waveform is not significantly affected, at least visually, for the two extreme filter selections. Waveforms filtered for classes 180 and 600 fall between these extremes.

Once the analog data was filtered and digitized the various kinematic parameters were calculated. Tables 3 and 4 show the effect of each filter on the vehicle's aceleration, velocity and position as well as the occupant risk and ridedown acceleration for the two tests. For each parameter the change between the class 60 and class 1000 filter was minor. The variation is somewhat large for test ST-10 since it was a much more severe collision. The magnitude of the errors in both tests is not great enough to alter the interpretation of the data.

Filtering has only limited effects on the final crash test evaluation parameters. The difference between data gathered with 60 class filters is not significantly different from data gathered with 1000 class filters. For example, the final longitudinal velocity in test GR-1 would have been reported as 78.4 using the 60 class filter and as 78.3 using the 1000 class filter; the tests are essentially identical. In summary, the type of filter used to acquire test data need not prevent the use of that data for evaluation using the Report 230 criteria. Although data processed with higher filter classes will inhibit higher frequency content, data processed with the lower filter classes provide information that is adequate for reassessing nonstandard crash tests.

Estimating Occupant Risk With Vehicle Acceleration Data

Introduction

This section describes a method for calculating the occupant-interior impact velocity given position-time data from a full-scale crash test. As the previous section indicates, the filter selection used to process the data is not critical; therefore old accelerometer data obtained using the

Table 3. Data processing effect on findings from typical vehicle/barrier redirection, test GR1.

Test Factor	SAE J211b Filter Class** 60	180	600	1000	Max Diff
Vehicle Accelerations (50 ms peak g's)					
Longitudinal	-2.52	-2.50	-2.53	-2.55	0.05
Lateral	7.30	7.35	7.27	7.35	0.08
Vehicle Final Velocity (fps)+					
Longitudinal	78.44	78.80	78.35	78.28	0.52
Lateral	10.53	10.96	10.35	11.65	1.30
Vehicle Final Position+					
Longitudinal (f)	19.22	19.27	19.20	19.21	0.07
Lateral (f)	-2.96	-3.01	-2.93	-3.05	0.12
Heading Angle (deg)	1.3	1.5	1.5	1.9	0.6
Occupant Risk (fps)					
Longitudinal - ORR	8.02	7.97	8.38	8.59	0.64
Lateral - ORS++	10.65	10.55	10.50	10.35	0.30
Longitudinal Accel (g's)	-	-	-	-	-
Lateral Accel (g's)	7.33	8.34	7.94	7.93	1.01

---

*Test GR1 conditions: 1800-lb Honda, 88.17 fps, 15.52° angle, flex beam guardrail.

**Data recorded in analog format on magnetic tape at frequency response in excess of 2000 Hz. Subsequently data played back through appropriate filter, then digitized and processed for vehicle kinematics and dynamics.

+At time of 0.290 sec.

++6-in. flail distance.

Table 4. Data processing effect on findings from typical guardrail terminal collision, test ST-10.

Test Factor	SAE J211b Filter Class* 60	180	600	1000	Max Diff
Vehicle Accelerations (50 ms peak g's)					
Longitudinal	-13.32	-13.03	-13.08	-13.18	0.29
Lateral	-4.71	-3.03	-3.11	-3.17	1.68
Vehicle Final Velocity (fps)+					
Longitudinal	-30.58	-24.66	-24.76	-25.72	5.92
Lateral	-3.38	0.40	0.39	0.40	2.99
Vehicle Final Position+					
Longitudinal (f)	5.76	5.92	5.81	5.65	0.27
Lateral (f)	-4.97	-4.14	-4.10	-4.17	0.87
Heading Angle (deg)	52.0	52.1	50.6	49.8	2.20
Occupant Risk (fps)					
Longitudinal	35.97	35.66	35.90	36.09	0.43
Lateral	-3.50	-3.89	-2.92	-2.41	3.54
Longitudinal Accel (g's)	-15.67	-17.35	-15.04	-14.31	3.04
Lateral Accel (g's)	3.92	8.17	7.48	7.82	4.25

---

*Test SwRI ST-10 conditions: 1800-lb car, 86.0 fps, 1.5° end-on impact.

**Data recorded in analog format on magnetic tape at frequency response in excess of 2000 Hz. Subsequent data played back through appropriate filter, then digitized and processed for vehicle kinematics and dynamics.

+At time of 0.29 sec.

pre-Report 230 criteria filters can be used to obtain good estimates of the occupant impact velocity.

This mathematical model has been used at Southwest Research Institute for a number of years for analyzing accelerometer and film data as well as serving as a post processor to the BARRIER VII(2) computer simulation.

The flail space concept is illustrated in figure 3. Let x-y be a fixed global coordinate system and r-s be a local coordinate system that moves with the vehicle. At time t = 0, the occupant is sitting over point P at coordinates (r_p, s_p) and is moving at the same velocity as point P.

