
Human Subject Responses to Repeated Low Speed Impacts Using Utility Vehicles

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Baker Materials Engineering Ltd.

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ABSTRACT

Adult volunteers occupied vans and pickup trucks in a series of repeated low speed aligned front and rear collisions. Occupant response was examined and compared to our physician test volunteer's subjective evaluation of the level of induced disturbance. The data base correlating collision severity with damage has been expanded to include vehicles equipped with rigidly mounted bumper assemblies. A procedure is proposed to predict the severity of collisions (a parameter critical in evaluating injury potential) using data from repeated low speed impacts. No injuries were reported by our test volunteers indicating the test conditions were at a level where the potential for injury is remote.

INTRODUCTION

Injury is frequently claimed as a consequence of the low speed rear impact. One of the most influential parameters governing an individual's risk of exposure to injury is collision severity. Much effort has been expended by various research groups to relate collision severity with post-impact damage and artifacts exhibited by vehicles. Most of this work has focused on vehicles equipped with bumper assemblies that utilize bumper isolators as an energy absorbing medium. Presently, however, there exists little data correlating collision severity and post-impact deformation damage exhibited by vehicles with rigidly mounted bumper systems. A series of low speed impact tests was conducted for the purpose of, first, expanding the test data base of volunteer exposures to low speed impacts, and second, examining whether a correlation between collision severity and damage sustained by utility vehicles fitted with rigidly mounted bumper systems could be established.

A selection of pickup trucks and vans was subjected to a number of repeated impacts with sequentially increasing collision severity. Damage sustained by the test vehicles was recorded after each impact and is reported in detail in the appendix. A method for calculating a speed change (ΔV) that would represent the severity of a single collision required to produce the damage accumulated in all impacts, including the current impact, is proposed.

Advantage was taken of the test series to record the induced transient disturbances of volunteers occupying both the striking and struck vehicles. The occupant data captured in this series was confined to video and test volunteer subjective comments, intended to supplement accumulated data from other low speed rear collision test programs.

BACKGROUND

Quantifying the severity of a collision is a task that the accident reconstructionist is often called upon to perform. This task can be difficult where little or no damage occurs to the subject vehicles, because few valid tools are available. Computer based algorithms that incorporate crush damage and stiffness parameters to calculate collision severity (i.e. the CRASH program or like derivations) are not applicable to low speed events because of the manner in which the crush coefficients are derived. Recent investigations into low speed collisions¹⁻⁵ have established correlations between the magnitude of bumper isolator compression and vehicle speed change for a number of selected isolator equipped vehicles. These works are useful when reconstructing low speed accidents involving vehicles similar to those tested. However, a dearth of low speed data currently exists to guide the reconstructionist on other classes of bumpers, such as the rigidly mounted type fitted to utility vehicles.

Strother et al⁶ examined the appropriateness of frontal stiffness coefficients used in the CRASH 3 algorithm. Included in this work is a discussion of the crush behaviour of a 1979 Ford F250 pickup truck and a 1979 Ford Econoline E150 van. The pickup truck, after being subject to a barrier impact of 15 km/h, demonstrated residual crush of 8 cm across the entire width of its front bumper. This pickup truck had 5 cm of residual crush across the entire width of its rear bumper after being subject to a barrier impact of 16 km/h. The Ford van experienced frontal and rear barrier impacts of 17 km/h and 14 km/h, respectively. These two impacts produced 6 cm of crush across the entire widths of the front and rear surfaces.

The data collected by Strother can be used to assess the collision severity of moderate speed impacts involving pickup trucks and vans similar to those tested. It also indicates that the threshold for damage exists at impact intensities less than that represented by the barrier impact speeds used in the tests. It does not serve to guide the reconstructionist in quantifying the severity of low speed collisions. To this end, seven test series involving pickup trucks and vans have been conducted and are described herein.

TEST METHOD

Eight vehicles were acquired for testing. The chassis of each vehicle was intact so that it was free to roll. Each vehicle was free of damage to its front and/or rear bumper assemblies. The right front door was removed from each test vehicle to facilitate video recording of occupant motion. All vehicles were weighed. Documentary photographs were taken prior to collision testing. Seven test series (A through G) having a total of 25 impacts were performed.

The test volunteers were all males; one was a physician/kinesiologist, the remainder were members of our engineering staff. All had participated in previous low speed rear collision tests to greater levels of intensity without ill effects. A volunteer occupied the driver's position of both the struck and striking vehicles. For the struck vehicle the test subject was lightly applying the brake pedal and was instructed to relax. Visual and auditory cues of the impending impact were defeated. The video cameras were earth fixed, located so as to capture occupant disturbance during the first phase of the collision interaction.

The striking vehicle was manually guided into the rear of the stationary target vehicle to cause aligned, bumper-to-bumper contact. The speed of the striking vehicle, at the beginning of each test series, was chosen to be at a level initially thought to be below the threshold where damage would occur (excluding test series E). The two collision bumper assemblies were scrutinized for damage at the conclusion of each impact. Relevant damage was recorded

photographically, and measurements of the deformed bumper structures were taken. The selected vehicle pairs were subjected to repeated impacts in which the striking speeds were increased sequentially.

Video analysis was used to measure the striking vehicle's speed as well as the speed change of both the struck and striking vehicles. This was done by counting the number of video frames required for a fixed distance on the vehicle to pass a reference point. This method was judged to provide sufficient precision, given the low speeds at which all tests were conducted. Pneumatic speed traps and an optical timing device were also used and the aggregate speed data compared.

Test details and results are listed in Appendix A.

CALCULATING A REPRESENTATIVE ΔV

An individual's risk of exposure to injury is heavily influenced by collision severity. Therefore, when assessing the potential for a collision to expose an occupant to injury, it is essential to correctly evaluate the magnitude of the collision severity. The damage sustained by the test vehicles can be compared with the damage incurred in a real world accident in order to quantify the speed change of the collision of interest. The speed changes, however, can not be directly compared with damage because the damage exhibited by the test vehicle bumper assembly can be the result of multiple impacts.

A parameter that describes the severity of a single collision that will produce the damage accumulated in all previous impacts, as well as the current impact of the repeated test procedure, is required before the method of comparison can be used to predict collision severity. The required descriptor is introduced here as the representative speed change (ΔV_{rep}). A procedure for calculating ΔV_{rep} is proposed in the following discussion.

Prasad⁷ examined the crush behaviour of vehicles exposed to the Repeated Test Technique - a test in which the same vehicle is repeatedly impacted into a rigid barrier at low, but sequentially increasing speeds to yield data points that can be used to predict impact behaviour at higher speeds. This technique is based on the assumption that the total crush energy is equal to the sum of the energy absorbed in all previous impacts, and the energy absorbed in the current impact. The equation used within the CRASH 3 algorithm to calculate speed change was used by Prasad to calculate ΔV_{rep} . For an aligned impact, this equation becomes:

$$\Delta V_1 = \sqrt{\frac{2m_2 \Sigma E}{m_1 (m_1 + m_2)}} \quad (1)$$

Where: ΣE is the Sum of crush energy of all preceding impacts, as well as the current impact
 m_1 = mass of vehicle 1
 m_2 = mass of vehicle 2. For barrier impacts m_2 (the barrier mass) is assumed to be infinite

Equation 1 was used to calculate the ΔV_{rep} for the striking vehicle of test series A (m_2 was equated to the mass of the struck vehicle: 2235 kg). The results are listed in Table 1 below:

The representative speed change is expected to be greater than the measured speed change for all impacts, other than the first impact. However, the entries of Table 1 show that ΔV_{rep} is less than the measured speed change for all but the final impact of the series (test A7). Clearly, Equation 1 underestimates the value of ΔV_{rep} . This shortcoming was identified by Prasad who concluded that the repeated technique would give acceptable results for barrier impacts having speeds of 16 km/h or higher. Sources of error in this method were stated by Prasad to include: 1) the velocity sensitivity of crushing behaviour 2) restitution effects and 3) loss of energy to sinks other than vehicle deformation. Restitution effects were concluded to be the principal factor responsible for ΔV_{rep} (calculated using equation 1) being less than the measured speed changes.

A modification of Equation 1, to account for restitution effects, was obtained by combining the equations of conservation of momentum, conservation of energy, and coefficient of restitution. When energy losses from sinks external to the two collision vehicles (i.e. brake forces) are ignored, the modified equation becomes:

$$\Delta V_1 = \left(\frac{e + 1}{1 + \frac{m_1}{m_2}} \right) \sqrt{\frac{2 \Sigma E (m_1 + m_2)}{(1 - e^2) m_1 m_2}} \quad (2)$$

Where: ΣE = the sum of crush energy
 e = coefficient of restitution
 m_1 = mass of vehicle 1
 m_2 = mass of vehicle 2

Application of measured values of coefficient of restitution (e_{meas}), obtained from each impact, to calculate ΔV_{rep} by Equation 2, was found to overestimate the collision severity for impacts occurring at the end of a test series. The source of this error was identified as being the consequence of the initial few impacts of a test series first causing damage to the softest elements of the bumper assembly. A vehicle's resistance to deformation damage (i.e. its stiffness) is increased by removing these soft structures during the initial few impacts of a test series. Consequently, the soft structures are not available to participate in the later collisions of the repeated test procedure. Therefore, in the final impact test of a series, the test vehicle's stiffness would be greater than the stiffness presented by an undamaged vehicle subject to a single impact having a collision severity equal to ΔV_{rep} .

