Confidence limits for impact speed estimation from pedestrian projection distance

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Abstract: A key element of study of the biomechanics of pedestrian injuries from vehicle collisions is the determination of pre-impact vehicle speed. Pedestrian projection distances are an important means to determine collision speed, particularly as tyre brake marks are not readily observable with ABS brakes. A number of models have been developed by the authors, which include recent analytical models for forward [1] and wrap projection [2] impact. These models are novel as they include explicit modeling of the impact phase. They have been validated against the available test data, showing very good comparisons, and are therefore ideal for further statistical analysis.

Confidence limits for speed estimates are set out for various purposes including injury research and litigation. The models show that the distribution of predicted collision speeds from projection distance can be large when a high degree of confidence is required. Some of this uncertainty is due to the impact phase where parameters such as duration and restitution are unknown for individual collisions, in addition to other confounding factors that are difficult to quantify. However the effects of the coefficient of retardation during the projection phase and the mass ratio between pedestrian and the striking vehicle can be readily determined. This paper analyses the influence of reduced variability of the input parameters on the predicted range of impact velocities. Analysis for known coefficients of retardation and mass ratio values yields the minimum prediction uncertainty due to the variability of the impact phase parameters alone. Results show that significant improvements in prediction uncertainty can be achieved by exact knowledge of the pedestrian to vehicle mass ratio and of the coefficient of retardation between the pedestrian and the road surface. In practice, while the mass ratio can be determined for individual collisions there is significant uncertainty as to the coefficient of retardation values, as these are influenced by the kinematics of the pedestrian during projection and ground impacts, in addition to factors such as road surface condition and contamination. However, overall data is available for wet and dry road conditions. Tables are presented for impact speed prediction from projection distance for various conditions and confidence levels.

Key words: Pedestrian collisions, throw distance, prediction uncertainty, confidence limits

NOTATION

V_{col}	= Vehicle speed at impact (m/s)
V_{proj}	= Pedestrian projection velocity following impact (m/s)
M_r	$= \dfrac{M_{vehicle} + M_{pedestrian}}{M_{vehicle}}$ = Vehicle/Pedestrian Mass ratio
S	= Pedestrian throw distance (m)
A, B, C, D, S_o	= Regression parameters

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INTRODUCTION

Pedestrian fatalities from vehicle collisions vary with environment, urban or rural and country. In the European Community 16% of road deaths are pedestrians. The corresponding figures for the United States and Japan are 13% and 27% respectively while in the developing world pedestrian fatalities are up to 47% of all road deaths [3]. While the age and state of health of the pedestrian, the nature of the impact and vehicle design all affect the injury outcome, the prime factor in injury risk is the vehicle speed. This has implications for legislators in designing speed limits for built up areas, for safety engineers to reduce vehicle aggressivity, biomechanics research into injury causation and legal implications in determining driver culpability and pedestrian compensation following an accident.

Methods traditionally used to estimate vehicle speed include the use of witness statements, tyre skid marks on the road, impact locations on the vehicle, and pedestrian projection distance. However, witness statements are unreliable, tyre skid marks are largely absent in the case of ABS braking and impact locations on the vehicle are highly dependent on the collision circumstances and, at high speed, substantially independent of impact speed. The use of pedestrian projection distance as a measure of pre-impact vehicle speed is therefore increasingly important, and a variety of methods are used by accident investigators to measure the projection distance from physical evidence at the scene of the accident.

The methods used to predict speed from projection distance can be categorised as empirical [4,5,6], deterministic [7,8,9] or statistical [1,2,10]. Empirical models are derived from test data and/or real life collisions where collision speeds are known from other sources using regression curves and do not contribute towards understanding the physical nature of the impact and projection processes. Deterministic models derive from fundamental equations while statistical models allow for variability of the collision circumstances. Thus empirical and statistical models provide a range of predicted vehicle speeds for a given projection distance, while deterministic models provide a single estimate of vehicle speed without confidence bounds.

In reality, all the factors relating the precise projection distance to impact speed cannot be determined, and a degree of uncertainty is inevitable. In this paper two validated analytical statistical models for forward and wrap type pedestrian impacts are analysed to provide overall confidence limits for collision speeds from projection distance. The models are used to determine the reduction of prediction uncertainty that can be achieved if further knowledge of the input parameters is available. Unlike other models that concentrate on the pedestrian projection phase of pedestrian-vehicle collisions, the models used here explicitly model both the impact and projection phases.

CONFIDENCE LIMIT CRITERIA

Impact speed estimates in pedestrian-vehicle collisions are required for a variety of purposes: general traffic safety studies, biomechanical injury research, crashworthiness design for injury reduction, personal injury litigation and criminal prosecutions. Each requires differing degrees of certainty regarding the accuracy of the speed estimates. The mean speed prediction is not of great value as no single real world collision is likely to conform to the mean. Statistical models yield a range of predicted collision speeds for a given projection distance. To cater for the various applications it is proposed that three different confidence levels be considered:

1. The $50\%^{ile}$ range between the lower $25\%^{ile}$ to the upper $25\%^{ile}$ limits. This is the 'Probable' range, as there is 50% likelihood that the vehicle speed is bounded by these limits. This confidence range is of value in general injury and traffic safety studies and in civil law when the confidence required of the speed estimate is only that of 'on the balance of probability'.
2. The $95\%^{ile}$ range from the lower $2.5\%^{ile}$ to the upper $2.5\%^{ile}$ limits. This is the 'Normal' confidence limit and corresponds to the range of collision speeds in the majority of impacts. This range has application in general civil law and in-depth biomechanics research.
3. The $99.8\%^{ile}$ range from the lower $0.1\%^{ile}$ to the upper $0.1\%^{ile}$ limit. These are the 'Overall' confidence limits where the likelihood of the collision speed being less than or more than the confidence range is each 1 in 1000. The lower limit corresponds to the stringent requirement of 'beyond reasonable doubt' required for criminal law cases.

