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An Evidence Based Method to Calculate Pedestrian Crossing Speeds in Vehicle Collisions (PCSC)

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Abstract: Pedestrian accident reconstruction is necessary to establish cause of death, i.e. establishing vehicle collision speed as well as circumstances leading to the pedestrian being impacted and determining culpability of those involved for subsequent court enquiry. Understanding the complexity of the pedestrian attitude during an accident investigation is necessary to ascertain the causes leading to the tragedy. A generic new method, named Pedestrian Crossing Speed Calculator (PCSC), based on vector algebra, is proposed to compute the pedestrian crossing speed at the moment of impact. PCSC uses vehicle damage and pedestrian anthropometric dimensions to establish a combination of head projection angles against the windscreen; this angle is then compared against the combined velocities angle created from the vehicle and the pedestrian crossing speed at the time of impact. This method has been verified using one accident fatality case in which the exact vehicle and pedestrian crossing speeds were known from Police forensic video analysis. PCSC was then applied on two other accident scenarios and correctly corroborated with the witness statements regarding the pedestrians crossing behaviours. The implications of PCSC could be significant once fully validated against further future accident data, as this method is reversible, allowing the computation of vehicle impact velocity from pedestrian crossing speed as well as verifying witness accounts.

Keywords: Accident reconstruction, pedestrian, vehicle damage, walking, running, PCSC

Nomenclature:

A	Visible impact point on the bonnet leading edge
B	Head impact strike on the windscreen
C	Planar projection of point B to the bonnet leading edge
D	Pedestrian head centre of gravity
H	Planar horizontal distance between vehicle dent and windscreen damage
W	Planar car-line distance between vehicle dent and windscreen damage
β	Angle (BCE) measuring the angle between the actual pedestrian head centre of gravity to from the location of strike to its location on the windscreen along the vehicle travelling direction
λ	Is the theoretical angle between the pedestrian velocity and the vehicle velocity
Γ	Head offset to the bumper impact location. It compensates offset by half a pedestrian stride length
Δ	Combined offset including the head strike on the windscreen ad gait head offset
α	Pedestrian crossing angle relative to the vehicle direction

1.0 Introduction

Pedestrian collisions are tragic events, which can lead to death. When death occurs, the Police Force is responsible for investigating the causes leading to the accident. These causes can be various and complex and rely on physical evidence at the scene of the accident, as well as witness statements, driver interviews, CCTV evidence and on-board vehicle systems (ECU, RCM, GPS, AV, Telcoms, etc...). The vehicle speed, should no other suitable video evidence be available, is calculated using various pedestrian throw distance disciplines, perhaps the most widely used in the UK is that of Searle [1]. Conveniently, Searle's equations relate well to real life pedestrian throw distances from Happer [2], as illustrated in Figure 1. Searle's equation impact speed range (V_{min} and V_{max}) bear some use in UK court proceedings.

Searle's equations are useful, however they are limited as they depend on witness evidence on the ground, i.e. debris from the vehicle as well as the resting pedestrian location. Should any of this information not be available, then the vehicle impact speed range cannot be calculated. This is also true when the pedestrian contacts against street furniture during the post-impact bouncing and sliding phases (Figure 2), as the final pedestrian resting location is not what it should have been had there been no contact. Searle uses a universal road friction parameter of 0.7 [1] to calibrate his theory displayed in Figure 1, meaning that there may be measurement discrepancies should in real life the road be icy (road friction near 0.1). Consequently, the Searle vehicle velocity calculation depends on events taking place after the collision, which in some cases may influence or void the use of this method. Nevertheless, the Searle method is also in agreement with the latest computer science tools, like the THUMS full Finite Element Model, using various pedestrian stance (Standing facing the car – SF; Standing sideways (left side impact) – SS; Walking (left side impact, right food forward) – WLR; Waking (right side impact, right foot forward) - WRR and Running (left side impact, left foot forward) – RLL) [3] illustrated in Figure 1, as well as using multi-body computer models [4]. These computer models are expensive, complex to setup and take sometimes days to compute on High Performance Computing (HPC) clusters, making them to date, a useful tool but still only accessible to specialist computer scientists.

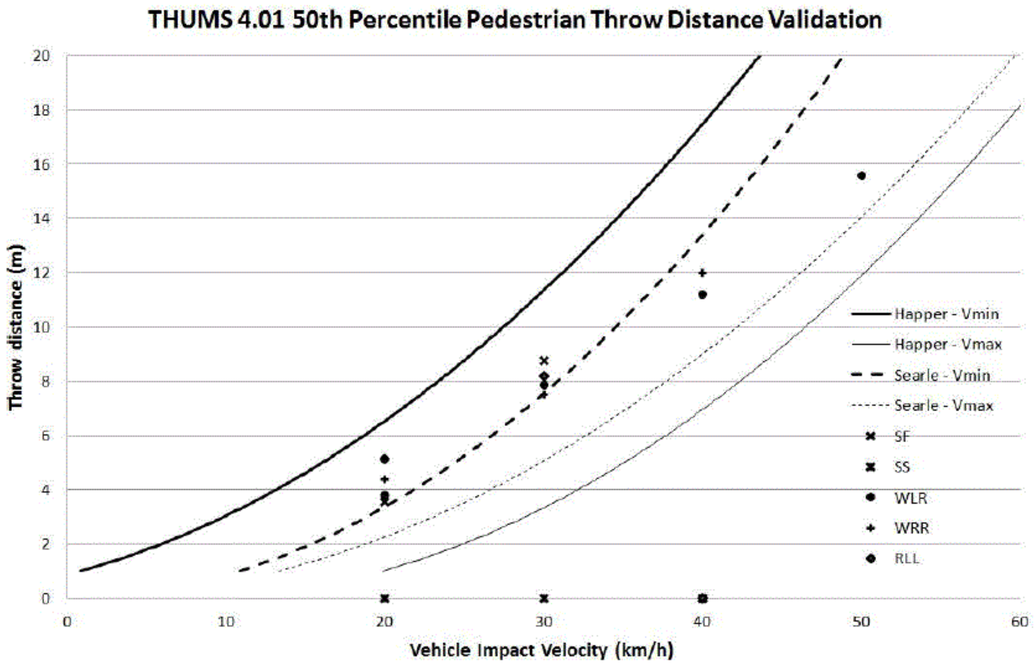


Figure 1: Comparison of pedestrian throw distance between Searle, Happer and THUMS (Real life data) [3]

The Searle equations relate to the pedestrian projection in a plane alongside the vehicle direction, meaning that conveniently, the pedestrian crossing velocity is not relevant to obtain realistic vehicle impact speed values.

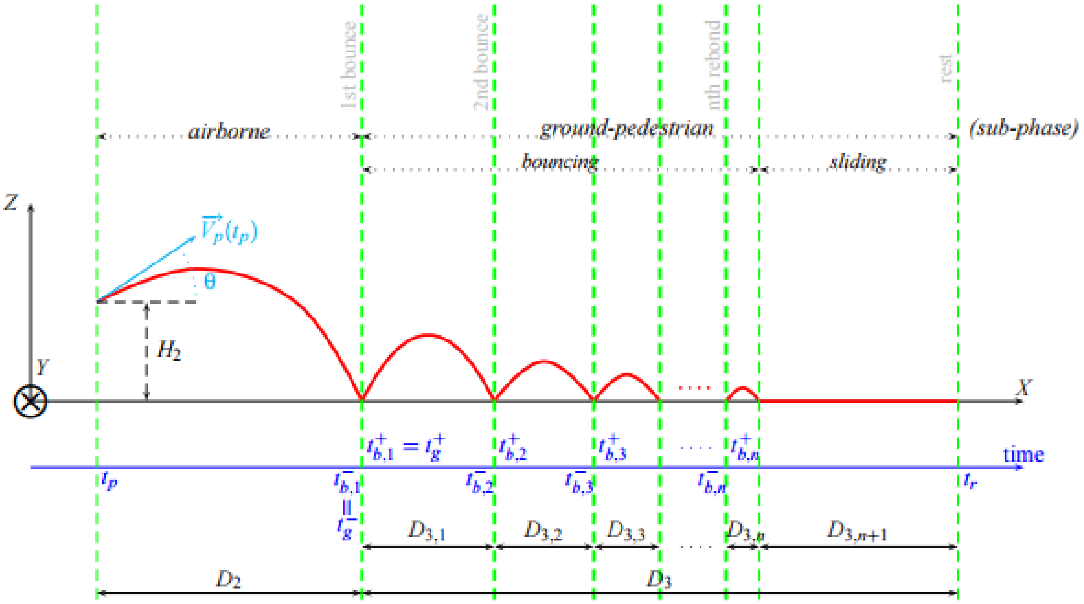


Figure 2: Theoretical kinematics computed from Searle's equations [1]