A method for predicting a representative value for the coefficient of restitution for the nth impact of a test series (e_{rep}) is required before ΔV_{rep} can be calculated by Equation 2.

The method for predicting e_{rep} should have the characteristic that e_{rep} decreases for an increasing ΔV_{rep} . A procedure for predicting e_{rep} should be governed by the amount of energy absorbed by the collision vehicles, because coefficient of restitution is related to the square root of absorbed energy. The following method for predicting e_{rep} is proposed:

Table 1. ΔV_{rep} as calculated by equation 1.

Test	A1	A2	A3	A4	A5	A6	A7
Measured ΔV_1 (km/h)	2.9	4.1	5.3	6.7	6.9	9.4	9.2
ΔV_{rep} (km/h)	n/a	3.0	4.4	5.6	6.3	8.1	9.7

The relationship between e_{rep} and the square root of absorbed energy is modelled as linear. Thus, a graph of these two parameters would have the following form:

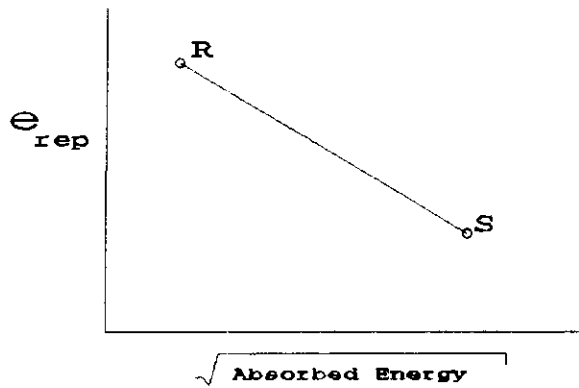


Figure 1

Location R on the above graph is determined for the initially undamaged test vehicle from data obtained in the first impact of a test series: e_{rep} is set to equal e_{meas} . The energy absorbed by the two collision vehicles is taken to be the decrease in the kinetic energy of the system (the system being the two vehicles).

Location S can be determined experimentally by colliding test vehicles, identical to those of the test series of interest, at a speed approaching the upper limit of the low level collision event. This requires two identical pairs of test vehicles (four vehicles in total) to conduct one test series. In the absence of such resources, the location of S can be approximated based on the work of Siegmund et al². Its location was assumed to correspond to a collision having a coefficient of restitution of 0.25 and a speed change, experienced by the lighter vehicle, of 13 km/h.

The amount of energy absorbed by the two collision vehicles, for a 13 km/h ΔV impact having a coefficient of restitution of 0.25 ($E_{(13,0.25)}$), can be calculated by rearranging Equation 2:

$$E_{(13,0.25)} = \frac{\Delta V^2}{K^2} \frac{(1 - e^2)}{(1 + e)^2} \quad (3)$$

$$\text{where: } K = \sqrt{\frac{2(m_1 + m_2)}{(1 + \frac{m_1}{m_2})^2 m_1 m_2}}$$

and m_1 = mass of the lighter vehicle
 m_2 = mass of the heavier vehicle

After generating the curve of restitution versus the square root of absorbed energy (connecting points R and S on the restitution versus absorbed energy graph), the representative speed change for the nth impact of a test series can be calculated. The energy absorbed by all collisions up to and including the nth impact are summed. This value is used with the generated graph to obtain e_{rep} for the nth impact. The summed energy is then used, along with the obtained value of e_{rep} , in Equation 2 to calculate ΔV_{rep} . Appendix B contains a calculation demonstrating the generation of the graph of e_{rep} versus the root of absorbed energy for test series A, and the calculation of ΔV_{rep} for impact A6.

The above procedure was followed to calculate ΔV_{rep} for the lighter of the two collision vehicles tested in all tests other than the barrier impacts of series E. The representative speed change of the heavier vehicle was calculated by assuming momentum was conserved for all tests, with the exception of Series F. The front of the striking Ford van used in Series F had been previously damaged in test series C. Consequently, it was deemed inappropriate to determine ΔV_{rep} for the Ford van. The results of these calculations are listed in the tables of Appendix A.

DISCUSSION

Examination of the calculated values for ΔV_{rep} and e_{rep} (Appendix A) shows a good agreement exists between the calculated values and those expected to be possessed by these two parameters. For example, ΔV_{rep} is greater than ΔV_{meas} for all impacts except for the striking vehicle's ΔV of test C2. Also, e_{rep} is less than e_{meas} for all test impacts, excluding tests A2, D2, and D3. These few discrepancies are addressed below.

Of all tests performed, only in series A, C, and D were both test vehicles free of damage after the first impact. This suggests that the use of the first impact of these test series to generate the graph of restitution versus the root of absorbed energy is inappropriate. The source of this error could be the assumption that there is no loss of energy to sinks other than vehicle crush. More likely, the error is the non-linear behaviour of changes in restitution with respect to changes in absorbed energy, owing to the non-homogeneous structure of bumper assemblies.

To resolve the perceived error of e_{rep} being greater than e_{meas} for series A2, D2, and D3, and ΔV_{rep} being less than ΔV_{meas} in series C, the second impacts of these test Series (A, C, and D) were used to establish point "R" on the restitution versus the root of absorbed energy curve. The second impact was chosen because it was the first collision of these series where observable damage was noted. This procedure resulted in the calculated values of ΔV_{rep} and e_{rep} being in agreement with the expected trend, i.e. $\Delta V_{meas} < \Delta V_{rep}$ and $e_{rep} < e_{meas}$. The results of these calculations are

listed in the tables of Appendix A under $e_{rep}(R2)$ and are reported as ΔV_{rep} in the tables describing the test results of series A, C, and D.

The sum of the Mazda's measured speed change of impacts C1, C2, and C3 totals 10.8 km/h, and the Mazda's ΔV_{rep} for test C3 was evaluated to be 11.0 km/h. This suggests the magnitude of the calculated value of ΔV_{rep} was excessive. The source of this error was either one or both of the value of e_{rep} for impact C3, or the value representing the accumulated energy absorbed by the collision were too high. Video analysis of the Mazda's post-impact dynamics revealed a significant amount of vertical motion was imparted to the Mazda. Therefore, a portion of the kinetic energy absorbed by the system (the two vehicles) was dissipated in damping the vertical motion rather than deforming the vehicles. Consequently, the accumulated energy used to calculate ΔV_{rep} overestimated the energy absorbed.

The representative speed change at which threshold damage was sustained by the front bumpers of the striking vehicles used in all tests ranged between 5 ½ to 7 ½ km/h. The 1990 Ford pickup truck, from test series A, had the lowest threshold at which damage became evident. In test A2 this vehicle's bumper became misaligned with its fenders after experiencing a ΔV_{rep} of 5 ½ km/h. The 1993 Ford van of series C didn't exhibit visible damage until the fourth impact - a collision for which ΔV_{rep} was calculated to be 7.4 km/h.

The representative speed change at which the struck vehicles first exhibited damage to their rear bumper assemblies, excluding the Mazda used in series B and C, ranged from 5.5 to 8.7 km/h. A slight shift of the Toyota's bumper mounting bracket occurred in test F1 - an impact where this vehicle experienced a speed change of 5 ½ km/h. The Jeep Cherokee's bumper collapsed about its mounting brackets after being subject to a ΔV_{rep} of 8.7 km/h. It is suspected that the threshold speed change at which damage would become evident on the rear of the Jeep would be less than this value, considering the extent of damage produced in the second impact of test series D.

The Mazda of test series B, without its rear bumper, sustained visible damage to its end panel after experiencing a 2.4 km/h speed change. When the bumper was installed on this vehicle, visible and obvious damage resulted only after the vehicle experienced a ΔV_{rep} of 13.1 km/h in test C5. The calculated values of ΔV_{rep} for the Mazda of series C, however, are suspect because of the inappropriateness, identified in the above discussion, of equating the change of the systems kinetic energy to the energy absorbed by the deforming bumper structures of test series C. Therefore, the threshold at which visible and obvious damage to the Mazda's bumper bar can be stated to exist at a level greater than the measured

collision severity of test C4, i.e. greater than a ΔV of 7.3 km/h, and less than a ΔV_{rep} of 13.1 km/h.

OCCUPANT RESPONSE

Each vehicle involved in test Series A through G was occupied by an adult male volunteer. Occupant response to the rear impact was similar for the various test subjects at a given level of impact severity, except for series C where the struck vehicle's collision induced motion included a significant vertical component. A summary of the tests in which our seven test volunteers participated is given in Table 2 below.