PEDESTRIAN IMPACT AND PROJECTION: KINEMATIC OBSERVATIONS

The preponderance of pedestrian collisions is with the fronts of vehicles. Some of these frontal collisions are with the corners of the vehicles where the pedestrian is deflected to one side without coming into full contact with the vehicle front. However the majority of pedestrian collisions involve a full impact with the vehicle [11], and these are classified as either 'Wrap' or 'Forward' projection collisions.

Forward projection occurs when a high-fronted vehicle strikes a pedestrian, or a passenger vehicle strikes a child pedestrian. Here the pedestrian's centre of gravity is below the leading edge of the bonnet and above bumper level. The impact essentially projects the pedestrian horizontally with the pedestrian's feet in contact with the ground, though the shoulders and head may rotate about the bonnet edge and impact its upper surface. After the impact phase there follows the pedestrian fall-over phase and subsequent pedestrian to ground impacts with slide, roll and bounce to rest.

There are a variety of confounding factors during each phase including vehicle geometry, impact duration, restitution effects between the pedestrian and vehicle front, pre-impact pedestrian transverse velocity, vehicle braking, the extent of contact between the pedestrian's feet and the ground during fall-over and the nature of the bounce-roll-slide to rest.

Wrap projection occurs when the centre of gravity of the pedestrian is higher than the leading edge of the bonnet resulting in rotation (wrap) of the pedestrian over the bonnet. The front of the vehicle strikes the legs and thigh/

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pelvic areas (primary impact) and this is followed by secondary (head and/or shoulder) impact with the vehicle after which continued interaction with the vehicle can occur, or a flight phase or a combination of both, which is followed by ground impact(s) and slide, roll and bounce to rest. However, as with forward projection, a variety of confounding factors determines the precise kinematics. Wrap projection typically occurs for an adult pedestrian struck by a passenger car.

MODELS

Forward projection

The forward projection model considers pedestrian movement during the three phases of initial impact, falling over and slide/roll/bounce to rest, Figure 1. The mathematical basis has been previously reported and includes the impact elements of mass ratio, impact duration and restitution effects [1].

Validation

The Monte Carlo method was used to account for the statistical uncertainty of the input parameters. The resulting scatter of velocity prediction data as a function of throw distance was compared to the available test data for real life adult [12,13] and child [14] forward projection cases, see Figure 2. The model clearly encompasses the test data very well in both cases. Furthermore, the correlation between $S^{1/2}$ and V_{col} is clear and a linear regression of the form

$$V_{col} = A\sqrt{S} + B \qquad [1]$$

yields very high correlation coefficients in both adult and child cases, see Table 1. Using these regressions, the predicted velocities were evaluated at each of the experimental throw distances. A student t test revealed no significant difference between the test and predicted velocities at a 95% confidence level for both adult and child models ($t = -0.38, -1.4$ respectively). It is therefore concluded that the model provides a very good method of predicting collision velocity from throw distance for forward projection cases.

Wrap projection

The wrap model presented in this paper considers pedestrian movement during the three phases of pedestrian to vehicle impact including wrap over the bonnet and restitution, flight and slide/roll/bounce to rest, see figure 3. The mathematical basis of this model has been previously reported [2,15].

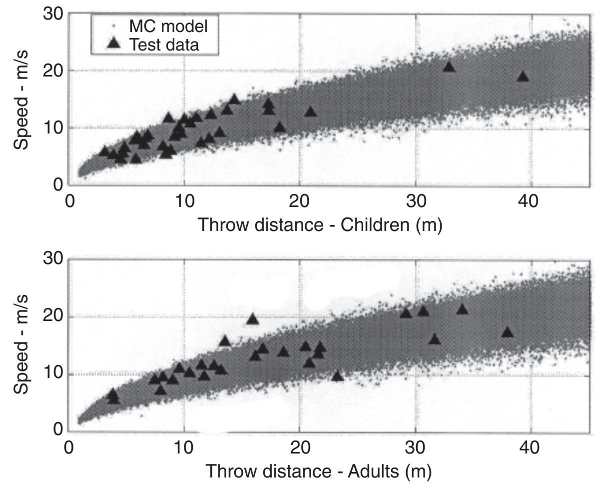

Figure 2 Forward projection models compared to real accident data (▲).

Validation

As with forward projection, this model was run using the Monte Carlo method to account for statistical uncertainty of the input parameters. The resulting scatter of data was compared to the available test data for real life cases [13,16,17,18,19,20,21], see Figure 4. The scatter of the model clearly encompasses the test data very well. For the wrap model, the linear relationship between $S^{1/2}$ and V_{col} does not hold at very low speeds and a power regression of the form

$$V_{col} = C \times [S - S_0]^D \qquad [2]$$

is more appropriate. The value of S_o was chosen to maximise the regression correlation and the model parameters are given in Table 1. Using these regressions, the predicted velocities were evaluated at each of the experimental throw distances. A student t test revealed no significant difference between the test and predicted velocities at a 95% confidence level ($t = -0.61$). It is therefore concluded that the model provides a very good method of predicting collision velocity from throw distance for wrap projection cases.

