LOW SPEED REAR-END COLLISION TESTING USING HUMAN SUBJECTS

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ABSTRACT

Human volunteer subjects were exposed to the forces of low speed rear impacts. The subjects were seated in passenger vehicles and were exposed to impacts up to, and exceeding, the current Canadian bumper standard of an 8 km/h (5 mph) barrier impact. The test data included the vehicle velocities and accelerations, occupant accelerations, vehicle damage assessment, and video recording of vehicle and occupant response to the collision forces.

The tests revealed that human subjects can be used to assess occupant dynamics in low speed impacts without risk of injury to the subjects. The levels of head acceleration and neck extension were found to be well below published thresholds where cervical soft tissue injury would be expected for healthy individuals.

KEYWORDS:

Whiplash, rear-end impacts, cervical strain

INTRODUCTION

Low speed rear impacts which result in little or no damage to the struck vehicle comprise a significant percentage of the total number of motor vehicle accidents, particularly in urban areas. While the damage resulting from these impacts is minimal or non-existent, claims of neck or back injury often result.

In the past seven years, Baker Engineering Ltd. has investigated thousands of collisions of this type. In order to quantify the forces and displacements experienced by the occupants of the struck vehicle, a number of staged collision tests have been performed. The low speeds involved in these impacts enabled us to use human volunteers to assess the occupant dynamics without risk of injury, thereby overcoming the drawbacks of using anthropometric dummies or cadavers. This paper summarizes the results of some of the tests we have conducted.

BACKGROUND

In Canada, Motor Vehicle Safety Regulation 215[1] requires that vehicles be equipped with bumpers capable of absorbing the forces occurring in an 8 km/h (5 mph) fixed barrier impact without sustaining damage to the lighting, fuel or exhaust systems and also that the hood, trunk, and doors operate properly following these tests. The energy absorption capabilities of such bumpers are commonly achieved through the use of either rigid bumper beams which are attached to the vehicle structure via hydraulic isolators, or, rigidly mounted bumpers which are overlaid with energy absorbing foam cushions. It is these energy absorbing bumper systems which enable vehicles to undergo a substantial impact without sustaining any residual deformation.

The current medical literature concerning the "whiplash" phenomenon describes that this type of injury occurs as a result of the hyper-extension of the cervical portion of the spine. Mertz and Patrick[2] have reported that cervical extension should be limited to 60 degrees in order to prevent such injury. However, for levels of cervical extension approaching the physiological limit, cervical torque may be a better measure of injury-causing potential. The non-injury level for a 50th percentile male has been reported[3] to occur at a torque, measured about the occipital condyles, of 47 N-m (35 ft-lb) while the torque level at which ligamentous injury occurred was 57 N-m (42 ft-lb).

One of the earliest investigations of the whiplash phenomenon was reported by Severy et al[4]. They conducted rear impact tests in which human volunteers were seated in the struck vehicle. The vehicles involved were not equipped with energy absorbing bumpers and no head restraints were available. Little other published research has been conducted in which the response of humans, rather than dummies or cadavers[5], has been documented. The absence of energy absorbing bumpers or seat backs of adequate height to provide head support limits the applicability of the Severy results to motor vehicles of current design.

The rear impact studies which our company has conducted have been designed to simulate specific real world impacts. The results of several of these tests are described in the following paragraphs.

TEST METHOD

The test results reported in this publication were organized to duplicate specific accident scenarios. The vehicles were selected to duplicate the scenarios under consideration, and as such, there was no intent to assess any particular vehicle performance or relative performance. The human test subjects were all males and ranged in age from 25 years to 43 years. The subjects were of normal physical condition for their ages and none had any pre-existing spinal deficiencies.

Each subject wore a helmet which was firmly attached to the head. On the helmet, three accelerometers were attached to record accelerations in the X, Y, and Z direction. Accelerometer capabilities were + 20.00 g with a sensitivity of 0.01 g.

A single triaxial accelerometer was mounted onto the test vehicle. The ability to adequately secure this accelerometer to the vehicle proved to be a significant consideration to avoid vibrational interference. The impact speed of the vehicle was recorded using a pneumatic treadle system.