Pedestrian crossing speed is however, a very important parameter in the crime scene investigation, as it helps to understand whether the driver had time to see the pedestrian prior to taking any evasive manoeuvres. Pedestrian crossing speeds, are currently evaluated thanks to witness statements and research papers. The crossing speed is difficult to define, and is mainly estimated using the investigator's experience. Some literature classify crossing speeds being age dependant [5][6][9], while some also include the pedestrian percentile effect [7][8]. From anecdotal Police accident reconstruction investigations, pedestrians were also known to speed up, slow down, hesitate, turn round and even freeze to the spot. These parameters are also difficult to establish from works as everyone is physically and behaves differently. If walking relates to motion between 0.85m/s to 1.5m/s and running between 1.5 to 4.0m/s [10][11], there are no current known methods to verify or to refine the velocity of a pedestrian crossing the road, except by using complex and lengthy design of experiments using advanced human computer models [11]. These methods have also their limitations, especially the definition of the vehicle geometry, local stiffness, as well as runtime and cost [3]. The only tools calculating pedestrian crossing velocity are used in the development of road layouts [12][13]. They do not cater for instantaneous pedestrian crossing speeds, consequently these tools as well as crossing policies [14] cannot be used in pedestrian forensic accident analysis.

This paper will therefore propose a new forensic method, named Pedestrian Crossing Speed Calculator (PCSC), which will calculate the pedestrian crossing speed at the moment of impact. The use of results from this proposed methodology should be considered together with other available evidence when attempting to determine the speed at which a pedestrian crossed a carriageway - and therefore determine the time available to be seen by the driver (and conversely, the time available for the pedestrian to observe the vehicle).
This method will use selected anthropometric features from the deceased, the vehicle profile as well as the damage witnessed on the vehicle, as illustrated in Figure 3.

Figure 3: Evidence usually observed in car to pedestrian collision.
(Real life accident, Left; Schematics, Right, W and H respective planar dimensions)

2.0 Theoretical Derivation of the PCSC Method

This method starts from a general observation suggesting that the misalignment of the bumper cover damage and the head strike on the windscreen are caused by the pedestrian transverse velocity, or crossing speed. This assumption is correct if the pedestrian is a point mass, as assumed in Searle's equations [1]; the impact vector is a combination of vehicle and pedestrian velocities, as illustrated in Figure 4 . The base point mass equation from this premise are derived (Equation 1); adjustments for pedestrian posture (or gait), anthropometry as well as crossing direction (angle) are then formulated. The pedestrian crossing velocity is computed by equating the point mass theory and the effects from the adjustments (Equation 7).

The final equations are validated in Section 3.0 by correlating the theoretical approach to a real life pedestrian accident.

2.1 Derivation of absolute angle pedestrian – car.

The proposed method is based on vector algebra and velocity angle derivation. The velocity angle derivation is built from the compound velocity vector of the crossing pedestrian and the vehicle in planar view. This vector is derived, on the vertical plane, as illustrated in Figure 4.

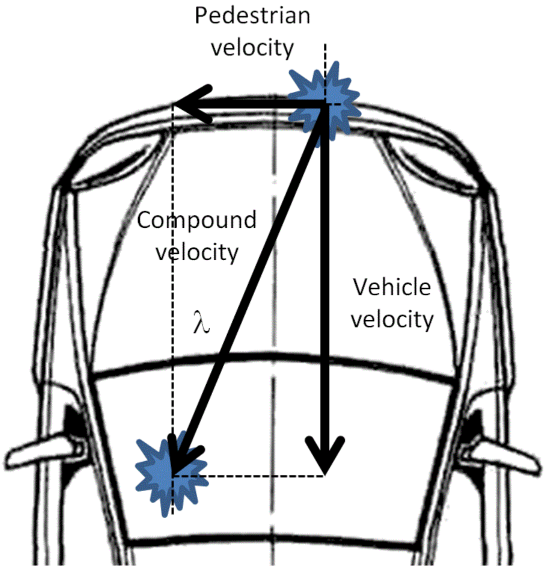


Figure 4: Vector algebra for pedestrian head impact trajectory computation

The angle λ between the pedestrian and the vehicle velocities is calculated using Equation 1, providing the true ratio of velocities between the vehicle and the pedestrian, here assuming the pedestrian crossing perpendicularly to the vehicle.

Equation 1: Absolute relative angle between pedestrian and vehicle velocities

$$\lambda = \tan^{-1}\left(\frac{V_{ped\_perpendicular}}{V_{vehicle}}\right)$$

Equation 1 means that there is a family of λ values for the range of pedestrian and vehicle velocities. The pedestrian crossing speed can vary from 0 (static) to 4.0m/s (running) [10][11] [15] whilst at the same time the vehicle velocity usually varies from 0m/s to 20m/s. The family of λ values generated will be true and absolute. It can be noted that there is more than one solution to λ, as there are multiple ratios between pedestrian and vehicle collision speeds which can fulfil it.

2.2 Considerations for pedestrian gait/ posture and anthropometry

A pedestrian accident is a complex event and different parameters, like pedestrian height, length of legs, which leg is impacted, bonnet leading edge height and stride. Stride is also a function of the pedestrian velocity, the stride being longer if someone is running compared to walking [10][11].

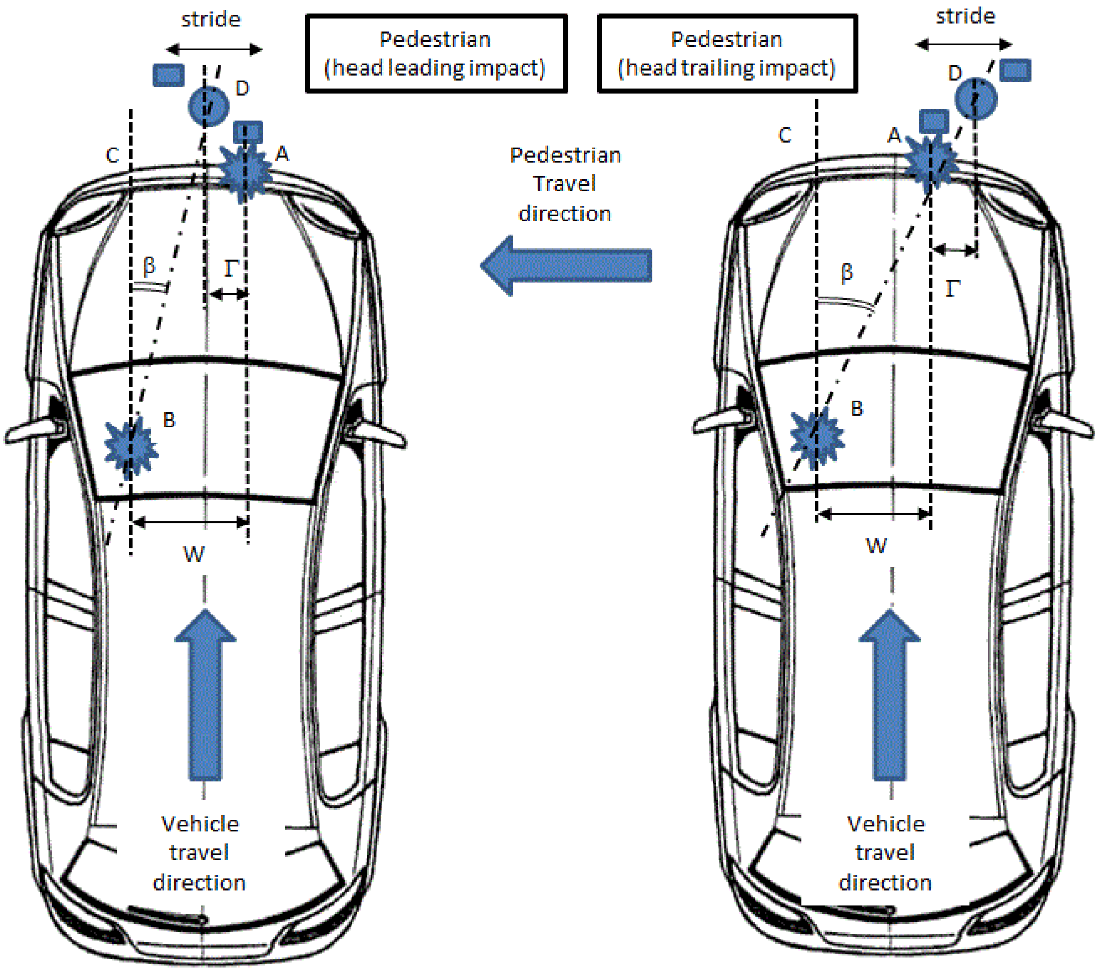


Figure 5: Schematics of a pedestrian impact (Left: pedestrian ahead of impact, Right: pedestrian lagging on impact)

Should the pedestrian's head be forward of the impact point (dent left on the bonnet leading edge), then the head approach angle β will be shallower than λ, while it will be greater than λ should if the pedestrian is lagging the impact point, as illustrated in Figure 5.