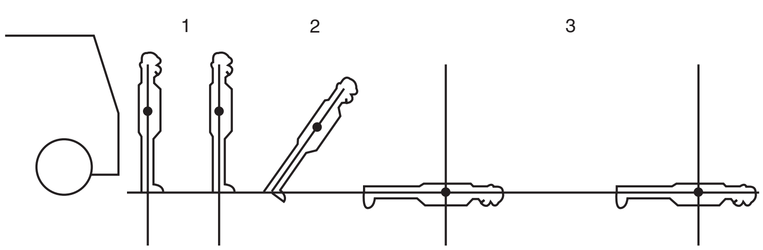

Figure 1 Forward projection model: impact (1), fall over (2) and slide to rest (3).

Table 1 **Global Wrap and FP model limits: Collision velocity estimation when only throw distance and impact type are known**

Confidence level for velocity Prediction	Forward projection ($V_{col}(m/s) = A\sqrt{S(m)} + B$)						Wrap projection ($V_{col}(m/s) = C \times [S(m) - S_o]^D$)			
	Adults			Children						
	A	B	r	A	B	r	So	C	D	r
Probable Lower	3.5	–1.7	0.99	3.4	–1.6	0.99	1.8	3.7	0.47	0.99
Probable Upper	3.9	–1.5	0.99	3.8	–1.4	0.99	1.4	4.3	0.46	0.99
Normal Lower	3.0	–1.6	0.99	2.9	–1.5	0.99	1.9	2.9	0.49	0.99
Normal Upper	4.3	–1.4	0.99	4.1	–1.2	0.99	1.2	4.8	0.46	0.99
Overall Lower	2.5	–1.3	0.99	2.4	–1.2	0.99	1.9	2.3	0.51	0.99
Overall Upper	4.6	–1.2	0.99	4.4	–1.0	0.99	1.2	5.3	0.46	0.99

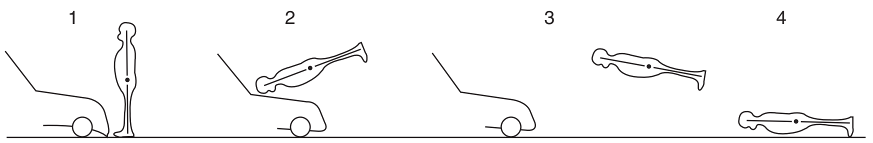

Figure 3 Schematic showing three stages of wrap projection: impact (1–2), projection & flight (2–3) and slide to rest (4).

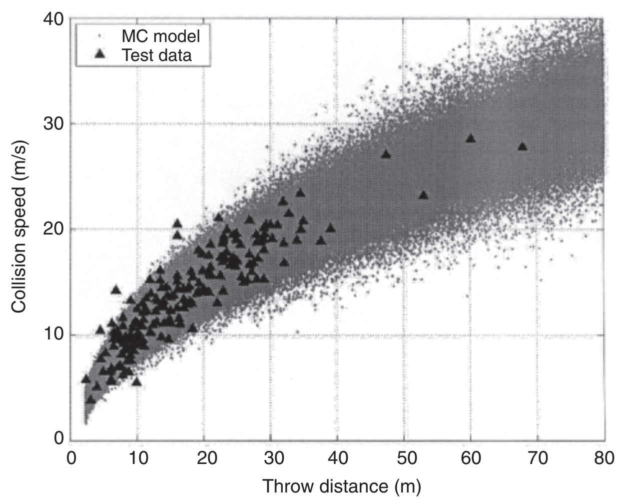

Figure 4 Wrap model comparison to real accident data (▲).

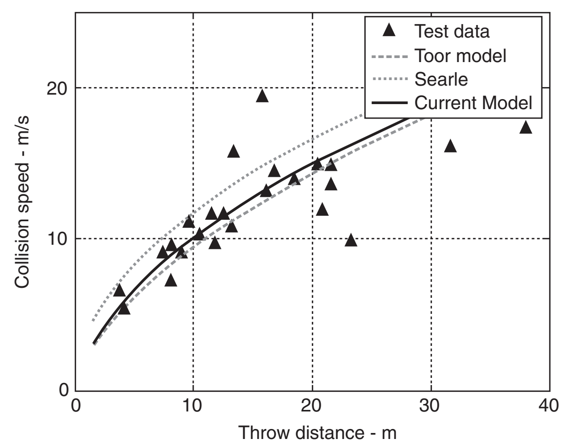

Figure 5 Comparison of current adult forward projection model with previous work.

Previous models: forward projection

Searle [9,10] derived a particle model for pedestrian projection, and provided a prediction for forward projection which overestimates the test data, mainly due to the high value of retardation he used ($\mu = 0.7$), see Figure 5. Previous analysis [22] has shown that the mean coefficient of retardation from tests by a variety of researchers is ($\mu = 0.561$) with a standard deviation of 0.101, see Table A.1. The deficiency of Searle's model is that it does not model the impact phase of the collision. More recently, Toor et al [6] derived an empirical model yielding mean velocity for forward projection cases, see Figure 5. The mean prediction for the current model is also shown. The Toor et al. model over-predicts velocity at high throw distances, despite being empirically derived. This highlights the pitfalls of an empirical approach – the predictions are only correct for the test cases considered.