THE REAR IMPACT - Typical response began when the struck vehicle was accelerated forward by the collision impulse. The occupant moved rearward relative to the forward moving seat. Contact with the seat back was first made by the torso. This compressed the seatback and accelerated the torso forward. The head remained initially stationary, relative to the now forward moving torso. For impacts of sufficient severity, the forward acceleration of the head lagged behind the torso, leading to a rearward bending of the neck. In the presence of adequate head support, the head was seen to contact the headrest, preventing significant cervical extension.

A rebound phase was initiated when the seatback unloaded - this caused the occupant to move forward relative to the vehicle interior. This forward motion was influenced by the elastic properties of the seatback and the collision severity. It was typically self limiting until collision severities approached the 5 to 7 km/h ΔV level, where the seat belt began to take part in arresting the forward motion. No significant cervical flexion was observed during the interval where the torso's forward motion was slowed by the seat belt. A detailed description of occupant response to the rear impact can be found in McConnell's works^{8,18}.

Occupant response to various levels of the rear impact are typified by test series A. In these seven impacts our physician volunteer (subject TT) underwent collisions ranging in severity from 1.8 to 7.0 km/h ΔV . The subjective evaluation of each of these seven impacts, provided by volunteer TT, is juxtaposed here with general features of his kinematic response determined by video analysis.

Table 2. Test volunteer data.

Test Volunteers				
Occupant	Age (yrs)	Height (cm)	Weight (kg)	Test Series Occupied by Volunteer
TT	55	168	65	A struck, B striking
UU	34	183	80	C struck
VV	36	171	61	A striking, B struck, D struck, G striking
WW	46	183	83	G striking
XX	32	169	70	B struck, C striking, E striking
YY	35	185	93	F striking
ZZ	47	178	100	D striking, F struck, G struck

Test A1 ($\Delta V = 1.8$ km/h) - Kinematic Response: Slight movement of shoulders relative to the seatback. The head bobbed rearward but didn't contact the seatback. (Note the head restraint is integral to seatback and was evaluated to provide adequate head support for subject TT).

Subjective Evaluation: - "Totally trivial bump, hardly felt any head motion at all, maybe 2 or 3 cm backwards if anything. The noise level was so low, and the jostling so little, that if there was other intervening surrounding noises such as traffic sounds, that the event might be missed and the perception being that no accident or impact occurred. This event imposed less jostle to my head-neck region than a simple gentle sneeze, it felt similar to driving over a small stone on the road."

Test A2 ($\Delta V = 2.0$ km/h) - Kinematic Response: The torso moved rearward and gently compressed seatback. The head moved rearward but didn't contact the head restraint. The head gently returned to its pre-impact posture.

Subjective Evaluation: - "Similar to A1, very minimal backwards motion to head, no touch to head restraint. Barely perceptible head bob. Visual gaze broken momentarily, but did not blink. The impact was now noticeable enough that a person in such a collision might ask themselves, "what was that, did someone bump me?" The impact magnitude felt about the same as a routine sneeze, but not more."

Test A3 ($\Delta V = 2.8$ km/h) - Kinematic Response: The head and torso moved rearward together the shoulders gently compressed the seatback followed by head contact with the headrest. The head then gently bounced forward from the headrest to its pre-impact position. No cervical flexion occurred.

Subjective Evaluation: - "Similar to A1 and A2, but now recognizable as a rear-end bump. Felt as if head came close to head restraint, but did not actually touch it. The impact magnitude would compare to a slightly rough sneeze or cough, or driving through a rough spot on the road."

Test A4 ($\Delta V = 4.2$ km/h) - Kinematic Response: Motion identical to test A3.

Subjective Evaluation: - "This was now a noticeable bump, my head actually touched the head restraint, or at least I recall the touch. It was not a bump against the head, only a touch feeling. I felt my head being propelled backwards, and then it shifted gently forward to its previous position, but I did not think my head went forward of the neutral pre-impact position. This impact magnitude felt slightly more than a rough sneeze or cough, or similar to driving through a shallow pot-hole in the road. There was no hint of any strain to the neck."

Test A5 ($\Delta V = 4.9$ km/h) - Kinematic Response: Shoulders and head moved rearward together with shoulders gently compressing the seatback. Very minor ramping of the torso up the seatback occurred. The head contacted the top of the head restraint then bounced forward. There was no relative motion of the low back with the buttocks. Forward rebound of the torso was partially arrested by the torso belt. There was no forward flexion of neck about the torso belt.

Subjective Evaluation: - "Similar to A4, but now felt a distinct blink reflex, and my head actually bumped against the headrest. This was not disturbing, and the headrest bump could have been missed if I was not paying attention to it. The forward rebound was a little more pronounced than A4, but still only to about the

neutral position. This was similar to routinely plopping down into a chair as if tired at the end of a day."

Test A6 ($\Delta V = 5.6$ km/h) - Kinematic Response: Response of the test volunteer was essentially identical to the 'typical response' to the rear impact discussed previously. A minor variation to the 'typical response' was that a slight amount of torso ramping up the seatback occurred which resulted in the back of the volunteer's head making contact with the top of the head restraint, rather than the front of the head restraint. No flexion occurred when the forward rebound was arrested by the torso belt.

Subjective Evaluation: - "Similar to A5, but with again slightly more head bump on the restraint, and more forward rebound this time perhaps an inch or more forward of the neutral position. I involuntarily blinked this time. Following this impact, I felt a very subtle warm feeling at the top of my neck, but no ache or pain. This feeling lasted maybe about 30 seconds. This feeling would not normally be noticed if I had not been involved in an impact and was paying close attention to any possible neck sensations. This was similar to or greater than plopping down hard into a chair, it was the limit of expected jostling from activities of daily living."

Test A7 ($\Delta V = 7.0$ km/h) - Kinematic Response: Motion was the same as test A6.

Subjective Evaluation: - "This was the last of the rear-ender impacts. A7 had the most dramatic noise of them all, each being louder than previous. This time I felt my head hit the restraint with a jolt, and felt a subtle ramping upwards of my shoulders and upper back. This was greater impact magnitude than comparable activities of daily living, but similar to neck disturbances that would be common in many sporting activities when you bump (not collide) into something or someone. The rebound pushed me forward of the neutral position a little, but not enough to feel any restraint from the shoulder belt. Although with A7 I felt the jostle at the head-neck, I did not feel any strain or motion, not even subtle, in my shoulders, arms, jaw, mid back, low back, hips or legs. The ramping feeling at my upper back would not have been noticed if I was not paying attention. I did not feel as if my buttocks shifted on the seat, or my legs or feet lifted from the peddles. Afterwards, I felt the same subtle ache in my neck at about the C2 region, it lasted for about 4 minutes and then faded away."

Occupant responses to the rear impact for all other test series were essentially identical to that experienced by volunteer TT, other than volunteer UU involved in series C. In this series the vertical component of motion, resulting from the downward displacement of the Mazda's rear bumper, caused the occupant motion to deviate from the typical occupant response. Of this series, the occupant's response to impact C1 and C5

bound the observed range of kinematic responses. They are described as follows:

The Mazda underwent a speed change of 1.7 km/h in test C1. The driver's seat was initially displaced down, with the test volunteer remaining stationary. This caused a reduction in the gap between the volunteer's head and the roof, but no roof contact was made. An increase in lap belt tension resulted in the occupant beginning to move down relative to the vehicle. By this time the vehicle was beginning to return from its downward deflected position. The upward moving seat caused the volunteer to compress the seat, then move up. Three cycles were completed before the vertical oscillation was completely damped. No contact with the headrest was made.

In test C5 ($\Delta V_{\text{Mazda}} = 9.0$ km/h) the Mazda's forward displacement dominated the accompanying vertical movement. The occupant moved rearward into contact with the seatback. Tension in the lap belt, arising from the downward displacement of the vehicle, caused the occupant to be simultaneously pulled down during the rearward compression of the seatback. Head contact was made with the top of the head restraint with rearward cervical extension being less than 20 degrees. Rebound was forward and up. Head contact was made with the roof. The torso's forward motion was arrested by the torso belt and no cervical flexion occurred.

THE FRONTAL IMPACT - Response to the frontal impact was consistent for all volunteers - at a given level of impact severity. Upon impact the occupant moved forward, relative to the vehicle interior. This forward motion was typically self limiting, until impacts exceeded the 5 km/h speed change level. Loads applied by the torso belt would arrest the occupant's forward motion for collisions exceeding the 5 km/h speed change level. The neck would bend in flexion as the head rotated about the restrained upper body, then return to its pre-impact posture. Articulation of the volunteer's neck and back were seen to be well within voluntary limits of motion.

SYMPTOMS OF INJURY - Following both the frontal and rear end impacts, only two volunteers (VV and TT) both involved in multiple test series on the same day, reported symptoms. At the conclusion of series G volunteer VV reported having a headache. This headache completely resolved without treatment within 4 hours.