At time t = 0 an impact occurs, changing the trajectory of the vehicle. The basic assumption of the flail space concept is that the occupant continues with the same velocity as the pre-impact vehicle. Thus, as shown in figure 3 for $t + \Delta t$ and $t + 2 \Delta t$, the relative position of the occupant with respect to point P changes since the vehicle velocity is decreasing and the occupant continues with the initial pre-impact velocity. The occupant is assumed to impact the interior of the vehicle when this relative movement is 24 inches forward (r-direction) or 12 inches (30 cm) laterally (s-direction). Kinematic quantities of interest are the relative velocities and accelerations of the occupant with respect to the vehicle at these displacements; such values represent the occupant-interior impact velocity.

Relative Displacements

Between the time of the vehicle's first impact with the barrier and the occupant's collision with the vehicle interior the occupant travels at the pre-impact velocity of the vehicle. The occupant impact velocity in the flail space model is defined as the impact velocity when the occupant has traveled 1 foot (0.3 m) and 2 feet (0.6 m) in the lateral and longitudinal directions, repsectively, with respect to the vehicle. Calcuating the relative displacements of the occupant, with respect to the vehicle,

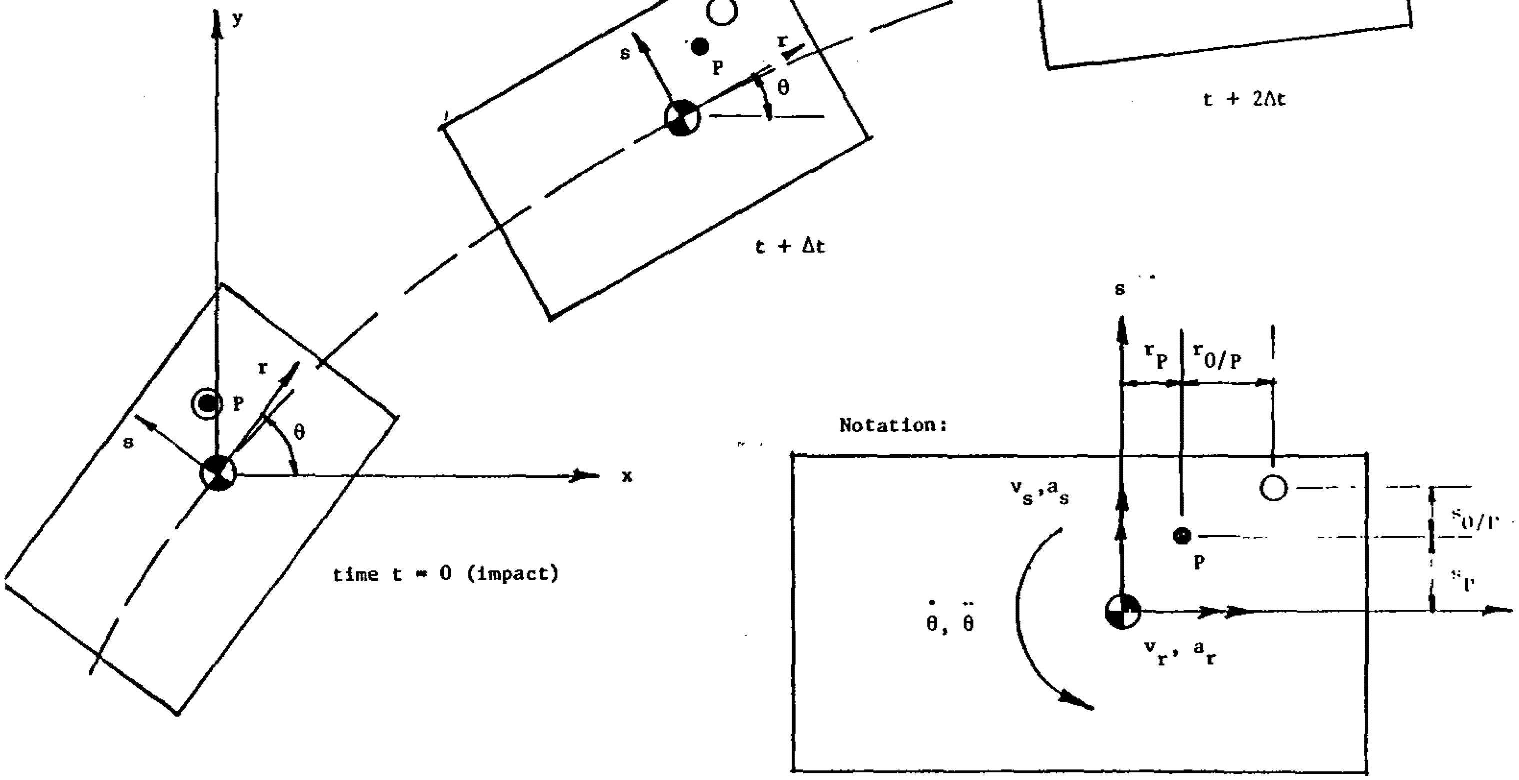


Figure 3. Flail space concept.

