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ABSTRACT

Considerable research has been conducted over the past decade on the response of both vehicles and occupants to low speed rear impacts. This research has employed various conditions of target vehicle braking and target occupant awareness. Relatively little effort has been devoted to quantitatively comparing vehicle and occupant responses under different braking and awareness. Given the variety of potential braking and awareness conditions in actual rear impacts, it is desirable to better understand the influence of these reactions on both vehicle and occupant dynamics.

Low speed vehicle-to-vehicle rear end collisions were conducted with instrumented vehicles and an instrumented human subject. Six conditions were evaluated: 1) unaware occupant without braking, 2) aware occupant without braking 3) unaware occupant braking "normally", 4) aware occupant full-braking, 5) unaware occupant with brakes mechanically fully applied, and 6) aware occupant with brakes mechanically fully applied. Three closing speeds were investigated (nominal 4, 8 and 13 km/h). The same occupant and vehicles were used for all impacts.

Vehicle chassis velocity and acceleration were measured using 5th wheels and accelerometers, respectively. Occupant response was measured by accelerometers attached to the occupant's head and lumbar spine. Accelerations at the head static center of gravity were obtained via a 9-accelerometer headgear array.

Little difference was found between vehicle kinematics for conditions in which the unaware occupant was not braking and the unaware occupant was braking "normally".

Decreased target vehicle velocity changes and increased bullet vehicle velocity changes were observed with fully or mechanically applied braking. Full or mechanical braking decreased the collision duration for the target vehicle, while bullet vehicle collision durations were not affected. Awareness of the impending impact decreased occupant head kinematic parameters and the target vehicle occupant described those impacts for which he was prepared as feeling less severe than those for which he was unaware. No differences were found in target vehicle occupant head kinematics for the unbraked and fully braked tests.

INTRODUCTION

VEHICLE KINEMATICS

Momentum transfer between two colliding bodies is a well-defined phenomenon. The momentum of two bodies colliding within a given system is conserved. The Law of Conservation of Momentum states that the pre-impact momentum is equal to the post-impact momentum. For a two body system:

$$m_1 v_1 + m_2 v_2 = m_1 v_1^I + m_2 v_2^I \quad (\text{Eq. 1})$$

The coefficient of restitution, "e", is defined as the ratio of the separation velocity and the closing velocity:

$$e = \frac{v_{\text{separation}}}{v_{\text{closing}}} = \frac{v_2^I - v_1^I}{v_1 - v_2} = \frac{v_s}{v_c} \quad (\text{Eq. 2})$$

Combining the momentum and restitution equations yields expressions for the change in velocity (or Delta V) of the bullet (ΔV_1) and target (ΔV_2) vehicles as a function of the closing speed and coefficient of restitution:

$$\Delta v_1 = \frac{m_2(1+e)v_c}{m_1 + m_2} \quad (\text{Eq. 3})$$

$$\Delta v_2 = \frac{m_1(1+e)v_c}{m_1 + m_2} \quad (\text{Eq. 4})$$

These equations form the foundation for many calculations and analyses in accident reconstruction. In higher speed impacts, the vehicles deform significantly and the restitution approaches zero, thus simplifying the equations even further. In low speed impacts however, research has found the coefficient of restitution may not approach zero and can significantly affect the dynamics of an impact. Low speed impact testing has yielded values of “e” ranging from 0.1 to 0.8, and has generally found increasing coefficients of restitution for decreasing closing speeds (Bailey et al., 1991; Bailey et al., 1995₁; Bailey et al., 1995₂; Emori and Horiguchi, 1990; Howard et al., 1993; King et al., 1993; King and Ptucha, 1996; King and Siegmund, 1994; Malmsbury and Eubanks, 1994; Siegmund et al., 1994; Siegmund et al., 1996; Szabo and Welcher, 1992). Accordingly, the “e” term in the equations cannot be ignored for low speed impacts.

Equations (1), (3) and (4) make the inherent assumption that *no significant unbalanced external forces act on either body*. Such an assumption is appropriate for high speed impacts since the impulse from the tires on the roadway is negligible compared to the momentum transfer between vehicles. In low speed collisions, this assumption may not be appropriate, however. Impulse from the tires on the roadway is not negligible relative to the momentum transfer and must be accounted for (Bailey et al., 1995₁; Emori and Horiguchi, 1990; Howard et al., 1993; Siegmund et al., 1994). In fact Bailey et al. (1995₁) define a minor or low speed impact as one in which the effects of restitution and tire forces cannot be ignored.

Equations (3) and (4) can be modified to include unbalanced external forces:

$$\Delta v_1 = \frac{m_2(1+e)v_c + \sum F_{ext} \Delta t}{m_1 + m_2} \quad (\text{Eq. 5})$$

$$\Delta v_2 = \frac{m_1(1+e)v_c - \sum F_{ext} \Delta t}{m_1 + m_2} \quad (\text{Eq. 6})$$

Where $\sum F_{ext} \Delta t$ is the sum of all unbalanced external forces acting on the system.

The most commonly encountered unbalanced external force occurs in a rear impact in which the target vehicle is braked at the time of impact. If the braking contributes a significant force, this must be accounted for computationally. Closer examination of equations (5) and (6) allows a theoretical prediction of the effects of target vehicle braking. For a given closing speed, increased target vehicle braking increases the bullet vehicle change in velocity and decreases that of the target vehicle. This phenomenon is intuitive and has been reported by others (Bailey et al., 1995₁; Emori and Horiguchi, 1990; King and Siegmund, 1994; Siegmund et al., 1994).

The collision duration for a given vehicle may be defined as the point at which the acceleration on that vehicle's chassis first returns to zero. Treating each vehicle as a rigid mass (ignoring the sprung mass), increased target vehicle braking theoretically decreases the impact duration for the target vehicle chassis. Vehicle impact tests with varying degrees of braking have borne this out in prior research (Emori and Horiguchi, 1990; Siegmund et al., 1994). Theoretically this phenomenon occurs in part because the effective acceleration on the target vehicle chassis will become zero before the end of the applied impulse from the bullet vehicle, since the unbalanced external braking impulse completely counteracts the collision impulse at some point toward the end of the impact. It is important to note that the collision duration, as defined here, may be different for the bullet and target vehicle chassis when significant target vehicle braking exists.