Data from the accelerometer was acquired at 500 samples per second by a Hewlett Packard computer, the acceleration curves were displayed through an HP Colour Jet printer, and the acceleration maximums were tabulated through the software. Signal conditioning and filtering were accomplished in accordance with SAE guidelines[6]. The acquisition package is proprietary and was prepared by Weir-Jones Engineering Consultants Ltd. Video records were made of the occupant and vehicle dynamics for later study.

TEST RESULTS

Series A

Our earliest test was intended to simulate a simple rear-end collision in which the struck vehicle was stationary. The test vehicle was struck in the rear by a tow truck.

Striking vehicle	- Tow truck with steel push bumper		
Struck vehicle	- 1979 Plymouth Horizon, 5 door		
	- Bumper design	- isolator	
		- stroke length 64 mm (2.5 inches)	
	- Head support	- integral	
		- 81 cm (32 inches) high	
	- Occupant stature	- 183 cm (72 inches)	

Striking Speed (km/h)	Vehicle Peak Acceleration (g)	Occupant Peak Head Acceleration x* (g)	*y* (g)	*z** (g)	Vehicle Displacement (cm)	Isolator Compression Left (mm)	Isolator Compression Right (mm)
1.8	0.9	*	*	*	13	13	13
2.9	0.9	1.5	1.1	0.5	13	22	29
3.2	1.0	1.2	1.7	0.5	14	22	29
4.7	1.5	2.3	1.8	0.5	96	48	44
5.5	1.5	1.9	1.0	1.0	31	48	44
6.1	1.7	2.3	1.3	1.8	46	48	44
7.2	1.9	4.5	2.0	1.8	*	full	full
7.2	2.4	3.8	1.8	1.8	*	full	full
8.0	3.0	4.8	3.0	2.8	*	full	full
8.7	2.8	7.5	3.3	2.9	124	full	full
9.8	2.9	7.0	3.4	2.8	104	full	full
11.6	3.1	8.3	3.4	2.8	152	full	full

* not measured

** orientation x-longitudinal, y-lateral, z-vertical

TABLE I - Results of the rear impact tests involving a tow truck and a Plymouth Horizon.

These tests were conducted with the subject seated in a normal driving properly belted posture. The rearview mirror was removed so that the subject would not be aware when the impact would occur. The transmission was in gear and the subject's foot was on the brake.

The rear bumper of the Horizon consisted of a steel channel which was attached to the vehicle structure via a pair of energy absorbing isolators. The exposed length of the pistons of these isolators was 95 mm (3.7 inches) and the maximum stroke length was 64 mm (2.5 inches).

The results of these tests are shown in Table I.

For the first three impacts, the displacement of the test subject's head was insufficient to cause his head to contact the head support. Significant rebound of the subject's head from the head support did not occur until the striking speed was 8.7 km/h (5.4 mph) or greater.

The high vehicle displacement which occurred as a result of the 4.7 km/h (2.9 mph) impact was due to the test subject's foot slipping off the brake pedal. The final impact to the Horizon, at a striking speed of 11.6 km/h (7.2 mph), resulted in the breakage of one of its taillight lenses.

Series B
This test was intended to simulate a chain reaction rear-end collision in which the two front vehicles were stopped and the impact to the middle vehicle caused it be displaced forward into contact with the front vehicle.

Striking vehicle	- 1975 Pontiac Ventura, 4 door, automatic transmission		
	- Bumper design	- isolator	
Struck vehicle	- 1977 Saab 99GL, 2 door, standard transmission		
	- Bumper design	- foam core	
	- Head support	- integral	
		- 81 cm (32 inches) high	
	- Occupant stature	- 170 cm (67 inches)	
Front vehicle	- 1975 Plymouth Valiant, 4 door, automatic transmission		
	- Bumper design	- isolator	

The tests were conducted with the subject in the Saab seated in a normal driving posture with his foot on the brake. The rearview mirrors were aligned so as not to provide the subject with any forewarning of the impact.

The front bumper of the Ventura consisted of a steel channel which was attached to the vehicle structure via a pair of energy absorbing isolators. The maximum stroke length of these isolators was 34 mm (1.3 inches). The front and rear bumpers of the Saab consisted of rigidly mounted beams which were overlaid with foam cushions and rubber outer covers. The rear bumper of the Valiant consisted of a rigid steel channel which was mounted on energy absorbing isolators. The Valiant was positioned 1.5 metres (4.9 feet) ahead of the Saab.

The results of these tests are detailed in Table II.