Comparison to other models: wrap projection

Searle's particle model predicts a minimum projection velocity for a given throw distance, launch angle, projection velocity and coefficient of retardation (again, Searle assumed $\mu = 0.7$, which is too high [22]). The resulting minimum velocity prediction fails to provide a reliable lower bound of the test data, see Figure 6a. Furthermore, as previously mentioned, the impact phase is not modeled. More recently, Evans & Smith [4] and Toor et al. [6] developed empirical models for velocity prediction based on regressions of test data, see Figure 6a&b. The available real life data for wrap projection cases, and the predictions from the current work are also shown. Evans & Smith provide a mean and minimum velocity prediction, while Toor et al. only present only a mean curve. Finally, Han & Brach [10] developed a semi-analytic model and used regression techniques to derive a mean velocity prediction,

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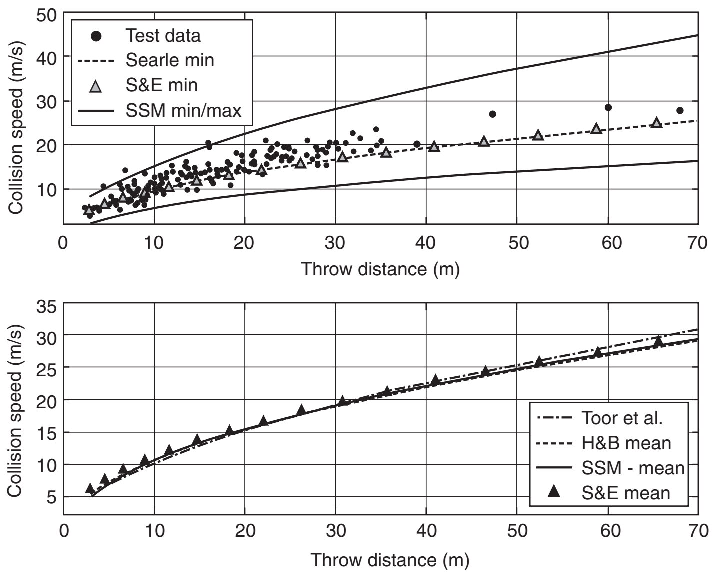

Figure 6 Comparison of the current (SSM) wrap model to previous work & test data.

see Figure 6b. Han & Brach are the only other researchers to consider the impact phase of the collision. However, they have done so using an arbitrary function that has not been validated.

It is clear that the mean velocity predictions from all of these models are very similar, and hence difficult to distinguish in the figure. However, the upper and lower velocity predictions (where available) are subject to considerable variation between researchers. The minimum predictions of Searle [9] and of Evans & Smith [4] are similar but are not reliable as there are many real world cases with impact velocities lying below these limits, particularly at low throw distances. In contrast, the minimum prediction resulting from the current wrap model is substantially robust.

PREDICTIONS

Global predictions

The impact velocity predictions corresponding to each of the three confidence limits were found as follows: the V_{col} versus $S^{1/2}$ data presented in Figures 2&4 were divided into twenty equal-width $S^{1/2}$ bins. The upper & lower V_{col} limit at each confidence level was then found in each bin. Subsequent data reduction was model specific: the forward projection data were regressed using equation 1 and the wrap projection data was regressed using equation 2. The resulting parameters are presented in Table 1 – this table is appropriate for 'global' predictions, i.e. where only projection distance and collision type (Wrap or Forward Projection – adult or child) are known.

In addition to providing upper and lower confidence limit predictions, the models can be used to provide a measure of the prediction uncertainty. The normalized velocity range is defined as

$$\text{norm vel } (\%) = \left[\frac{V_{max} - V_{min}}{V_{mean}}\right] \times 100 \qquad [3]$$

The global 'Probable', 'Normal' and 'Overall' percentage ranges for adult & child Forward Projection and for Wrap Projection respectively are plotted as a function of mean impact speed in Figure 7.

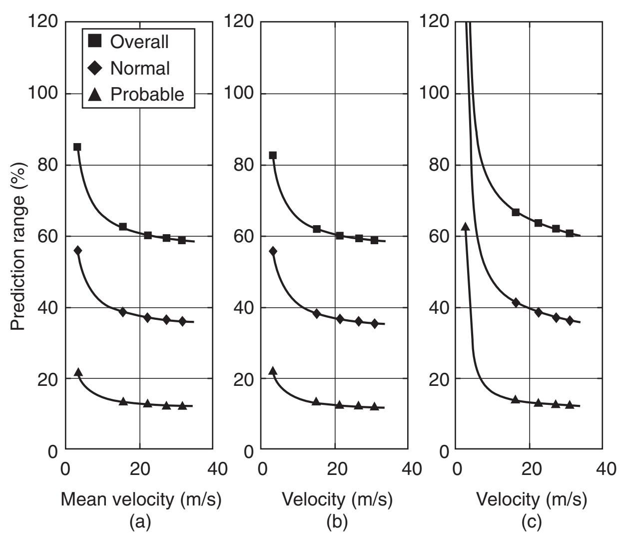

Figure 7 Percentage velocity prediction range for probable, normal and overall limits: Forward projection adults (a), forward projection children (b), SSM wrap model (c).