will establish the time of occupant contact. The global x and y positions of the occupant are given by:

$$x_{occ-t} = r_p \cos \theta_o - s_p \sin \theta_o + V_{ox}t + x_o$$

and (1)

$$y_{occ-t} = r_p \sin \theta_o + s_p \cos \theta_o + V_{oy}t + y_o$$

where

x_{occ-t} = occupant's x position at time t (ft)
y_{occ-t} = occupant's y position at time t (ft)
r_p = initial r distance between occupant and c.g. (ft)
s_p = initial s distance between occupant and c.g. (ft)
θ_o = vehicle impact angle (deg)
V_o = vehicle impact velocity (ft/sec)
x_o = x position of the vehicle c.g. at t=0
y_o = y position of the vehicle c.g. at t=0.

The global x and y position of the original position of the occupant, point P, is given as:

$$x_{pt} = x_{vt} + r_p \cos \theta_t - s_p \sin \theta_t$$

and (2)

$$y_{pt} = y_{vt} + r_p \sin \theta_t + s_p \cos \theta_t$$

where

x_{vt} = x position of the vehicle c.g.
y_{vt} = y position of the vehicle c.g.
x_{Pt} = x position of point P
y_{Pt} = y position of point P
θ_t = vehicle heading at time t.

The occupant risk is the relative velocity of the occupant to the vehicle when the occupant has displaced 2 feet (0.6 m) in the r direction and 1.0 foot (0.3 m) in the s direction. The relative displacement of the occupant with respect to his original position in the veicle at time t is given by:

$$(x_{occ/P})_t = x_{occ-t} - x_{P-t}$$

and (3)

$$(y_{occ/P})_t = y_{occ-t} - y_{P-t}$$

where $(x_{occ/P})_t$ is the relative x displacement of the occupant with respect to the point P on the automobile. The occupant's relative global displacement can be calculated using equations (1) and (2). The relative x and y displacements can then be transformed into the r and s coordinate system.

$$(r_{occ/P})_t = (x_{occ/P})_t \cos \theta_t + (y_{occ/P})_t \sin \theta_t$$

and (4)

$$(s_{occ/P})_t = -(x_{occ/P})_t \sin \theta_t + (y_{occ/P})_t \cos \theta_t$$

Thus given the instantaneous position of the vehicle c.g., the initial position of the occupant and the vehicle impact conditions, the occupant's position relative to his initial position can be calculated for any time. In this way the time of impact can be found by observing when the r and s flail distances reach 2 and 1.0 feet (0.6 and 0.3 m), respectively.

Relative Velocities

The relative velocity between the decelerating vehicle and the occupant moving at the pre-impact velocity is defined as the occupant risk. The occupant risk factor is calculated by determining the velocities of the vehicles and the occupants. At the instant of impact, time t = 0, the ocupant is traveling at the pre-impact speed. An additional term is included to account for the pre-impact yaw rate, $\dot{\theta}$.

$$\begin{aligned} \dot{r}_{occ} &= \dot{r}_{v-t=0} - s_P \dot{\theta}_{t=0} \\ \dot{s}_{occ} &= \dot{s}_{v-t=0} - r_P \dot{\theta}_{t=0} \end{aligned} \qquad (5)$$

where

$\dot{r}_{occ}$ = occupant velocity in the r direction (ft/sec)

$\dot{s}_{occ}$ = occupant velocity in the s direction (ft/sec)

$\dot{r}_v$ = r velocity of vehicle c.g. (ft/sec)

$\dot{s}_v$ = s velocity of vehicle c.g. (ft/sc)
$\dot{\theta}$ = yaw rate (rad/sec)

The velocity of the initial position of the occupants in the vehicle, point P, can be calculated using:

$$\dot{r}_{P-t} = \dot{r}_{v-t} - s_P\dot{\theta}_t \qquad (6)$$
$$\dot{s}_{P-t} = \dot{s}_{v-t} + r_p\dot{\theta}_t$$

where the subscript P indicates the position of point P. Since the r-s coordinate system is attached to the vehicle c.g. equations (5) and (6) only share the same coordinate space at t = 0. In order to combine equations (5) and (6) they must be transformed into the global x-y coordinate system.

$$\dot{x}_{occ} = \dot{r}_{occ} \cos \theta_{t=0} - \dot{s}_{occ} \sin \theta_{t=0} \qquad (7)$$
$$\dot{y}_{occ} = \dot{r}_{occ} \sin \theta_{t=0} + \dot{s}_{occ} \cos \theta_{t=0}$$
$$\dot{x}_{P-t} = \dot{r}_{P-t} \cos \theta_t - \dot{s}_{P-t} \sin \theta_t \qquad (8)$$
$$\dot{y}_{P-t} = \dot{r}_{P-t} \sin \theta_t + \dot{s}_{P-t} \cos \theta_t$$