A target vehicle braking force applied over a certain duration constitutes an unbalanced external braking impulse which must be accounted for during momentum calculations. Siegmund et al. (1994) quantified this force both theoretically and in tests with varying degrees of mechanical braking of the target vehicle. No tests were reported in which live occupant-imposed braking effects were quantified. For an occupant in a target vehicle equipped with an automatic transmission, the braking employed at a stop light is typically just sufficient to counteract the forward idle of the vehicle. It is unclear whether this brake force is significant relative to the overall momentum transfer when the vehicle is struck from the rear at low speed, although King and Siegmund (1994) and Siegmund et al. (1994) hypothesized that it was negligible. Since most low speed rear collisions are over within 0.25 seconds (Malmsbury and Eubanks, 1994; Siegmund et al., 1994; Siegmund et al. 1996; Szabo and Welcher, 1992; Szabo et al., 1994; Szabo and Welcher, 1996; Thompson and Romilly, 1993) it is clear this braking force cannot be *increased* during the impact, given typical perception-reaction times of 0.75 to 1.5 seconds (Olson, 1989; Sens et al., 1989). No prior research was found in which this “stop-light” braking was evaluated using live human occupants.

An occupant who is aware and braced for the impending impact by pressing against the brake pedal may impose significantly greater braking force than an unaware occupant or one who is just resisting the forward idle. Moreover, the perception-reaction period may significantly precede the actual impact, and an increase in braking impulse during the actual impact may occur. No prior research was found quantifying the braking force for a braced occupant.

The current study endeavors to quantify several target vehicle braking conditions using a live human occupant so the theoretical momentum transfer relationships can be more accurately applied to actual rear impacts.

OCCUPANT KINEMATICS

An occupant in a stationary vehicle that is impacted from the rear remains at rest relative to the ground as the vehicle is accelerated beneath him. This motion is consistent with the laws of physics and has been well documented in the literature (Geigl et al., 1994; Matsushita et al., 1994; McConnell et al., 1993 and 1995; Severy et al., 1955; Szabo et al., 1994). The occupant essentially remains at rest relative to the ground until the seat back and head restraint interact with the occupant. For many occupants, the interaction between the seat back and head restraint and the occupant's upper torso and head occurs after the vehicle's acceleration is essentially complete. Occupant head and neck kinematics are thus largely a function of the final velocity change for the target vehicle as opposed to the shape of the acceleration pulse (King et al., 1993; McConnell et al., 1993; Siegmund et al 1996; Romilly et al., 1989; Severy et al., 1955; Siegmund et al, 1994; Szabo and Welcher, 1996). Occupant cervical injury tolerances for a given occupant-seat pairing are thus likely a function of the target vehicle change in velocity.

Occupant tolerance to rear impacts is likely also influenced by the occupant's preparedness for impact. Occupants who brace and actively tense their muscles in response to an impending impact can typically withstand impacts with a greater severity than occupants who are unaware of the impending impact (Emori and Horiguchi, 1990; Mertz and Patrick, 1971; Severy et al., 1955; States, 1969). The current study also compares head kinematics and subjective impressions of impact between an aware and unaware target vehicle occupant.

METHODOLOGY

VEHICLES – The bullet vehicle was a 1996 Pontiac Bonneville (1541 kg) while the target vehicle was a 1990 Dodge Shadow (1196 kg). Both vehicles were equipped with piston-type energy absorbing bumpers. The Shadow was chosen in part because testing has shown that model vehicle capable of withstanding a 8 km/h (5 mph) barrier impact without damage (IIHS, 1990), and was therefore thought to allow repeated impacts without necessitating vehicle repairs. The bullet vehicle was

accelerated via a ramp and struck the stationary target vehicle in an aligned, bumper-to-bumper manner.

Vehicle Instrumentation – Both vehicles were instrumented with MacInnis Engineering 5th Wheels (MEA 5th wheel). Fifth wheel data was collected at 128 Hz. Tri-axial accelerometers were mounted at each vehicle's approximate static center of gravity on the vehicle chassis. Acceleration data was collected at 1000Hz. A rotational velocity sensor was mounted at the target vehicle approximate static center of gravity, and oriented such that target vehicle pitch rate could be measured.

OCCUPANTS – Both the bullet and target vehicles contained human subjects in the driver's position. Both wore the available lap and shoulder restraint and the target vehicle driver's head restraint was maintained in the up position. Horizontal head-to-head restraint distance for the target vehicle occupant was approximately 9 cm. Table 1 lists the anthropometric data for each occupant.

Table 1. Occupant Anthropometry

Occupant	Gender	Age	Standing	Seated	Weight (kg)
			Height (m)	Height (m)	
Bullet	M	23	1.8	0.9	100
Target	M	38	1.8	1.0	93

The target vehicle occupant underwent pre-test and post-test neurologic and orthopedic evaluations by a medical doctor. Post-test evaluations were conducted immediately following each test, at the immediate conclusion of the entire test series, and 9 days following the test series. A post-test MRI examination of the cervical spine was also conducted for the target vehicle occupant.

Occupant Instrumentation – Only the occupant in the target vehicle was instrumented. A 9-accelerometer array (previously described in Szabo and Welcher, 1996) measured peripheral head accelerations and calculated linear and angular accelerations at the head center of gravity. A uniaxial accelerometer was affixed to the occupant's back at the approximate level of L5-S1 with medical adhesive and a tightly fitted belt.

TEST PROTOCOL – Nominal impact speeds of 4, 8 and 13 km/h were investigated. The bullet vehicle was in neutral for each impact, and rolled down the ramp without braking before or during impact. For each impact speed, 4 target vehicle braking conditions were used. These were defined as follows:

- *None*: Target vehicle in neutral, no braking until well after impact.
- *Normal*: Occupant with foot resisting automatic transmission of vehicle (in drive), simulating braking at a stop light.
- *Full*: Occupant depressing brake fully in anticipation of impact.
- *Mechanical*: Brakes locked via application of a mechanical device on brake pedal.