Speed ranges

Figure 7 shows that the prediction ranges for all three models follow very similar trends. In all cases, the prediction uncertainty is high at low impact speeds. The 'Probable' confidence range is about 12% at collision speeds above

15 m/s. The 'Normal' confidence ranges for the two Forward Projection cases and for Wrap projection are wide (between 35–40% above 15 m/s). The 'Overall' ranges are similar for both forms of projection and are even wider (60–70% above 15 m/s). This represents a 2:1 range between minimum and maximum speed estimates for the 'Overall' range. When only the 'Probable' speed range is required the confidence ranges from these models are acceptable. However, the 'Normal' and 'Overall' variations are so large that it is worthwhile exploring the possibilities of reducing the confidence ranges.

POTENTIAL TO REDUCE UNCERTAINTY

The vehicle-pedestrian collision can be divided into two major stages: impact and projection. Modelling of the impact stage can be improved by specifying the masses of the pedestrian and the vehicle. These can be readily determined post accident. The other factors in the impact stage such as coefficient of restitution, impact duration, influence of pedestrian movement, vehicle structural behaviour and continued vehicle-pedestrian interaction can be statistically represented but cannot be measured post accident. In the projection stage, the key factor is the coefficient of retardation, and again, the other factors such as pedestrian orientation at the instant of ground impact and roll and bounce effects are, in general, unknown. Thus, the two principal parameters to analyse for the purpose of reducing prediction uncertainty are vehicle/pedestrian mass ratio and the coefficient of retardation between the pedestrian and the ground.

Theoretical minimum prediction uncertainty

When both mass ratio and retardation coefficient are known as single values rather than as a statistical distribution, the models yield the theoretical minimum prediction uncertainty. Figure 8 shows this theoretical minimum velocity uncertainty as a function of impact velocity for the three models at each of the three confidence limits. The regression equations are detailed in Table A.2.

Mass ratio effect

The effect of mass ratio follows from momentum considerations and the immediate post impact vehicle velocity is linearly related to pre impact vehicle velocity via the mass ratio. In order to account for this, the models were amended such that the pedestrian/vehicle mass ratio (M_r) was removed and the models then relate throw distance to projection velocity (V_{proj}) rather than collision velocity (V_{col}). The collision velocity is then easily found for a known mass ratio (M_r) using equation 4 (in practice M_r can be readily obtained):

$$V_{col} = V_{proj} * M_r \quad [4]$$

Table A.3 (see Appendix) details the regression parameters of the *projection* velocity predictions. This table is appropriate for accident reconstruction when projection distance, projection type and the pedestrian/vehicle mass ratio are known.

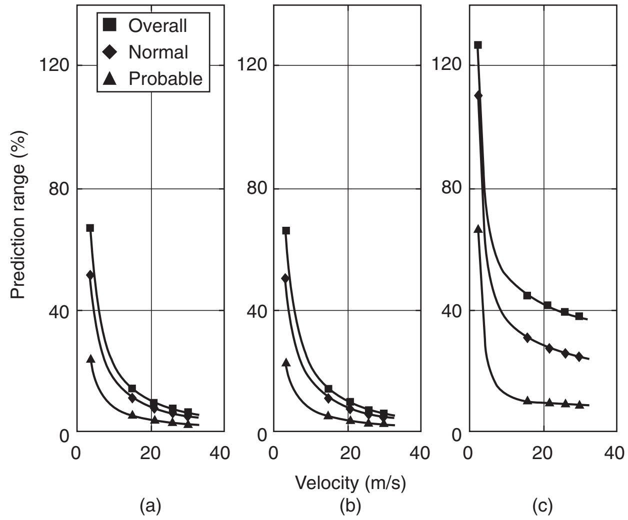

Figure 8 Minimum theoretical velocity prediction ranges: Forward projection adults (a), forward projection children (b), ssm wrap model (c).

Known weather conditions (μ distribution)

The coefficient of friction between the road and the clothing worn by the pedestrian can be measured, but there is no published work to show how such measurements correlate with the coefficient of retardation during the specific collision under consideration. In addition, the actual measurement of coefficient of friction is subject to considerable variation due to slip-stick effects, etc. However, weather conditions at the time of an accident are readily recorded and a literature search revealed data on friction coefficient divided into wet and dry friction data, (Table A.1 in Appendix) [22]. As can be seen, a single data set for wet friction was available, and to determine a standard deviation for this and for the combined wet & dry μ cases, it was assumed that the coefficient of variation (COV) for all sample sets was the same. The COV for the dry μ data was then used to calculate standard deviation for the wet μ model. Tables A.4 & A.5 detail the regression parameters of the collision velocity predictions for the wet and dry cases respectively. These are appropriate for reconstruction when projection distance, projection type and the weather conditions but not mass ratio at the time of the accident are known.

Mass ratio and weather conditions combined

In some cases, it will be possible to have information on both the mass ratio and the weather conditions at the time of the accident, and Tables A.6 & A.7 detail the regression parameters of the collision velocity predictions for the wet and dry cases respectively. These are appropriate where projection distance, projection type, mass ratio and the weather conditions at the time of the accident are all known. The prediction uncertainty for these cases is shown

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in Figures 9 and 10 for the wet and dry conditions respectively.

