# STATISTICAL PREDICTION OF PEDESTRIAN PRE-IMPACT SPEED BASED ON POST-ACCIDENT VEHICLE DAMAGE

**JR Elliott[1], S Augy[1], CK Simms[1], DP Wood[2]**
**[1]Trinity Centre for Bioengineering, Trinity College, Dublin, Ireland**
**[2]Denis Wood Associates, Dublin, Ireland**

**ABSTRACT**

For vehicle-pedestrian accidents, knowledge of pedestrian pre-impact speed aids in understanding post-impact kinematics, injury patterns and legal culpability. It is hypothesised that the transverse offset between the primary and secondary impact locations on the vehicle, which is often measureable from vehicle damage patterns, can be used to deduce pedestrian pre-impact speed. Following validation, a statistical tool based on a Constant Inertial Property (CIP) pedestrian model was used to evaluate this hypothesis. Results show that limits of pedestrian pre-impact speed can be predicted based on the transverse offset, if independent estimates of vehicle impact speed and possibly pedestrian stance are available.

**Keywords:** Pedestrians, accident reconstructions, inertia, kinematics.

**ROAD TRAFFIC INJURIES/FATALITIES** are predicted to become the third leading contributor to the global burden of disease by 2020 unless appropriate countermeasures are taken (WHO, 2004). Accident reconstruction is crucial in linking pedestrian injuries to impact severity. Theoretical and empirical findings show that impact speed is the key determinant for pedestrian injury risk (Anderson et al., 1997, Simms and Wood, 2009). However, there is no reliable method in the literature to date for ascertaining pre-impact pedestrian speed. The Constant Inertial Property (CIP) pedestrian model was originally derived to predict vehicle speed from pedestrian projection distance by regression of Monte Carlo predictions. The current model extends the approach to pedestrian speed estimation for the first time.

## METHODS

Wood's momentum-based Single Segment Model (1988) was implemented in Matlab and used as a basis for the development of the CIP. It has been revised and expanded in three dimensions to reflect the variation in pedestrian inertial properties resulting from different phases of gait. Any stance can be modelled, whereafter the pedestrian inertial properties are assumed to remain constant throughout the collision sequence. The momentum-based formulation of the model avoids requiring explicit knowledge of the contact characteristics of the vehicle front, and the model is therefore well suited to large scale DOE-type analyses and accident reconstructions where the contact characteristics are not known.

Vehicle damage measures can be used in accident reconstructions. One such measure is the transverse offset, which is the offset between the primary and secondary impact locations of the pedestrian on the vehicle. This can often be measured from post-accident vehicle damage. The available transverse offset data is very limited. The approach used for validation of the CIP model was as follows: The transverse offsets predicted by the CIP model were compared to two staged dummy tests carried out by the German Crash Test Service (CTS), and to MADYMO simulations of these staged tests. A real accident was modelled (Yao et al., 2008) and the transverse offset predicted by the CIP model was compared to the actual vehicle damage. The CIP model was then used to reproduce four staged cadaver tests (Subit et al., 2008). The transverse offsets were not known. However, the head trajectories and longitudinal offsets obtained were compared to the test data, and to MADYMO simulations of these staged tests. The transverse offsets predicted by the CIP model were then compared to those obtained from the MADYMO simulations. A comparison of transverse offsets predicted by the CIP model and the MADYMO model was then carried out for 4 pedestrian stances, pedestrian speeds of 0, 1.4 and 2.8m/s and vehicle speeds of 5, 10 and 15m/s. i.e. 36 simulations.

Following validation, the model was used to predict the transverse offset between the primary and secondary impact locations of the pedestrian on a typical mid-sized sedan-type vehicle. Monte Carlo simulations were applied (N=50,000) to include uncertainty in pedestrian speed/stance and vehicle speed/dive, and the effects on the resulting transverse offset were statistically characterised.

