VEHICLE SPEED DETERMINATION FROM FUZZY EVIDENCE IN A MULTIPLE PEDESTRIAN COLLISION

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Abstract

The authors were respectively prosecution and defence expert witnesses in relation to a multiple pedestrian impact double fatality vehicle crash that occurred on Edgeware Road, Christchurch, New Zealand, in 2007. The incident was unusual in the number of pedestrian impacts (28), the number of eye witnesses, and the preparation of a joint experts' report to the court. In the absence of measured pedestrian throw distances, the speed of the vehicle where the two fatal impacts occurred was estimated using a combination of approximate methods including assessment of vehicle damage, pedestrian injuries, and witnesses speed estimates (although the latter were not finally included in court evidence). The upper limit on possible vehicle impact speed was assessed by considering maximum vehicle acceleration from a known starting point.

1. INTRODUCTION

The authors were asked to provide an expert opinion on an incident on the night of 5th May 2007, involving a vehicle striking a number of people on Edgeware Road, Christchurch, in the vicinity of a private but well advertised party. A Honda Integra vehicle, **Figure 1**, had pulled out from its parked position on the left side of the road heading west. It accelerated hard, moving over to the right side of the road and drove through a crowd of people, substantially travelling in the wrong (eastbound) lane before subsequently turning right into Cranford Street and leaving the scene. Not all of the visible damage occurred from pedestrian contact as collisions with two other vehicles and a roadside pole occurred shortly after the vehicle left Edgeware Road. These subsequent collisions created some difficulty in assessing which damage could be attributed to pedestrian impacts.

Figure 1: Honda Integra Vehicle Involved in Multiple Pedestrian Collision Incident

Figure 2 shows Police Relmo plots of a number of witness recollections of the vehicle path along Edgeware Road. These illustrate the travel by the vehicle on the wrong side of the road. (The vehicle path is discussed further in Section 3.7).

Two people struck by the vehicle suffered fatal injuries. Ten more people suffered moderate to serious injuries. A number of other people also appear to have been struck by the vehicle but did not suffer injuries of note. The vehicle driver was charged with murder (x2) and subsequently convicted.

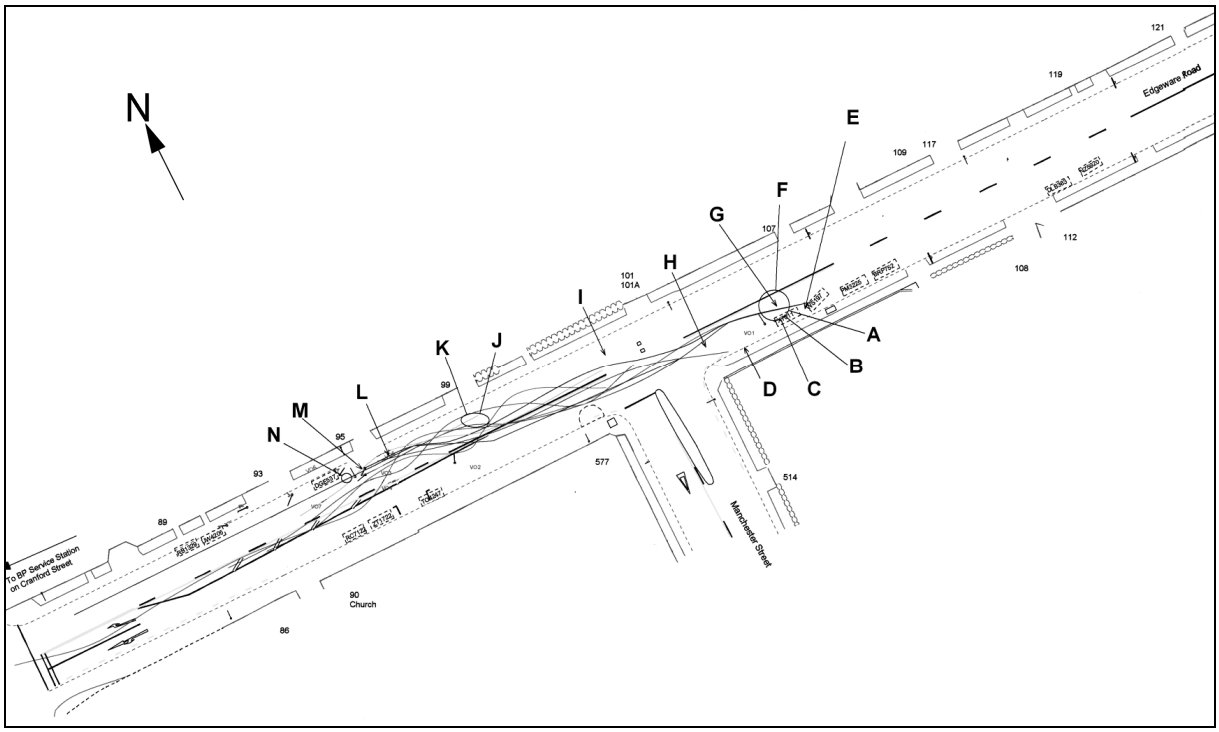

Figure 2: Path of Honda Vehicle from Witness Recollections. Some Witness and Victim Locations indicated by letters A to N

At the time of the incident, several hundred people who had gathered for the party were standing on the road, with the consequence that a large number of people witnessed the vehicle–pedestrian collisions. The majority of witnesses were in their mid-to-late teens and many were intoxicated to some extent. A number of factors may have influenced the judgement of witnesses to this event, including:

- Youthful inexperience
- Intoxication
- Being startled by their proximity to the vehicle path
- Spatial confusion caused by movement of surrounding people and the unexpected vehicle travel lane
- Confusion/disorientation after being struck by the vehicle.

Traditional methods [1] of vehicle-pedestrian collision analysis use pedestrian throw distance to estimate vehicle speed. Whilst the rest positions of the deceased were well documented, the impact locations along the road were impossible to determine with any certainty.

Other methods of analysis were therefore required. Depriester et al [2], of the Criminal Research Institute of the French National Gendarmerie, note that a number of methods of analysis should be used for vehicle-pedestrian collisions of an atypical nature. This was done for the analysis of this incident, and the results were compared. This paper outlines the approaches to analysis used and the process by which the authors' reached a concluded estimate of the vehicle speed at the point where the two fatal impacts occurred. Other aspects of the incident such as vehicle path, vehicle acceleration and headlight operation were also investigated.

2. OVERVIEW OF ANALYSES USED

2.1 Witness Statements and Estimates of Vehicle Speed

Witness statements were examined for comments relating to perceived vehicle speed, acceleration and steering, headlight operation, vehicle path and the orientation of the two deceased young women to the vehicle at the time of impact.

2.2 Throw Distance, Vehicle Damage, and Pedestrian Injuries

The vehicle-pedestrian impact speed could not be determined from pedestrian throw distances because of uncertainties around the point of impact on the two deceased, although a basic pedestrian trajectory analysis was conducted.

The injuries sustained by the pedestrians were analysed in regard to likely vehicle impact speed, which was also evaluated in relation to the headstrike location on the driver's side of the windscreen.

Computer models of the vehicle and a pedestrian were created. The pedestrian model was assigned the mass and height characteristics of one of the deceased women. Various scenarios were simulated, with varying vehicle impact speed, acceleration and pedestrian orientation with respect to vehicle. The simulation results were appraised based on headstrike location and simulated injury severity.

2.3 Vehicle Speed Versus Distance Analysis

A basic speed versus distance analysis was conducted for the vehicle as it travelled along Edgeware Road. Consistent vehicle speed ranges estimated by witnesses were evaluated against the distance travelled by the vehicle to determine a likely range of vehicle acceleration. Upper limits to this acceleration were established by conducting acceleration tests with an exemplar Honda Integra vehicle at Ruapuna Park Raceway, Christchurch. The influence of pedestrian impacts on vehicle acceleration was also appraised. The limiting speed range for successfully negotiating the turn onto Cranford St was also explored.

3. ANALYSIS OF EYE WITNESS EVIDENCE

Normally, vehicle speed determination from eye witness statements yields results that are too broad to be useful, as the credibility and accuracy of witness statements need to be treated with caution. In this instance, however, the very large number of witnesses made an analysis worthwhile. 117 witness statements were analysed by considering observations of maximum estimated vehicle speed, perceived vehicle acceleration, headlight operation, vehicle steering and vehicle path. Patterns of evidence were determined, and vehicle speed estimate bias checks were performed, including the effect of self-reported witness intoxication, gender and age.

3.1 Vehicle Acceleration

Witness statements were examined for comments on the acceleration of the Honda Integra as it travelled along Edgeware Road. This was of interest in the assessment of both driver behaviour and maximum vehicle speed. Where possible, three different determinations of perceived acceleration of the vehicle were made:

1. When the vehicle was first observed.
2. As the vehicle passed the witness or, alternatively, midway along the viewed portion of vehicle travel. This latter option was used for witnesses located near the vehicle starting location.
3. When the vehicle was last observed by the witness.