DISCUSSION

The Wrap and Forward Projection models presented in this paper provide a very good fit to the respective test data and they are therefore suitable as a basis for analyzing the uncertainty present in the velocity prediction for a given throw distance. The global predictions at each confidence level given in Table 1 represent the best velocity estimates that can be achieved if the throw distance is the only information available for reconstruction. The corresponding prediction uncertainty shown in Figure 7 is satisfactory when only the "Probable" speed range is required, i.e. generalised injury and safety studies. However for detailed injury research and criminal litigation the prediction uncertainty is high, especially for the 'Overall' Confidence level. The benefits of more accurate information about the collision, i.e. vehicle and pedestrian masses, and pedestrian/ground retardation coefficient are now assessed.

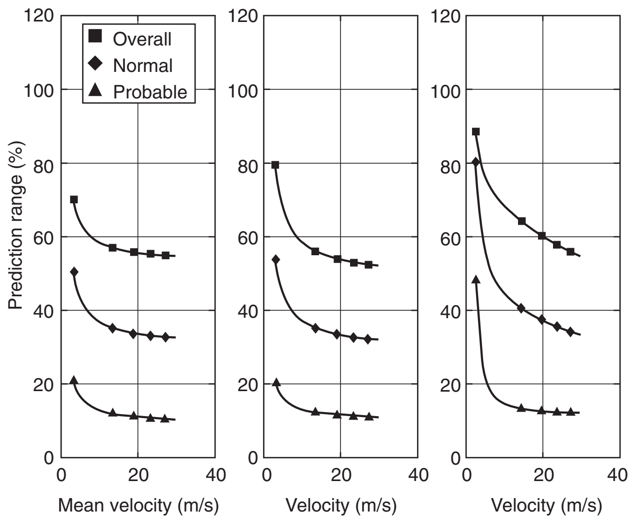

Figure 9 Prediction uncertainty: wet conditions, mass ratio M_r known: Forward projection adults (a), forward projection children (b), SSM wrap model (c).

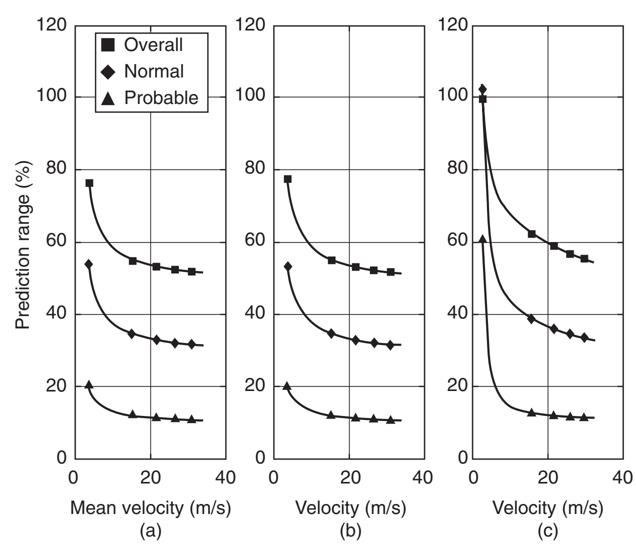

Figure 10 Prediction uncertainty: dry conditions, mass ratio M_r known: Forward projection adults (a), forward projection children (b), SSM wrap model (c).

Theoretical minimum prediction uncertainty

Figure 8 shows the theoretical minimum prediction uncertainty. These are the minimum confidence ranges achievable under ideal conditions of known mass ratio and coefficient of retardation. The theoretical uncertainty for the forward projection cases is smaller than for wrap projection, because the projection angle remains a major source of variation in the latter. Table A.2 (see Appendix) details the regression parameters of the collision velocity predictions. In all models, the theoretical minimum uncertainty (i.e. when retardation coefficient and mass ratio are known) is much lower than the uncertainty in cases where mass ratio is known but retardation coefficient can only be narrowed down to weather type – compare Figure 8 to Figures 9 and 10. The only difference between the two cases is the level of information available for the coefficient of retardation. This analysis therefore strongly indicates that further significant reduction in prediction uncertainty will only occur if improved knowledge of the coefficient of retardation between the pedestrian and the ground can be achieved for the specific collision under consideration.

Known mass ratio (M_r) and weather conditions (μ distribution)

The reduction in prediction uncertainty due to knowledge of the mass ratio (M_r) is masked when using the normalized expression in equation 3. This is because the mass ratio is a linear multiplier applied equally to V_{min}, V_{mean} and V_{max}. Figure 11 shows the probability distribution of the mass ratio, where it is seen that M_r ranges from 1.02–1.18 with the mode at ca. 1.06. This small range in mass ratio produces

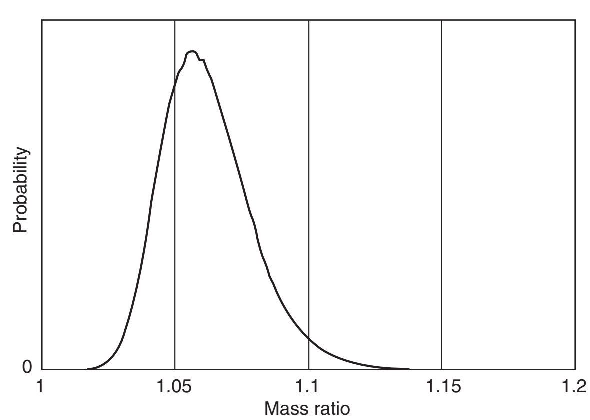

Figure 11 Pedestrian/vehicle mass ratio.