Mechanical Braking was included to establish a theoretical maximum braking condition and is not necessarily a "real world" realizable braking condition.

Two occupant awareness conditions were studied for each impact speed. These were defined as follows:

- *Aware*: Occupant aware of impending impact and braced in anticipation.
- *Unaware*: Occupant unaware of the impending impact. Protocol used was previously described in Szabo and Welcher (1996) and shown to successfully reproduce an impact in which the occupant was unaware and essentially relaxed at the time of impact.

Six tests were conducted at each of the three nominal impact speeds, for a total of 18 tests. Tables 2 and 3 describe the tests. Each test carried a two character designation which indicated the test series and the test description (i.e. Test B2 was a nominal 8 km/h impact with an aware occupant in the target vehicle with no braking). All tests were conducted on one day in Phoenix, AZ in July of 1997.

Table 2. Test Series

Series	Nominal Impact Speed
A	4 km/h
B	8 km/h
C	13 km/h

Table 3. Test Descriptions

Test	Braking	Awareness
1	none	no
2	none	yes
3	normal	no
4	full	yes
5	mechanical	no
6	mechanical	yes

RESULTS

VEHICLE DAMAGE – The ramp provided good repeatability in bullet vehicle impact velocity and allowed for within series comparisons. Bumper-to-bumper contact was observed for tests in all series. No damage was sustained by either vehicle in Series A (4 km/h impacts). Scuffing to the upper surface of the Dodge's rear bumper cover was observed after the 8 km/h impacts, a result of contact between the bumper cover and the rear body panel as the bumper temporarily compressed. Scuffing to the upper leading surface of the bullet vehicle (Pontiac) bumper cover was observed after the Series B (8 km/h) impacts in which the target vehicle (Dodge) had the brakes fully or mechanically applied. This occurred because the Dodge's rear end had a tendency to ride up during the impact when its brakes were fully applied, resulting in direct contact between the Dodge rear bumper and the upper surface of the Pontiac front bumper cover.

Series C impacts (13 km/h) resulted in progressive central deformation of the rear reinforcement of the Dodge, likely a function of the somewhat pointed front end of the Pontiac. The Dodge's damage ultimately included deformation of its spare tire well. The Pontiac sustained increased amounts of damage to the front bumper cover for those impacts in which the brakes on the Dodge were either fully or mechanically applied. In the first test in Series C (Test C1) both front parklamp lenses of the Pontiac popped out upon impact.

Additional tests were conducted near the conclusion of the series C impacts to assess the effects of the damage on the vehicle response. A stiffer response was demonstrated by slightly higher peak accelerations, and shorter impact durations, but the velocity change was essentially equal (<0.2 km/h difference). As head and neck kinematics are largely a function of the vehicle's final velocity change, the slightly stiffer response did not affect the target occupant's head and neck kinematics.

Isolator compressions for the 1990 Dodge Shadow (target vehicle) were measured after each test, and average isolator compressions are plotted as a function of change in velocity in Figure 1.

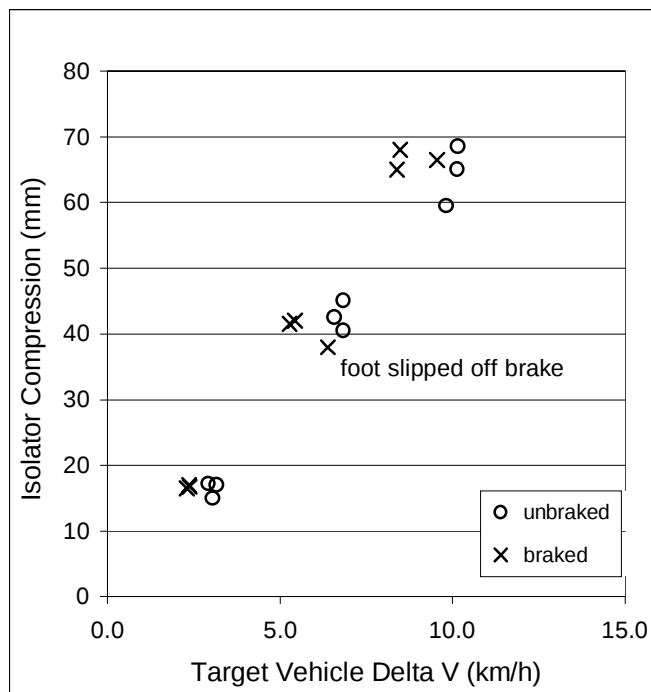


Figure 1. Target Vehicle Average Isolator Compression vs. Velocity Change

VEHICLE KINEMATICS

Vehicle velocities were determined from analysis of the 5th wheel traces. Collision durations were calculated for each vehicle and obtained from the acceleration traces for both vehicles, and defined as the time at which the chassis acceleration essentially returned to zero. Note these values are not necessarily equal when duration is defined relative to the vehicle chassis and an unbalanced external force is present on one vehicle. Target vehicle pitching (as measured by the angular rate sensor) was found to be negligible for all tests. Table 4 contains a description of the vehicle kinematics for all tests.

The coefficient of restitution was calculated only for those tests in which no unbalanced external forces were applied (Tests A1, A2, B1, B2, C1 and C2). For those impacts in which braking was applied, a calculation of “e” based on empirical test data inherently includes the unbalanced external forces. Using such a value of “e” in equations (5) or (6) to predict vehicle changes in velocity would then ostensibly account for the unbalanced external forces twice. Table 5 shows the calculated coefficients of restitution for the unbraked tests.

OCCUPANT KINEMATICS – The occupant in the target vehicle was observed to initially move rearward with respect to the vehicle for all impacts. Peak head linear acceleration, peak head angular acceleration and peak lumbar acceleration for each impact are given in Table 6. Head accelerations were calculated at the head approximate center of gravity and positive and negative values for each are reported. The positive peak head angular acceleration refers to the first positive peak following the

negative peak associated with rearward head rotation during the initial rearward body motions within the target vehicle.