**RESULTS**

MODEL VALIDATION: The ability of the CIP model to reproduce the transverse offset between primary and secondary impact locations on the vehicle compared to staged dummy tests performed by CTS was good (errors of <10%) - see Table 1.

**Table 1 - Transverse Offset Between Primary and Secondary Impact Locations (CTS, CIP Model, MADYMO Model)**

| Test | Transverse Offset CTS (cm) | Transverse Offset CIP Model (cm) | Transverse Offset MADYMO Model (cm) |
|---|---|---|---|
| **1** | 27 ± 4 | 30.3 | 22 |
| **2** | 28 ± 2 | 27.4 | 28 |

A real accident described and reconstructed by Yao et al. (2008) was modelled. A wide range of pedestrian speeds, 1.5-4m/s, was given in the paper. This was estimated based on detailed accident data, including eyewitness accounts. The transverse offset was estimated to be 43-44cm. Monte Carlo modelling was performed (N = 50,000). For a transverse offset range of 43-44cm, the corresponding pedestrian speed range was 2.5-4m/s, which compares well with the range given by Yao et al.

The ability of the CIP model to predict head trajectories and longitudinal offsets from cadaver tests presented by Subit et al. (2008) was good (errors of <10%) - see Figure 1 and Table 2.

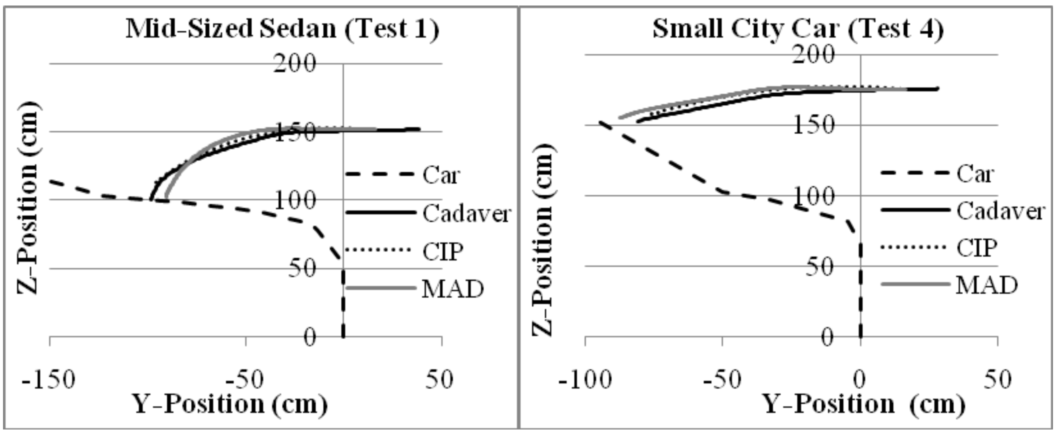


**Fig. 1 - Head Trajectories (Cadavers - Subit et al., CIP Model, MADYMO Model (MAD))**

**Table 2 - Longitudinal Offset Between Primary and Secondary Impact Locations (Cadavers - Subit et al., CIP Model, MADYMO Model)**

| Test | Longitudinal Offset Cadaver (cm) | Longitudinal Offset CIP Model (cm) | Longitudinal Offset MADYMO Model (cm) |
|---|---|---|---|
| **1** | 95 | 89 | 87 |
| **2** | 141 | 131 | 122 |
| **3** | 74 | 67 | 71 |
| **4** | 77 | 82 | 90 |

Comparison of the CIP model response to the MADYMO pedestrian model, which has been validated for a variety of impact conditions (Hoof et al., 2003), showed that the predictive capability for modelling the transverse offset between the primary and secondary impact locations of the pedestrian on the vehicle was similar for the two models, as shown in Figure 2. This graph also shows that, for a given vehicle speed, there is a broadly linear relationship between transverse offset and pedestrian speed (lowest $R^2$ value: 0.9955). Note: In this figure, the data points for a pedestrian speed of 0m/s are practically coincident for CIP 5m/s, CIP 10m/s, CIP 15m/s, and for MAD 10m/s, MAD 15m/s.