Findings are summarised in Table 1. It is not surprising that Table 1 shows that as the vehicle progressed along Edgeware Road, an increasing proportion of witnesses were uncertain or did not state their perception of vehicle acceleration. Not only would the increasing distance between many of the witnesses and the vehicle have made an appraisal of the vehicle's acceleration more difficult, but

witnesses would have been have been distracted/distressed by injured people in the field of view. Furthermore, those witnesses in the vehicle's path who were either forced to take evasive action or were struck by the vehicle were less likely to be able to observe the vehicle once it had passed them.

Table 1: Eye Witness Perceived Acceleration for Honda Integra on Edgeware Road		
Instant of Observation	Number of witnesses who thought vehicle was heavily accelerating	Number of witnesses who were uncertain or did not state perception of acceleration
When first observed	66%	26%
As vehicle passed witness or midway through observation	44%	50%
When last observed	11%	88%

Throughout its travel on Edgeware Road, very few witnesses thought that the vehicle accelerated moderately or slowly, that the vehicle speed was constant, or that the vehicle decelerated.

Overall, witness statements indicated that the vehicle accelerated heavily for most of its travel along Edgeware Road, although the large number of pedestrian impacts would have acted to slow the vehicle slightly and this effect would have been more pronounced when striking a relatively dense group of people.

3.2 Maximum Observed Vehicle Speed

Out of 117 witness statements examined, 58 witness gave indications of perceived vehicle speed, divided into three categories as for acceleration in 3.1.

The highest (and invariably the last) speed noted by a given witness was plotted to produce a distribution of perceived vehicle speed, as shown in **Figure 3**.

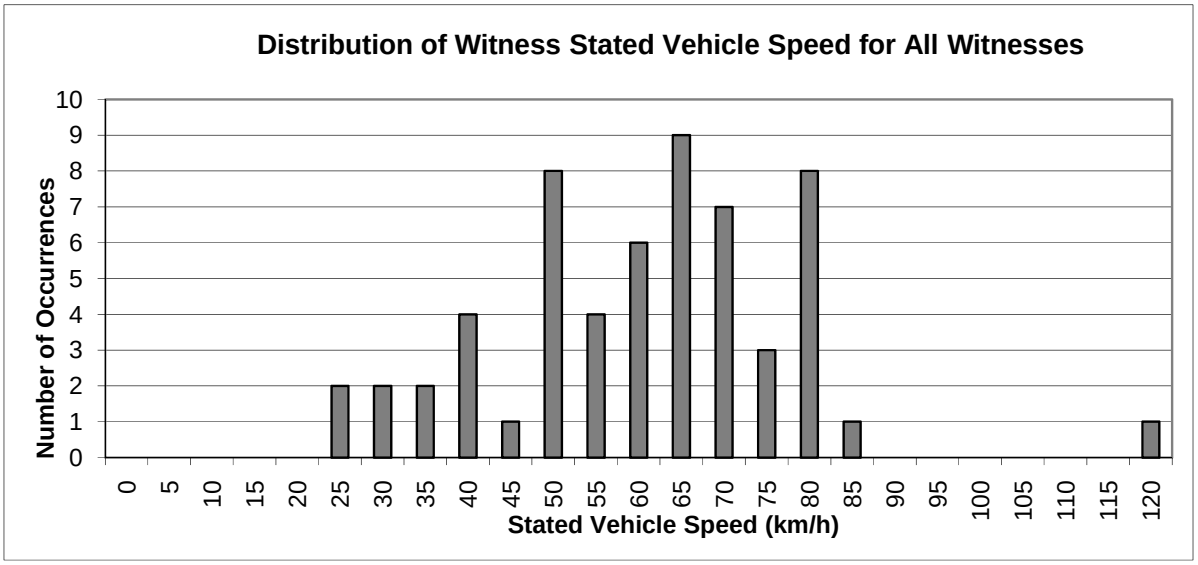

Figure 3: Distribution of maximum observed vehicle speed.

45 out of 58 witnesses who indicated a vehicle speed, estimated a maximum speed of between 50 to 80 km/h. In the vicinity of the party address, later referred as Zone 4 and where fatalities occurred, the mean speed estimated by 39 witnesses was 68.7 km/h with a standard deviation of 12.9 km/h. 49 out of 58 witnesses were unable to provide an estimate of vehicle speed when the vehicle was last viewed, i.e. most witness estimates of vehicle speed occurred when the vehicle was either first viewed by the witness, or part way through the viewed portion of vehicle travel.

As the weight of eye witness evidence indicated that the vehicle was accelerating heavily for most of its travel, the range of perceived vehicle speed is likely to be conservative relative to the maximum speed that the vehicle reached on Edgeware Road.

An analysis of maximum observed vehicle speed in relation to the self-reported level of intoxication of the witness showed that there was no effective difference between the estimates of sober and mildly intoxicated witnesses. Only five witnesses classified themselves as 'Noticeably Intoxicated' or 'Very Intoxicated'. One of these witnesses estimated the maximum observed vehicle speed to be 120 km/h. Gender and age biases on maximum observed vehicle speed were also analysed. No noticeable gender or age bias was apparent.

3.3 Maximum Observed Vehicle Speed Versus Acceleration

The 58 witnesses who gave an estimate of vehicle speed were located at different points along Edgeware Road. Many had their view of the vehicle obscured by people standing on the roadside. Witnesses near the vehicle's starting point were generally unable to see the vehicle as it approached Cranford Street, whereas witnesses near the fatal impact zone outside 95 Edgeware Road generally did not observe the vehicle as it started to move.

It is of interest to correlate the perceived vehicle speed when last observed with the level of vehicle acceleration evident to the witnesses at that time. Observations are summarised in Table 2. This shows that, as the vehicle progressed along Edgeware Road, the number of witnesses who thought that the vehicle was accelerating decreased as a proportion of the observations for a given speed range, and a greater number of witnesses were uncertain or did not state whether the vehicle was accelerating.

Table 2: Eye Witness Perceived Speed and Acceleration for Honda Integra on Edgeware Road

	Number	No. witnesses who thought vehicle heavily accelerating when last observed	No. witnesses who were uncertain did not state perception of acceleration
No. of witnesses indicating a vehicle speed	58	52%	N/A
No. of witnesses whose last observed speed was $\leq$ 50km/h	19	74%	21%
No. of witnesses whose last observed speed was 55 to 70 km/h	26	42%	46%
No. of witnesses whose last observed speed was over 75km/h	13	38%	62%
No. witnesses who thought vehicle speed was constant when last observed	2	N/A	N/A

3.4 Driver's Steering Actions

Of the 117 witness statements examined, 64 witnesses indicated their perception of the driver's steering actions and 53 witnesses (45%) did not. 32 witnesses thought that the vehicle appeared to change direction erratically, 24 witnesses thought that the vehicle was steered towards people, 6 witnesses indicated that they thought the vehicle was travelling in a straight line and 2 witnesses stated that they thought that driver was trying to steer away from people. These results are shown in **Figure 4**.

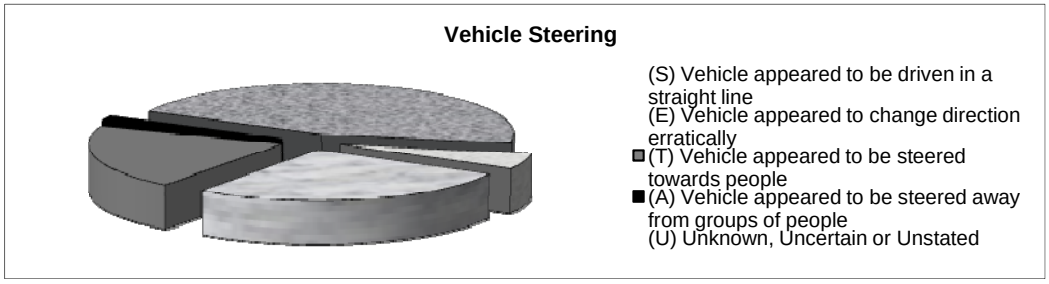

Figure 4: Driver's steering Actions.

3.5 Vehicle Headlights

33 witnesses (28%) thought that the vehicle's headlights were on at some stage during the vehicle's travel along Edgeware Road, 17 witnesses thought that they were off and 67 witnesses were either uncertain or did not state whether they thought that the vehicle's headlights had been on or off, as shown in **Figure 5**.

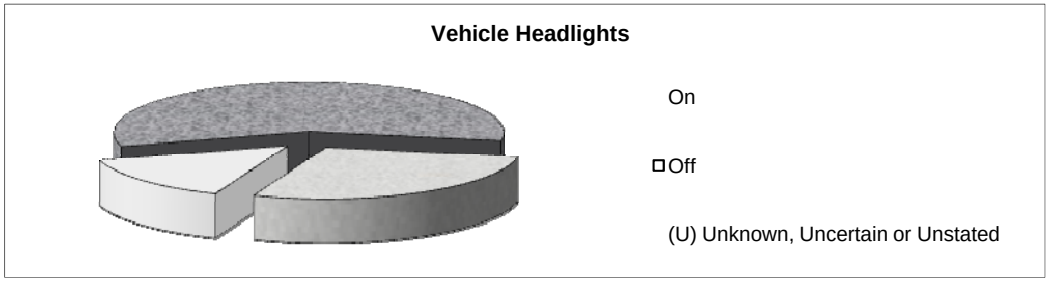

Figure 5: Vehicle headlights.