Occupant Symptoms/Subjective Comments – The bullet vehicle occupant indicated posterior neck soreness the day following the tests. Symptoms resolved within 4 days. The target occupant exhibited anterior neck soreness the day following the exposures. These symptoms resolved the 3rd day post-test and did not return. A post-test cervical MRI a week following the tests was interpreted as showing no clinically significant abnormality. For the unaware condition, the target occupant indicated that he was unprepared and described these impacts as a “surprise.” Appendix 1 contains a summary of the target occupant symptoms, subjective descriptions of impact, and medical evaluations for each test and the post-test period.

Table 5. Calculated Coefficients of Restitution

Test	Impact speed km/h	e
A1	3.8	0.52
A2	4.1	0.48
B1	8.2	0.52
B2	8.2	0.51
C1	12.8	0.42
C2	12.9	0.44

Test #	Braking		Aware/ brace		Bullet Vehicle				Target Vehicle				
					Impact Speed (km/h)	Delta V (km/h)	Peak X Acc ⁿ (g)	Impact Duration (sec)	Delta V (km/h)	Peak X Acc ⁿ (g)	Impact Duration (sec)	Piston Compression	
												Left (mm)	Right (mm)
A1	none	no	3.8	2.8	-0.7	0.211	3.1	1.0	0.197	15	15		
A2	none	yes	4.1	2.8	-1.0	0.205	3.2	0.9	0.201	18	16		
A3	normal	no	3.8	2.9	-1.2	0.212	2.9	1.0	0.203	17	17.5		
A4	full	yes	4.1	3.7	-1.0	0.214	2.4	0.7	0.172	18	16		
A5	mech	no	4.1	3.6	-0.8	0.219	2.4	0.7	0.169	17.5	16		
A6	mech	yes	4.1	3.7	-1.1	0.222	2.3	0.8	0.173	18	15		
B1	none	no	8.2	5.6	-1.4	0.204	6.8	1.9	0.182	45	45		
B2	none	yes	8.2	5.6	-1.6	0.193	6.8	1.9	0.171	32	49		
B3	normal	no	8.1	5.5	-1.5	0.205	6.6	1.8	0.177	40	45		
B4	full	yes	8.1	5.9	-1.5	0.203	6.4	2.0	0.166	37	39		
B5	mech	no	8.2	6.4	-1.7	0.194	5.3	1.7	0.161	40	43		
B6	mech	yes	8.2	6.3	-1.6	0.195	5.4	1.6	0.163	41	43		
C1	none	no	12.8	8.4	-2.1	0.170	9.8	2.8	0.176	69	50		
C2	none	yes	12.9	8.4	-2.6	0.169	10.2	3.4	0.167	67	70		
C3	normal	no	12.9	8.7	-2.6	0.159	10.1	3.4	0.157	65	65		
C4	full	yes	12.8	8.8	-2.6	0.161	9.5	2.8	0.179	65	68		
C5	mech	no	12.8	9.0	-2.6	0.202	8.4	3.4	0.150	57	73		
C6	mech	yes	12.7	9.0	-2.9	0.175	8.5	3.3	0.153	63	73		

Table

Table 4 - Vehicle Kinematics

Test #	Braking	Aware/ brace	Head X (pos) (g)	Head X (neg) (g)	Head Resultant (g)	Head Ang.y (neg) (rad/sec^2)	Head Ang.y (pos-after neg) (rad/sec^2)	Lumbar X (g)
A1	none	no	1.2	-0.3	1.4	-34.62	3.13	0.8
A2	none	yes	0.8	-0.3	1.4	-30.84	14.14	0.9
A3	normal	no	1.2	-0.3	1.4	-25.43	17.25	0.8
A4	full	yes	0.6	-0.7	1.0	-21.09	10.32	0.8
A5	mech	no	1.3	-0.9	1.3	-35.92	2.02	0.8
A6	mech	yes	0.7	-0.4	1.2	-27.17	9.15	0.8
B1	none	no	2.2	-1.2	4.5	-258.30	88.77	2.0
B2	none	yes	1.7	-0.7	3.0	-89.31	60.06	2.3
B3	normal	no	2.3	-1.0	3.6	-125.22	63.02	1.8
B4	full	yes	1.8	-0.5	3.1	-105.53	35.23	1.7
B5	mech	no	2.2	-1.2	3.8	-188.97	39.31	1.5
B6	mech	yes	1.3	-0.7	2.5	-59.15	29.70	1.7
C1	none	no	6.0	-2.5	10.1	-898.11	144.89	3.6
C2	none	yes	2.6	-1.3	5.7	-476.17	75.20	3.3
C3	normal	no	5.3	-3.2	11.7	-604.75	144.20	3.9
C4	full	yes	1.6	-1.3	4.1	-246.44	103.10	3.0
C5	mech	no	5.5	-2.9	9.9	-921.42	125.23	3.6
C6	mech	yes	4.7	-2.0	8.9	-762.19	134.04	3.4

Table

Table 6 - Peak Occupant Accelerations

DISCUSSION

VEHICLE DAMAGE – The 1996 Pontiac Bonneville bullet vehicle sustained cosmetic damage to the bumper cover in the Series B impacts (bullet Delta V's from 5.6 to 6.4 km/h). The 1990 Dodge Shadow target vehicle also sustained cosmetic damage in this series (target Delta V's from 5.4 to 6.8 km/h). Most of this damage was to the upper surfaces of the bumper covers, which were scratched and scuffed after those impacts in which the brakes were fully or mechanically applied in the Dodge. In these tests, the loading on both bumpers became somewhat eccentric, resulting in the cosmetic damage. In Series C, the Dodge's rear reinforcement bar began to deform in the center (Delta V's from 8.4 to 10.2 km/h). This was likely a function of the relatively pointed front end of the Pontiac which concentrated the loading to the Dodge between the isolator supports. It appears the vehicle geometries were influential in producing vehicle damage. Given the Dodge's capacity to withstand a barrier impact of 8 km/h (likely a Delta V of over 10 km/h) without damage, (IIHS, 1990), prediction of vehicle change in velocity based on barrier impact tests for circumstances where bumper geometry significantly contributes to the damage on one or both vehicles may result in an overestimation of impact severity.