The head position relative to the bumper dent will therefore be offset forward or backwards depending on the leg length and the pedestrian stride. The opening angle of the legs is function of the hip angle (θ). Some research have documented that the hip angle varied with the pace of walking, as illustrated in Table 1.

Table 1: Hip maximum angle as function of walking speed

Crossing speed (m/s)	0 - 0.85	0.85 - 1.3 [10]	1.5 - 3.5 [11]
Type of crossing	Slow walk	Brisk walk	Run
θ_{max} Maximum hip angle gait (deg.)	5 (estimate)	20	30

Unfortunately, the angle θ cannot divulge the crossing speed, as it could relate for example to a slow walking person as well as a running person for which the feet are in the process of changing of pressure side. The maximum values in Table 1 imply that the gait (hip angle gait) of the 'slow walk' is a subset of a 'brisk walk', which is also a subset of 'run'.

It is therefore proposed to categorise the gait angle as a function of the dent or smear marks left on the bonnet. Indeed, the wider the bonnets dent/ smear, the wider the pedestrian gait (Wide), as the pedestrian body bonnet in-print will be larger. If a standing pedestrian is hit from the side, then his silhouette will be smaller (Narrow) and leave a linear print on the bonnet, as illustrated in Table 2. Any intermediate bonnet in-print will be classified as ‘Medium’.

Table 2: In-print classification as a function photographic evidence

Gait type	Narrow	Medium	Wide
θ hip angle gait (deg.)	5	20	30
Appendix		B and C	A
Case id	3	2	1
Bonnet in-print example	Minor damage		

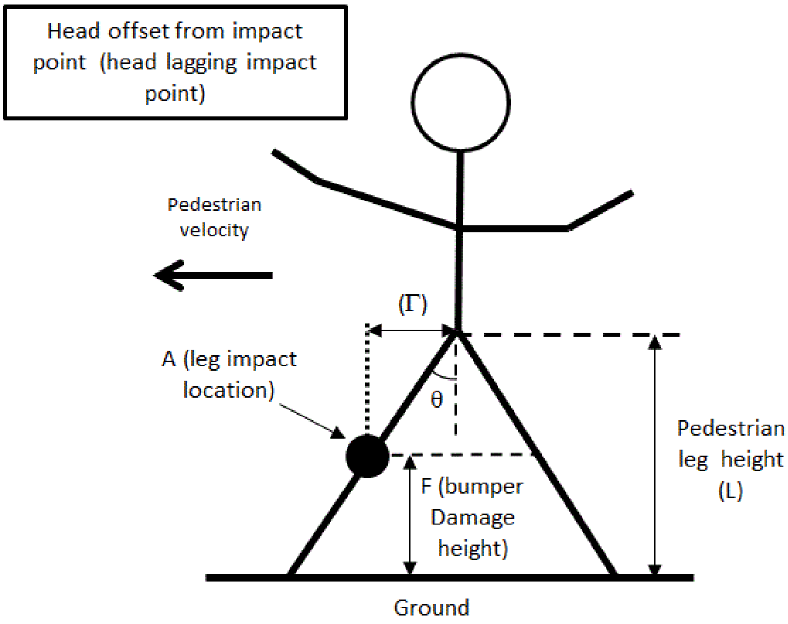


Figure 6: Head offset calculation

Head offset from impact point is given by Equation 2. The relative sign means that the offset depends on whether the pedestrian’s head is lagging or leading the impact point. Equation 2 relates to a pedestrian crossing perpendicularly to the vehicle direction, i.e. assuming the impact to be orthogonal. The gait offset is calculated by extracting the part of the pedestrian which is located above the bumper dent. This gait compensation is calculated by subtracting the bumper dent height from the pedestrian leg length and factoring at the same time for gait hip angle (θ).

Equation 2: Impact offset (Γ) taking into account pedestrian gait

$$\Gamma_{perpendicular} = \pm(L - F)\tan\theta$$

2.3 Considerations for pedestrian crossing direction

In some cases, the pedestrian does not cross perpendicularly to the vehicle, or the vehicle is swerving while the pedestrian is crossing the road orthogonally. If α is the angle between the crossing pedestrian and the vehicle, then a generic head offset to the bumper marker, $\Gamma_{generic}$, can be extracted from Equation 3. The projection of $\Gamma_{generic}$ will be less than or equal to $\Gamma_{perpendicular}$, which is the head offset to the bumper marker when the impact between the vehicle and the pedestrian is orthogonal. It can be noted that for orthogonal impacts, Equation 3 reverts to Equation 2.

Equation 3: Generic head offset including pedestrian crossing angle

$$\Gamma_{generic} = \Gamma_{perpendicular} \cdot (1 - \sin\alpha)$$

Consequently, the total horizontal offset dimension Δ, will comprise of W increased by $\Gamma_{generic}$, as depicted in Equation 4. Equation 4 now includes any pedestrian crossing directions.

Equation 4: Head approach angle including gait and anthropometry compensation

$$\Delta = W + \Gamma_{generic}$$

$$\beta_{generic} = \tan^{-1}\left(\frac{\Delta}{H}\right) = \tan^{-1}\left(\frac{W \pm (L-F)\tan\theta \cdot (1-\sin\alpha)}{H}\right)$$

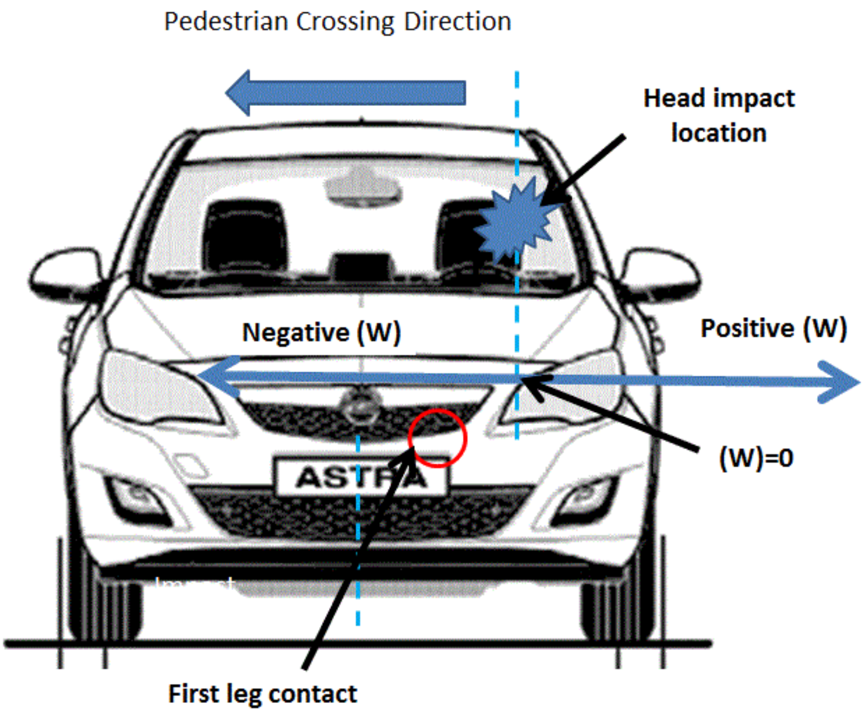


Figure 7: Sign of (W) relative to the windscreen head strike location

In order to respect the laws of vector algebra, β is only meaningful if Equation 5 is met.