Three witnesses stated that they either saw or thought they saw the vehicle's lights turn on as it travelled along Edgeware Road. Overall, it would appear likely that the vehicle's lights were on or turned on after the vehicle had started moving along Edgeware Road. It is also possible that the left headlight was broken from a pedestrian collision and that the view of the headlights was obstructed for some witnesses, preventing some witnesses from determining if the vehicle's headlights were on.

3.6 Orientation of Victims at Time of Impact

The orientation and movement of a pedestrian at the time of impact with a vehicle has considerable influence on the outcome of the interaction (Anderson and McLean [3], Simms and Wood [4]). The witness statements were therefore examined for information relating to the orientation and movement of the two fatally injured pedestrians at the time of impact. This information was required for the simulation of vehicle-pedestrian interaction. Sufficient information was only available for one of the victims, and the vehicle-pedestrian interaction for was simulated only for this person. It was likely that one of the deceased women was struck from behind, while witness evidence relating to the other deceased woman's orientation at the moment of impact was inconclusive.

3.7 Vehicle Path

96 witness statements provided an indication of either the path taken by the Honda Integra or its location at some point of its travel along Edgeware Road. Many of these statements provide conflicting evidence as to the path taken by the Integra. Analysis of these statements was conducted by dividing the section of Edgeware Road travelled by the Integra into 6 Zones:

Zone 1: Area where 1st group was struck
Zone 2: Area opposite Manchester St
Zone 3: Area between Manchester St and 95 Edgeware Road
Zone 4: Area outside 95 Edgeware Road
Zone 5: Area opposite 93 Edgeware Road
Zone 6: Area between 93 Edgeware Road and Cranford St intersection

These Zones and their approximate extent can be seen in **Figure 6.** The beginning of Zone 1 coincides with the starting position of the Integra.

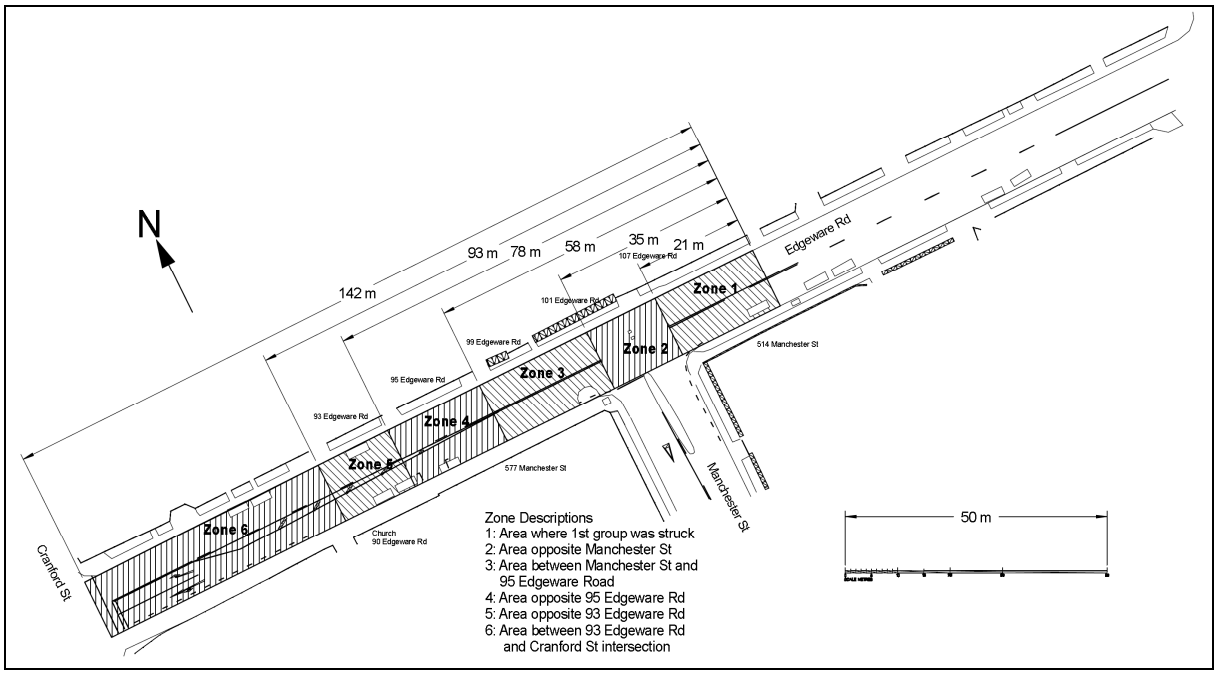

Figure 6: Speed Zones along Edgeware Road.

The results of this analysis can be seen in **Figure 7**.

Not shown in the bar graph of Figure 7 but noted in the legend are the large number of 'Unknown, Uncertain or Unstated' responses that resulted from the method of analysis. If a witness provided a vehicle position indication for a single zone only, this created an 'Unknown, Uncertain or Unstated' entry in each of the other five zones. For example in zone 1, the data graphed represent 55% of the witnesses who gave statements that related to vehicle path. Only 11 of the 96 witness statements/diagrams analysed gave an indication of vehicle path/placement for all six zones. 57 out of the 96 witness statements/diagrams analysed failed to clearly indicate a perceived vehicle position/placement for four or more zones

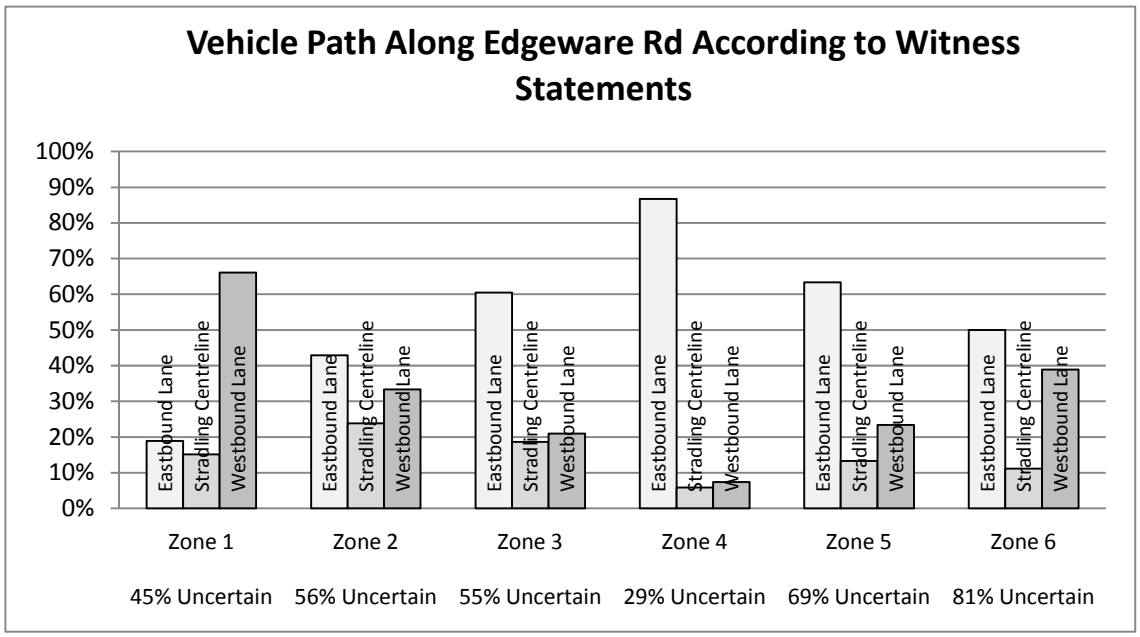

Figure 7: Vehicle path along Edgeware Road according to witness statements.

Figure 7 indicates that the Integra was most likely in the westbound lane in Zone 1, i.e. prior to the Manchester Street intersection. In Zone 2, opposite the Manchester Street intersection, it was likely that the Integra was changing lanes. For Zone 3, between the Manchester Street intersection and 95 Edgeware Road the Integra was most likely in the eastbound lane (i.e. the wrong side of the road). For Zone 4, opposite 95 Edgeware Road, most (61%) of the witnesses stated that the Integra was in the Eastbound lane. In Zone 5, opposite 93 Edgeware Road, it appears that the Integra remained in the eastbound lane. In Zone 6, between 93 Edgeware Road and the Cranford St intersection, there was no consensus on the vehicle's path from the witness statements. The Police plots of witness recollections of the vehicle path, **Figure 2,** support the bar graph representation of **Figure 7**.

4. VEHICLE SPEED FROM HEADSTRIKE LOCATION

Bellion [5], analysed a number of vehicle pedestrian collisions, mostly with large cars, e.g. Holden Commodore, and reported that windscreen headstrikes in vehicle-pedestrian collisions are unlikely for impact speeds of less than 50 km/h. He noted that headstrikes in the lower portion of the windscreen indicate an impact speed between 50 to 60 km/h, a headstrike in the middle portion of the windscreen indicates an impact speed of 70 to 80 km/h and that for impact speeds of approximately 100 km/h or greater the headstrike was likely to occur near the top of the windscreen or on the roofline of the vehicle. **Figure 8** defines the lower, middle and upper portions of the windscreen.