VEHICLE KINEMATICS – The calculated coefficients of restitution ranged from 0.42 to 0.52 for the three test series. These values are consistent with those reported by others for low speed impacts (Bailey et al., 1991; Bailey et al., 1995₁; Bailey et al., 1995₂; Emori and Horiguchi, 1990; Howard et al., 1993; King et al., 1993; King and Ptucha, 1996; King and Siegmund, 1994; Malmsbury and Eubanks, 1994; Siegmund et al., 1994; Siegmund et al., 1996; Szabo and Welcher, 1992). Consistent with observations of prior research, the coefficient of restitution was lower for the higher impact speeds, although no difference was noted between "e" for the nominal 4 km/h and 8 km/h impact speeds.

Effects of Braking – Figure 1 shows the influence of target vehicle braking on the relationship between isolator compression and target vehicle velocity change. For a given amount of isolator compression, the Target vehicle velocity change decreases with braking. Theoretically, this would be expected due to the fact that for a given impact force and isolator compression (assuming a similar loading rate), some of the momentum would be dissipated by the impulse of the target vehicle braking. Decreased target vehicle velocity change for a given amount of isolator compression with target vehicle braking was previously described by Siegmund et al., 1994.

The effects of braking on the bullet and target vehicle velocity changes were examined. Figures 2 and 3 show the comparison.

Minimal differences in velocity change (≤ 0.2 km/h) were noted between the tests in which no braking was applied and those tests in which normal or "stop-light" braking was applied. The initial brake pedal force was thus insufficient to affect kinematics of either vehicle, or the occupant's foot moved away from the brake pedal during the impact and negated any effects the initial braking may have had. Regardless, the impacts with normal braking can be treated as if no braking was applied from a reconstruction perspective, consistent with the hypotheses of King and Siegmund (1994) and Siegmund et al. (1994).

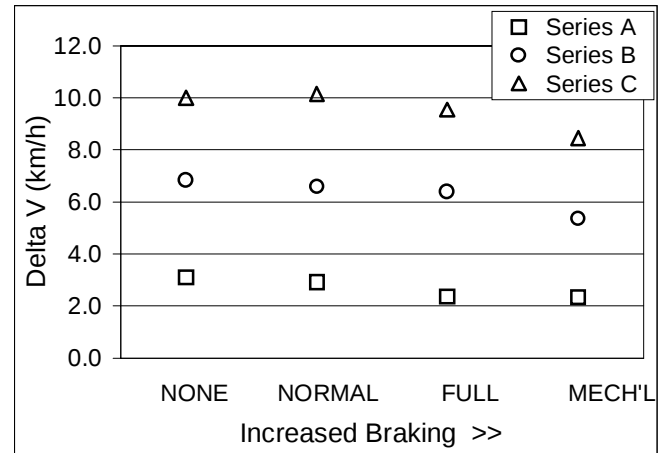


Figure 2. Effects of Target Vehicle Braking on Target Vehicle Velocity Change

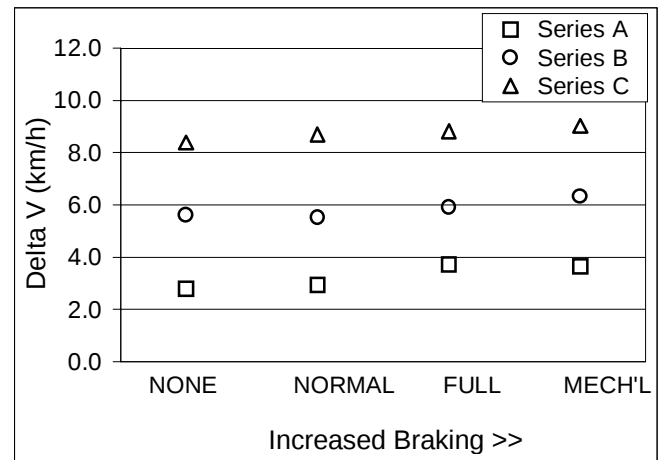


Figure 3. Effects of Target Vehicle Braking on Bullet Vehicle Velocity Change

Table 7 shows average velocity changes for the bullet and target vehicles for different braking conditions. Since the unbraked and normally braked tests were ostensibly similar, they were grouped together for comparison in Table 7.

Series	Target ΔV (km/h)			Change from Unbraked (km/h)	
	None/normal	Full	Mechanical	Full	Mechanical
A	3.1	2.4	2.4	-0.7	-0.7
B	6.8	6.4	5.4	-0.4	-1.4
C	10.0	9.5	8.4	-0.5	-1.6
	Bullet ΔV (km/h)			Change from Unbraked (km/h)	
	None/normal	Full	Mechanical	Full	Mechanical
A	2.9	3.7	3.7	+0.8	+0.8
B	5.6	5.9	6.3	+0.3	+0.7
C	8.5	8.8	9.0	+0.3	+0.5

Table 7: Effect of Target Vehicle Braking on Bullet and Target Delta V's

Mechanical braking decreased target vehicle velocity changes an average of 1.2 km/h and increased bullet vehicle velocity changes an average of 0.7 km/h as compared to the unbraked tests. In the Series A impacts (nominal 4 km/h closing speeds), full braking by the occupant affected the bullet and target velocity changes in a similar manner to the mechanical braking tests. The occupant was thus successful in simulating full mechanical braking throughout the impact for the Series A impacts.

In the Series B and C impacts (nominal 8 km/h and 13 km/h closing speed), full occupant braking of the target vehicle did not affect the bullet and target vehicle velocity changes as much as full mechanical braking, although it had an effect. Occupant full braking was 29% and 31% as effective as full mechanical braking in lowering target vehicle velocity changes for Series B and C impacts, respectively. Occupant full braking was 38% and 60% as effective as full mechanical braking in raising bullet vehicle velocity changes for Series B and C impacts, respectively. It is likely the inertia of the occupant's lower torso resulted in a transient lowering of brake pedal force during the occupant full braking tests at the higher closing velocities, ultimately reducing braking efficiency somewhat. As noted in Appendix 1, in some tests the target occupant noticed his foot had come off the brake pedal.