Striking Speed	Vehicle Peak Acceleration	Occupant Peak Head Acceleration			Vehicle Displacement	
	x	x*	*y*	*z**	Saab	Valiant
(km/h)	(g)	(g)	(g)	(g)	(m)	(m)
5.6	2.4	6.1	3.2	6.7	1.15	0.00[1]
9.7	3.9	14.8	5.4	5.6	1.52	0.00
10.2	5.0	13.8	8.8	5.2	1.50	0.00
13.8	10.4	16.4	7.6	8.3	1.48	0.04
17.0[2]	5.8	8.5	3.3	3.4	1.54	0.06
16.3[3]	7.8	13.2	8.3	15.7	1.68	0.28
19.6[3]	7.7	14.1	8.2	13.9	1.75	0.33

[1]No contact between the front of the Saab and the rear of the Valiant occurred.
[2]The front bumper of the Ventura underrode the rear bumper of the Saab, resulting in lower than expected accelerations.
[3]Occupant of Saab restrained by seat belt. Rear quarter panels of Saab buckled.

TABLE II - Results of the rear impact tests intended to simulate a three vehicle rear-end collision.

The integral head support in the Saab was canted forward relative to the seat back. Contact between the test subject's head and the head support occurred at even the lowest impact speed. This contact effectively prevented the subject from experiencing any cervical extension and no pain or discomfort was reported by the subject even at the highest speeds involved.

The high levels of head acceleration recorded in these tests reflect the contact between the subject's head and the head support. This acceleration is not due to the actions of the soft tissues of the neck and thus does not reflect the potential for these impacts to result in a cervical strain injury. The maximum levels of head acceleration were recorded before impact to the front vehicle occurred.

Series C
These tests were conducted using a moving vehicle which was driven backwards into a rigid barrier.

Test vehicle	- 1975 Pontiac Ventura, 4 door	
	- Bumper design	- isolator
		- stroke length 42 mm (1.7 inches)
	- Head support	- adjustable
		- 71 cm (28 inches) high retracted
		- 80 cm (31.5 inches) high extended
	- Occupant stature	- 183 cm (72 inches)

The rear bumper of the Ventura consisted of a steel channel which was attached to the vehicle structure via a pair of energy absorbing isolators. The maximum stroke length of these isolators was 42 mm (1.7 inches).

The subject was seated in the right front seat in a relaxed posture and was facing forward. The head support in this vehicle (used in its fully raised position) did not provide adequate head support for the test subject.

The results of these tests are summarized in Tables III and IV.

Impact Speed	Vehicle Peak Acceleration	Isolator Compression	
(km/h)	x (g)	Left (mm)	Right (mm)
3.8	4.2	25	25
5.0	5.8	*	*
5.3	7.3	40	40
6.0	7.5	25	32
6.4	11.1	35	42 (full)
7.8	11.6	42 (full)	full
8.2	11.8	full	full
9.0	12.0	full	full
9.5	14.8	full	full
10.0	13.4	full	full
11.3	17.1	full	full

* not recorded

TABLE III - Summary of fixed barrier impact tests involving 1975 Pontiac Ventura - Vehicle Data.

Impact Speed (km/h)	Occupant Peak Head Acceleration x (g)	y (g)	z (g)	Notes	Head Contact to Head Support	Rebound
3.8	2.3	0.6	1.6	Subject relaxed	No	No
5.0	2.9	0.7	1.3	Subject relaxed	No	No
5.3	2.3	0.7	2.5	Subject braced	No	No
6.0	4.3	0.9	2.6	Subject relaxed	Yes	No
6.4	5.4	0.8	3.9	Subject leaning forward	No	No
7.8	7.5	2.8	7.9	Subject relaxed	Yes	Yes
8.2	7.4	2.4	6.1	Subject relaxed	Yes	Yes
9.0	6.5	4.4	7.8	Subject relaxed	Yes	Yes
9.5	12.0	11.2	9.0	Subject relaxed	Yes	Yes
10.0	13.4	12.5	10.1	Subject relaxed	Yes	Yes
11.3	17.9	19.3	12.4	Subject relaxed	Yes	Yes

TABLE IV - Summary of fixed barrier impact tests involving 1975 Pontiac Ventura - Occupant Data.

The rear bumper of the Ventura sustained residual damage for impacts in excess of 7.8 km/h (4.8 mph). Significant elastic flex of the rear quarter panels and trunk lid of the Ventura occurred for impacts in excess of 9.0 km/h (5.6 mph).