The relative velocity of the occupant with respect to point P on the vehicle can then be written as:

$$(\dot{x}_{occ/P})_t = \dot{x}_{occ} - \dot{x}_{P-t} \qquad (9)$$
$$(\dot{y}_{occ/P})_t = \dot{y}_{occ} - \dot{y}_{P-t}$$

The relative velocity terms can then be calculated using equations (7) and (8) and transformed back into the r-s coordinate system.

$$(\dot{r}_{occ/P})_t = (\dot{x}_{occ/P})_t \cos \theta_t + (\dot{y}_{occ/P})_t \sin \theta_t \qquad (10)$$
$$(\dot{s}_{occ/P})_t = -(\dot{x}_{occ/P})_t \sin \theta_t + (\dot{y}_{occ/P})_t \cos \theta_t$$

Using equation (4) the time when the occupant impacts the vehicle interior can be found. Once this time is known the occupant's impact velocity, or occupant risk, can be calculated using equation (10).

Yaw Rate Considerations

The foregoing equations for the relative velocity of the occupant with respect to the velocity include a term for the yaw rate or the angular speed of rotation about a vertical axis. The quantity is denoted as $\dot{\theta}$ in the previous equation.

Two methods are typically used to calculate the occupant risk: one includes the yaw rate effects and one neglects yaw rate effects. The foregoing discussion represents the former method. Although the yaw rate has physical meaning, it appears that neglecting angular velocity effects does not introduce significant error in the calculations of occupant risk.

Of course, yaw rate has little importance in nondirectional tests such as head-on collisions with terminals or attenuators. The yaw rate is likely to be most significant in redirectional tests where the preimpact direction of the vehicle is changed. Two typical redirection crash tests were analyzed using both methods of calculating the occupant risk.

Test SPI-1 was a test using a 4500-lb (2053-kg) car impacting a standard G4(1S) guardrail at 25 degrees and 60 mph (97 kph). A full test report of this test can be found in appendix B of volume II. The second test, WE4-1, used a 3400-lb (1542-kg) passenger car ballasted to 4000-lb (1814-kg). The vehicle struck a standard G4(1S) guardrail at 25 degrees and 60 mph (97 kph). The test report for WE4-1 can be found in appendix A of volume VI. Test SPI-1 was chosen since it represents a typical smooth redirection collision. Test WE4-1 represents a collision where severe snagging caused the vehicle to experience high angular velocities. If the yaw rate were a significant factor, it should be noteable in test WE4-1.

Tables 5 through 8 show the tabular results of calculating the occupant impact velocity with and without the effects of yaw rate. Table 4e shows a summary of the reuslts. In test SPI-1, the longitudinal forces were not sufficient to cause the occupant to displace 2 feet, therefore only the lateral occupant impact velocity is shown. As shown in table 9,

Table 5. Occupant risk calculations with the effects of yaw rate included, test WE4-1.

```
TEST ID ------- WE4-1
TEST DATE ----- 06-19-85
VEHICLE CLASS - STANDARD
IMPACT SPEED --   88.01 FPS


OCCUPANT RISK SUMMARY
NOTE: INSTANTANEOUS 10-MS AVERAGE ACCELERATIONS

         (------- VEHICLE --------)(------------ OCCUPANT ------------)
 TIME      ACCEL. (G'S)    ANG. VEL     VEL. (FPS)          DISP. (F)
  (S)     LONG.      LAT.  (RAD/S)   LONG.     LAT.    LONG.     LAT.
------   -------   -------   ------   -------   -------   -------   -------
  .000     -.24      -.48       .01       .00       .00       .00       .00
  .010    -1.89     -3.11      -.12       .03       .05       .00       .00
  .020    -2.37     -5.95      -.06      1.10      2.20       .01       .01
  .030    -2.28     -4.42      -.73       .67      3.04       .01       .04
  .040    -2.46     -2.05      -.65      1.69      4.10       .03       .07
  .050     -.96     -3.35      -.65      2.26      5.11       .05       .12
  .060    -3.93     -5.92      -.74      2.90      5.85       .07       .17
  .070    -3.66     -3.85      -.59      4.26      8.35       .11       .24
  .080    -3.78     -6.21     -1.29      4.51      9.14       .14       .33
  .090    -5.69    -10.40     -1.68      5.40     12.00       .19       .43
  .100    -5.96     -7.31      -.50      8.63     16.39       .24       .57
  .110    -1.02     -6.99     -1.79      7.82     16.78       .32       .73
  .120    -7.75     -5.52     -1.87      8.42.    18.23*      .38       .91*
  .130    -4.08     -7.36     -2.17     10.02                 .45
  .140    -6.12     -3.54     -1.94     11.11                 .54
  .150    -6.46     -2.01     -1.58     13.20                 .63
  .160    -5.97     -3.63     -1.65     14.86                 .74
  .170    -7.99     -5.48     -1.46     16.54                 .86
  .180    -5.13     -4.24     -1.47     18.65                1.01
  .190    -6.47     -2.65     -1.63     19.33                1.16
  .200    -4.85     -2.46     -1.63     22.01                1.31
  .210    -4.58     -9.47     -2.09     20.54                1.46
  .220    -8.54     -4.45     -1.25     23.59                1.63
  .230    -6.63     -2.40     -1.16     25.71+               1.84+

OCCUP. RISK FACTORS                              TIME    VELOCITY
                                                  (S)     (FPS)
                                               -------  ---------

  >LONG. VEL. AFTER 2.0 FT. DISP. --             .238      27.40
  >LAT.  VEL. AFTER 1.0 FT. DISP. --             .125      18.82

MAX. ACCEL. AFTER OCCUPANT IMPACT              TIME(S)  ACC.(GS)
                                               -------  ---------
  >LONG. ACCELERATION                 --         .391      -7.88
  >LAT.  ACCELERATION                 --         .208     -10.57
```