The collision duration for a given vehicle was defined as the time at which the vehicle's chassis acceleration first returned to zero. Collision durations were on the order of 175 to 200 milliseconds, which is at the high end for low speed impacts, but still within the ranges reported by others (Malmsbury and Eubanks, 1994; Siegmund et al., 1994; Siegmund et al.1996; Szabo and Welcher, 1992; Szabo et al., 1994; Szabo and Welcher, 1996; Thompson and Romilly, 1993). Prior testing on the Dodge Shadow with a 1976 Chevrolet Nova as the bullet vehicle also resulted in relatively long duration impacts (BRT/BA, 1996). The Dodge's bumper and suspension system were thus likely relatively compliant, and promoted longer duration impacts. Figures 4 and 5 show the effect of braking on collision durations.

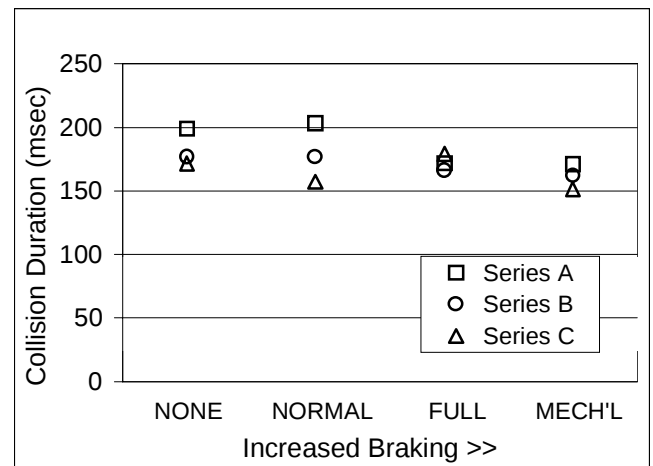


Figure 4. Effects of Target Vehicle Braking on Target Vehicle Collision Duration

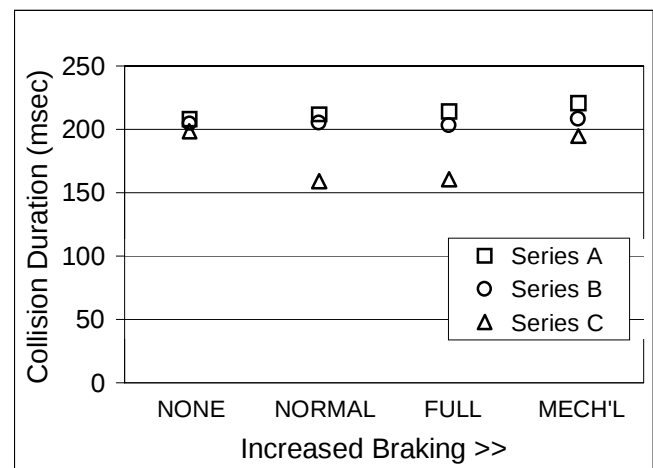


Figure 5. Effects of Target Vehicle Braking on Bullet Vehicle Collision Duration

For the unbraked and normally braked tests, the bullet and target collision durations were essentially similar, which is expected in the absence of any significant external force. Figure 6 demonstrates the similarity between the collision durations for the bullet and target vehicles in the unbraked tests.

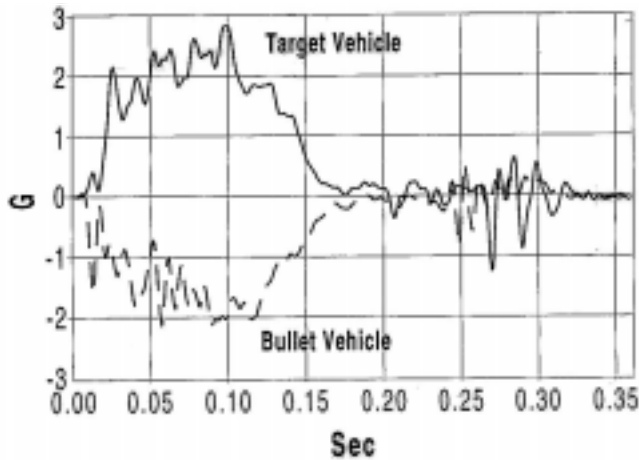


Figure 6. Bullet and Target Vehicle X-Acceleration for Unbraked Test [C1]

The duration of the impact for the target vehicle chassis decreased somewhat with full or mechanical braking, while that for the bullet vehicle did not exhibit any trends with increased braking. The decrease in collision duration for the target vehicle with increased braking has been observed in prior research (Emori and Horiguchi, 1990; Siegmund et al., 1994). Toward the end of the impact the externally applied force acting through the target vehicle's tires (negative X impulse) likely served to completely counteract the force from the bullet vehicle front bumper (positive X impulse), resulting in a net zero acceleration on the target vehicle chassis while the acceleration on the bullet vehicle was still non-zero. Figure 7 demonstrates this graphically at approximately 150 msec.

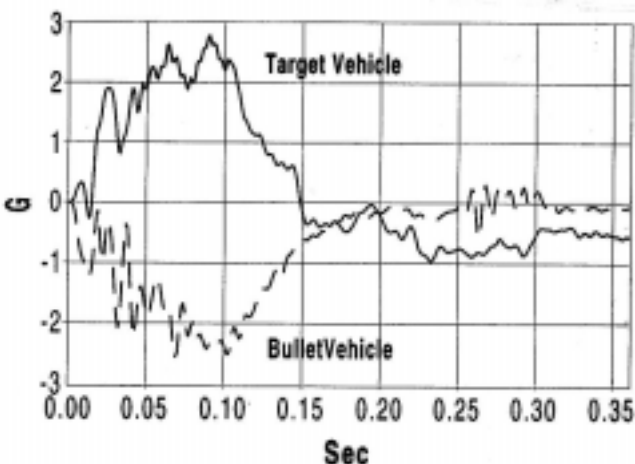


Figure 7. Bullet and Target Vehicle X-Acceleration for Mechanically Braked Test [C5]

Figures 6 and 7 demonstrate that when applying equations (5) and (6) for impacts with full braking, a shorter impact duration should be used in comparison to the unbraked or normally braked conditions.