Equation 5: Boundaries of β

$$\Delta = W + \Gamma_{generic} \geq 0$$

The β values must be 0 or positive as negative values of β are physically meaningless, as depicted in Figure 7. Should this condition not be met, then the computed head strike on the windscreen will not be physically possible.

2.4 Generalisation of the Pedestrian Crossing Speed Calculator (PCSC)

If the pedestrian is crossing with an angle α to the vehicle path, then part of his velocity vector will be aligned with the vehicle velocity. If the pedestrian crosses towards the vehicle, the impact combined velocity will be the sum of the vehicle speed and the pedestrian velocity. If the pedestrian crosses away from the vehicle, the combined velocity will be a reduced vehicle impact speed. Consequently, Equation 1 will be adjusted to reflect the statements above and become Equation 6.

Equation 6: Projection angle for combined pedestrian and vehicle speed

$$\lambda_{generic} = \tan^{-1}\left(\frac{V_{ped\_perpendicular}}{V_{vehicle} \pm V_{pedes\_along}}\right) = \tan^{-1}\left(\frac{V_{ped\_perpendicular}}{V_{vehicle} \pm tg(\alpha)\cdot V_{ped\_perpendicular}}\right)$$

It can be observed that in Equation 6, that if α of ‘0’, then $\lambda_{generic}$ reverts to Equation 1, which represents a pedestrian crossing perpendicularly to the vehicle. In order to understand the circumstances of the accident, it is possible to equate Equation 4 and Equation 6 to extract the ratio of pedestrian crossing to vehicle speeds which are equal. This is performed in the step given in Equation 7.

Equation 7: Pedestrian and vehicle speeds correlation condition

$$\lambda_{generic} = \beta_{generic}$$

$$\tan^{-1}\left(\frac{V_{ped\_perpendicular}}{V_{vehicle} \pm tg(\alpha)\cdot V_{ped\_perpendicular}}\right) = \tan^{-1}\left(\frac{W + \Gamma_{generic}}{H}\right)$$

Equation 7 represents the theoretical underpinning of PCSC.

2.5 Considerations for which leg is impacted first

In order to narrow down the matching of permutation ratios, it is possible to reduce the search by looking into the Post Mortem reports (PM), as well as the pedestrian impacting side, as listed in

Table 3.

Table 3 allows selecting the sign of $\Gamma_{generic}$ needed in Equation 7.

Table 3: Gait selection from impact side and head injury location based on computer kinematics [3]

Car colliding pedestrian from	Left			Right		
Leg contacting bumper (PM or video)	Left	Left	Right	Right	Right	Left
Location of windscreen impact head contact (PM)	Frontal	Occipital	Occipital	Frontal	Occipital	Occipital
Caused by	front of head hits windscreen	back of head hits windscreen	back of head hits windscreen	front of head hits windscreen	back of head hits windscreen	back of head hits windscreen
Head COG position prior to contact	Head forward of leg contact	Head rearward of leg contact	Head forward of leg contact	Head forward of leg contact	Head rearward of leg contact	Head forward of leg contact

Gait to consider	Rear Leg Hit	Front leg hit	Rear Leg Hit	Rear Leg Hit	Front leg hit	Rear Leg Hit
$\Gamma_{generic}$ value	Negative	Positive	Negative	Negative	Positive	Negative

Note that if a W value is negative, the only gait to consider is “Front leg hit”, as a “Rear leg hit” will produce automatically a negative $\Gamma_{generic}$ which will not meet the requirements of Equation 5.

Consequently, when the vehicle velocity range is provided, say from Searle’s throw distance equations, then the range of pedestrian crossing speeds can be narrowed down and extracted.

3.0 Validation of the PCSC Method

The validation method (Equation 7) was performed using accident Case 1 event which was recorded by the Police Force [17]. This research has received support and ethical approval from the Senior Coroner, permitting CT Post Mortem (CTPM), performed by the University Hospital of Coventry and Warwickshire, to be provided alongside standard PM to assist accident research investigation. The Police Force have given Coventry University access to their Road Traffic Collision (RTC) accident database. All data in this study is anonymised.

Accident Case 1 involved a pedestrian collision for which vehicle photographic evidence is included in Appendix A (Figure 9). In this instance, the vehicle was fitted with a dashboard camera, which allowed the recording of the pedestrian motion prior and during the collision. Using the camera frames, the vehicle speed was calculated. The vehicle was travelling at 45mph when the driver saw the pedestrian 11.4m from collision. Upon braking, the vehicle velocity reduced to 34mph (15m/s) when the collision took place [17]. Looking at the video, the Police Force was able to determine the time elapsed between two frames as 0.583 seconds. From the survey data the distance between fixed points on the road was found to be 2.2 m. By dividing this distance by the time, it was calculated that the pedestrian was crossing between these two points at 3.77 m/s [17]. Video evidence clearly showed that the pedestrian ran perpendicular to the vehicle at time of impact, therefore α is ‘0’.

Table 4: Summary of evidence for Case 1

Accident Data (see Appendix A)	**Case ID: 1**	
Damage marks measured on vehicle	Vehicle impacting pedestrian from	Left
	Relative distance across vehicle between bumper dent and head strike (W) (mm)	470
	Distance of head strike from bonnet (plan view) (H) (mm)	1531
	Dent top of grille from ground height (mm)	822
Pedestrian anthropometry	Length of legs (mm) – from PM	930
Accident derived parameters from evidence	Leg impacted	Right
	α: pedestrian crossing direction	0
	Gait	Rear Leg Hit

Critical vehicle damage dimensions were extracted to the best of the authors’ ability from a blueprint [23], as the vehicle was destroyed before true impact measurements were taken.

Using Equation 4, the angle β is calculated in Table 5. Using the photographic evidence that the bonnet in-print was 'Wide', it was assumed a hip gait of 30 deg. as per Table 2. This was also supported by the video evidence.

Table 5: Calculation of β

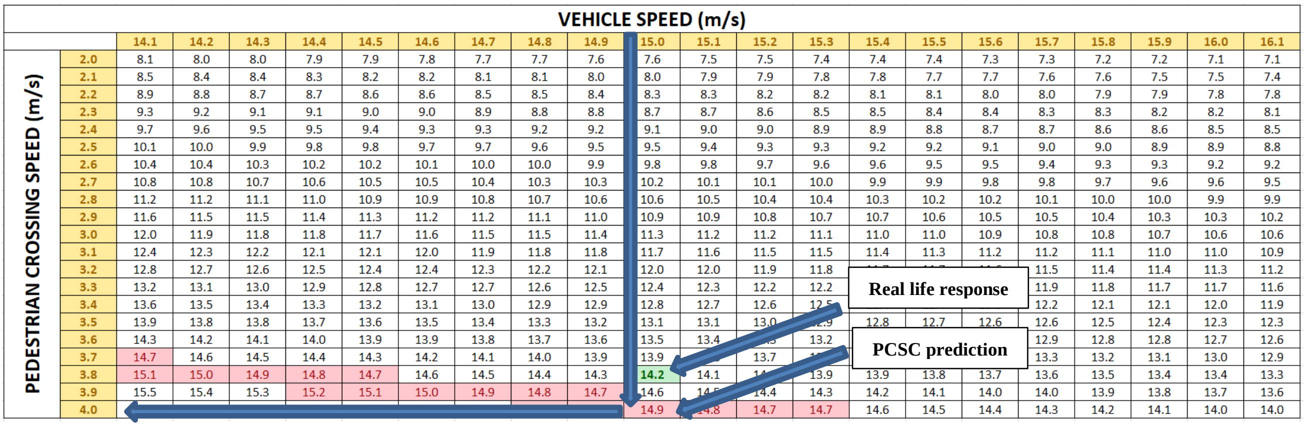
Hip angle gait (deg.)	30
Γ offset to centre of head COG (mm)	118.36
β angle (deg.) - Rear Leg Hit scenario	14.91

In order to find the closest λ, a window search of 2% is applied to capture rounding errors.