Martinez [6] suggested a likely impact speed of approximately 45 mph (72 km/h) for a headstrike in the middle region of a vehicle's windscreen.

A further reference in this area is the study of Happer et al [7]. This paper, although less relevant because the Honda was apparently not braking, suggests that head contact near the middle of the windscreen for a typical braking low fronted vehicle corresponds to an impact speed of 50-55 km/hr.

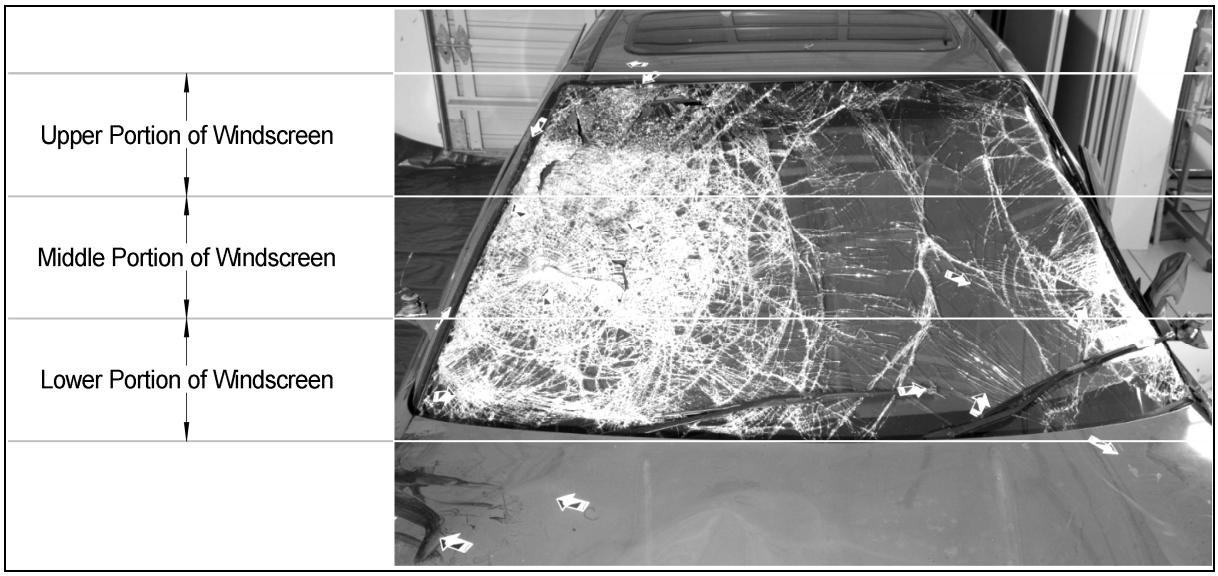

Figure 8: Lower, middle and upper portions of the windscreen mapped onto Honda Integra involved in Edgeware Road Collisions

DNA forensic analysis of human trace evidence (hair, skin, blood) indicated that most of the significant windscreen damage present on the driver's side of the vehicle probably resulted from the impact with one of the deceased women.

Significant penetration into the windscreen was evident, as shown in **Figure 9**. Mizuno and Kajzer [8] noted from impact tests a lack of penetration into windscreen for pedestrian head impacts of 50 km/h. However, multiple impacts on the windscreen may influence this result. It is also possible that the driver of the vehicle further damaged the windscreen in order to create an opening to see through after the pedestrian impacts.

Taking only the location of the headstrike into account and not the severity of windscreen damage, the vehicle speed for the pedestrian impact causing windscreen headstrike in front of the driver was judged to have been in the vicinity of 70 km/h.

Figure 9: Penetration into windscreen.

5. ANALYSIS OF PEDESTRIAN INJURIES

5.1 Introduction to the AIS, MAIS and the ISS

The Abbreviated Injury Scale (AIS) denotes risk of fatality for a given injury level (AAAM [9]). The six injury levels are:

AIS 1: Minor
AIS 2: Moderate
AIS 3: Serious
AIS 4: Severe
AIS 5: Critical
AIS 6: Maximum (also referred to as 'Untreatable' and 'Fatal')

The Maximum AIS (MAIS) denotes the highest AIS code in a patient with multiple injuries and is often expressed as the three highest injury codes for different body regions in descending order of severity.

The Injury Severity Score (ISS) is a measure of the probability of survival where multiple injuries occur. It is the sum of the squares of the highest AIS code in three different body regions. The six body regions are the head/neck, face, chest, abdomen/pelvis contents, extremities/pelvic girdle and external. Where an AIS 6 injury exists, an ISS of 75 (maximum possible ISS) is automatically assigned.

Walz at al [10] examined 952 vehicle-pedestrian collisions and related ISS to chance of survival for a pedestrian struck by a motor vehicle. These findings are shown in **Figure 10**. Chances of survival are considerably reduced for pedestrians suffering an ISS of more than 20.

McLean et al [11] plotted ISS versus Impact Speed but had no data beyond 57 km/h. At that speed the predicted ISS for an impacted pedestrian was 45. The injury patterns of the pedestrians struck on Edgeware Road are examined in 5.2 – 5.5.

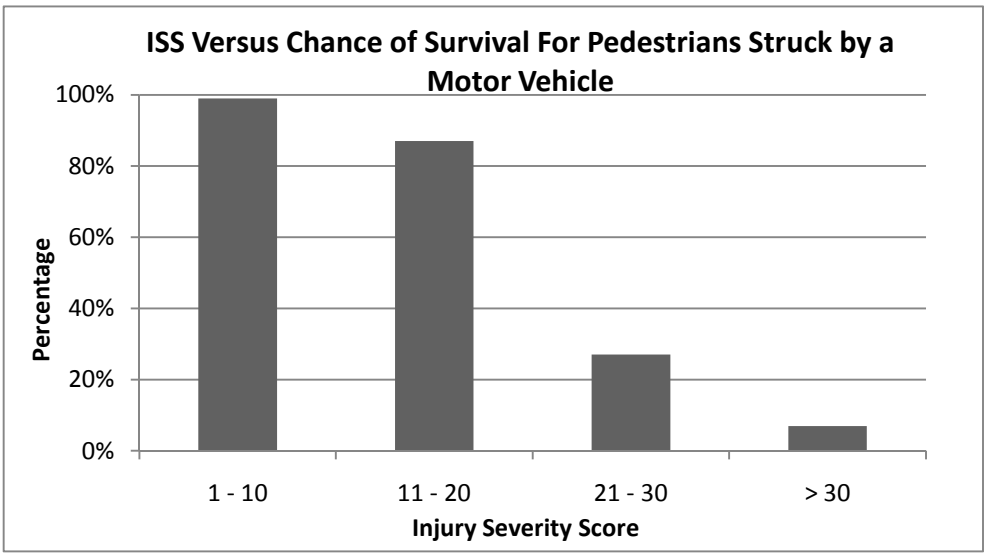

Figure 10: ISS Versus Chance of Survival for Pedestrians Struck by a Motor Vehicle (Source: Walz et al[10])

5.2 Injury Summary for Deceased Female #1

Deceased female #1, aged 16 years, had an injury pattern typical of a standing pedestrian struck from left rear by a vehicle resulting in fatal head injuries. She had an MAIS (Maximum Abbreviated Injury Scale) of 5, 4, 2 and an ISS (Injury Severity Score) of 50/75**.** Her lower limb injuries from vehicle contact, included a horizontal linear abrasion across the back of the right calf some 155 mm above the sole of the foot. There was predominantly blunt trauma to the left upper calf and a penetrating injury to the left thigh which may have resulted from the leading point of the vehicle's right front guard. This has a height above ground of approximately 640 mm and is likely to have incurred damage prior to impact with deceased female #1. This injury extended vertically along the thigh from 480 to 630 mm above the sole of the foot.

The contact force from the front right corner of the car on the lower body of deceased female #1 would have caused her body to rotate, most probably about both the vertical and horizontal axis, causing her upper body and head to strike the vehicle. It appeared that her head and left shoulder struck and quite possibly penetrated the vehicle's windscreen causing the laceration to the lower left forehead.

Her body would likely have continued to rotate both in a backwards flip and a clockwise (looking at the body headfirst) spin. This motion, coupled with the continued forward motion of the vehicle caused the girl's body to exit the broken windscreen at an acute angle, resulting in the large area of lacerations across her upper back and left shoulder and the deep laceration to the right-rear of her head. DNA analysis also confirmed the presence of her DNA at the top of the windscreen.

The vehicle then passed beneath the girl's body. While some injury from ground contact would have been expected, it appears that fatal brain injury resulted from the head-windscreen contact.

5.3 Injury Summary for Deceased Female #2

Deceased female #2, aged 16 years, had severe head injuries. Her MAIS (Maximum Abbreviated Injury Scale) was 6, 3, 1, with an ISS (injury Severity Score) of 75/75. External head injuries were apparent on opposite sides of the head: a compound fracture above the right eye at the hairline and a patch abrasion above and behind the left ear. An injury to the front of her head was notably free of abrasion, suggesting an impact with a smooth surface and not the ground. Impact with a vehicle appears likely, but limited DNA testing was unable to locate a likely point of contact between the girl's head and the Honda Integra. It is possible that this injury may have occurred from secondary contact with another vehicle.