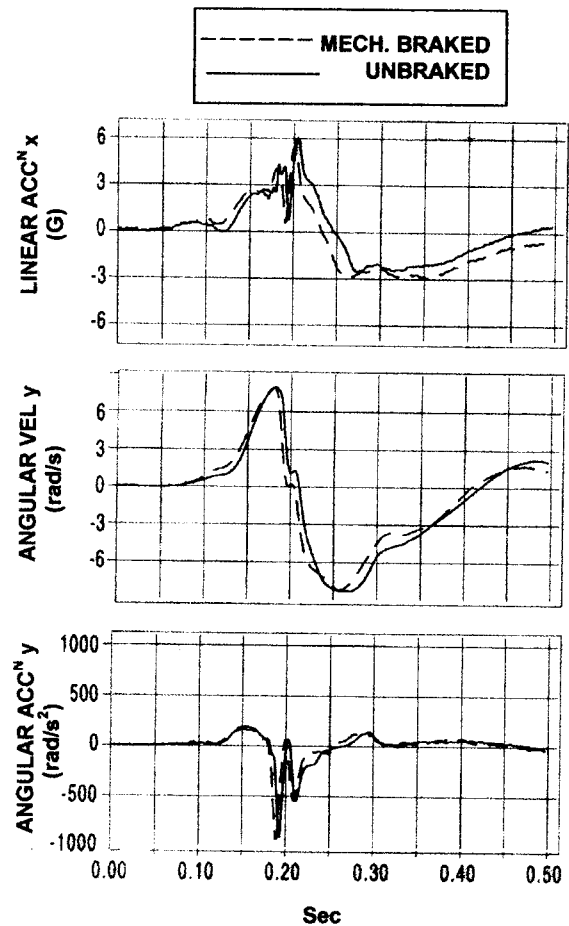


Figure 9. Unaware Occupant Head Center of Gravity Kinematics for Mech. Braked and Unbraked Impacts [Tests C1, C5]

OCCUPANT KINEMATICS

Effects of Awareness – Awareness of the impending impact resulted in decreased target vehicle occupant head center of gravity X linear accelerations, Y angular accelerations, and Y angular velocities. The occupant also reported those impacts for which he was aware as being much less severe, and more comfortable to undergo. This is consistent with the observations of Emori and Horiguchi (1990), Mertz and Patrick (1971), Severy et al.(1955) and States(1969). It is likely the occupant braced his neck and upper torso by contracting his muscles, thereby creating stiff “springs” which mitigated the movement of his head and upper torso during the impact. For the unaware case, muscle activity is likely not implemented until there is significant occupant motion relative to the vehicle (Szabo and Welcher, 1996), and any mitigation of head and torso motion would not be as effective. Figure 8 demonstrates the effect of occupant awareness and bracing for the impending impact.