Table 6: λ search window (2% about β)

	Rear leg hit	
	Min angle	Max angle
β angle (deg.) - angle range search	14.61	15.21

Table 7: Angle search as per Equation 7 for Case 1



		VEHICLE SPEED (m/s)																				
		14.1	14.2	14.3	14.4	14.5	14.6	14.7	14.8	14.9	15.0	15.1	15.2	15.3	15.4	15.5	15.6	15.7	15.8	15.9	16.0	16.1
PEDESTRIAN CROSSING SPEED (m/s)	2.0	8.1	8.0	8.0	7.9	7.9	7.8	7.7	7.7	7.6	7.6	7.5	7.5	7.4	7.4	7.4	7.3	7.3	7.2	7.2	7.1	7.1
	2.1	8.5	8.4	8.4	8.3	8.2	8.2	8.1	8.1	8.0	8.0	7.9	7.9	7.8	7.8	7.7	7.7	7.6	7.6	7.5	7.5	7.4
	2.2	8.9	8.8	8.7	8.7	8.6	8.6	8.5	8.5	8.4	8.3	8.3	8.2	8.2	8.1	8.1	8.0	8.0	7.9	7.9	7.8	7.8
	2.3	9.3	9.2	9.1	9.1	9.0	9.0	8.9	8.8	8.8	8.7	8.7	8.6	8.5	8.5	8.4	8.4	8.3	8.3	8.2	8.2	8.1
	2.4	9.7	9.6	9.5	9.5	9.4	9.3	9.3	9.2	9.2	9.1	9.0	9.0	8.9	8.9	8.8	8.7	8.7	8.6	8.6	8.5	8.5
	2.5	10.1	10.0	9.9	9.8	9.8	9.7	9.7	9.6	9.5	9.5	9.4	9.3	9.3	9.2	9.2	9.1	9.0	9.0	8.9	8.9	8.8
	2.6	10.4	10.4	10.3	10.2	10.2	10.1	10.0	10.0	9.9	9.8	9.8	9.7	9.6	9.6	9.5	9.5	9.4	9.3	9.3	9.2	9.2
	2.7	10.8	10.8	10.7	10.6	10.5	10.5	10.4	10.3	10.3	10.2	10.1	10.1	10.0	9.9	9.9	9.8	9.8	9.7	9.6	9.6	9.5
	2.8	11.2	11.2	11.1	11.0	10.9	10.9	10.8	10.7	10.6	10.6	10.5	10.4	10.4	10.3	10.2	10.2	10.1	10.0	10.0	9.9	9.9
	2.9	11.6	11.5	11.5	11.4	11.3	11.2	11.2	11.1	11.0	10.9	10.9	10.8	10.7	10.7	10.6	10.5	10.5	10.4	10.3	10.3	10.2
	3.0	12.0	11.9	11.8	11.8	11.7	11.6	11.5	11.5	11.4	11.3	11.2	11.2	11.1	11.0	11.0	10.9	10.8	10.8	10.7	10.6	10.6
	3.1	12.4	12.3	12.2	12.1	12.1	12.0	11.9	11.8	11.8	11.7	11.6	11.5	11.5	11.4	11.3	11.2	11.2	11.1	11.0	11.0	10.9
	3.2	12.8	12.7	12.6	12.5	12.4	12.4	12.3	12.2	12.1	12.0	12.0	11.9	11.8	[illegible]	[illegible]	[illegible]	11.5	11.4	11.4	11.3	11.2
	3.3	13.2	13.1	13.0	12.9	12.8	12.7	12.7	12.6	12.5	12.4	12.3	12.2	12.2	[illegible]	[illegible]	[illegible]	11.9	11.8	11.7	11.7	11.6
	3.4	13.6	13.5	13.4	13.3	13.2	13.1	13.0	12.9	12.9	12.8	12.7	12.6	12.5	[illegible]	[illegible]	[illegible]	12.2	12.1	12.1	12.0	11.9
	3.5	13.9	13.8	13.8	13.7	13.6	13.5	13.4	13.3	13.2	13.1	13.1	13.0	12.9	12.8	12.7	12.6	12.6	12.5	12.4	12.3	12.3
	3.6	14.3	14.2	14.1	14.0	13.9	13.9	13.8	13.7	13.6	13.5	13.4	[illegible]	13.2	[illegible]	[illegible]	[illegible]	12.9	12.8	12.8	12.7	12.6
	3.7	14.7	14.6	14.5	14.4	14.3	14.2	14.1	14.0	13.9	13.9	[illegible]	13.7	[illegible]	[illegible]	[illegible]	[illegible]	13.3	13.2	13.1	13.0	12.9
	3.8	15.1	15.0	14.9	14.8	14.7	14.6	14.5	14.4	14.3	14.2	14.1	[illegible]	13.9	13.9	13.8	13.7	13.6	13.5	13.4	13.4	13.3
	3.9	15.5	15.4	15.3	15.2	15.1	15.0	14.9	14.8	14.7	14.6	14.5	14.4	14.3	14.2	14.1	14.0	14.0	13.9	13.8	13.7	13.6
	4.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	14.9	14.8	14.7	14.7	14.6	14.5	14.4	14.3	14.2	14.1	14.0	14.0

Table 7 is showing the vehicle-pedestrian speeds for which the PCSC requirements are respected. These permutations are highlighted in red in the table. Looking at Table 7, it can be observed that the PCSC predicts a pedestrian walking speed of 4.0m/s for a vehicle impact speed on 15.0m/s (extracted by the Police Force). In reality, the pedestrian crossing speed extracted from video was 3.77m/s for a vehicle impact speed of 15.0 m/s, which represents a difference of 6% in pedestrian crossing speed estimation. These results confirms the hypothesis that misalignment of the bumper cover damage and the head strike on the windscreen is caused by the pedestrian transverse velocity, or crossing speed, stated in Section 2.0 and illustrated in Figure 4.

This difference is likely influenced by the measures taken from the blueprint. As the values observed in real-life were accurately recorded and are true values, it can be concluded that the proposed PSCS methodology predictions are believable and valid.

4.0 Application of the PCSC method – Witness statement validation

It has been demonstrated that the methodology can link pedestrian crossing speed with vehicle impact velocity. This section will look at the application of the PCSC is two real life cases, with the purpose of confirming witness statements.

4.1 Pedestrian crossing speed validation. Case ID: 2 [18]:

An accident between a vehicle and a pedestrian took place and was recorded as Case 2. Vehicle damage evidence is provided in Appendix B. At the time of the accident the driver testified that the pedestrian was running. The Police were not able to determine how long the pedestrian was on the carriageway because this is entirely dependent upon their pace and the distance travelled. There is evidence provided by driver that the pedestrian was running rather than walking, the faster they were moving the less time they would have been in the carriageway" [18]. The term 'evidence' should have been replaced by allegation', as objective evidence was not present, but just a verbal statement from the driver. As the impact was clear, the Searle's equations estimated a vehicle impact speeds ranging from 11.0 m/s to 13.3 m/s. As no evasive manoeuvre was performed by the driver and that the pedestrian ran, i.e. likely took the shortest path to cross the road, it is assumed that the pedestrian ran perpendicular to the vehicle at time of impact, therefore α is '0'.

At the time of this investigation, the deceased had not been CT-scanned; only a PM was performed.

The length of the leg was not measured, but the pedestrian height was available from the PM (1650 mm). By using anthropometric means and standard deviation techniques [20], assuming a mean height of 1782.8 mm and a standard deviation of 72.78 mm, the pedestrian was estimated to belong to the first 3 percentile of the population. Using 3 percentile on the leg length, assuming a standard body proportion, with a mean length of 1068.8 mm and a standard deviation of 57.49 mm, a probable leg length was estimated at 964 mm. From the PM, the left leg was broken, which meant that it is highly probable that it was load bearing and hit first. The damage to the head is in the occipital region; consequently, the pedestrian body had to roll on his back before the head contacted the windscreen. For this to happen the right leg had to lag, hence the front impacted leg was the left one (

Table 3). All the accident information were summarised in Table 8 and the range or crossing speeds extracted in Table 9. Critical vehicle damage dimensions were extracted from the blueprint [24], as the vehicle was destroyed.