Our physician test volunteer (subject TT) reported a subtle cervical ache that resolved in 4 minutes. He commented:

"Although I was not injured or strained in any manner by these repeated rear-enders, the part that startled me the most was the drama of the

noise. Rear-end crashes sound horrible, the whole vehicle reverberates with the echo of the impact. Yet upon looking at the bumpers afterwards, only minor dents were noted. It occurred to me that in persons who are emotionally fragile or dysfunctional, the fright from all this noise could be quite disturbing, and they might presume that certainly something could have happened to them. Fear can be very convincing, and it is possible that for some individuals, this in itself could lead to the display of injury behaviour. This is a matter for further consideration.

In the course of performing these low speed rear impact tests we have exposed 6 volunteers to a total of 25 rear impacts (two occupants were in the struck vehicle of series B) ranging in severity from 1.7 to 9.0 km/h ΔV . Each of the test volunteers were instructed to relax. They were normally seated, and facing forward at impact. None sustained injury. These results support the findings of previous research into occupant response to the low speed rear impact done using adult volunteers^{8-12, 18-26} (364 volunteer exposures are summarized in Appendix C). The potential for a normally seated healthy occupant with adequate head support to receive cervical, lumbar or thoracic strain injury resulting from rear impacts of 8 km/h ΔV or less, is considered to be remote.

Our test volunteers were subjected to a total of 25 frontal impacts having speed changes that ranged from 2.2 to 11.0 km/h. None reported injury. This suggests that the severity of a frontal collision must exceed the 11 km/h speed change level before symptoms of injury are expected. This agrees with the findings of Bailey¹, who, after reviewing various research works involving human volunteers in staged frontal collisions¹³⁻¹⁷, commented that the onset of symptoms are associated with frontal impacts having collision severities at around 12 to 20 km/h ΔV .

SUMMARY

A total of 23 vehicle-to-vehicle impacts, and two vehicle-to-barrier impacts, involving utility type vehicles fitted with rigidly mounted bumper assemblies was performed. A pair of vehicles was selected for each test series with sequential impacts of increasing severity. The speed changes of the struck and striking vehicles were measured. Volunteer test subjects occupied the test vehicles.

Damage accumulated in each impact was recorded. The form of damage ranged from barely perceptible displacement of the bumper bar, and subtle deformation of the bumper bar about its mounts, to gross buckling of the bumper and adjacent body panels. The aggregate damage exhibited by each test vehicle increased with every impact.

The aggregate damage displayed by the test vehicles was thought to be useful to the accident reconstructionist for the purpose of quantifying the severity of low speed motor vehicle accidents. A parameter describing the severity of a single impact that would produce the demonstrated aggregate damage was needed before the acquired test data could be directly applicable to quantifying low speed collisions. Representative speed change was proposed as the required descriptor.

A method for calculating the representative speed change of the *n*th impact of a test series was developed. It was based on the work of Prasad⁶, but was modified to account for restitution effects that are prevalent in the low speed collision. The calculated values of ΔV_{rep} were in good agreement with the expected properties of this descriptor of collision severity. It increased with each sequential impact of a test series, and its value for the *n*th impact was always greater than the measured speed change of the *n*th collision. Of the vehicles tested in this work, the representative speed change at which threshold damage first became evident was in the range of 5.5 to 7.5 km/h for front bumpers, and 5.5 to 8.7 km/h for rear bumpers.

The video recording of occupant motion was studied. The pattern of disturbance experienced by each occupant, for a given level of impact, was seen to be similar for a wide variety of male test subjects. At the higher level speed changes of this work, the induced transient motion was similar to occupant kinematic response described in McConnell's works, and witnessed in previous tests conducted by our firm.

Our physician test subject provided a subjective evaluation of the disturbance to which he was exposed. His comments were juxtaposed with the measured collision severity and a description of his actual response determined from video analysis. These data were presented in this format with the aim of illustrating the level of disturbance to which our test subjects were exposed.

Symptoms of injury were recorded. Two test subjects reported minor symptoms. One sustained a headache after repeated exposures. The headache spontaneously resolved without treatment within four hours. The second subject reported a subtle cervical ache that resolved within minutes.

CONCLUSIONS

Relating collision severity to damage accumulated in the low speed repeated test procedure is meaningful if the descriptor of collision severity takes into account the accumulated energy absorbed during previous impacts. Representative speed change (ΔV_{rep}) is proposed as the required descriptor of collision severity.

Further work is required to explore the validity of the model used to calculate ΔV_{rep} .

The representative speed change at which threshold damage was sustained by the front bumpers of the striking vehicles used in these tests ranged between 5.5 to 7.5 km/h. The struck vehicles didn't exhibit damage to their rear bumpers until undergoing representative speed changes of 5.5 km/h to 8.7 km/h ΔV .

Test volunteer VV was exposed to 10 frontal impacts (ΔV 's ranging from 2.9 to 9.2 km/h) and 5 rear impacts (ΔV 's ranging from 2.2 to 8.2 km/h), all within a period of 8 hours. This volunteer reported a headache that resolved within four hours without treatment. Test subject TT reported a subtle ache in the cervical spine that disappeared within four minutes. No other symptoms of injury were reported by our volunteers.

This study exposed our test volunteers to 25 rear impacts ranging in severity from ΔV 's of 1.7 to 9.0 km/h, and 25 frontal impacts of between 2.9 and 11.0 km/h ΔV . The rear impact tests extend the reviewed data base of volunteer exposure to 389 low level rear impacts. No volunteer in this study sustained cervical, lumbar, or thoracic strain injury. The impact conditions to which our volunteers were exposed are considered to have been at a level at which the likelihood of injury is remote.

ACKNOWLEDGEMENTS

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ABOUT THE AUTHOR

Geoffrey P. Nielsen is a professional mechanical engineer with accident reconstruction experience beginning in 1990. Mr. Nielsen has been a test volunteer in numerous studies including the present work (subject YY), and Siegmund's bumper car paper¹³. Of the rear impact test studies reviewed in Appendix C, the most severe symptom of injury was reported by Mr. Nielsen - minor neck discomfort lasting one week after multiple exposures. Enquiries are welcome at Baker Materials Engineering Ltd., 2221 Manitoba Street, Vancouver, B.C. Canada V5Y 3A3 (604) 879-3585 e-mail bakereng@mindlink.bc.ca.

APPENDIX A

TEST RESULTS

SERIES A (Figures 2 through 6, and Table 3) - The striking vehicle was a 1990 Ford F150 pickup, with a mass of 1660 kg. Its bumper configuration was a pressed steel shell rigidly mounted to the frame horns. This vehicle was guided into the rear of a 1993 Ford E250 van (2235 kg) a total of seven times. Striking

speeds for the seven tests were 2.9, 4.1, 5.3, 6.7, 6.9, 9.4, and 10.8 km/h.

The van's bumper configuration was a pressed steel shell, rigidly mounted to the frame rails via two metal brackets. The shell was a "C" section, joined by weldments to the leading edge of the horizontal elements forming the frame rails. A plastic impact strip covered the bottom half of the bumper face.

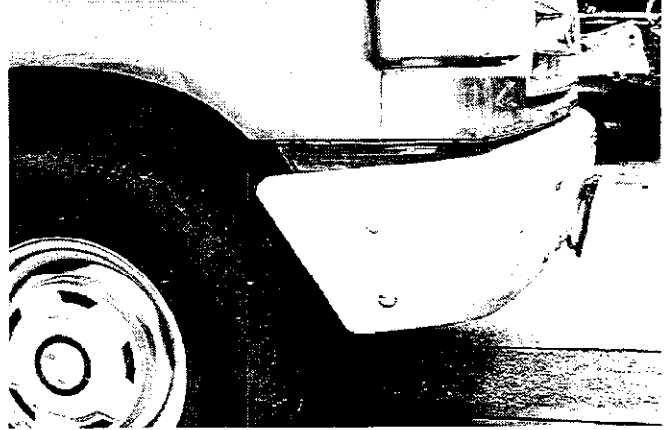


Figure 2. Striker damage after test A3.

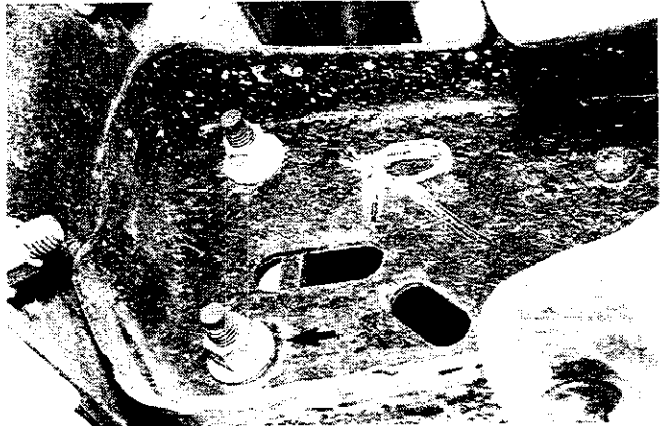


Figure 3. Shift of striker's bumper bolts, test A4.