Following completion of these tests, both the driver, who braced himself, and the right front occupant, who was not braced, reported minor neck pains lasting one to two days. The videotape records of these tests revealed that for the highest impact speeds, both occupants experienced significant cervical extension as a result of the collision forces. It also revealed that the head excursions of both the passenger and the driver were equal. That is, the braced driver was unable to resist the collision forces.

Series D

In this test series vehicles were rolled backwards into a concrete barrier with and without test subjects. Sequential rear impacts were performed until visible damage was incurred to the test vehicles.

Test Vehicles

Vehicle 1	- 1981 Ford Granada, 4 door sedan, automatic	
	- Bumper design	- isolator
		- stroke length 67 mm (2.6 inches)
	- Head support	- adjustable
		- retracted - 71 cm (28 inches)
		- extended - 80 cm (31.5 inches)
	- Occupant stature	-170 cm (67 inches)
Vehicle 2	- 1984 Volvo 760, 4 door sedan	
	- Bumper design	- isolator
		- isolator piston covered with shroud
	- Head support	- integral
		- 78 cm high (30.5 inches)
	- Occupant stature	- 183 cm (72 inches)

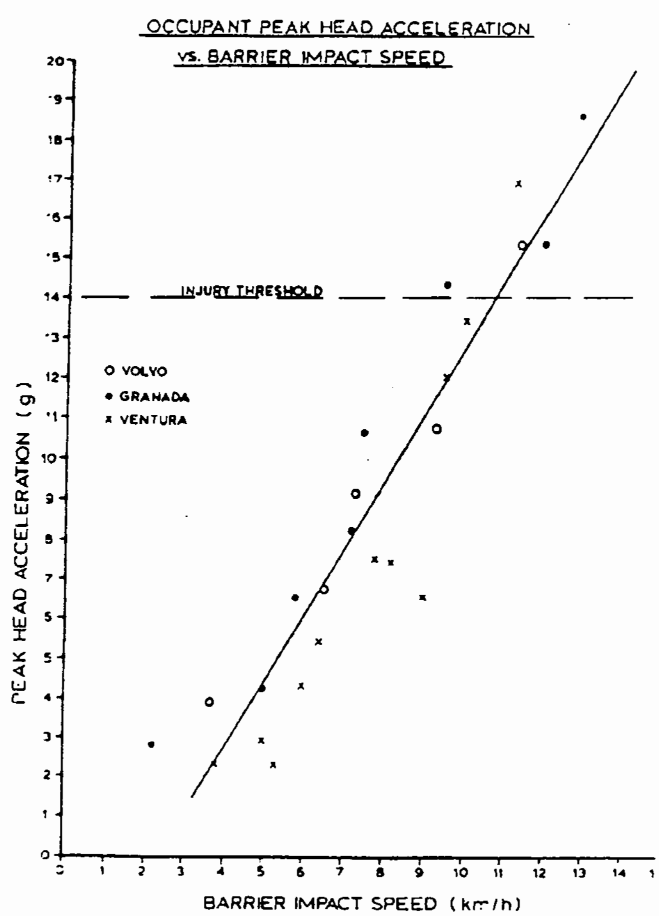

Figure 1: Graph showing the peak head acceleration in the sagittal plan as a function of barrier impact speed.

The Granada tests were conducted with the head support retracted, up to impact speeds of 9.5 km/h (5.9 mph) into the barrier. At this point the subject requested that the head support be extended to full height before he would submit to higher impact magnitudes. At full extension, the head support provided good support for the head of the 170 cm (67 inch) tall subject.

The Granada did not exhibit any damage until the 15.4 km/h (9.6 mph) impact. After this impact, the left rear fender buckled, the bumper was shifted forward and the roof panel buckled at both B-pillars. Tables V and VI summarize the test results of the Granada impacts.