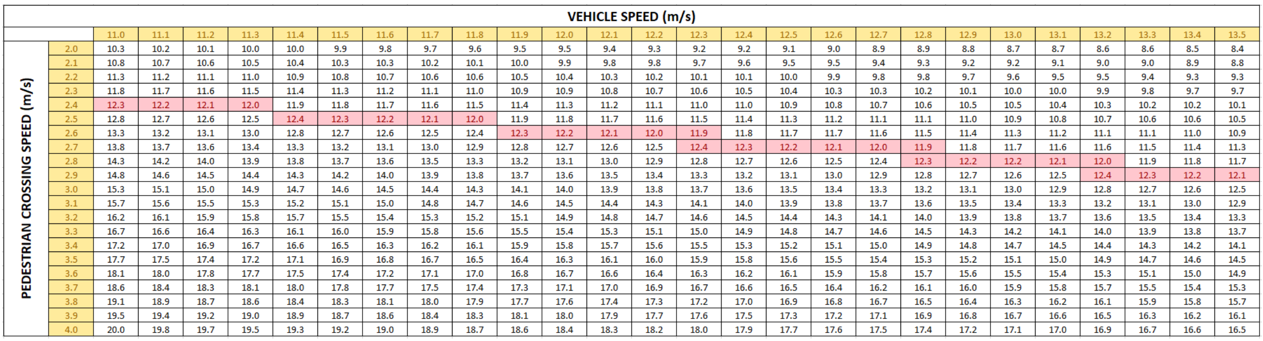
Looking at the photographic evidence in Appendix B, the bonnet in-print is 'Medium'; hence a gait angle of 20 deg. will be assumed in the calculations.

Table 8 Summary of evidence for Case 2:

Accident Data (see Appendix B)	**Case ID: 2**	
Damage marks measured on vehicle	Vehicle impacting pedestrian from	Left
	Relative distance across vehicle between bumper dent an head strike (W) (mm)	112

	Distance of head strike from bonnet (plan view) (H) (mm)	1237
	Dent top of grille from ground height (mm)	540
Pedestrian anthropometry	Length of legs (mm) – from statistics	964
Accident derived parameters from evidence	Leg impacted	Left
	α: pedestrian crossing direction	0
	Gait	Front Leg Hit

Table 9: Angle search as per Equation 4 for Case 2



		VEHICLE SPEED (m/s)																									
		11.0	11.1	11.2	11.3	11.4	11.5	11.6	11.7	11.8	11.9	12.0	12.1	12.2	12.3	12.4	12.5	12.6	12.7	12.8	12.9	13.0	13.1	13.2	13.3	13.4	13.5
PEDESTRIAN CROSSING SPEED (m/s)	2.0	10.3	10.2	10.1	10.0	10.0	9.9	9.8	9.7	9.6	9.5	9.5	9.4	9.3	9.2	9.2	9.1	9.0	8.9	8.9	8.8	8.7	8.7	8.6	8.6	8.5	8.4
	2.1	10.8	10.7	10.6	10.5	10.4	10.3	10.3	10.2	10.1	10.0	9.9	9.8	9.8	9.7	9.6	9.5	9.5	9.4	9.3	9.2	9.2	9.1	9.0	9.0	8.9	8.8
	2.2	11.3	11.2	11.1	11.0	10.9	10.8	10.7	10.6	10.6	10.5	10.4	10.3	10.2	10.1	10.1	10.0	9.9	9.8	9.8	9.7	9.6	9.5	9.5	9.4	9.3	9.3
	2.3	11.8	11.7	11.6	11.5	11.4	11.3	11.2	11.1	11.0	10.9	10.9	10.8	10.7	10.6	10.5	10.4	10.3	10.3	10.2	10.1	10.0	10.0	9.9	9.8	9.7	9.7
	2.4	12.3	12.2	12.1	12.0	11.9	11.8	11.7	11.6	11.5	11.4	11.3	11.2	11.1	11.0	11.0	10.9	10.8	10.7	10.6	10.5	10.5	10.4	10.3	10.2	10.2	10.1
	2.5	12.8	12.7	12.6	12.5	12.4	12.3	12.2	12.1	12.0	11.9	11.8	11.7	11.6	11.5	11.4	11.3	11.2	11.1	11.1	11.0	10.9	10.8	10.7	10.6	10.6	10.5
	2.6	13.3	13.2	13.1	13.0	12.8	12.7	12.6	12.5	12.4	12.3	12.2	12.1	12.0	11.9	11.8	11.7	11.7	11.6	11.5	11.4	11.3	11.2	11.1	11.1	11.0	10.9
	2.7	13.8	13.7	13.6	13.4	13.3	13.2	13.1	13.0	12.9	12.8	12.7	12.6	12.5	12.4	12.3	12.2	12.1	12.0	11.9	11.8	11.7	11.6	11.6	11.5	11.4	11.3
	2.8	14.3	14.2	14.0	13.9	13.8	13.7	13.6	13.5	13.3	13.2	13.1	13.0	12.9	12.8	12.7	12.6	12.5	12.4	12.3	12.2	12.2	12.1	12.0	11.9	11.8	11.7
	2.9	14.8	14.6	14.5	14.4	14.3	14.2	14.0	13.9	13.8	13.7	13.6	13.5	13.4	13.3	13.2	13.1	13.0	12.9	12.8	12.7	12.6	12.5	12.4	12.3	12.2	12.1
	3.0	15.3	15.1	15.0	14.9	14.7	14.6	14.5	14.4	14.3	14.1	14.0	13.9	13.8	13.7	13.6	13.5	13.4	13.3	13.2	13.1	13.0	12.9	12.8	12.7	12.6	12.5
	3.1	15.7	15.6	15.5	15.3	15.2	15.1	15.0	14.8	14.7	14.6	14.5	14.4	14.3	14.1	14.0	13.9	13.8	13.7	13.6	13.5	13.4	13.3	13.2	13.1	13.0	12.9
	3.2	16.2	16.1	15.9	15.8	15.7	15.5	15.4	15.3	15.2	15.1	14.9	14.8	14.7	14.6	14.5	14.4	14.3	14.1	14.0	13.9	13.8	13.7	13.6	13.5	13.4	13.3
	3.3	16.7	16.6	16.4	16.3	16.1	16.0	15.9	15.8	15.6	15.5	15.4	15.3	15.1	15.0	14.9	14.8	14.7	14.6	14.5	14.3	14.2	14.1	14.0	13.9	13.8	13.7
	3.4	17.2	17.0	16.9	16.7	16.6	16.5	16.3	16.2	16.1	15.9	15.8	15.7	15.6	15.5	15.3	15.2	15.1	15.0	14.9	14.8	14.7	14.5	14.4	14.3	14.2	14.1
	3.5	17.7	17.5	17.4	17.2	17.1	16.9	16.8	16.7	16.5	16.4	16.3	16.1	16.0	15.9	15.8	15.6	15.5	15.4	15.3	15.2	15.1	15.0	14.9	14.7	14.6	14.5
	3.6	18.1	18.0	17.8	17.7	17.5	17.4	17.2	17.1	17.0	16.8	16.7	16.6	16.4	16.3	16.2	16.1	15.9	15.8	15.7	15.6	15.5	15.4	15.3	15.1	15.0	14.9
	3.7	18.6	18.4	18.3	18.1	18.0	17.8	17.7	17.5	17.4	17.3	17.1	17.0	16.9	16.7	16.6	16.5	16.4	16.2	16.1	16.0	15.9	15.8	15.7	15.5	15.4	15.3
	3.8	19.1	18.9	18.7	18.6	18.4	18.3	18.1	18.0	17.9	17.7	17.6	17.4	17.3	17.2	17.0	16.9	16.8	16.7	16.5	16.4	16.3	16.2	16.1	15.9	15.8	15.7
	3.9	19.5	19.4	19.2	19.0	18.9	18.7	18.6	18.4	18.3	18.1	18.0	17.9	17.7	17.6	17.5	17.3	17.2	17.1	16.9	16.8	16.7	16.6	16.5	16.3	16.2	16.1
	4.0	20.0	19.8	19.7	19.5	19.3	19.2	19.0	18.9	18.7	18.6	18.4	18.3	18.2	18.0	17.9	17.7	17.6	17.5	17.4	17.2	17.1	17.0	16.9	16.7	16.6	16.5

Using the PCSC, it was confirmed that, within the velocity impact range calculated from Searle, the pedestrian was crossing the highway with a speed varying from 2.4 to 2.8 m/s. This scientifically corroborate with the driver’s statement that the pedestrian was running.

4.2 Pedestrian crossing speed validation. Case ID: 3 [19]

The final accident took place in the UK, where vehicles drive on the left hand side. A pedestrian crossed the road from left to right at a pelican crossing located after a roundabout. The pedestrian was intoxicated and did not action the light. A first vehicle driving on the left hand side saw the pedestrian crossing at ‘slow speed’ and braked. A second vehicle overtook the first vehicle and hit the pedestrian after it had passed the stopped car. Vehicle damage evidence for this case is listed in Appendix C.