She had a fracture of the superior pubic ramus, commonly associated with a fall onto one's side. This injury may have occurred through ground contact following the vehicle impact. Given the relatively low leading edge of the bonnet, it is unlikely that this injury occurred from vehicle contact.

There were extensive abrasions indicating that a considerable portion of post-impact travel occurred along the road surface.

There was a fracture of the left tibia and fibula resulted from an impact moving from the girl's left to her right. A horizontal laceration of the left shin was 320 mm above the sole of the foot. Damage to the vehicle made it difficult to obtain frontal height measurements but allowing for shoe heel height it is possible that the injury to her shin was caused by the lower edge of the vehicle's licence plate.

5.4 Analysis of Fatal Injuries

Both deceased females #1 and #2 exhibited severe head trauma resulting in fatality, and greater head trauma than would normally be expected as a result of a vehicle-pedestrian collision in a 50 km/h speed zone. Deceased female #1's head injury was determined to be of AIS 5 severity whilst deceased female #2's head injury was noticeably greater at AIS 6. Forensic analysis of glass fragments found in the hair and clothing of both girls indicated a likely match with the front windscreen of the Integra. The greater severity of head injury to deceased female #2 could have occurred as a result of:

- The probable sustained interaction between deceased female #1's leg and the front of the vehicle. This would have accelerated her to a higher percentage of vehicle speed, reducing the speed differential when her head impacted the vehicle
- Deceased female #2 possibly being struck at higher speed, or striking either the windscreen frame or A-pillar. Significant A-pillar deformation is evident in **Figure 9**.

The NASS PCDS (National Automotive Sampling System Pedestrian Crash Data Study)[12] study evaluated pedestrian injuries resulting from a vehicle impact. Of the 552 injured pedestrians evaluated in this only 3.4% suffered an AIS 6 injury.

Mizuno [13] noted that there was a 50% risk of a pedestrian receiving an AIS 4 or greater injury for a vehicle impact speed of 50 km/h, rising to 80% at 65 km/h.

Anderson et al [14] analysed four vehicle-pedestrian collisions cases which resulted in severe head trauma. The impact speed range was noted to be between 50 – 74 km/h. In the worst case the head trauma was comparable to that suffered by deceased female #1. In none of the cases was the trauma as severe as that for deceased female #2.

5.5 Other Reported Injuries

A considerable proportion of the people struck by the Integra received only a glancing blow or sideswipe. This section focuses only on pedestrians who incurred a significant injury which may be indicative of vehicle impact speed.

Casualties 10155, 10809 and 10090 below (these numbers are witness reference numbers) were in the first group that were struck (in Zone 1) and suffered relatively minor injuries. Their injuries would all be classified as AIS 2 and assigned an Injury Severity Score (ISS) of 4. Mizuno [13] indicates a 50% risk of an AIS 2 or greater injury at 34 km/h. At least seven other people were struck by the Integra along this part of Edgeware Road. Their injuries were all AIS 1 or less (i.e. negligible):

- Casualty 10155: damage to the ligaments of right knee
- Casualty 10809: concussion
- Casualty 10090: right fracture of the base of the first metacarpal, complete rupture of the acromio-clavicular ligament, undisplaced right clavicular and scapular fractures, left forehead contusion.

The other casualties listed below were struck further west along Edgeware Road than the first group, Their injuries were generally more serious, with three having ISS in the range 12 to 30. All the non-deceased people that were fully struck by the vehicle (i.e. not a glancing blow) outside 95 Edgeware Road were fortunate to survive:

- Casualty 10224: fractured tibia (required a titanium rod) and ankle (required pinning).
- Casualty 10538: comminuted right distal tibia and fibular fracture
- Casualty 10631: mild to moderate brain injury with left frontal lobe concussion and subarachnoid haemorrhage, left upper lob contusion of the lung, left inferior pubic ramus fracture, left elbow fracture, right femoral fracture and lacerations to the front of the head and left thigh
- Casualty 10645: head injury, 2 fractured cervical vertebrae, 1 fractured thoracic vertebra, 1 fractured lumbar vertebra, two fractured ribs on right-hand side, right midshaft tibia and fibula fractures and maxilla (upper jaw) fracture
- Casualty 11160: concussion
- Casualty (10220): medial tibial plateau fracture of right knee
- Casualty (no witness number): significant head injury, chest and abdominal wall injury, with left lower chest wall and left upper abdominal abrasions, right knee injury, consisting of deep abrasions to the antero-medial aspect of the knee.

5.6 Vehicle Speed from Pedestrian Injuries

The injury analysis indicates the following:

(1) The injuries incurred by the first group struck by the Integra suggest a likely vehicle speed between 30 and 40 km/h at the time of impact.

(2) The injuries incurred by people further west along Edgeware Road were generally more serious, with a number of people receiving severe injuries and in two instances, fatal injuries, implying a significantly higher vehicle speed.
(3) The injuries sustained by the two deceased females suggested a vehicle speed in excess of 60 km/h.

One factor to consider is that all the pedestrians struck were aged between 15 and 20. Research in the U.S.A. which analysed 23,831 vehicle-pedestrian collisions indicated that at any given impact speed people aged between 15 and 24 were less likely to be killed in a vehicle-pedestrian collision than older pedestrians (Leaf and Preusser [15]). This results from teenagers and young adults:

(1) Recovering better from injury than older adults.
(2) Being more resistant to injury than older adults.

These factors suggest that the analysis of vehicle speed from pedestrian injury was likely to have been conservative i.e. if a group of older adults had been struck, more serious injuries and a higher incidence of mortality would probably have occurred.

6. SIMULATION OF VEHICLE PEDESTRIAN INTERACTION

A simulation was conducted using the software package MADYMO (MAthematical DYnamic MOdelling) version 6.3 by TNO Automotive Safety Solutions (TASS), The Netherlands (http://www.tass-safe.com/cms/index.php). The vehicle was modelled using AutoCAD and HyperMesh.

6.1 Vehicle Modelling

The vehicle was modelled using a combination of measurements from the actual vehicle (using a Sokkia Total Station) and factory specifications (to correct for accident damage). Vehicle height as modelled was 15 mm lower than factory specifications to account for suspension sag with age (1310 mm versus 1325 mm). The vehicle body-shell as modelled weighed 218 kg and a virtual mass of 1182 kg was added to take the complete vehicle mass to 1400 kg.

Most of the vehicle was modelled (**Figure 11**) as a rigid surface to aid computational efficiency. Exceptions to this included the lighter-coloured elements at the front of the vehicle including the windscreen, bonnet and front bumper.

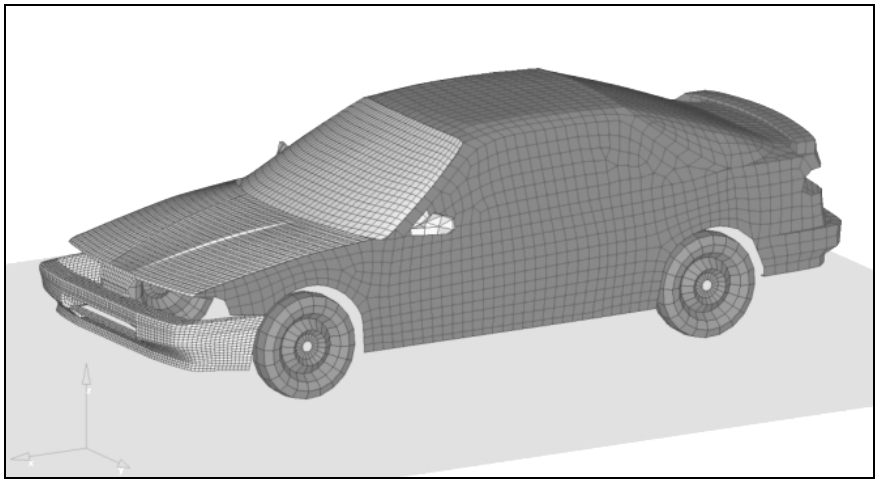

Figure 11: Vehicle as modelled.

The bumper stiffness was modelled as 200 Nmm^{-1} for the first 10 mm of deflection increasing to 400 Nmm^{-1} at 100 mm deflection. Bonnet stiffness was modelled as 300 Nmm^{-1}. Vehicle sections bordering the bonnet, bumper and windscreen were modelled as having a stiffness of 300 Nmm^{-1}.

Windscreen stiffness was modelled non-linearly according to the measurements taken by Stammen and Barsan-Anelli [16].

Pedestrian-vehicle friction was set to 0.25 as per Yoshida et al [17] and Stammen and Barsan-Anelli. Pedestrian-ground friction was taken to be 0.7 (Stammen and Barsan-Anelli used a coefficient of friction of 0.67). Friction between pedestrian components (e.g. arms, legs, body etc) was taken to be 0.5.