Test No.	Impact Speed	Isolator Compression		Vehicle Data	
		Left	Right	X-axis	Pulse Duration
	(km/h)	(mm)	(mm)	(g)	(ms)
1	2.2	2	2	2.1	125
2	4.2	15	0	Not recorded	Not recorded
3	5.0	13	1	2.8	172
4	5.8	15	9	3.9	107
5	7.2	28	5	3.9	128
6	6.9	33	0	3.5	160
7	7.5	32	19	5.1	114
8	9.5	47	40	5.7	113
9	12.0	57	49	5.9	110
10	12.9	54	44	6.5	115
11	15.4	57	57	19.1	198

TABLE V - Summary of fixed barrier impact tests with

1981 Ford Granada - Vehicle Data

Test No.	Impact Speed	Occupant Peak Head Acceleration		
	(km/h)	x (g)	y (g)	z (g)
		Head Support Retracted		
1	2.2	2.8	0.6	-1.8
2	4.2	Not Recorded		
3	5.0	4.2	-1.2	-3.1
4	5.8	6.5	-4.1	-4.3
5	7.2	8.2	-4.9	-6.3
6	6.9	3.5	5.3	-3.9
7	7.5	10.6	-5.3	-9.0
8	9.5	14.3	6.3	-11.8
		Head Support Extended		
9	12.0	15.3	-14.3	-18.4
10	12.9	18.6	-19.0	-18.0
11	15.4	No occupant		

TABLE VI - Summary of Fixed barrier impact tests with 1981 Ford Granada - Occupant Data

The onset of damage to the Volvo was observed after the 7.3 km/h (4.5 mph) impact, after which the rear bumper shroud became loose. After the 11.4 km/h (7.1 mph) impact, the roof panel was buckled at the right B-pillar.

The head support in the Volvo was excellent for the 183 cm (72 inch) tall subject. Rearward head excursions were limited to less than 20 degrees neck extension. At the highest impact speed, the head rebounded off the head support and travelled forward to approximately 40 degrees of neck flexion. The occupant's head then returned to the neutral position. Tables VII and VIII summarize the vehicle and occupant response to the Volvo test series.

Test No.	Impact Speed	Isolator Compression		Vehicle Data	
		Left	Right	X-axis	Pulse Duration
	(kmh)	(mm)	(mm)	(g)	(ms)
1	3.7	11	1	2.1	151
2	6.5	18	5	5.8	134
3	7.3	25	23	5.5	125
4	9.3	35	32	7.5	117
5	11.4	31	50	6.7	126

TABLE VII - Summary of fixed barrier impact test with 1984 Volvo - Vehicle Data

Test No.	Impact Speed (km/h)	Occupant Peak Head Acceleration x (g)	y (g)	z (g)
1	3.7	3.9	1.3	- 1.9
2	6.5	6.7	2.6	- 3.9
3	7.3	9.1	7.6	- 6.7
4	9.3	10.7	7.1	- 8.4
5	11.4	15.3	14.1	-13.0

TABLE VIII - Summary of fixed barrier impact tests with 1984 Volvo - Occupant DataDISCUSSION

When a vehicle is rear-ended, it is shunted forward by the collision forces. The torsos of the vehicle occupants are in integral contact with their seat backs. As the vehicle is accelerated, so too are the torsos of the occupants. When impact occurs, the heads of the vehicle occupants are initially unsupported. As the torso is accelerated, through contact with the seat back, the head lags behind. If the vehicle is not equipped with head supports, or seat backs of adequate height, the neck may bend rearward beyond the normal physiological limit. It is this rearward bending of the neck which the medical community has associated with the causation of whiplash injuries.

When significant cervical extension occurs (ie. near the physiological limit), the injury-causing potential may increase rapidly for only small increases in the degree of extension. In such cases, cervical torque has been proposed as a more accurate measure of injury potential. When the head is not accelerated due to contact to a head support, the cervical torque is proportional to the acceleration of the head. If, however, the back of the head contacts the head support, high levels of acceleration of the head can be tolerated without injury.

The tests which our company has conducted have attempted to duplicate the situation where the occupant of the struck vehicle has no forewarning of the impact and is facing forward. In these instances, the forces experienced by the vehicle occupants for impacts with an EBS of less than 5 km/h (3 mph) are generally not sufficient to cause the heads of the vehicle occupants to be displaced rearward far enough to contact the head support. The maximum recorded levels of head acceleration for impacts of this magnitude were less than 3 g. Since no head contact to the head support is expected as a result of impacts of this magnitude, the presence or absence of adequate head support is of no significance. The minor displacements which the occupants' heads experienced were well within the normal physiological range. The maximum recorded levels of head acceleration would have generated cervical torque levels below those which researchers have associated with the pain threshold.