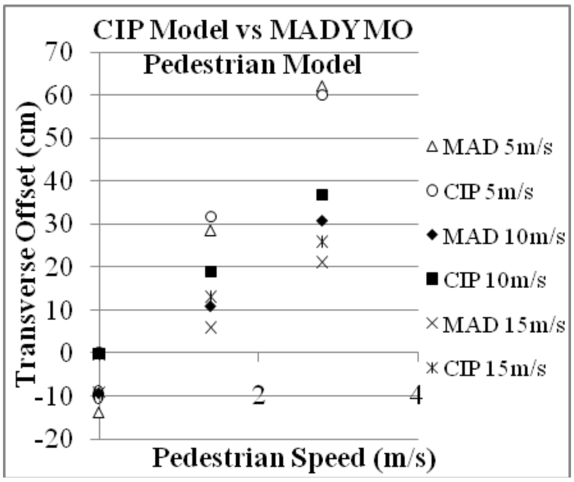


**Fig. 2 - Transverse Offset Between Primary and Secondary Impact Locations (CIP Model and MADYMO Model (MAD))**

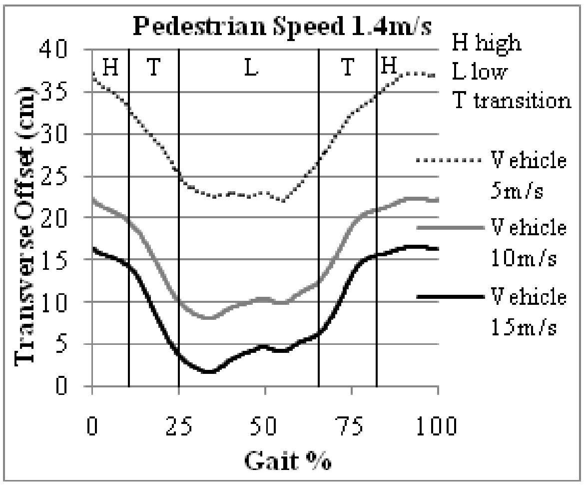


**Fig. 3 - Transverse Offset vs % Gait Cycle (0% - Right Heel Strike)**

PREDICTIVE CAPABILITY OF TRANSVERSE OFFSET: The transverse offset varies according to pedestrian stance at impact. Figure 3 shows the variation throughout a full gait cycle for a fixed pedestrian speed of 1.4m/s and vehicle speeds of 5, 10 and 15m/s. This variation demonstrates the advantage of the CIP model's ability to model any stance. This graph shows that the transverse offset can be broadly divided into a high value region and a low value region. These regions correspond approximately to 80-10% gait and 25-65% gait respectively, connected by two transitional regions, as indicated on the graph. It is hypothesised that if the stage of the gait cycle could be estimated, for example from injury or vehicle damage patterns, then a narrower estimate of pedestrian speed could be made. Early work suggests that the location of the impact on the head is related to the pedestrian stance. This is currently being investigated further.