The road was modelled as a plane 5 metres wide by 20 metres long. The road stiffness was modelled as 40 $kNmm^{-1}$.

6.2 Pedestrian Modelling

The female pedestrian model created to replicate deceased female #1 was approximately 10 mm shorter than the pathologist's measurement to account for posture. A shoe sole thickness of 5 mm was measured by the Police and this height was applied in the simulation by standing the pedestrian on a small, flat plane. The pedestrian as modelled weighed 66.4 kg versus the pathologist's measurement of 66 kg.

A standard 50^{th} percentile male pedestrian model was used for comparative purposes. This model stood 1.71 metres tall and weighed 74.4 kg. A shoe sole thickness of 5 mm was also used for consistency. The results from this modelling were as expected, with a taller pedestrian typically exhibited a longer Wrap-Around-Distance (WAD) at a given vehicle speed.

A simulation was not carried out for deceased female #2.

6.3 Simulation Methodology

A simulation matrix (Table 3) was run to determine the relationship between head injury risk, head-strike location on vehicle and lower limb injury risk for the pedestrian's struck by the Honda Integra to examine the interaction of deceased female #1 with the vehicle.

Table 3: MADYMO Simulation Matrix

Variable	**Unit**	**Test Values**					**No. of Simulations**
Vehicle Speed	(km/h)	40	50	60	70	80	5
Vehicle Acceleration	(ms^{-2})	0	3				2
and Pitch	(deg)	0	1				
Pedestrian Orientation	(deg)	-25	0	25			3
Total No. of Simulations							30

Vehicle acceleration levels of 3.0 ms^{-2} and 0 ms^{-2} (i.e. constant speed) were evaluated. Although the witness statements generally indicate that the vehicle was accelerating heavily as it drove through the pedestrians, multiple pedestrian collisions may have slowed the vehicle, or at least reduced the acceleration of the vehicle momentarily. It was considered that a constant speed approximation for these transient conditions was the most suitable approach.

The witness statements also indicated that deceased female #1 was standing still and facing away from the vehicle at the time of impact. A range of orientations between 25 degrees either side of facing away from the vehicle were used. These pedestrian orientations with respect to the vehicle can be seen in **Figure 12**. The vehicle pitch adjustment of 1 deg for acceleration resulted in the leading bonnet edge lifting by approximately 30 mm.

The impact sequence suffered by deceased female #1 was paid particular attention due to the distinctive injury on the back of the left thigh that would appear to have resulted from contact with the tip of the right-front guard of the vehicle and the penetrating windscreen impact which would appear to have resulted in her neck and shoulder injuries.

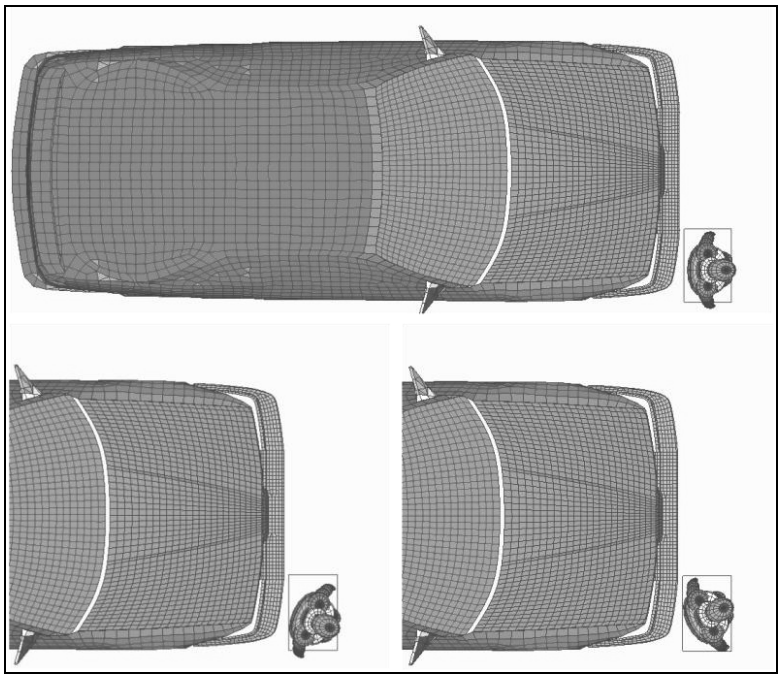

Figure 12: Pedestrian Orientation in relation to Vehicle 0º, 25º to left, and 25º to right

6.4 Simulation Appraisal

Simulations were appraised based on the position of the headstrike on the vehicle's windscreen. The output signal of the linear displacement of the head was analysed, with a small offset applied to compensate for the radius of the model's head. The resulting height at which the model contacted the vehicle's windscreen was then plotted against vehicle speed for the different simulated pedestrian orientations (with respect to the vehicle).

The height of the base of the windscreen, as defined in **Figure 13** was taken to be 870±20 mm (the base was difficult to measure because of the wiper cowl) and the height of the top of the windscreen was taken to be 1275±15 mm. The ranges were applied to account for uncertainties relating to vehicle loading (occupants and impacting pedestrians), vehicle pitch (as occurs when a vehicle accelerates) and potential measurement error.

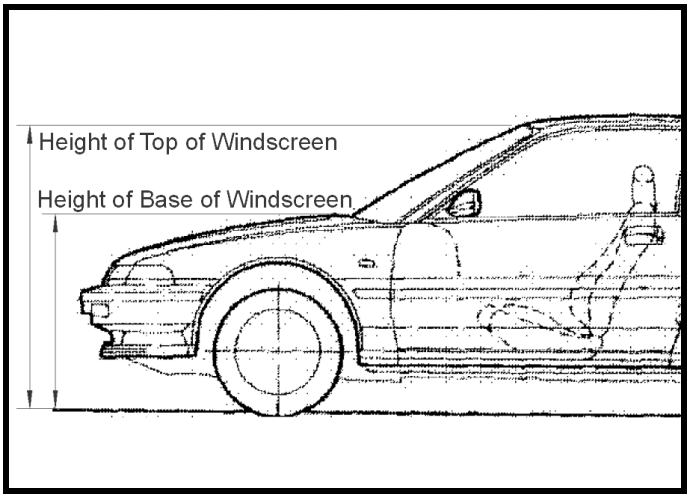

Figure 13: Windscreen height definition.

The height of the headstrike was taken to be 1036±18 mm. The Wrap Around Distance (WAD), as shown in **Figure 14**, was measured and found to be approximately 2080 mm.

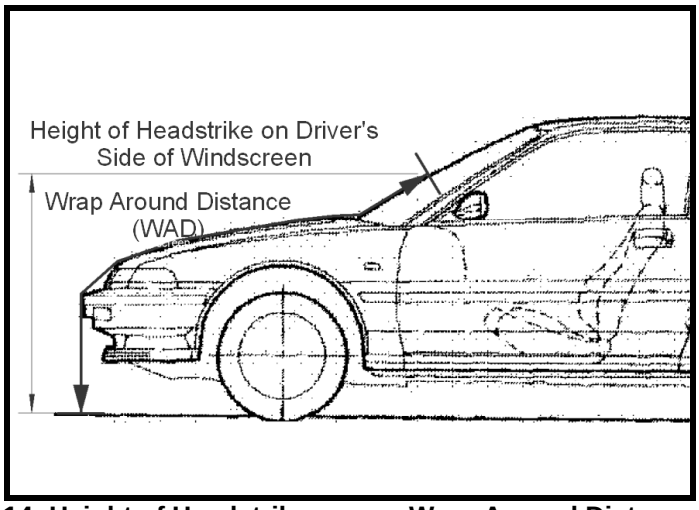

Figure 14: Height of Headstrike versus Wrap Around Distance (WAD)

For a vehicle travelling at constant speed the vehicle impact speed was identified as not being less than approximately 60 km/h for the three pedestrian orientations. This is illustrated in **Figure 15.**

For an accelerating vehicle a minimum impact speed of approximately 72 km/h was required for a headstrike in the correct location, depending on the pedestrian's orientation. This is illustrated in **Figure 16.**

With the deceased female having been struck from behind (per eye witness statements), and a headstrike in the correct area of the vehicle's windscreen, the computer simulation indicated a vehicle impact speed of at least 60 km/h for a vehicle travelling at constant speed, and in excess of 72 km/h for an accelerating vehicle.