a proportional change in calculated collision velocity that is 'swamped' by the much larger variation in the other parameters (coefficient of retardation, launch angle etc). For this reason, a prediction uncertainty plot of the type shown in Figure 7 for the global model is not presented for these known mass ratio (M_r) cases. Nonetheless, when all other parameters are fixed, knowledge of M_r reduces the overall uncertainty in the velocity predictions by a proportion equal to the variation in M_r seen in Figure 11. For example, in a forward projection case with a 50 m throw distance involving a large adult male of mass 100 kg with a small passenger car mass 800 kg (i.e $M_r = 1.125$), the global model overall lower bound velocity prediction (i.e. no knowledge of M_r or weather conditions) is found using Table 1:

$$V_{\text{col}} = (2.5\sqrt{50} - 1.3) \times 3.6 = 59 \text{ km/h}$$

whereas the mass fix model overall lower bound velocity prediction is (using Table A.3)

$$V_{\text{col}} = 1.125 \times (2.4\sqrt{50} - 1.3) \times 3.6 = 63.5 \text{ km/h}$$

The ratio of the predicted velocities is simply the ratio of the known M_r used in the mass fix model to the mean M_r in the global model. It is concluded that the difference between the two velocity predictions is small but this may still be significant in legal cases.

Comparison of Figures 9 and 10 with Figure 7 shows that knowledge of the mass ratio and weather conditions at the time of the accident produces a reduction in prediction uncertainty. In particular, for the 'Overall' Confidence level at an impact velocity of 20 m/s (ca. 70 km/h), the prediction uncertainty is reduced from 60% to 53–55% in both Forward Projection cases, and a slightly smaller reduction is achieved for the Wrap Projection case, as the launch angle still provides considerable variation.

CONCLUSIONS

The Wrap and forward projection models presented in this paper provide a very good fit to the test data and are therefore suitable as a basis for predicting collision velocity from pedestrian throw distance. In addition, the statistical nature of the models makes them suitable for analyzing the uncertainty present in the velocity prediction for a given throw distance. The models show that knowledge of the pedestrian/vehicle mass ratio has a small influence on the resulting velocity prediction. However, there are more substantial benefits to applying the refined model in cases where a distinction between wet and dry road conditions can be established. Tables are presented to enable reconstruction of vehicle impact speed from throw distance depending on the level of information available and the confidence levels required. Further reduction in prediction velocity uncertainty will require better characterisation of the coefficient of retardation between the pedestrian and the ground.

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APPENDIX

Table A.1 **Pedestrian/ground coefficient of retardation data [22]**

	Wet μ	Dry μ	Combined wet & dry μ
Mean	0.466	0.595	0.561
Std	0.076	0.097	0.1015
Data sets	1	9	10

Table A.2 **Wrap and FP model limits: coefficient of retardation known, mass ratio known. This is the theoretical minimum prediction uncertainty**

Confidence level	Forward projection $\left(\frac{V_{col}(m/s)}{M_r} = A\sqrt{S(m)} + B\right)$						Wrap projection $\left(\frac{V_{col}(m/s)}{M_r} = C \times [S(m) - S_o]^D\right)$			
	Adults			Children						
	A	B	*r*	A	B	*r*	So	C	D	*r*
Probable Lower	3.5	–1.9	0.99	3.4	–1.8	0.99	1.8	3.7	0.47	0.88
Probable Upper	3.5	–1.1	0.99	3.4	–1.0	0.99	1.3	4.0	0.46	0.99
Normal Lower	3.5	–2.4	0.99	3.5	–2.3	0.99	1.7	2.8	0.51	0.99
Normal Upper	3.4	–0.6	0.99	3.4	–0.5	0.99	1.0	4.3	0.47	0.99
Overall Lower	3.5	–2.6	0.99	3.5	–2.5	0.99	1.6	2.5	0.53	0.99
Overall Upper	3.4	–0.3	0.99	3.4	–0.1	0.99	0.9	4.6	0.47	0.99

Table A.3 **Wrap and FP model limits: Mass ratio (M_r) known, weather conditions unknown. This table is appropriate for accident reconstruction when projection distance, projection type and the pedestrian/vehicle mass ratio are known**

Confidence level	Forward projection $\left(\frac{V_{col}(m/s)}{M_r} = A\sqrt{S(m)} + B\right)$						Wrap projection $\left(\frac{V_{col}(m/s)}{M_r} = C \times [S(m) - S_o]^D\right)$			
	Adults			Children						
	A	B	*r*	A	B	*r*	So	C	D	*r*
Probable Lower	3.3	–1.6	0.99	3.3	–1.5	0.99	1.8	3.5	0.47	0.99
Probable Upper	3.7	–1.4	0.99	3.7	–1.3	0.99	1.4	4.0	0.46	0.99
Normal Lower	2.9	–1.5	0.99	2.8	–1.5	0.99	1.9	2.8	0.5	0.99
Normal Upper	4.0	–1.3	0.99	4.0	–1.1	0.99	1.2	4.5	0.46	0.99
Overall Lower	2.4	–1.3	0.99	2.3	–1.1	0.99	1.9	2.2	0.51	0.99
Overall Upper	4.3	–1.2	0.99	4.2	–1.0	0.99	1.2	4.9	0.46	0.99