The Police Force could not use the Searle’s equations in-spite of the fact that the throw distance could be measured. The driver confirmed that the pedestrian head stayed attached to the windscreen for a small duration. Damage to the windscreen suggested that the impact was not instantaneous and that the pedestrian was carried by the vehicle, hence the Searle’s method could not be used.

The Police Force estimated that, based on literature review on vehicle damage [10], the vehicle speed would be in excess of 35mph (16.44m/s), but no definitive speed could be given [16]. The impact was typical of a summersault/ roof vault category [21], in which the pedestrian hit the vehicle more than once, i.e. roof and boot as well. This is accident pattern is caused by a high speed impact (37mph and above) in which the pedestrian centre of gravity is higher than the bonnet leading edge.

The pedestrian leg length is extracted from the CT-scan. The smear marks of the left hand side off the centre line of the bonnet were caused by a bag the pedestrian was carrying at the time of the accident.

The point of impact is around 50mm past the windscreen impact; consequently, it has been counted as -50 mm (negative) in the accident table.

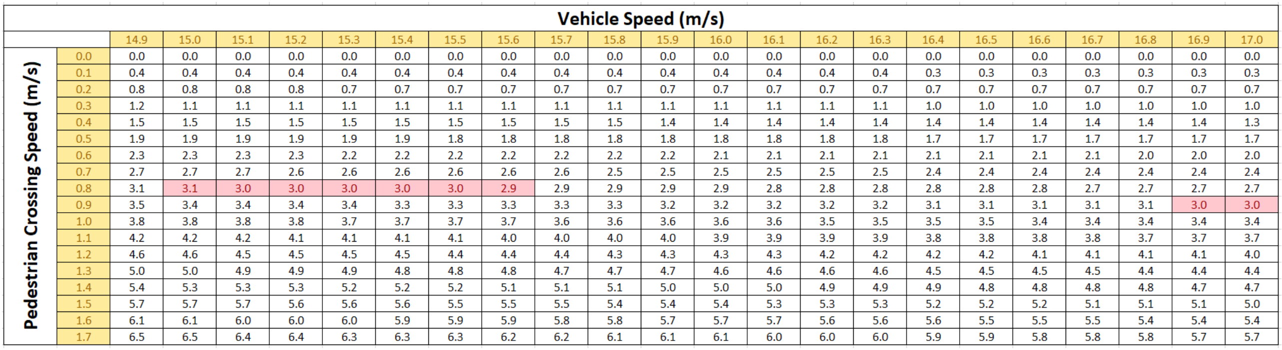
Both legs were broken (CT-Scan), however the right leg displayed a vehicle lower spoiler feature, meaning that the right leg was impacted first. The impact on the bumper is aligned with the head strike, as can be observed vehicle picture in Appendix C. Critical vehicle damage dimensions were extracted from the blueprint [25], as the vehicle was also destroyed. As no evasive manoeuvre was performed by the vehicle and that the pedestrian crossed at a light, it is assumed that the pedestrian’s path was perpendicular to the vehicle at the time of impact, therefore α is ‘0’.

Table 10: Summary of evidence for Case 3

Accident Data (see Appendix C)	**Case ID: 3**	
Damage marks measured on vehicle	Vehicle impacting pedestrian from	Right
	Relative distance across vehicle between bumper dent an head strike (W) (mm)	-50
	Distance of head strike from bonnet (plan view) (H) (mm)	1945
	Dent top of grille from ground height (mm)	454
Pedestrian anthropometry	Length of legs (mm) – from PM	871
Accident derived parameters from evidence	Leg impacted	Right
	α: pedestrian crossing direction	0
	Gait	Front Leg Hit

The pedestrian was seen walking by the first vehicle driver; however, this was not possible to prove this.
By observing the damage on the in-print of the bonnet, the pedestrian damage is suggested to be of medium importance; hence the gait will be expected to be around 20 deg.

Table 11: Angle search as per Equation 4 for Case 3



		Vehicle Speed (m/s)																					
		14.9	15.0	15.1	15.2	15.3	15.4	15.5	15.6	15.7	15.8	15.9	16.0	16.1	16.2	16.3	16.4	16.5	16.6	16.7	16.8	16.9	17.0
Pedestrian Crossing Speed (m/s)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.1	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	0.2	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	0.3	1.2	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	0.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.3
	0.5	1.9	1.9	1.9	1.9	1.9	1.9	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.7	1.7	1.7	1.7	1.7	1.7	1.7
	0.6	2.3	2.3	2.3	2.3	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.0	2.0	2.0
	0.7	2.7	2.7	2.7	2.6	2.6	2.6	2.6	2.6	2.6	2.5	2.5	2.5	2.5	2.5	2.5	2.4	2.4	2.4	2.4	2.4	2.4	2.4
	0.8	3.1	3.1	3.0	3.0	3.0	3.0	3.0	2.9	2.9	2.9	2.9	2.9	2.8	2.8	2.8	2.8	2.8	2.8	2.7	2.7	2.7	2.7
	0.9	3.5	3.4	3.4	3.4	3.4	3.3	3.3	3.3	3.3	3.3	3.2	3.2	3.2	3.2	3.2	3.1	3.1	3.1	3.1	3.1	3.0	3.0
	1.0	3.8	3.8	3.8	3.8	3.7	3.7	3.7	3.7	3.6	3.6	3.6	3.6	3.6	3.5	3.5	3.5	3.5	3.4	3.4	3.4	3.4	3.4
	1.1	4.2	4.2	4.2	4.1	4.1	4.1	4.1	4.0	4.0	4.0	4.0	3.9	3.9	3.9	3.9	3.8	3.8	3.8	3.8	3.7	3.7	3.7
	1.2	4.6	4.6	4.5	4.5	4.5	4.5	4.4	4.4	4.4	4.3	4.3	4.3	4.3	4.2	4.2	4.2	4.2	4.1	4.1	4.1	4.1	4.0
	1.3	5.0	5.0	4.9	4.9	4.9	4.8	4.8	4.8	4.7	4.7	4.7	4.6	4.6	4.6	4.6	4.5	4.5	4.5	4.5	4.4	4.4	4.4
	1.4	5.4	5.3	5.3	5.3	5.2	5.2	5.2	5.1	5.1	5.1	5.0	5.0	5.0	4.9	4.9	4.9	4.8	4.8	4.8	4.8	4.7	4.7
	1.5	5.7	5.7	5.7	5.6	5.6	5.6	5.5	5.5	5.5	5.4	5.4	5.4	5.3	5.3	5.3	5.2	5.2	5.2	5.1	5.1	5.1	5.0
	1.6	6.1	6.1	6.0	6.0	6.0	5.9	5.9	5.9	5.8	5.8	5.7	5.7	5.7	5.6	5.6	5.6	5.5	5.5	5.5	5.4	5.4	5.4
	1.7	6.5	6.5	6.4	6.4	6.3	6.3	6.3	6.2	6.2	6.1	6.1	6.1	6.0	6.0	6.0	5.9	5.9	5.8	5.8	5.8	5.7	5.7

Using the same method in section 3.0 and selecting the vehicle impact speed range from literature for such impacts (37mph and above), it was confirmed that the pedestrian crossing speed was under 1.0m/s. A toxicology report confirmed that the pedestrian was intoxicated, which confirms that the crossing speed extracted is believable.

5.0 Discussion

This validation phase has shown that the Pedestrians Crossing Speed Calculator (PCSC) has the capability to extract the pedestrian crossing velocity when the vehicle impact range in known. The PCSC has been validated against one real life accident scenario, in which the extract vehicle and pedestrian velocities were known. As there are no other numerical methods available, this makes PCSC a useful forensic tool, especially when video evidence is not available. PCSC has also managed to vindicate witness statements (Case 2 and Case 3), hence allowing the Police Force to assess the time allowable for the driver to perform evasive manoeuvres.

Case 1 suggests that the method is also reversible, meaning that if the pedestrian speed is known then it is theoretically possible to calculate the vehicle impact speed. However, because this method is using a direction vector method, it is not possible to extract all the time an accurate and useful vehicle impact speed from the pedestrian crossing speed. This can be shown in Figure 8, which illustrates two impact cases with different pedestrian projections $\lambda1$ and $\lambda2$, with $\lambda2 > \lambda1$. Should information be provided about the pedestrian crossing speed by a witness, then assuming a crossing margin, it is possible to extract the vehicle impact speed range. In Figure 8, it can be observed that the narrower the pedestrian projection value of λ, the greater the error in estimating the vehicle speed as its speed range will be greater than with a wider value of λ.