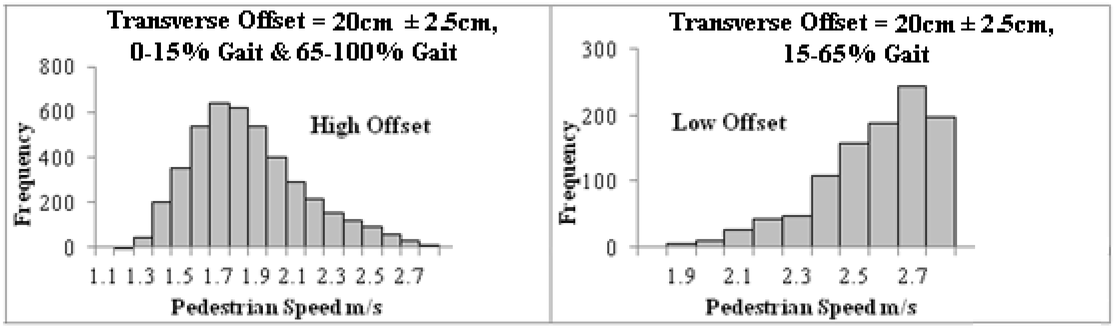


**Fig. 4 – Distributions of Pedestrian Speeds for High and Low Transverse Offset Ranges**

Monte Carlo methods were applied (N = 50,000) to test this hypothesis. As an example, the pedestrian and vehicle speeds were randomly chosen from 0-2.8m/s (0-10km/hr) and 12.5-15.3m/s (45-55km/hr) respectively. The gait cycle was arbitrarily divided in half, comprising a high offset region (0-15% gait and 65-100% gait) and a low offset region (15-65% gait). Analysis of the model results shows that limits of pedestrian walking speed can be predicted based on the transverse offset distance, e.g. the model predicts that the pedestrian cannot have been stationary at impact for an offset exceeding 10cm, and that the minimum pedestrian speed exceeds 1m/s for an offset of 20cm. Figure 4 shows the distributions of pedestrian speeds corresponding to the high and low transverse offset regions associated with 65-15% gait and 15-65% gait respectively, for a sample transverse offset range of 20cm ± 2.5cm. For the high offset region, the mode speed is 1.7m/s and the probable range (50$^{th}$ percentile limits) is approximately 1.6-1.9m/s. For the low offset region, the mode speed is 2.7m/s and the probable range is approximately 2.6-2.8m/s. These results therefore yield two distinct pedestrian speed distributions. Such distributions could provide a means of narrowing the pedestrian speed range predicted by the CIP, if an estimation of the stage of the gait cycle was available.

## CONCLUSIONS

A fixed stance, Constant Inertial Property (CIP) model has been shown to adequately predict the longitudinal and transverse offsets between the primary and secondary impact locations for vehicle-pedestrian collisions. The predictive capability of the model for these cases was found to be similar to the MADYMO pedestrian model. For a known vehicle speed, a broadly linear relationship exists between transverse offset and pedestrian speed. Application of the CIP model showed that limits of pedestrian pre-impact speed can be predicted based on the transverse offset. By arbitrarily dividing the gait cycle in half, distinct pedestrian speed distributions were obtained. The estimated pedestrian speed range could thus potentially be narrowed if a means of estimating the stage of the gait cycle at impact was available, such as analysis of injury or vehicle damage patterns.

## REFERENCES

Anderson, R. et al., “Vehicle Travel Speeds and the Incidence of Fatal Pedestrian Crashes”, Accident Analysis and Prevention, Vol.29, 1997, pp.667-674.

Hoof J. van et al., “Improving Pedestrian Safety Using Numerical Human Models”, Stapp Car Crash Journal, Vol.47, 2003, pp.401-436.

Peden, M. et al., World Health Organisation, 2004, pp.1-244.

Simms, C.K., Wood, D.P., “Pedestrian and Cyclist Impact”, G.M.L. Gladwell ed., Springer, the Netherlands, 2009.

Subit, D. et al., “Pedestrian-Vehicle Interaction: Kinematics and Injury Analysis of Four Full-Scale Tests”, IRCOBI Conference Proceedings, 2008, pp.275-294.

Wood, D.P., “Impact and Movement of Pedestrians in Frontal Collisions with Vehicles”, Proceedings of Institution of Mechanical Engineers, 1988, pp.101-110.

Yao et al., “Investigation of Head Injuries by Reconstruction of Real-World Vehicle-Versus-Adult-Pedestrian Accidents”, Safety Science, Vol.46, 2008, pp.1103-1114. Personal correspondence: J Yang.