Table 6. Occupant risk calculations with the effects of yaw rate excluded, test WE4-1.

```
      TEST ID ------- WE4-1
      TEST DATE ----- 06-19-85
      VEHICLE CLASS - STANDARD
      IMPACT SPEED -- 88.01 FPS

OCCUPANT RISK SUMMARY
NOTE: INSTANTANEOUS 10-MS ACCELERATIONS

          (----------VEHICLE---------------)  (---------OCCUPANT---------)
 TIME       ACCEL. (G'S)        VEL. (FPS)      DISP.(FT)     VEL. (FPS)
 (S)        LONG.     LAT.      LONG.    LAT.   LONG.    LAT.   LONG.   LAT.
------    ------    ------     ------   ------  ------ ---------------  ------
 0.000     -0.24     -0.48     88.01    -1.36   0.00     0.00    0.00    0.00
 0.010     -0.45     -2.56     87.82    -1.60    .00      .00    0.19    0.24
 0.020     -2.45     -6.66     86.80    -3.72   0.01     0.01    1.21    2.36
 0.030     -3.71     -2.49     86.37    -5.31   0.02     0.04    1.64    3.95
 0.040     -2.66      0.24     85.44    -6.23   0.04     0.09    2.57    4.87
 0.050     -0.45      0.52     84.86    -7.23   0.07     0.14    3.15    5.87
 0.060     -4.34    -11.26     84.01    -8.21   0.10     0.20    4.00    6.85
 0.070     -5.70     -2.35     82.77   -10.36   0.15     0.28    5.24    9.00
 0.080     -2.34     -8.10     81.62   -12.02   0.21     0.37    6.39   10.66
 0.090     -4.55    -18.65     80.01   -15.42   0.28     0.49    8.00   14.06
 0.100    -16.20    -14.85     77.85   -18.09   0.36     0.64   10.16   16.73
 0.110     -3.92      6.81     77.04   -19.68   0.47     0.81   10.97   18.32
 0.120     -5.49     -9.46     75.96   -21.32   0.58  *  1.00   12.05   19.96
 0.130     -0.77    -10.82     73.57   -24.07   0.72     1.21   14.44   22.71
 0.140     -9.80      1.52     72.18   -26.05   0.86     1.44   15.83   24.69
 0.150     -9.17     -5.29     70.08   -25.74   1.03     1.69   17.93   24.38
 0.160     -4.65      0.38     67.98   -26.51   1.22     1.94   20.03   25.15
 0.170     -7.80     -4.36     65.99   -27.75   1.43     2.19   22.02   26.39
 0.180     -2.97     -0.91     63.52   -29.88   1.66     2.47   24.49   28.52
 0.193     -9.80     -8.02     61.05   -30.82 * 1.99     2.85   26.96   29.46

OCCUPANT RISK FACTORS                          TIME      VELOCITY
                                                (S)        (FPS)
                                               -----     --------

   >LONG. VEL. AFTER 2.0 FT. DISP. --          .193        26.96
   )LAT.  VEL. AFTER 1.0 FT. DISP. --          .120        19.96
```