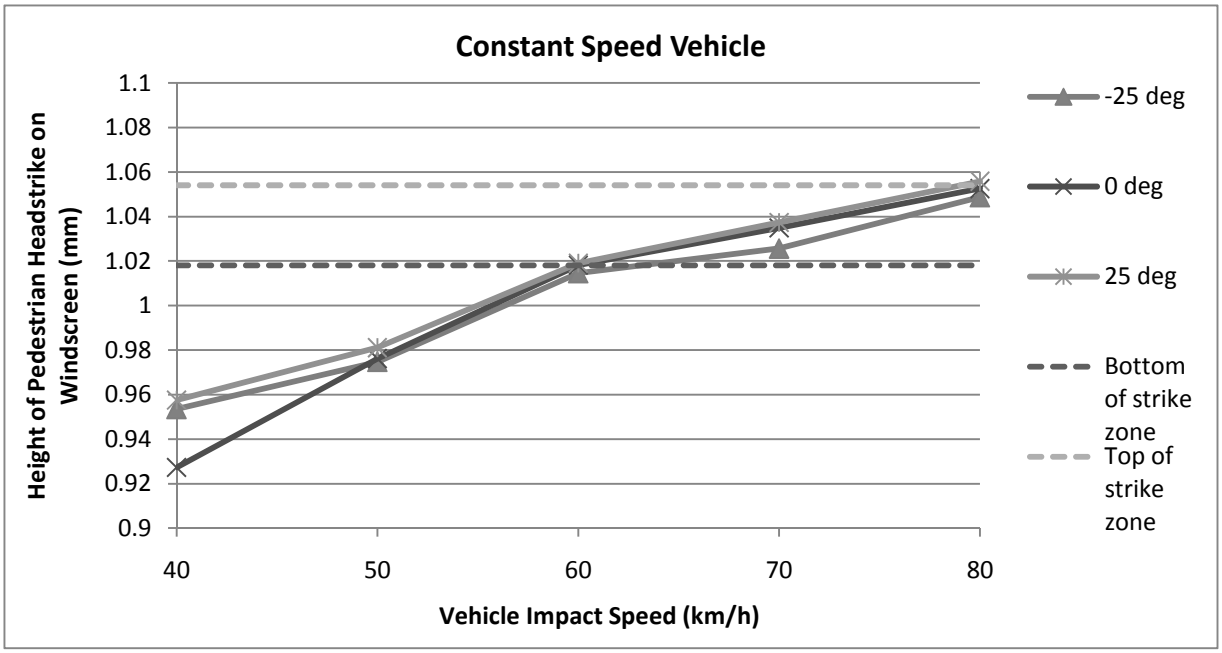

Figure 15: Headstrike height results for simulations using a constant speed vehicle.

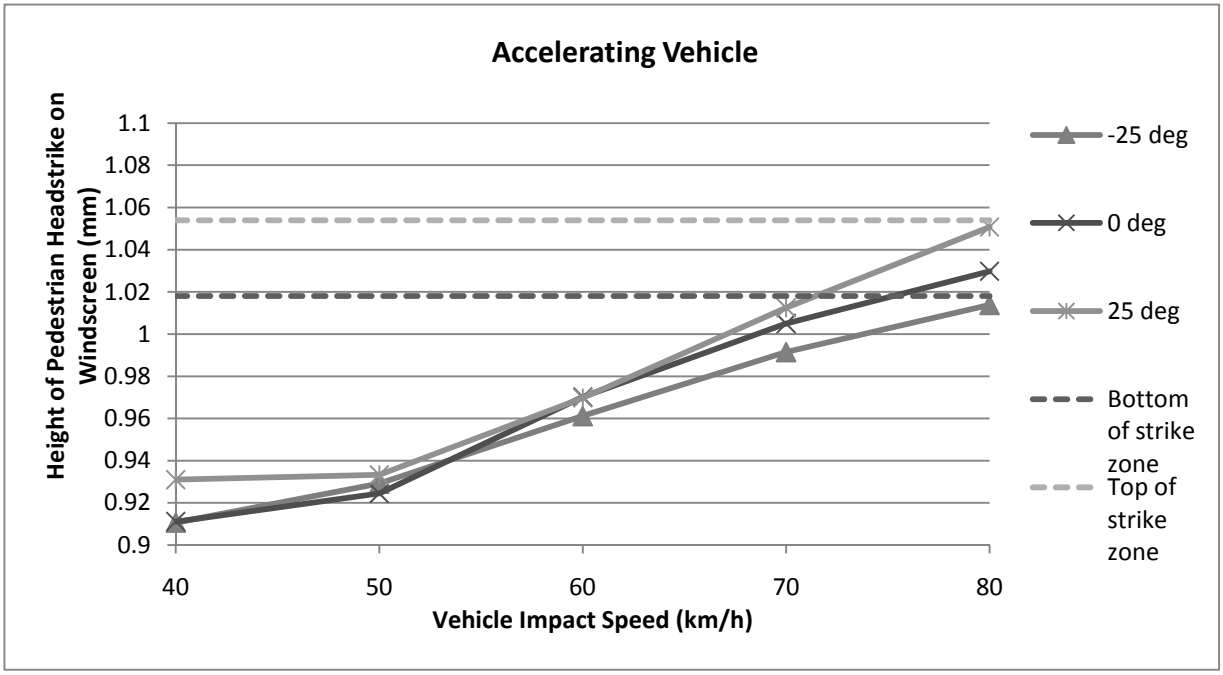

Figure 16: Headstrike height results for simulations using an accelerating vehicle.

6.5 Simulated Injury Analysis and Correlation

6.5.1 Lower Limb Injury

The simulation model included fracture joints in the lower limbs. The modelling and replication of deceased female #1's injury patterns required there to be no lower limb fracture, and none occurred in the scenarios defined in the simulation matrix. A short set of simulations was also run with the pedestrian model at an orientation of 75 degrees to the vehicle (i.e. nearly entirely side-on to the vehicle). A high probability of lower limb fracture was discovered for vehicle speeds higher than 50 km/h. This would suggest that:

(1) It was likely that deceased female #1 was indeed facing away from the vehicle at the time of impact (per eye witness statements).
(2) It would appear that the pedestrians who suffered lower limb fracture were not facing away from the vehicle at the time of impact.

6.5.2 Head Injury

Head injury potential was appraised using the Head Injury Criterion (HIC) (Versace [18]. The risk curve generated by Prasad and Mertz [19] was used to relate HIC to injury risk, as can be seen in **Figure 17**. The plotted curve indicates risk of an AIS 4 or greater injury.

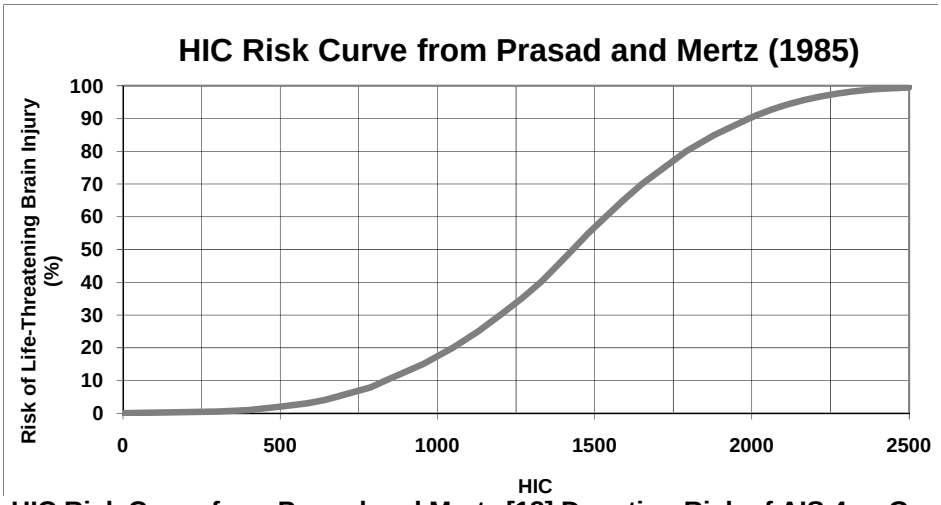

Figure 17: HIC Risk Curve from Prasad and Mertz [18] Denoting Risk of AIS 4 or Greater Head Injury

HIC values can be correlated with the chance of a specific AIS level to assess injury risk. e.g., for an HIC of 1000, the Mertz head injury curves indicated a 17% chance of an AIS level 4 or greater. For an AIS level 4, the fatality range is 7.9% to 10.6%, i.e. a fairly small risk of fatality. For an HIC of 2000 there is a 90% risk of an AIS level 4 or greater. In the simulation series conducted for a vehicle travelling at constant speed, only the 40 km/h scenario has a low risk of head injury, as shown in **Figure 18**.

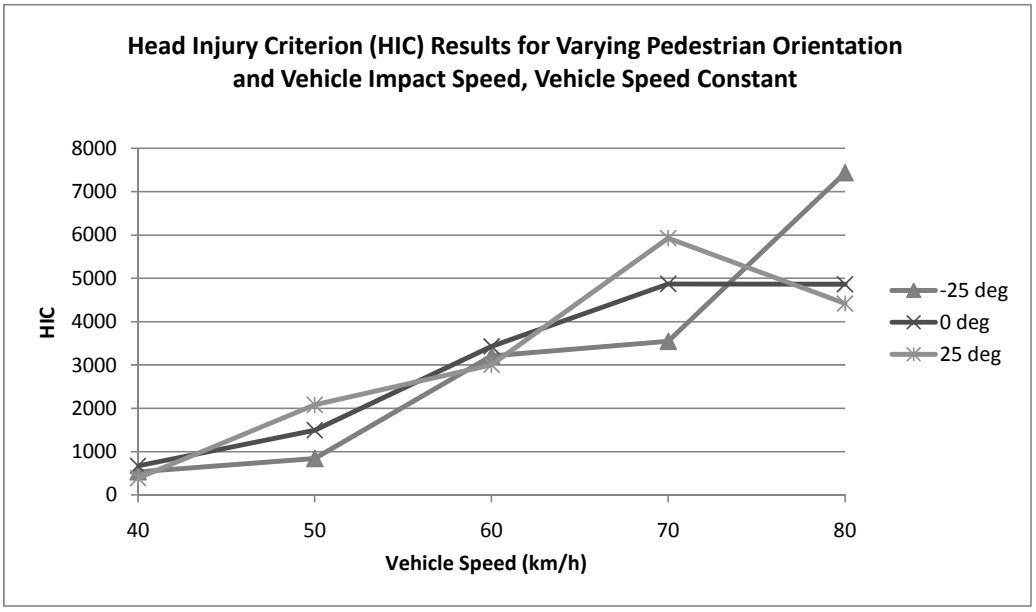

Figure 18: Head Injury Criterion (HIC) results for constant speed vehicle impacts.