Figure 4. Accumulated damage to striker, test A7.



Figure 5. Bent rear bumper mounting plate, test A4.

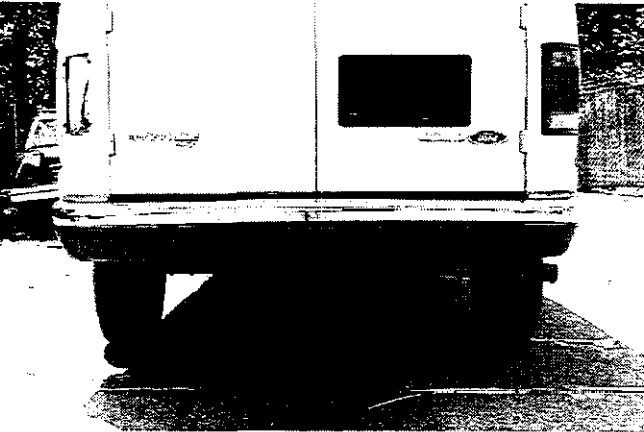


Figure 6. Slight bumper deformation, test A6.

SERIES B (Figure 7 and 8, and Table 3) - A 1988 Toyota Celica GTS 4 wheel drive ($m = 1617$ kg) was guided into the rear of a 1989 Mazda B2200 pickup truck ($m = 1311$ kg). The pickup truck's rear bumper was removed for this test series¹. The Toyota's front bumper made contact with the Mazda's rear end panel at striking speeds of 4.3 and 5.2 km/h. No damage was sustained by the Toyota.



Figure 7. Bent end panel, test B1.

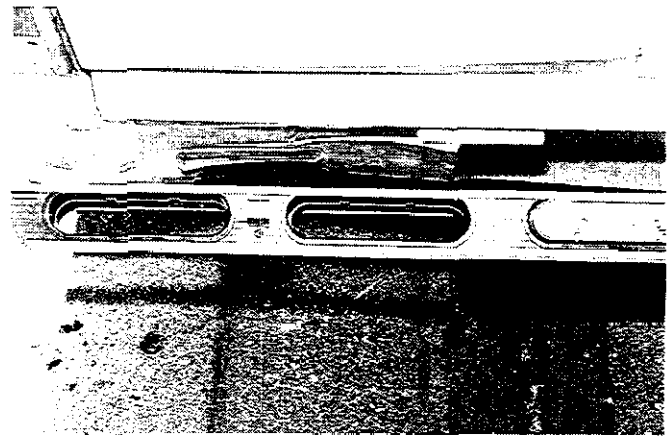


Figure 8. Increased panel deformation, test B2.

SERIES C (Figure 9 and 10, and Table 3) - The Ford E250 van (the struck vehicle from test series A) was utilized here as the striking vehicle ($m = 2240$ kg). The change in mass from test A was calculated based on a heavier test volunteer occupying this vehicle. The bumper bar was fitted to the rear of the Mazda B2200 pickup truck ($m = 1321$ kg). A total of five impacts was conducted with striking speeds of 2.6, 5.2, 6.3, 8.8 and 10.1 km/h.

The front bumper on the Ford van was mounted via two steel plates that were bolted to the left and right frame rails. Thin rubber pads were present between the bumper bar and the mounting plates. A plastic impact strip covered the lower half of this bumper's front surface. Viewed edge on, the lower half of the bumper's front surface was canted rearward.

The Mazda's rear bumper was at a lower elevation than the Ford van's front bumper. Contact between these two vehicles occurred with the rearward canted section of the Ford's front bumper striking the top edge of the Mazda's rear bumper. Consequently, the struck vehicle's induced motion consisted of two components: 1) The forward speed change normally associated with rear impacts, and 2) a vertical displacement initiated as the striking vehicle's front bumper forced the Mazda's rear bumper down during collision contact.

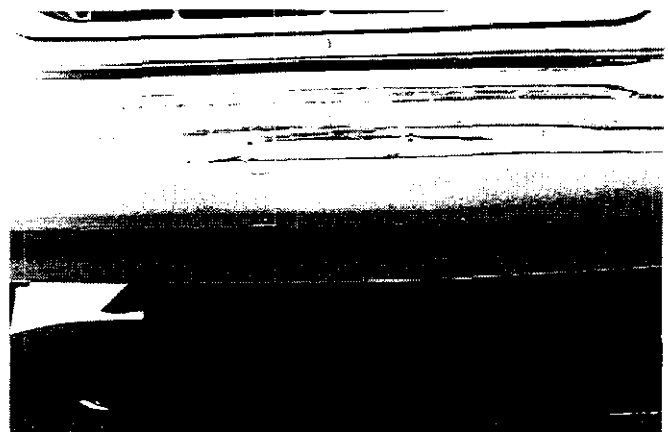


Figure 9. Flattening of striker bumper, test C5.

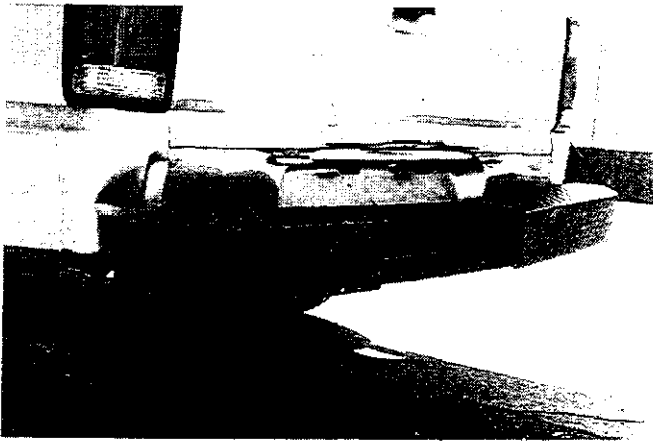


Figure 10. Damage to step bumper, test C5.

SERIES D (Figure 11 through 13, and Table 3) - A 1988 Jeep Cherokee (m = 1570 kg) was struck from behind by a 1985 Dodge 250 van (m = 2160 kg). Three tests were conducted with striking speeds of 3.8, 8.0, and 10.2 km/h.

The Jeep's rear bumper was constructed of a lightweight metal "C" channel that was attached to the chassis via two metal brackets. Plastic end caps flanked the bumper bar. Two vertical plastic bumper guards were mounted on the bumper's rear surface. They projected rearward of the Jeep's bumper bar. Contact between the two vehicles occurred with the relatively flat face of the Dodge van's front bumper striking the two plastic vertical guards.

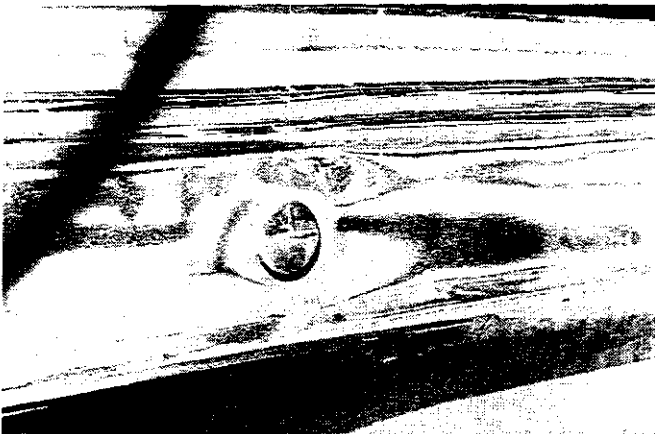


Figure 11. Deformation about mounting bolt, test D2.

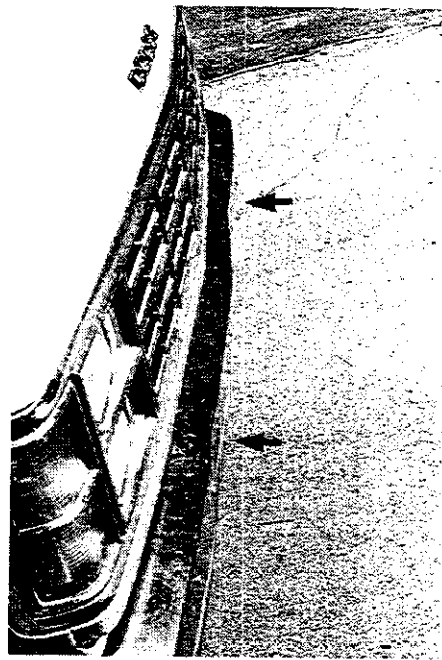


Figure 12. Two dents to bumper bar, test D3.



Figure 13. Damage about bumper guard, test D2.