Table 7. Occupant risk calculations with the effects of yaw rate included, test SPI-1.

```
     TEST ID ------- SPI-1
     TEST DATE ----- 07-03-85
     VEHICLE CLASS - STANDARD
     IMPACT SPEED --   86.19 FPS

OCCUPANT RISK SUMMARY
NOTE: INSTANTANEOUS 10-MS AVERAGE ACCELERATIONS

        (------- VEHICLE --------)(------------ OCCUPANT -----------)
 TIME     ACCEL. (G'S)   ANG. VEL    VEL. (FPS)         DISP. (F)
  (S)    LONG.     LAT.  (RAD/S)  LONG.      LAT.    LONG.      LAT.
------  -------  -------  ------  -------  -------  -------  -------
  .000     .67      .26     -.73     .00      .00      .00      .00
  .010    -.56    -4.68     -.58     .48     1.06      .00      .01
  .020   -1.00    -3.50     -.73     .28     1.76      .01      .02
  .030   -1.03    -3.66     -.77     .69     3.40      .01      .05
  .040   -3.66      .10    -1.02    1.06     3.63      .02      .08
  .050    -.97    -3.77    -1.13    1.25     3.85      .03      .12
  .060   -2.79    -4.29    -1.43    1.77     4.93      .04      .16
  .070   -3.63    -5.94    -1.61    2.36     6.24      .06      .22
  .080   -3.04    -3.98    -1.81    2.91     7.99      .08      .29
  .090   -3.36    -3.60    -1.74    3.97     9.29      .11      .38
  .100   -3.91    -3.47    -2.15    4.32    10.02      .14      .48
  .110   -2.57    -3.18    -2.47    4.72    10.74      .18      .59
  .120    -.95    -5.98    -2.64    4.16    12.52      .21      .71
  .130    -.91    -4.24    -2.66    4.50    14.09      .23      .84
  .140   -3.78    -1.91    -2.74    4.67    15.30*     .25     1.00*

OCCUP. RISK FACTORS                               TIME     VELOCITY
                                                   (S)      (FPS)
                                                -------  ---------

  >LONG. VEL. AFTER 2.0 FT. DISP. --              .576      -12.94
  >LAT.  VEL. AFTER 1.0 FT. DISP. --              .140       15.30

MAX. ACCEL. AFTER OCCUPANT IMPACT               TIME(S)  ACC.(GS)
                                                -------  ---------
  >LAT.  ACCELERATION                      --     .207       -7.62
```

Table 8. Occupant risk calculations with the effects of vehicle yaw rate excluded, test SPI-1.

```
         TEST ID ------- SPI-1
         TEST DATE ----- 07-03-85
         VEHICLE CLASS - STANDARD
         IMPACT SPEED -- 86.19 FPS


          (-------------VEHICLE--------------)  (------OCCUPANT-----------)
TIME      ACCEL. (G'S)       VEL. (FPS)          DISP. (FT)   VEL. (FPS)
 (S)      LONG.     LAT.     LONG.     LAT.     LONG.    LAT.  LONG.  LAT.
------    ------   ------   ------    ------   ------  ------------ ------
 0.000     0.67     0.26     86.19     -0.67    0.00     0.00   1.82  -0.69
 0.010     4.07    -3.38     85.98     -1.61    0.02    -0.01   2.03   0.25
 0.020    -1.94    -1.45     85.86     -2.51    0.04      .00   2.15   1.15
 0.030     7.26    -0.09     85.53     -4.14    0.06     0.02   2.48   2.78
 0.040    -6.96     6.85     84.56     -4.54    0.09     0.05   3.45   3.18
 0.050     5.17    -1.95     84.37     -5.01    0.13     0.09   3.64   3.65
 0.060    -5.29    -1.95     83.24     -6.43    0.17     0.13   4.77   5.07
 0.070    -2.62    -8.66     82.35     -8.04    0.22     0.19   5.66   6.68
 0.080    -5.13    -4.80     81.36     -9.88    0.28     0.26   6.65   8.52
 0.090    -3.72    -2.73     80.20    -10.95    0.35     0.35   7.81   9.59
 0.100    -2.88     0.34     79.11    -12.00    0.43     0.45   8.90  10.64
 0.110    -2.36    -3.23     78.03    -13.00    0.53     0.56   9.98  11.64
 0.120    -1.53    -5.30     77.97    -14.85    0.63     0.69  10.04  13.49
 0.130     0.77    -6.37     77.24    -16.29    0.74     0.83  10.77  14.93
 0.140    -2.57     5.13     76.37    -17.18    0.85     0.99  11.64  15.82
 0.141    -8.00    -2.38     76.11    -17.28    0.86   * 1.00  11.90  15.90

 OCCUPANT RISK FACTORS                                TIME     VELOCITY
                                                       (S)       (FPS)
                                                      ----     --------
   >LAT. VEL. AFTER 1.0 FT. DISP. --                  .141       15.90
```

Table 9. Comparison of occupant risk factors where yaw rate is excluded and included.

	YAW RATE INCLUDED		YAW RATE NEGLECTED		ERROR	
	Time (msec)	Velocity (fps)	Time (msec)	Velocity (fps)	Time (%)	Velocity (%)
WE4-1						
Long.	238	27.4	193	27.0	19	2
Lat.	125	18.8	120	20.0	4	6
SPI-1						
Lat.	140	15.3	141	15.9	1	4

the results were similar for both tests. In each case, the error in the velocity calculations introduced by neglecting the yaw rate was 6 percent or less.