Table A.4 **Wrap and FP model limits: wet conditions, mass ratio (M_r) unknown. This table is appropriate for accident reconstruction when projection distance and projection type are known and wet conditions prevailed**

Confidence level	Forward projection $(V_{col}(m/s) = A\sqrt{S(m)} + B)$						Wrap projection $(V_{col}(m/s) = C \times [S(m/s) - S_o]^D)$			
	Adults			Children						
	A	B	*r*	A	B	*r*	So	C	D	*r*
Probable Lower	3.2	–1.6	0.99	3.1	–1.4	0.99	1.7	3.4	0.47	0.99
Probable Upper	3.5	–1.3	0.99	3.4	–1.2	0.99	1.3	4.0	0.47	0.99
Normal Lower	2.8	–1.5	0.99	2.7	–1.4	0.99	1.9	2.8	0.49	0.99
Normal Upper	3.8	–1.1	0.99	3.7	–1.0	0.99	1.1	4.5	0.46	0.99
Overall Lower	2.4	–1.2	0.9	2.3	–1.1	0.99	1.9	2.2	0.52	0.99
Overall Upper	4.1	–1.0	0.99	3.9	–0.8	0.99	1.1	4.9	0.46	0.99

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Table A.5 **Wrap and FP model limits: dry conditions, mass ratio (M_r) unknown. This table is appropriate for accident reconstruction when projection distance and projection type are known and dry conditions prevailed**

Confidence level	Forward projection ($V_{col}(m/s) = A\sqrt{S(m)} + B$)						Wrap projection ($V_{col}(m/s) = C \times [S(m) - S_o]^D$)			
	Adults			Children						
	A	B	*r*	A	B	*r*	So	C	D	*r*
Probable Lower	3.6	–1.8	0.99	3.5	–1.7	0.99	1.9	3.9	0.46	0.99
Probable Upper	4.0	–1.6	0.99	3.8	–1.4	0.99	1.4	4.4	0.46	0.99
Normal Lower	3.2	–1.7	0.99	3.1	–1.6	0.99	1.9	3.0	0.5	0.99
Normal Upper	4.3	–1.3	0.99	4.2	–1.2	0.99	1.2	4.9	0.46	0.99
Overall Lower	2.7	–1.4	0.99	2.6	–1.4	0.99	1.9	2.4	0.52	0.99
Overall Upper	4.6	–1.3	0.9	4.4	–1.1	0.99	1.2	5.4	0.46	0.99

Table A.6 **Wrap and FP model limits: wet conditions, mass ratio (M_r) known. This table is appropriate for accident reconstruction when projection distance, projection type and mass ratio (M_r) are known and wet conditions prevailed**

Confidence level	Forward projection $\left(\frac{V_{col}(m/s)}{M_r} = A\sqrt{S(m)} + B\right)$						Wrap projection $\left(\frac{V_{col}(m/s)}{M_r} = C \times [S(m) - S_o]^D\right)$			
	Adults			Children						
	A	B	*r*	A	B	*r*	So	C	D	*r*
Probable Lower	3.0	–1.4	0.99	3.0	–1.4	0.99	1.6	3.2	0.47	0.99
Probable Upper	3.3	–1.1	0.99	3.3	–1.1	0.99	1.2	3.7	0.47	0.99
Normal Lower	2.6	–1.2	0.99	2.6	–1.3	0.99	1.2	2.3	0.52	0.99
Normal Upper	3.5	–1.0	0.99	3.6	–0.9	0.99	1.0	4.1	0.47	0.99
Overall Lower	2.2	–0.8	0.99	2.2	–1.1	0.99	0.6	1.8	0.54	0.99
Overall Upper	3.8	–0.9	0.99	3.8	–0.8	0.99	1.1	4.6	0.46	0.99

Table A.7 **Wrap and FP model limits: dry conditions, mass ratio known. This table is appropriate for accident reconstruction when projection distance, projection type and mass ratio (M_r) are known and dry conditions prevailed**

Confidence level	Forward projection $\left(\frac{V_{col}(m/s)}{M_r} = A\sqrt{S(m)} + B\right)$						Wrap projection $\left(\frac{V_{col}(m/s)}{M_r} = C \times [S(m) - S_o]^D\right)$			
	Adults			Children						
	A	B	*r*	A	B	*r*	So	C	D	*r*
Probable Lower	3.4	–1.7	0.99	3.4	–1.6	0.99	1.8	3.6	0.47	0.99
Probable Upper	3.7	–1.5	0.99	3.7	–1.3	0.99	1.4	4.1	0.46	0.99
Normal Lower	3.0	–1.7	0.99	3.0	–1.5	0.99	1.7	2.8	0.5	0.99
Normal Upper	4.0	–1.3	0.99	4.0	–1.1	0.99	1.2	4.6	0.46	0.99
Overall Lower	2.6	–1.4	0.99	2.6	–1.3	0.99	1.1	2.1	0.53	0.99
Overall Upper	4.3	–1.2	0.99	4.3	–0.9	0.99	1.2	5.0	046	0.99

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