SERIES E (Figure 14, and Table 3) - A 1971 Volkswagen van (m = 1400 kg) was twice guided into a rigid barrier. The barrier was constructed of concrete blocks fronted by two 13 x 13 cm cedar posts. The posts were stacked one on top of the other. They occupied an elevation of 36 to 62 cm above ground with the intention of simulating the geometry of a bus bumper. The first test saw this Volkswagen strike the barrier at a speed of 4.7 km/h. Contact with the barrier was made by the spare tire that was mounted to the Volkswagen's front panel. The front bumper did not touch the barrier. The van rebounded from the barrier at a speed of 2.3 km/h, resulting in a net speed change of 7.0 km/h. The spare tire was removed from the front of the Volkswagen prior to test E2. Contact with the barrier was made by the front bumper in the second test.

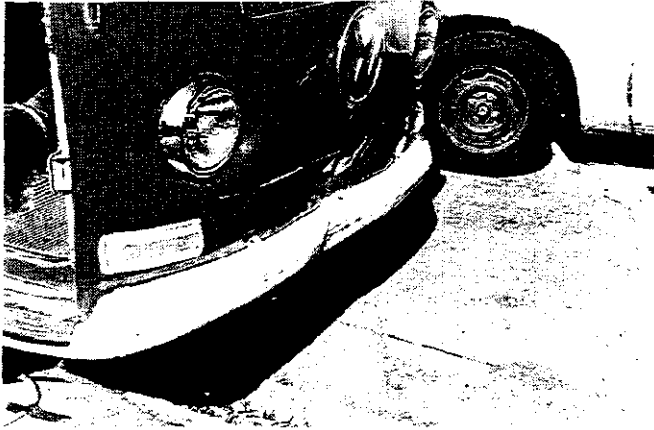


Figure 14. Front panel damage, test E2.

SERIES F (Figure 15 and 16, and Table 3) - The 1993 Ford E250 Econoline van ($m = 2265$ kg) used as the striking vehicle in test series C, was used in this series to strike the rear of a 1981 Toyota pickup truck ($m = 1475$ kg). A total of three collisions was performed with striking speeds of 6.2, 9.4, and 11.2 km/h.

The Toyota's rear bumper was constructed of checkered metal plate that formed left and right box channels. These two box channels were coupled together by an "L" shaped metal plate. The bumper assembly was cantilevered to the frame rails by two metal plates that were used as mounting brackets.



Figure 15. Bumper misalignment, test F2.

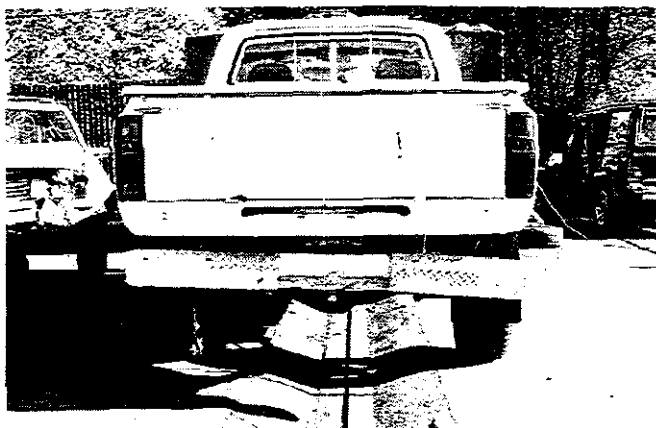


Figure 16. Increased bumper misalignment, test F3.

SERIES G (Figure 17, and Table 3) - In this test series the 1988 Jeep Cherokee from test series D was used as the striking vehicle ($m = 1590$ kg). The Jeep was propelled into the rear of a 1982 Dodge 150 van ($m = 1702$ kg), at striking speeds of 5.1, 7.3, and 12.4 km/h.

Alterations to the Dodge van's bumper mounting assembly, done prior to our acquisition of this vehicle, were thought to have changed the energy absorbing properties of this bumper system. Consequently, damage sustained by this vehicle in our tests was expected to be different than what would have occurred if stock mounting hardware was used. Thus, the damage sustained by the struck vehicle in this test series is not considered representative of what would actually occur and is not discussed here.

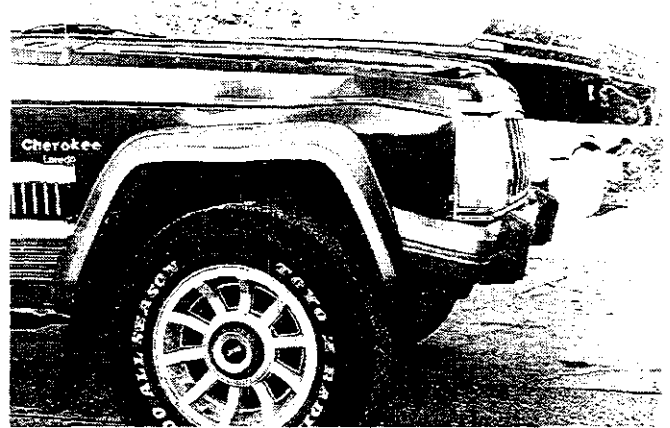


Figure 17. Bumper and fender damage, test G3.

Table 3. Vehicle damage for Test Series A - G

Test	Striking Vehicle		Struck Vehicle		Collision Parameters					
	ΔV (km/h)	ΔV_{rep}	Damage	ΔV (km/h)	ΔV_{rep}	Damage	e_{meas}	e_{rep}	e_{rep} (R2)	Delta KE (Joules)
A1	2.9	n/a	No damage or artifacts.	1.8	n/a	No damage or visible surface artifacts.	0.62	0.62	n/a	-260
A2	4.1	n/a	Left and right edges of bumper bar misaligned. Visible gap between fenders and top of bumper bar.	2.0	n/a	No damage. Visible black scuff transferred to van rear impact strip.	0.49	0.55	0.49	-734
A3	5.3	6.5	Increased gap at fenders and bumper bar. Bumper shell localized deformation about inboard mounting bolts (Figure 2).	2.8	4.8	Scuffs to rear bumper, shell set forward 3 mm at centre.	0.53	0.50	0.44	-1126
A4	6.7	8.2	Bumper mounting brackets shifted about mounting bolts (Figure 3).	4.2	6.1	Left bumper mounting plate deformed slightly forward (Figure 5).	0.63	0.44	0.40	-1359
A5	6.9	9.1	Flattening of bumper bar at centre, obvious gap at bumper/fenders, additional bracket shift.	4.9	6.8	Pronounced forward bend of the bumper bar. Both brackets deformed about the frame rails.	0.71	0.41	0.37	-984
A6	9.4	11.0	Pronounced flattening of bumper shell.	5.6	8.2	Similar to A5, but slightly increased deformation (Figure 6).	0.60	0.33	0.31	-2965
A7	9.2	12.7	Bumper shell set rear 20 mm at centre. Gross misalignment of bumper edges relative to fenders (Figure 4).	7.0	9.4	Bumper set forward 19 mm at right end, 20 mm at centre, and 13 mm at left end.	0.50	0.26	0.27	-3094

Test	Striking Vehicle			Struck Vehicle			Collision Parameters			
	ΔV (km/h)	ΔV_{rep}	Damage	ΔV (km/h)	ΔV_{rep}	Damage	e_{rears}	e_{rep}	e_{rep} (R2)	Delta KE (Joules)
B1	4.3	n/a	No damage.	2.4	n/a	15 mm of crush at 23 cm inboard of the vehicle's left edge, 25 mm crush at 31 cm inboard of the vehicle's left edge, and 20 mm crush at 43 cm inboard of the left edge (Figure 7).	0.35	0.35	n/a	-812
B2	5.2	n/a	No damage.	3.1	6.5	The crush at the three above referenced locations increased to 27 mm, 37 mm, and 25 mm respectively (Figure 8).	0.37	0.33	n/a	-1111
C1	2.2	n/a	No damage.	1.7	n/a	No damage.	0.50	0.50	n/a	-423
C2	4.7	n/a	No damage	3.8	n/a	Bumper set down 3 mm at the left edge, 5 mm at the left mounting bracket, and 1 mm at the right edge.	0.63	0.41	0.63	-1579
C3	4.7	6.5	No damage	5.3	11.0	No additional damage visible.	0.59	0.35	0.49	-1777
C4	5.0	7.4	Front bumper exhibited a slight rearward bow. It was set rearward 8 mm at the vehicle centre.	7.3	12.5	Bumper bar set down 3 mm at left edge, 10 mm at left mount, 1 mm at right edge, and up 5 mm at right mount.	0.40	0.29	0.35	-2729
C5	5.3	7.7	Visible flattening of bumper at the vehicle centre (Figure 9). Paint had transferred to the bumper bar from the Mazda's rear bumper. The left edge of the bumper bar was slightly misaligned with its adjacent fender.	9.0	13.1	Rear bumper set down 5 mm at the left edge, and 11 mm at the left bumper mount (Figure 10). Damage was considered obvious and visible.	0.42	0.23	0.23	-2696