The reason for the good correspondence in these tests is apparent from the tabulated data. In both tests the occupant strikes the vehicle interior early in the collision event. In test WE4-1 the occupant strikes the interior in both directions before 200 msec have elapsed. The collision itself took approximately 600 msec. The occupant is already in contact with the vehicle interior by the time yaw rates become significant in the collision.

While the inclusion of yaw rate as discussed in the presentation of the occupant risk model is a more complete model of the occupant kinematics, neglecting the yaw rate appears to be acceptable since the error introduced will generally be small. Errors introduced by neglecting the yaw rate will generally be less than 2 fps (0.6 m/s). A longitudinal barrier which results in a lateral occupant impact velocity of 22 fps (6.7 f/s) will probably be judged on equal terms to one yielding an impact velocity of 20 fps (6.0 m/s). Since the approval of roadside hardware does not demand strict conformance to the occupant risk criteria presented in Report 230, this small error is acceptable.

Summary

Since the only forces acting on the vehicle occupant are due to accelerations of the vehicle this method is analytically precise. The quality of the results only depend on the quality of the displacement-time history from the full-scale crash test. Since anthropometric dummies are only calibrated for either side impacts or full frontal impacts there is really no meaningful data to compare the results of this algorithm to.

Estimating Occupant Risk Without Vehicle Acceleration Data

It is often desirable to obtain a gross estimate of the occupant risk given only the impact speed, angle and the behavior of the barrier. Estimating the occupant risk is useful for evaluating the severity of reconstructed accident data as well as evaluating old or nonstandard tests. This section describes a method for estimating the lateral occupant risk given the impact speed, impact angle, maximum dynamic deflection of the barrier, and several vehicle dimensions. This model will be referred to as the collision model of occupant risk since it is a function only of the impact conditions.

Hirsch(4) describes a method for estimating various quantities such as exit velocity, average lateral and longitudinal accelerations, and interaction time using the gross behavior of the barrier system. Hirsch's development, and hence the model to be based upon it, is based on the following assumptions:

- The lateral acceleration is constant during the time interval required for the vehicle to become parallel to the barrier.
- Vertical and rotational effects are not considered. This analysis is therefore not valid in cases where the vehicle was observed to roll, override or underride.
- When the vehicle is parallel to the barrier rail it is presumed that the lateral velocity at that point is zero.
- The vehicle behaves as if all the mass were concentrated at the center of gravity. Deformation of the vehicle is assumed not to effect the general distribution of the vehicle's mass or the location of the c.g.
- No provision is made for snagging or pocketing therefore this model will not accurately represent collisions which display those features.

Most barrier collisions cannot, of course, satisfy all of these assumptions. For example, no collision will satisfy assumption number (1). The assumptions provide a means of assessing how applicable a particular collision is to the model and what degree of accuracy ought to be expected from applying it to specific impacts.

An equation for the hypothetical occupant risk can be developed from simple dynamics assuming that the occupants initial velocity relative to the vehicle is zero.

$$v_{ORS} = v_o + a_s\ t \tag{11}$$

$$d_s = 0.5\ a_s\ t^2 \tag{12}$$

where

v_o = initial occupant velocity relative to the vehicle (ft/s)
v_{ORS} = occupant's velocity relative to the vehicle (ft/s)
a_s = vehicle lateral acceleration (ft/s^2)
t = time (sec)
d_s = lateral flail distance (ft)

Combining equations (11) and (12) will produce the following expression for the occupant risk.

$$v_{ORS} = \sqrt{2\ d_s\ a_s} \tag{13}$$

Using the expression developed by Olsen for the average lateral deceleration and equation (13) the following expression can be used to estimate the lateral occupant risk.

$$v_{ORS} = v_o \sin\theta \sqrt{\frac{d_s}{[A \sin\theta - B(1-\cos\theta) + \Delta]}} \tag{14}$$

where

A = distance from the front bumper to the c.g. (ft)
B = vehicle half width (ft)
Δ = barrier deflection (ft)
θ = impact angle