A recent study by Allen et al[7] has revealed that sagittal plane head accelerations as high as 5.96 g were recorded when test subjects were instructed to "plop" into a chair. Levels of 4.53 g were recorded when the subjects hopped off a step. These levels are in excess of those which were measured for a 5 km/h impact.

For impacts with an EBS of between 5 and 8 km/h (3 and 5 mph), the forces experienced by the vehicle occupants were sufficient to cause their heads to be displaced rearward into contact with their head supports. No significant rebound from the head supports occurred. When adequate head support was not present, the maximum recorded levels of head acceleration were between 3 and 7.5 g. These levels of head acceleration were accompanied by significant rearward bending of the necks of the test subjects. The maximum level of cervical extension approached 60 degrees. Higher levels of head acceleration were recorded when good head support was available, however, rearward bending of the neck was limited to less than 20 degrees in these instances.

Neither the level of cervical bending nor the level of cervical torque measured in these tests reached the level at which injury to the vehicle occupant would be expected. Therefore, for an individual who does not have any predisposition to injury, a whiplash injury would not be expected for impacts of this magnitude.

For impacts with an EBS in excess of 8 km/h (5 mph), the levels of head acceleration measured for cases in which adequate head support was not available increased rapidly. However, when good head support was available, the degree of cervical extension was still limited to levels well below that which has been associated with injury. Therefore, with properly designed and utilized head restraints, impacts with an EBS in excess of 8 km/h (5 mph) can be tolerated without injury. Figure 1 has been prepared which shows the peak head accelerations from our tests plotted as a function of barrier impact speed. Superimposed upon this graph is the non-injury level established by Mertz and Patrick. The pain threshold was translated from torque into acceleration by assuming a head mass of 4.5 kg (10 lb) and a distance of 7.5 cm (3 inches) between the head centre of mass and the occipital condyles.

In assessing the potential for a specific incident to cause injury to a given individual, certain factors must be considered. These include the age, sex, stature, seated position, and prior physical condition of the subject individual.

Older individuals tend to have lower ranges of motion and lower muscular strength than younger individuals[8] and may therefore be more susceptible to injury. Studies have shown that females are more susceptible to whiplash injuries than males[9]. This is likely due to the lower relative strength of the musculature of the neck and also to the fact that females generally have longer necks than males. The range of motion which females can tolerate without injury is, however, generally greater than that for males[10].

The stature of the individual is important in that the effectiveness of the head support is dependent on its height relative to the seated height of the individual. A head support which provides adequate support for one individual may not be adequate for a taller individual.

Seated position is an important consideration. If an individual is seated with his head turned at the moment of impact, the range of motion which can be tolerated without injury may be reduced[11]. In addition, if the subject's torso is turned, the distance between the head and head support may be increased, thereby reducing the effectiveness of the head support in controlling the displacement of the head.

The significance of an individual's physical condition, whether due to prior injuries, degeneration of the spine, or other causes, is difficult to quantify. However, if such a condition does pre-date the incident, it must be considered. Ideally, this should be considered by a medical doctor who is aware of the magnitude of the collision forces and the degree of head support available to the individual, and, more importantly, one who is cognizant of the occupant dynamics which occur in rear impacts.

In our experiences, low back pain and injury to the temporal mandibular joint are often claimed as a result of minor low speed collisions. When seated normally within the vehicle seat, the thoracic and lumbar spines are fully supported by the seat back. Our testing has revealed that when exposed to a minor rear impact, the seat back bends in response to the collision forces but maintains full support of the lower spine.

A model has been proposed[12] to explain how TMJ injuries may result from an excessive opening of the mouth induced during a rear-end collision event. Review of the videotape records of the collision tests which we have conducted failed to demonstrate any opening of the jaw as a result of the impact forces. This is as expected as there are no forces present duirng the collision phase which would articulate the jaw, as suggested by the model.

Rebound, forward of a neutral position does not occur until collision magnitudes approach 8 km/h EBS and even at the highest level of testing we performed, significant relative movement between the thoracic and lumbar spine did not occur. If the current medical description (ie. that strain is the mechanism of low back injury) is valid, then our testing indicates that minor rear-end collisions have no potential to cause such injury. This suggests that either the medical community has improperly assessed the mechanism of such low back injury, or that such low back injury is not directly relatable to the collision. This implies that low back injury occurs as a consequence to cervical injury, which itself, may be attributable to the collision. However, our tests indicate that singular low back strain is not an expected consequence of low speed rear impacts.