Test	Striking Vehicle			Struck Vehicle			Collision Parameters			
	ΔV (km/h)	ΔV_{rep}	Damage	ΔV (km/h)	ΔV_{rep}	Damage	e_{meas}	e_{rep}	e_{rep} (R2)	Delta KE (Joules)
D1	3.8	n/a	No damage.	2.2	n/a	No damage.	0.58	0.58	n/a	-909
D2	4.6	n/a	The bumper bar was bent at the two locations where it came into direct contact with the Jeep's rear bumper guards. Visible deformation of the bumper bar was localized within a radius of about 2½ cm about the bumper mounting bolts (Figure 11) and the bumper bar had deflected rearward into contact with the centre rad support bar.	6.3	n/a	Bumper bar collapsed at locations about both rear bumper guards and about both mounting brackets (Figure 13).	0.36	0.47	0.36	-1963
D3	5.8	6.9	Bumper bar bent at the vehicle centre. Increased deformation of the bumper bar at the location where the bumper contacted the struck vehicle's bumper guards. At the conclusion of this test series the Dodge van's front bumper was set rearward 5 mm at its right edge, slightly greater than 8 mm at the vehicle centre, and set forward 4 mm at the left edge (Figure 12).	8.2	9.5	Bumper bar set forward into contact with the rear gate. Both bumper mounting brackets had collapsed. The bumper was set forward 40 mm at the left bumper guard, 40 mm at the vehicle centre, and 44 mm at the right bumper guard.	0.37	0.37	0.31	-297
E1	7.0	n/a	The front panel exhibited a large dent spanning the width between the front head lamps.	Barrier			0.52	n/a	n/a	-907
E2	11.0	n/a	The bumper bar was set rearward 27 mm at the right, 28 mm at the vehicle centre, and 25 mm at the left (Figure 14).	Barrier			0.22	n/a	n/a	-4040

Test	Striking Vehicle			Struck Vehicle			Collision Parameters			
	ΔV (km/h)	ΔV_{rep}	Damage	ΔV (km/h)	ΔV_{rep}	Damage	e_{meas}	e_{rep}	e_{rep} (R2)	Delta KE (Joules)
F1	4.3	n/a	Dent present in the plastic impact strip.	5.5	n/a	Minor shift (about 2 mm of displacement) of the right mounting bracket at the frame rail.	0.58	0.58	n/a	-1322
F2	6.4	n/a	Bumper set rearward 5 mm at the right, 5 mm at the centre, and 10 mm at the left. The gap between the front panel and the top edge of the bumper was visibly greater than the gap at the right.	7.7	11.0	The left mounting bracket buckled and the right mounting bracket rotated down. The gap between the end panel and bumper bar was increased at the left, and was visibly greater than the gap at the right (Figure 15). The bumper bar developed a clockwise twist that was readily visible when viewed edge on.	0.50	0.40	n/a	-3561
F3	6.5	n/a	Scratches and paint transfer. No significant increase in the rearward displacement of the van's front bumper.	8.2	13.2	The bumper bar underwent gross downward displacement (Figure 16). Both mounting brackets buckled, and the bolts used to attach the right bracket to the chassis had pulled through the frame rail.	0.31	0.24	n/a	-5205

Test	Striking Vehicle		Struck Vehicle		Collision Parameters				
	ΔV (km/h)	ΔV_{rep}	ΔV (km/h)	ΔV_{rep}	Damage	e_{meas}	e_{rep}	e_{rep} (R2)	Delta KE (Joules)
G1	4.4	n/a	4.1	n/a	n/a	0.35	0.35	n/a	-1155
G2	5.7	7.0	5.3	n/a	n/a	0.38	0.32	n/a	-1841
G3	8.5	10.7	7.9	n/a	n/a	0.31	0.28	n/a	-4606

APPENDIX B

Calculating e_{rep} and ΔV_{rep}

The initial impact of series A had a coefficient of restitution of 0.62. This value is the ordinate of point R of the graph. The energy absorbed in test A1 was approximated as the change in kinetic energy of the system (the two vehicles); measured to be 260 J. For convenience the horizontal axis of the graph depicting e_{rep} versus $\sqrt{E_{absorbed}}$ can be normalized. The absorbed energy ($E_{13,0.25}$) for the two vehicles of test Series A is calculated by Equation 3 to be 11310 joules. Therefore, the abscissa of point R on the graph is determined to be:

$$\frac{\sqrt{\sum E}}{E_{(13,0.25)}} = \frac{\sqrt{260}}{11310} = 0.15 \quad (B1)$$

Location S has an assumed value for e of 0.25. The normalization procedure sets the abscissa of point S equal to unity.

The graph has the form:

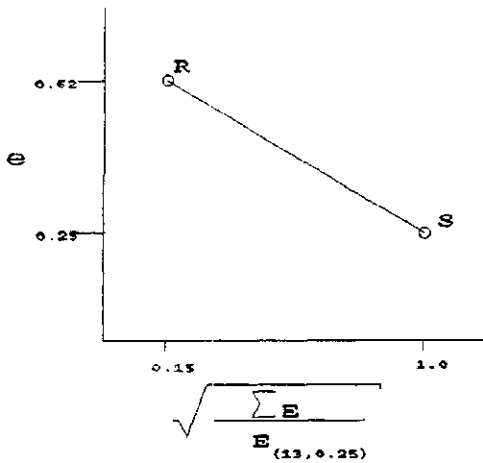


Figure 18

A general equation for e, application to test series A, is readily obtained:

$$e_A = 0.69 - 0.44 \sqrt{\frac{\sum E}{E_{(13,0.25)}}} \quad (B2)$$

ΔV_{rep} for each impact of a test series, following the initial collision, is calculated by first determining e_{rep} using Equation A1. This value is then substituted into Equation 2 to determine ΔV_{rep} .

For example, ΔV_{rep} corresponding to impact A6 is calculated as follows:

and:

$$e_{rep} = 0.69 - 0.44 \sqrt{\frac{7428}{11310}} \quad (B3)$$

$$e_{rep} = 0.33$$

$$\Delta V_{rep} = K_A \frac{\sqrt{\sum E (1 + e)^2}}{(1 - e^2)}$$

$$\Delta V_{rep} = 0.0263 \sqrt{\frac{7428 (1 + 0.33)^2}{(1 - 0.33^2)}}$$

$$= 3.2 \text{ m/s} \quad (11.5 \text{ km/h})$$

APPENDIX C

Table 4: Volunteer exposure summary

Source	Number of Human Occupant Impacts
Bailey et al ¹	26 (3 females)
Siegmund et al ²	37 (7 females)
McConnell et al ⁸	10
West et al ⁹	56
Szabo ¹⁰	7 (4 females)
Rosenbluth ¹¹	4 (1 female)
Severy ¹²	2
Siegmund ¹³	8
BME Testing	33
McConnell et al ¹⁸	18
Ono and Kanno ¹⁹	63*
Matsushita et al ²⁰	18 (3 females)
Geigl et al ²¹	37 (2 females)
SATAI 1995 ²²	11 (1 female)
TEES 1996 ²³	4
STAPP 1996 ²⁴	10 (2 females)
BRT 1996A ²⁵	5
BRT 1996B ²⁶	15 (15 females)
TOTAL	364 (38 females)

* The total number of tests was not explicitly stated, but there appear to have been a total of 63 impacts.

Collision severity ranges from 1½ to 16½ km/h ΔV.

Injuries/Symptoms

No symptoms of any kind were reported from 298 tests. Some transient symptoms were reported after 88 of the tests, usually after the subject had experienced multiple exposures. The symptoms were typically headaches and neck discomfort which resolved spontaneously, usually within hours. One subject who was leaning forward at impact reported a slight ache in the lumbar region.

Most Severe:

Minor neck discomfort lasting one week-BME test volunteer (GPN). Rear impacts of 5.2, 7.1, 9.5, and 12.8 km/h ΔV endured with inadequate head support due to poor design. Test subject also exposed to frontal impacts on same day at levels of ΔV = 7.8, 9.8, 12.4, and 14.0 km/h.

Next Most Severe:

Mild neck discomfort lasting three to four days after three impact exposures, two with head turned, over a two day period.