In the case of an accelerating vehicle the risk of serious head injury was noted to be much higher, as is evident in **Figure 19**. The high values obtained at 40 km/h resulted from the pedestrian's head striking the stiff area at the base of the windscreen. The simulations therefore confirmed the risk of serious head injury in vehicle-pedestrian collisions in all the scenarios simulated with the exception that modelling a vehicle travelling at a constant speed of 40 km/h.

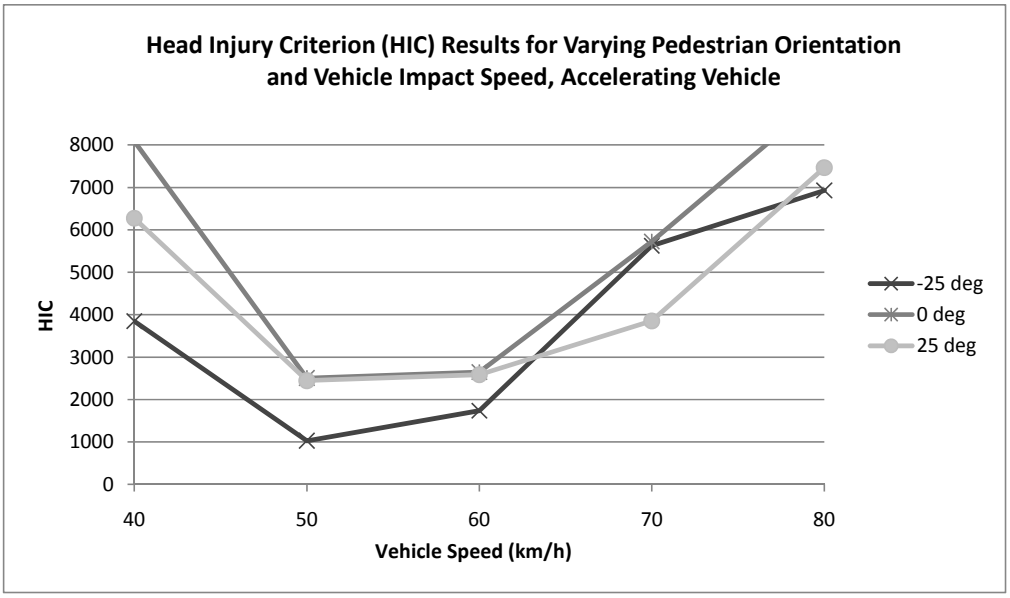

Figure 19: Head Injury Criterion (HIC) results for accelerating vehicle impacts.

6.5.3 Kinematic Analysis and Correlation for Deceased Female #1

A kinematic analysis, not reported in detail in this paper, was done for the pedestrian model for vehicle travel speeds of 40, 60 and 80 km/h. It was found that the headstrike was too low on the windscreen for the 40 km/h scenario. Under the 60 km/h scenario the headstrike was at the bottom of the expected height range of the headstrike. For the 80 km/h scenario the pedestrian significantly broached the windscreen resulting in a complex interaction between the vehicle and the pedestrian. Less significant windscreen penetrations were evident for the 70 km/h impacts.

6.6 Summary of Simulation of Vehicle-Pedestrian Interaction

For a headstrike to occur in the correct region of the windscreen a simulated vehicle speed of not less than approximately 60 km/h was required for a vehicle travelling at constant speed, and not less than approximately 72 km/h for an accelerating vehicle.

The injury analysis resulted in simulated injuries that were consistent with the severity of the actual injuries incurred.

The kinematic analysis produced pedestrian kinematics that were consistent with the expected kinematics of the initial and secondary vehicle contacts. Difficulties in modelling a potentially damaged windscreen resulted in some uncertainty regarding the manner in which the pedestrian model exited the broken windscreen.

7. PERFORMANCE VERIFICATION FROM VEHICLE TESTING

Comparison between the manufacturer's specified performance and estimates of vehicle speed along Edgeware Road suggested that the vehicle may have been at or close to its upper limit of acceleration. Witnesses also reported the vehicle swerving during its path along Edgeware Road. Testing was conducted using an exemplar vehicle to determine if the estimated vehicle speed ranges were achievable given the vehicle's likely path.

Testing was conducted at the Ruapuna Park motor racing circuit. The exemplar vehicle was instrumented using two Vericom accelerometers. Testing was also recorded using 'in-car' and external video cameras.

7.1 Comparison of Results

7.1.1 Vehicle Speed

Witness statements were quite consistent in regard to perceived vehicle speed. The vehicle speed during the series of collisions with the first group of people (i.e. to the east of the Manchester St intersection) was commonly perceived to be between 30 – 40 km/h. The injuries sustained by the people in this group were found to be consistent with an impact from a vehicle travelling at 40 km/h or less.

By the time the vehicle was passing 95 Edgeware Road witness estimates indicated a likely vehicle speed in the range 60 – 80 km/h. Injury analysis suggested a vehicle speed in excess of 60 km/h. As indicated in Section 4 of this paper, the headstrike on the windscreen indicated a vehicle impact speed of approximately 70 km/h. The simulation of vehicle-pedestrian interaction used to model the interaction of deceased female #1 with the vehicle (assuming the headstrike on the windscreen was attributable to her), indicated a vehicle speed of not less than 60 km/h and that it was likely to be in excess 70 km/h. The simulated injuries at these vehicle speeds matched the actual injuries incurred.

It was also determined that the driver could turn onto Cranford St without difficulty if he had passed 95 Edgeware Road at between 60 – 80 km/h.

7.1.2 Vehicle Acceleration

The witness statements indicated that the vehicle accelerated heavily for the greater part of its travel along Edgeware Road. Technical data sources indicated that 'heavy' acceleration of this vehicle would be in the range of 2.5 to 3.0 ms^{-2}. The exemplar vehicle tests showed that unimpeded acceleration of the vehicle at full throttle could have resulted in the vehicle attaining between 78 – 85 km/h by the time it had passed 93 Edgeware Road. The authors examined the likely effect of multiple pedestrian collisions on the vehicle's acceleration and concluded that these would have reduced the maximum attainable speed where the vehicle passed 93 Edgeware Road to between 54 – 69 km/h. This analysis also indicated that the highest vehicle speed, likely to have been 62 – 68 km/h, would have occurred just before the car struck the group of people outside 95 Edgeware Road.

While some loss of speed will have occurred through pedestrian impacts, the analysis indicated that it was highly likely that the vehicle's accelerator remained fully depressed for most of the vehicle's travel along Edgeware Road.

8. CONCLUSION

A number of methods of analysis were used to examine an incident where a vehicle struck a number of pedestrians on Edgeware Road, Christchurch on 5 May 2007. The analysis methods included:

- Witness statements and estimates of vehicle speed
- Vehicle-speed from pedestrian headstrike location on vehicle
- Evaluation and classification of pedestrian trajectories post-impact
- Analysis of pedestrian injuries and their relationship to vehicle impact speed
- Computer simulation of vehicle-pedestrian interaction
- A speed versus distance analysis for the vehicle based on data obtained from the testing of an exemplar vehicle, assuming maximum acceleration, but with disturbances to acceleration during simulated lane change manoeuvres

Based on consistent findings from the various methods of analysis, the authors concluded that:

1. The Honda Integra, was likely to have been driven at full throttle and maximum acceleration for most if not all of its travel from a starting position east of the Manchester St intersection westwards along Edgeware Road and that this level of acceleration was maintained until after the vehicle had passed 95 Edgeware Road and quite possibly until after it had passed 93 Edgeware Road. Prior to passing 95 Edgeware road, any throttle lift-off was momentary in nature, i.e. not greater than 0.4 ± 0.2 seconds, and difficult to distinguish from the effects of pedestrian impacts.
2. The maximum vehicle speed was likely to have been 36 ± 2 km/h as the vehicle drove through a group of people to the east of the Manchester St intersection.
3. The vehicle speed was likely to have been 65 ± 3 km/h immediately before striking a group of people outside 95 Edgware Road.

While conventional estimation of pedestrian impact speeds was not possible because of gross uncertainty around throw distances, the combination of methods covered in this paper were considered to give a consistent and ultimately reliable estimate of the vehicle speed during two significant phases of its travel and collision sequence with pedestrians.

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