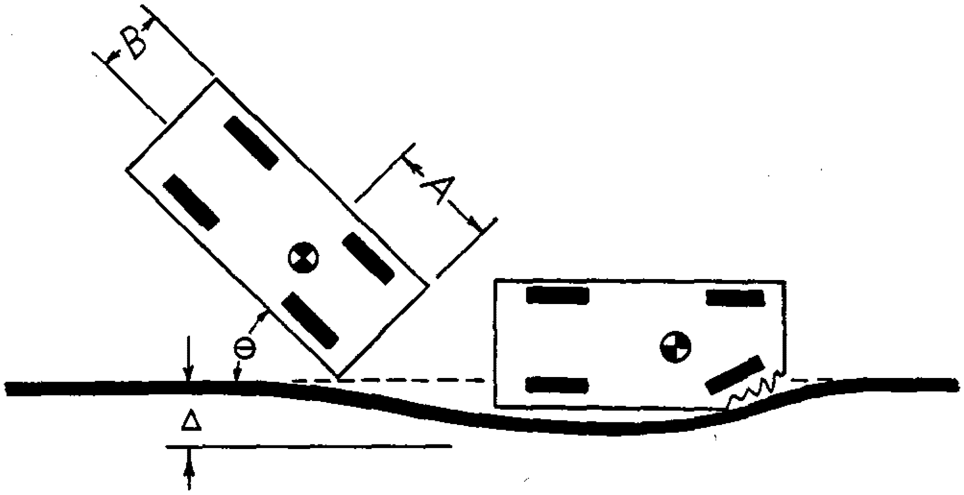
Attention should be directed once again at the required assumptions. This model is most appropriate for collisions in which the vehicle remains upright and is smoothly redirected.

Several full-scale crash tests were evaluated using this equation and compared to the actual values observed by measuring the accelerations of instrumented anthropometric dummies. The results of these comparisons are shown in table 10. As the table shows, the collision model of the occupant risk factor provides a resonable rough estimate of the occupant impact velocity in these tests.

In summary, the mathematical model of the occupant risk shown in figure 4 and equation (14) provides a fairly accurate and simple means of estimating the occupant-interior impact velocity given only the gross behavior of the vehicle and barrier. While the model works well in many cases it should be emphasized that violation of any of the five assmptions will denigrate the solution. This model is most appropriately used for "rule-of-thumb" estimates about collisions for which no acceleration time-history data is available.

Table 10. Comparison of the collision model of occupant risk to full-scale crash tests.

Test No.	Vehicle Weight	Impact Speed	Impact Angle	Observed Occupant Risk	Estimated Occupant Risk	Percent Error	Ref.
RF-22	2140	61.9	18.3	28.0	21.54	23.1	1
CMB-7	2250	57.1	16.5	22.4	18.83	15.9	1
CMB-9	2250	58.9	15.5	17.7	18.80	6.2	1
CMB-13	2250	56.4	14.3	16.2	17.26	6.5	1
SRB-4	2083	54.7	17.1	17.0	18.40	8.2	1
BR-1	1926	60.9	13.1	17.2	18.65	8.4	2
BR-2	1980	61.0	15.0	17.5	20.05	14.6	2
BR-3	1990	61.0	14.2	19.5	19.48	0	2
BR-4	1987	61.4	14.1	15.1	16.23	7.5	2
MB-1	1947	58.5	17.2	21.4	20.65	3.5	3
MB-2	1979	61.6	14.5	16.1	19.89	23.5	3
GR-1	1989	60.1	15.5	19.8	18.40	7.1	4
GR-2	1948	59.3	14.4	21.5	18.20	15.3	4
GR-3	1857	59.7	15.4	17.0	15.10	11.1	4
GR-4	1916	60.4	15.3	18.9	20.10	6.3	4
GR-5	1973	60.5	15.8	11.9	10.80	9.2	4



$$a_s = \frac{V^2 \sin^2\theta}{2\left[A\sin\theta - B(1-\cos\theta) + \Delta\right]}$$

$$ORS = \sqrt{2a_s d_s}$$

$$ORS = \sqrt{\frac{V^2 \sin^2\theta \; d_s}{\left[A\sin\theta - B(1-\cos\theta) + \Delta\right]}}$$

Figure 4. Collision model of the lateral occupant risk factor.

References

(1) Michie, J.D., "Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances," NCHRP Report 230, Transportation Research Board, Washington, DC, March 1981.

(2) "Instrumentation for Barrier Collision Tests," SAE J211b, Society of Automotive Engineers, New York, 1970.

(3) Powell, G.H., "Computer Evaluations of Automobile Barrier Systems," FHWA-RD-73-73, Federal Highway Adm., Washington, DC, August 1970.

(4) Hirsch, T.J., "Introduction to Roadside Crash Force Concepts," 27th Annual Proceedings, American Association for Automotive Medicine, Morton Grove, IL, October 1983.

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The Offices of Research and Development of the Federal Highway Administration are responsible for a broad program of research with resources including its own staff, contract programs, and a Federal-Aid program which is conducted by or through the State highway departments and which also finances the National Cooperative Highway Research Program managed by the Transportation Research Board. The Federally Coordinated Program of Highway Research and Development (FCP) is a carefully selected group of projects aimed at urgent, national problems, which concentrates these resources on these problems to obtain timely solutions. Virtually all of the available funds and staff resources are a part of the FCP, together with as much of the Federal-aid research funds of the States and the NCHRP resources as the States agree to devote these projects.*

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   Safety R&D addresses problems connected with the responsibilities of the Federal Highway Administration under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. **Reduction of Traffic Congestion and Improved Operational Efficiency**

   Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by keeping the demand-capacity relationship in better balance through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

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