Table 5. Low Speed Rear Impact Test Summary - Human Test Subjects

Vehicle	Test Subject Age	Test Subject Sex	Impact Severity	Symptoms	Source	Notes
1981 & 1982 Ford Escorts	27	F	ΔV approx. 8 km/h	transient headache, neck stiffness (1 day)	ref 10 Szabo	72 cm high seat back
	48	M		transient headache		168 cm subject
	58	F		" "		183 cm subject
	28	M		none		165 cm subject
	58	F		transient headache		191 cm subject
	27	F		" "		165 cm subject
	31	M		" "		168 cm subject
Bumper cars	25	M	$\Delta V = 6.9, 7.2, 7.7, 7.6, 7.6$ km/h	none	ref 13 Siegmund	no head support
	32	M	$\Delta V = 6.4, 5.8, 7.0$ km/h	" "		180 cm subject
1977 Chevrolet Caprice	?	M	$\Delta V = 3.7, 3.8, 4.4, 6.5, 7.0, 8.8$ km/h	Subject dizzy for approx. 15 mins following 6.5 km/h impact	ref 2 Siegmund	no information regarding stature of subjects or heights of headrests
1980 Toyota Corolla	?	M	$\Delta V = 1.7, 2.3, 2.9, 2.9, 3.0, 3.0, 3.2, 3.3, 3.3, 3.3, 3.6, 4.2, 4.2$ km/h	none		
1980 Toyota Corolla	?	F	$\Delta V = 2.3, 2.9, 2.9, 3.0, 3.1, 3.1, 3.2$ km/h	none		
1986 Chevrolet Cavalier	?	M	$\Delta V = 3.5, 3.7, 3.8, 3.8, 4.1, 4.2, 4.3$ km/h	none		
1992 Nissan p/u	?	M	$\Delta V = 2.3, 2.7, 3.6, 4.8, 5.2$ km/h	none		
1984 Ford Club Wagon Van	45-56	M	$\Delta V = 3.5$ km/h	none	ref 8 McConnell	no headrest
"	"	"	$\Delta V = 6.5$ km/h	minor neck pain lasting 2 hours		"

Vehicle	Test Subject Age	Test Subject Sex	Impact Severity	Symptoms	Source	Notes
1984 GMC 1500 p/u	"	"	$\Delta V \approx 3.0$ km/h	none		"
"	"	"	$\Delta V \approx 6.7$ km/h	none		"
1980 Dodge 600 Convertible	"	"	$\Delta V \approx$ not measured	mild neck discomfort lasting 3 days after two tests		headrest raised
"	"	"	$\Delta V \approx 8.1$ km/h			"
1984 Buick Regal Coupe	"	"	$\Delta V \approx 7.8$ km/h			headrest raised
1984 Ford Club Wagon Van	"	"	$\Delta V \approx 6.6$ km/h	neck ache of 4 to 5 hours after three tests		no headrest
1984 Buick Regal Coupe	"	"	$\Delta V \approx 3.9$ km/h			headrest raised
1984 GMC 1500 p/u	"	"	$\Delta V \approx 7.0$ km/h	none		no headrest
1979 Plymouth Horizon	38	M	$\Delta V \approx 1.7, 2.7, 3.0, 4.4, 5.2, 5.7, 6.8, 6.8, 7.5, 8.2, 9.2, 10.9$ km/h	none	rel 9 West	81 cm headrest 183 cm subject
1977 Saab 99GL	28	M	$\Delta V \approx 4.4, 7.7, 8.1, 10.9, 13.4, 12.9, 15.5$ km/h	none		81 cm headrest 169 cm subject
1975 Pontiac Ventura	30/42	M	EBS $\approx 3.8, 5.0, 5.3, 6.0, 6.4, 7.8, 8.2, 9.0, 9.5, 10.0, 11.3$ km/h	minor neck discomfort lasting one to two days		80 cm headrest 183 cm RF occupant 178 cm LF occupant
1981 Ford Granada	30	M	$\Delta V \approx 2.9, 5.8, 7.1, 7.5, 9.1, 10.0, 10.0, 12.1, 15.3, 16.5$ km/h	none		71 cm headrest except for 15.3 and 16.5 km/h impact speeds where headrest was raised to 80 cm
1984 Volvo 760	43	M	$\Delta V \approx 5.4, 9.8, 11.1, 14.0, 16.2$ km/h	none		169 cm subject 78 cm headrest 183 cm subject
1985 Dodge Aries	36	M	EBS $\approx 1.7, 1.5, 2.3, 1.9, 1.9, 2.7, 3.6$ km/h	none	BME demo	74 cm headrest 178 cm subject
1978 Toyota Celica	33	M	$\Delta V \approx 5.2, 7.1, 9.5, 12.8$ km/h	minor neck discomfort lasting less than 1 week	BME demo	80 cm headrest, too low. 185 cm subject
1976 Ford Granada	31	M	EBS $\approx 6.5, 5.7, 4.6, 4.4, 3.4$ km/h	none	BME demo	71 cm headrest 183 cm subject

Vehicle	Test Subject Age	Test Subject Sex	Impact Severity	Symptoms	Source	Notes
1979 Chevrolet Chevette	36	M	EBS = 3.5, 1.9, 2.7, 4.1, 3.8, 4.1, 3.4 km/h	none	BME demo	72 cm headrest 178 cm subject
1977 Toyota Corona	34	M	$\Delta V = 5.2, 6.2, 6.5, 9.0$ km/h	none	BME demo	183 cm subject
1980 Ford Mustang	46	M	$\Delta V = 1.8, 2.3, 3.6, 6.9, 6.7, 7.8$ km/h	none	BME demo	183 cm subject foot on brake at impact, vehicle displaced 1.1 m for $\Delta V = 3.6$ km/h
1974 Plymouth	?	M	$\Delta V = 6.6, 8.3$ km/h	none	ref 12 Severy	no headrest
1980 VW Rabbit	63	M	$\Delta V = 3.3, 7.8, 5.7$ km/h	none	ref 11 Rosenbluth	
1980 VW Rabbit	55	F	$\Delta V = 6.2$ km/h	none		
1976 VW Rabbit	not known	M	$\Delta V = 5.3, 5.8, 5.9, 6.4, 6.8, 7.6, 8.3, 8.6, 8.8$ km/h	none, except pain at back of head from contact with headrest after 8.8 km/h impact	ref 1 Bailey	
1984 Toyota Tercel	"	M	$\Delta V = 6.3, 7.9$ km/h	headache after 7.9 km/h		
1984 Toyota Tercel	"	F	$\Delta V = 3.1, 4.4, 5.8$ km/h	headache after 5.8 km/h		
1987 VW GTI	"	M	$\Delta V = 3.3$ km/h	none		
Honda Accord	"	M	$\Delta V = 4.0, 5.5, 5.5, 5.5, 6.2, 6.9$ km/h	none		
1991 Nissan P/U	"	M	$\Delta V = 2.1, 2.6, 3.5, 4.6, 5.0$ km/h	none		
Impact Sled	22-43	M	$\Delta V = 4.0$ to 8.0 km/h	none reported	ref 19 Ono	tests conducted with and without headrests, occupants both tensed and relaxed
Impact Sled	22-61 24-57	M F	$\Delta V \approx 2.7$ to 5.0 km/h $\Delta V \approx 2.5$ to 4.2 km/h	mild neck discomfort reported by 4 of 15 male subjects, resolved without treatment in 2 to 4 days. Mild low back discomfort reported by one forward leaning subject. No discomfort reported by female subjects.	ref 20 Matsushita	tests conducted with subjects relaxed or tensed, facing forward or rotated, upright or leaning forward

Vehicle	Test Subject Age	Test Subject Sex	Impact Severity	Symptoms	Source	Notes
1980 Dodge 600 1984 Buick Regal	32-59	M	$\Delta V = 5.8, 7.7, 7.7, 8.0, 8.0, 8.0, 8.0, 8.2, 8.7, 8.7, 8.9, 8.9, 9.2, 9.2, 10.0, 10.0, 10.3, 10.9, 10.9$ km/h	mild headaches and neck pain lasting up to 4 days	ref 18 McConnell	subjects 173 to 188 cm, 76 to 118 kg tests conducted with subjects facing forward or head rotated
Impact Sled	20-60	M F	$\Delta V = 6$ to 12.0 km/h	none	ref 21 Geigl et al	initial head rotation in sagittal plane $\pm 15^\circ$, head restraint gaps 0 to 8 cm
91 Dodge Caravan 88 Chev Caprice 87 Chev Camaro 86 Buick Century 86 Plymouth Conquest	38-55 24	M F	$\Delta V = 3.4$ to 9.1 km/h $\Delta V = 7.8$ km/h	none none	ref 22 SATAI	
84 Audi 4000 S	36	M	$\Delta V = 3.9$ to 8.6 km/h	none	ref 23 TEES	brakes on for 7.2 km/h impact, subject braced for 8.6 km/h impact
76 Volvo 242DL	25-54 28	M F	$\Delta V = 7.5$ to 10.0 km/h $\Delta V = 9.6$ to 10.0 km/h	none recorded	ref 24 STAPP	each subject experienced 2 impacts, second impact with modified head restraint
Honda Accord LX	28	M	$\Delta V = 1.3$ to 5.5 km/h	none	ref 25 BRT	
Dodge Shadow	28	F	$\Delta V = 0.6$ to 8.8 km/h	posterior neck stiffness on day following 15 impacts	ref 26 BRT	subject aware of impending impact and braced for 3.9 and 7.6 km/h impacts, full braking for 0.6, 1.5, 3.6, 5.9, and 6.7 km/h impacts, normal braking for 4.9 and 8.6 km/h impacts, no braking for 1.0, 3.0, 5.1, 5.4, 7.2, and 8.8 km/h impacts.