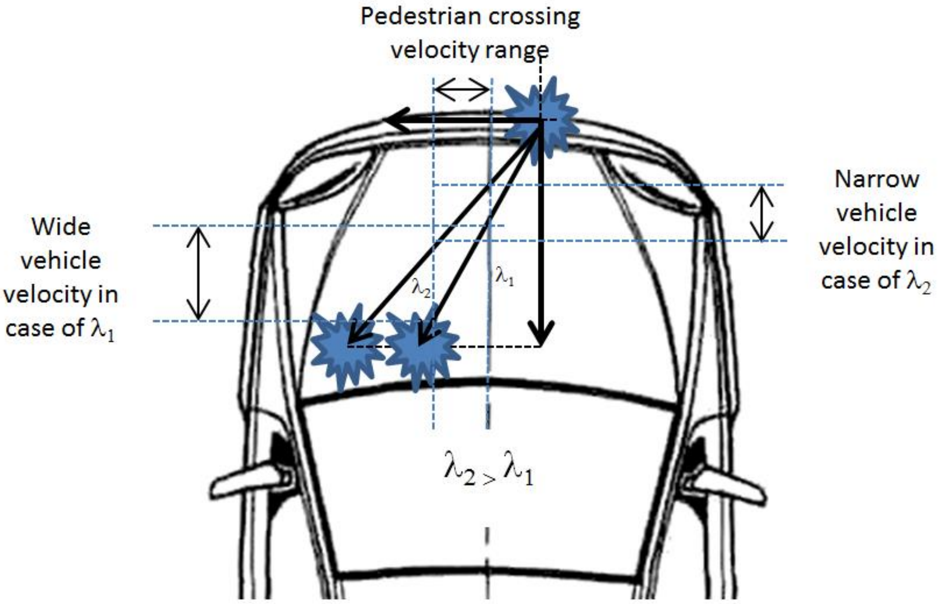


Figure 8: Effect of vehicle impact speed range extraction as function of λ

This can be confirmed from the 3 cases studied in this research, by observing the vehicle impact speed values

from

Table 7 for Case 1 and Table 9 for Case 2, in which the pedestrian is projected across the bonnet, and Table 11 for Case 3, where the pedestrian projection is nearly aligned with the vehicle direction. In Case 1, for a pedestrian crossing velocity between 3.5 m/s and 4.0 m/s (0.5m/s range), the vehicle speed range varies from 14.1 m/s to 16.1 m/s, or 2.0m/s. In Case 2 for a pedestrian crossing velocity of 2.4 m/s and 2.9 m/s (also 0.5m/s range), then the vehicle speed range changes from 11.0 m/s to 13.5 m/s, or 2.5 m/s. In Case 3, for the same pedestrian crossing speed range of 0.5m/s, the vehicle speed range is 8.7m/s, hence a lot larger, which is not desirable.

Hence the usefulness of this method to extract a narrow vehicle impact speed from the pedestrian crossing speed depends on a high pedestrian cross velocity component, as illustrated in Figure 8. Consequently, the condition to extract a narrow vehicle impact speed depends on knowing the pedestrian impact speeds as well as relying on a large cross projection angle. In Case 3, had the projection angle been wider, then the method would have been able to calculate the vehicle impact speed, using as crossing speed the witness statement from the first vehicle driver who alleged that the pedestrian was walking. Had this happened the proposed method would have been able to compute the vehicle speed at impact, which the Searle method would have been incapable to do, as the pedestrian's head stayed attached to the windscreen during the impact.

Searle's method usually represents a believable estimation of vehicle impact speed when compared to real-life accident data (Figure 1), is convenient, easy to use and well accepted in court proceedings. It is believed that Searle and PCSC methods are both complementary and can co-exist to provide a better understanding of pedestrian accidents, i.e. from the vehicle perspective (speed), the driver (time to react, state of mind) and the pedestrian (speed). Prior to the PCSC method, only the vehicle perspective was available.

In order to implement this new method, the following information will be needed for the investigation:

- Request from paramedics on site or the PM from the coroner:
    - Record pedestrian head skull damage and refer to
    -
    - Table 3,
    - Measure the pedestrian leg length in-situ or request dimension from PM or CT-Scan (or use anthropometric standard deviations, as used in Case 2). 3D laser scene scanning could also be useful to the capture the deceased geometry in situ,
- Measure vehicle dimensions:
    - (W) and (H) from 3D laser scene scanning or measuring tape (planar view),
    - (D) damage height from ground at impact point,
- Observe the bonnet damage or smear marks and classify the pedestrian gait as per Table 2.

Another use of this method is in the field on Computer Aided Engineering (CAE) accident reconstruction in which positioning pedestrian [22] as well as defining the crossing velocity is always cumbersome, lengthy and CPU intensive. The PCSC will speed up the pre-processing of accident reconstruction by allowing an early and plausible pedestrian positioning without the need to perform design of experiments and Monte-Carlo analysis to estimate the mostly likely gait and crossing velocity.

6.0 Conclusions

A new Road Traffic Accident forensic tool, Pedestrian Crossing Speed Calculator (PCSC), has suggested that it was possible to calculate pedestrian crossing velocities at impact, by considering vehicle damage markers, pedestrian anthropometric dimensions and vehicle speed range extracted using Searle equations. The method creates a family of pedestrian impact projection angles based on the real-life evidence which are then compared to angles created from theoretical pedestrian crossing and vehicle impact speeds to extract accident events. This new method correlated to a real life accident for which the vehicle impact speed and the pedestrian crossing speeds were accurately extracted from on-board camera video analysis performed by the Police Force, by predicting the pedestrian crossing speed with a 6% accuracy. It was successfully used to verify the veracity of witness statements in two other accident cases. The use of results from this proposed methodology should be considered together with other available evidence when attempting to determine the speed at which a pedestrian crossed a carriageway - and therefore determine the time they were available to be seen by the driver (and conversely, the time available for the pedestrian to observe the vehicle). The PCSC tool can also be reversed to compute the vehicle impact speed range from a known pedestrian crossing speed. The vehicle impact speed accuracy range increases with the pedestrian cross projection on the bonnet.

PCSC can also be a very useful pedestrian positioning tool for accident reconstruction computer modelling, as it can directly provide the right pedestrian gait and crossing velocity, reducing therefore lengthy and expensive statistical computation to evaluate the most likely pedestrian gait and crossing speed.

It is understood that more accident cases would be needed to fully validate this method, the challenge being to obtain such rare cases containing video evidence, accident report and PM data.

7.0 Limitations and future work

The authors agree that the PSCS theory which has been derived shows some potential; however, it has not been fully validated, as only one impact was used to test the methodology. With more real-life data permitting, the validation will be re-visited. In parallel, a numerical validation could be envisaged in order to quantify the hypothesis proposed in Table 2 which states that the gait is a function of the pedestrian in-print in the body structure. It has been observed using accident data that bonnet damage was not always fully detected because of the metallic springback effect, which suggests a smaller pedestrian contact area than during actual impact phase. Photographic evidence can however be used to estimate this area, as the bonnet dirt is smudged when a pedestrian is rolling on top of it. The gait hypothesis appears to work with the PCSC equations nevertheless some more investigation may still be required.

The validation case considered a perpendicular impact. It would be necessary to obtain an oblique impact to test the generic equations derived in this paper and investigate the sensitivity of the prediction accuracy as function of the pedestrian crossing angle α.

As such accident evidence is rare (Video with access to CT-scan and Post-Mortem report), it can be envisaged that the PCSC equations could be tested against Finite Element computer models, using human computer models like THUMS4.02 [26] impacting available numerical sedan vehicles [27]. Accident scenarios can be set with known vehicle speeds, pedestrian crossing velocities and angles and the theory evaluated. It is suggested that numerical simulations will be the next stage to validate the PCSC method, and as such provide a robust evidence gathering process for future court proceedings.

It is believed that PCSC is unsuitable from high frontend vehicles, like buses, because the value of β will be difficult to extract in such cases.

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Appendix A: Evidence case: 1

Figure 9: Vehicle involved in accident (Case: 1)

Appendix B: Evidence case: 2

Figure 10: Vehicle involved in accident (Case 2)

Appendix C: Evidence case: 3

Figure 11: Vehicle involved in accident (Case: 3)