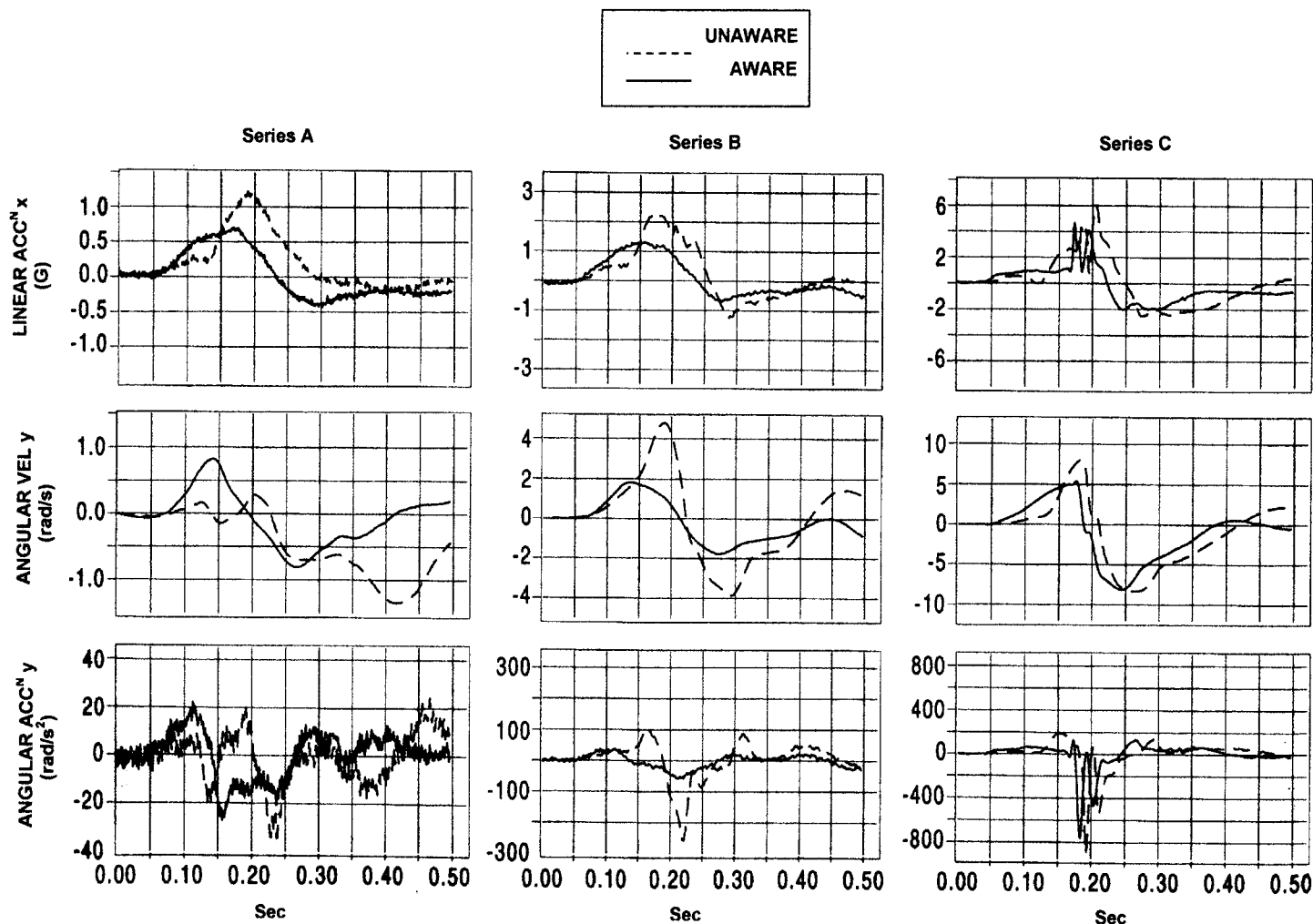


Figure 8. Occupant Head Center of Gravity Kinematics for Aware and Unaware Occupant in Unbraked Impacts [TESTS A1, A2, B1, B2, C1, C2]

Effects of Braking – Emori and Horiguchi (1990) hypothesized target vehicle braking increased the forces on the neck during flexion of the cervical spine (during the rebound phase). This hypothesis is not supported in this test series for this occupant and this target vehicle. Unaware occupant head center of gravity linear accelerations, angular velocities and angular accelerations during the flexion phase were only minimally different for the mechanically braked versus the unbraked condition. This similarity was observed for all three test series. Figure 9 shows the comparison for mechanically braked and unbraked tests in Series C.

CONCLUSIONS

1. Both bullet and target vehicles sustained cosmetic bumper damage in 8 km/h closing speed impacts. The target vehicle sustained structural damage in 13 km/h closing speed impacts. Vehicle geometry appeared to be influential in producing structural damage to the target vehicle in the 13 km/h tests.
2. Little difference was found between vehicle kinematics for conditions in which the unaware occupant was not braking and the unaware occupant was braking "normally."
3. Decreased target vehicle velocity changes and increased bullet vehicle velocity changes were observed with fully or mechanically applied braking. This effect diminished with increased impact severity.
4. For target vehicle velocity changes of approximately 3 km/h, the target occupant was able to brake the target vehicle with near 100% efficiency of mechanical braking. For target velocity changes of approximately 6.5 to 9.5 km/h, the target occupant's braking efficiency was approximately 30 to 60% of mechanical braking.
5. Full or mechanical braking decreased the target vehicle collision durations, while the collision durations of the bullet vehicle were not affected.
6. Awareness of the impending impact decreased occupant head kinematic parameters and was subjectively described by the target occupant as feeling less severe than those impacts for which he was unaware.
7. Only minimal differences were noted between head kinematics of the unaware target occupant in braked and unbraked impacts.

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APPENDIX

APPENDIX 1: Clinical and Subjective Target Occupant Data

Pre-Test Neurological Orthopedic Examination

Normal head, face, neck, upper extremity, chest, thoracic, lumbar, abdomen, pelvis, lower extremity exam with history of slightly symptomatic right epicondylitis/tennis elbow and old healed right metacarpal fractures.

Test number	Physical Complaints	Examination	Occupant Subjective Description of Impact
A1	head band irritating	normal	Jostled, no contacts.
A2	head band irritating	normal	No contacts.
A3	head band irritating	normal	Jostled, no contacts.
A4	head band irritating	normal	Looking at rear view mirror, jostle, no contacts.
A5	head band irritating	normal	No contacts.
A6	head band irritating	normal	Jostled, no contacts.
B1	none	normal	Minor rearward motion, head restraint contact, foot came off brake.
B2	none	normal	Teeth separated, came together slightly.
B3	none	normal	Head restraint contact, foot came off brake.
B4	none	normal	Foot came off brake.
B5	palms on steering wheel, felt slight pressure on both hypothenar	normal	Minor rearward motion, no contacts.
B6	none	normal	Felt 2 impacts.
C1	none	normal	Heard bullet vehicle, rearward motion with ramping, head restraint contact, hands came off steering wheel.
C2	none	normal	Rearward motion with ramping, head restraint contact, foot came off floor.
C3	parathoracic tenderness lasting 2 min.	normal	No ramping, head restraint contact, hands came off steering wheel, foot came off brake.
C4	lumbar accel tenderness	normal	Rearward motion with ramping, head restraint contact.
C5	none	normal	Rearward motion with no ramping, moderate head rest contact followed by mild head rest contact.
C6	mild right antecubital fossa pain lasting 20 sec.	normal with note- hx of epicondylitis	Rearward motion with no ramping, head restraint contact, foot came off floor.

*In tests B2 and C5 the occupant's teeth were initially separated. During the B2 collision his teeth came together slightly. His teeth did not close in the C5 collision. In the remainder of the Series B and C tests the occupant's tongue was initially positioned between his teeth, and he did not bite it during the collisions.

Immediate Post-Test Neurological Orthopedic Examination

Normal head, face, neck, upper/ lower extremity, chest, thoracic, lumbar, abdomen, pelvis exam; no contusions, lacerations, abrasions or tenderness; no headaches, TMJ, spinal, upper/lower extremity or seat belt related symptoms

Post-Test Symptoms

Bilateral sternocleidomastoid tenderness most noticeable just superior to the clavical and tender cervical ranges of motion the morning after the tests - resolved by the evening of the 3rd day post-test.

Neurological Orthopedic Examination (10 days post-test)

Normal head, face, neck, upper extremity, chest, thoracic, lumbar, abdomen, pelvis, lower extremity exam; no contusions, lacerations, abrasions or tenderness; no headaches, TMJ, spinal, upper or lower extremity symptoms.

Cervical MRI (16 days post-test)

Normal - no clinically significant abnormalities.