SUMMARY

The magnitude of the forces and displacements to which the occupants of a rear-ended vehicle are exposed can be assessed based on the equivalent fixed barrier speed (EBS) of the impact. If the EBS is less than 5 km/h (3 mph), the forces and displacements experienced by the vehicle occupants will be within the range which can be encountered during daily life. Such disturbances will not generate the levels of cervical extension or cervical torque which researchers have associated

with injury causation.

For impacts with an EBS in excess of 5 km/h (3 mph), the vehicle occupants may be exposed to forces sufficient to cause their heads to be displaced rearward into contact with their head supports, if available. However, the levels of cervical extension and cervical torque to which these individuals are exposed will be below the levels which researchers have associated with injury causation. If proper head support is available, impacts with an EBS in excess of 8 km/h (5 mph) can be tolerated without injury. The maximum barrier impact speed involved in these tests was approximately 13 km/h (8 mph).

DEFINITIONS & NOTES

Cervical Extension	- Rearward bending of the neck relative to the neutral axis of the torso.
EBS	- The speed at which a vehicle would have to strike a rigid, immovable barrier to produce the same force-time history.
Helmet	- The helmet which was worn by the test subjects was a conventional hockey helmet onto which three accelerometers were attached. The helmet was used as a simple means of affixing the accelerometers to the head and was not utilized due to safety concerns.
Integral Head Support	- A head rest which is an integral part of the seat back and is not adjustable.
Occipital Condyles	- The point at which the skull is attached to the upper portion of the first cervical vertebra.
Physiological Limit/ Physiological Range	- The range through which a particular joint or structure can move without inducing strain to the surrounding tissues.
Sagittal Plane	- A vertical plane through the longitudinal axis of the skull dividing the head into left and right halves.
TMJ	- Temperomandibular joint. The junction between the temporal bone of the skull and the mandible.

REFERENCES

1. "Consolidation of the Motor Vehicle Safety Act and Motor Vehicle Safety Regulations", Transport Canada TP4360E, April 1989.

2. Mertz, H.J., and Patrick, L.M., "Strength and Response of the Human Neck", SAE Paper 710855.

3. Mertz, H.J. and Patrick, L.M., "Investigation of the Kinematics and Kinetics of Whiplash", SAE Paper 670919.

4. Severy, D.M., Mathewson, J.H., and Bechtol, C.O., M.D., "Controlled Automobile Rear-End Collisions, An Investigation of Related Engineering and Medical Phenomena", *Canadian Services Medical Journal*, Volume XI, November 1955, No. 10.

5. Romilly, D.P., Thompson, R.W., Navin, F.P.D., MacNabb, M.J., "Low Speed Rear Impacts and the Elastic Properties of Automobiles", published in *Proceedings: Twelfth International Conference of Experimental Safety Vehicles, May 29 - June 1*, Gothenberg, Sweden.

6. SAE Recommended practice J211, June 1980, "Instrumentation for Impact Tests", 1984 SAE Handbook, Volume 4, "On Highway Vehicles and Off Highway Machinery".

7. Allen, M.E., Motiuk, D.R., Flewin, K.R., Goring, R.D., Kobetitch, R., Broadhurst, A., "Acceleration Forces at the Head/Neck During Commonly Experienced Controlled Sudden Movements", SFU, submitted for publication in *Spine*.

8. Ferlic, D., "The Range of Motion of the Normal Cervical Spine", *Hopkins Hospital Bulletin*, Volume 110, 1962.

9. Kihlberg, J.K., "Flexion Torsion Neck Injury in Rear Impacts", Proceedings: The Tenth Annual Meeting of the AAAM, HSRI, Ann Arbor: University of Michigan, 1969.

10. Buck, C.A., Dameron, F.B., Dow, M.J., Skowlund, H.V., "Study of Normal Range of Motion in the Neck Utilizing a Bubble Goniometer", Archives of Physical Medicine and Rehabilitation, Volume 40 (September 1959).

11. Schneider, L.W., et. al., "Biomechanical properties of the Human Neck in Lateral Flexion." SAE Paper 751156.

12. Foreman, S.M., and Croft, A.C., "Whiplash Injuries - The Cervical Acceleration - Deceleration Syndrome", Chapter 10, Temperomandibular Joint Injuries.