

Different Factors Influencing Post-crash Pedestrian Kinematics

Yoshiko Kawabe, Toshiyuki Asai, Daisuke Murakami, Chinmoy Pal and Tomosaburo Okabe
Nissan Motor Company Ltd.

ABSTRACT

Pedestrian crashes are the most frequent cause of traffic-related fatalities worldwide. The high number of pedestrian accidents justifies more active research work on passive and active safety technology intended to mitigate pedestrian injuries. Post-impact pedestrian kinematics is complex and depends on various factors such as impact speed, height of the pedestrian, front-end profile of the striking vehicle and pedestrian posture, among others. The aim of this study is to investigate the main factors that determine post-crash pedestrian kinematics. The injury mechanism is also discussed.

A detailed study of NASS-PCDS (National Automotive Sampling System - Pedestrian Crash Data Study, US, 1994-1998), showed that the vehicle-pedestrian interaction in frontal crashes can be categorized into four types: "*Thrown forward*", "*Wrapped position*", "*Slid to windshield*" and "*Passed over vehicle*". A Principal Component Analysis (PCA) was performed and 11 independent factors were identified for study from a set of 26 variables, as defined in NASS-PCDS. Pedestrian-vehicle size ratio and the impact speed are the two most influential factors that determine post crash pedestrian kinematics. However, the standing posture of a taller pedestrian can also cause rotational movement around the local Z axis, leading to a face-up/down mode of head-face impact before falling on the hood.

The findings from the NASS-PCDS study were also confirmed and verified with the help of numerical simulations performed using two modified JAMA human FE models. An adult model (male, 175cm and 72kg) and a properly scaled child model (6 years old, 120cm and 21kg) were effectively utilized to investigate the post-crash kinematics in different conditions.

CITATION: Kawabe, Y., Asai, T., Murakami, D., Pal, C. et al., "Different Factors Influencing Post-crash Pedestrian Kinematics," *SAE Int. J. Passeng. Cars - Mech. Syst.* 5(1):2012, doi:10.4271/2012-01-0271.

INTRODUCTION

Motor vehicle occupant fatalities are decreasing in many countries, thanks to developments in vehicle safety, infrastructure and campaigns promoting safer driving. However, the overall percentages of pedestrian casualties are increasing compared to that of vehicle occupants. Annual fatalities, for every 1,000,000 people, are 12.3 in Australia, 15.7 in the EC, 16.4 in the US and 21.8 in Japan. The numbers in developing countries are even higher. [Figure 1](#) shows the ratio of traffic fatalities in some selected countries. Japan and Korea have denser populations and more registered cars per square kilometer due to their small land areas, leading to remarkably high ratios of pedestrian fatalities. The Japanese pedestrian fatality percentage ([Figure 1](#)) and the number of fatalities by age group ([Figure 2](#)) indicate that those involving pedestrians 65 years old and older are predominant.

Mizuno et al. reported their detailed investigations of pedestrian accident databases from countries including Australia, Germany, Japan and the US (1605 cases, 9463

injuries, include 3305 AIS2+) [[1](#)]. According to their report, in one third of those cases, pedestrians are reported to have suffered injuries to their heads and/or lower extremities.

One of their target databases, NASS-PCDS [[2](#), [3](#), [4](#), [5](#), [6](#), [7](#)], shows the same trend. [Figure 3](#) shows combinations of injury source and body parts for AIS3+ cases in the NASS-PCDS database. The size of the circles indicates the respective frequencies of injury. 'Head - top component' and 'lower extremity - front component' combinations are most frequent. Previous studies on pedestrian crash cases pointed out that the vehicle front geometry, human height and posture affect the pedestrian injury mechanism [[8](#), [9](#), [10](#)]. Further studies [[11](#), [12](#)] targeting child pedestrians' injury distribution pointed out that anthropometry influences impact kinematics.

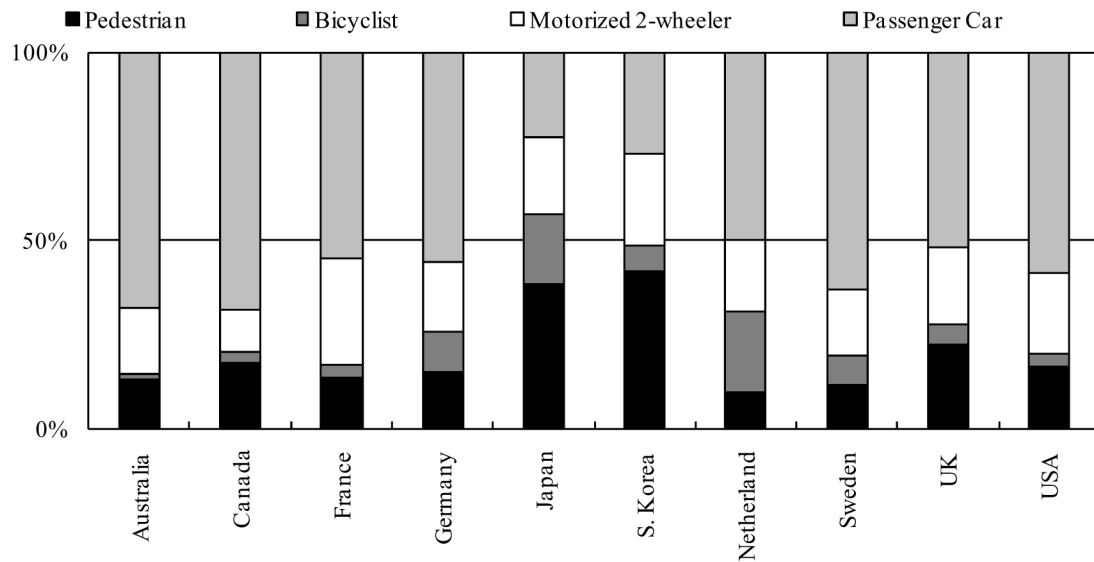


Figure 1. Percentage of fatalities in different countries of all road accidents in 2009 ⁽¹⁾

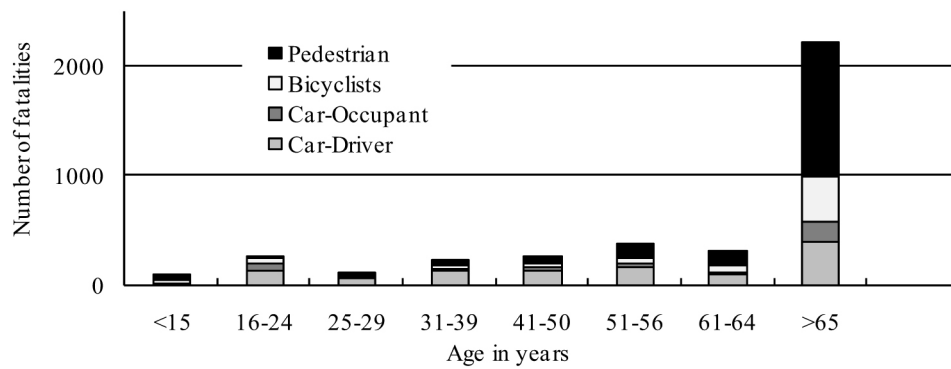


Figure 2. Number of fatalities with respect to ages groups (ITARDA-2009, Japan)

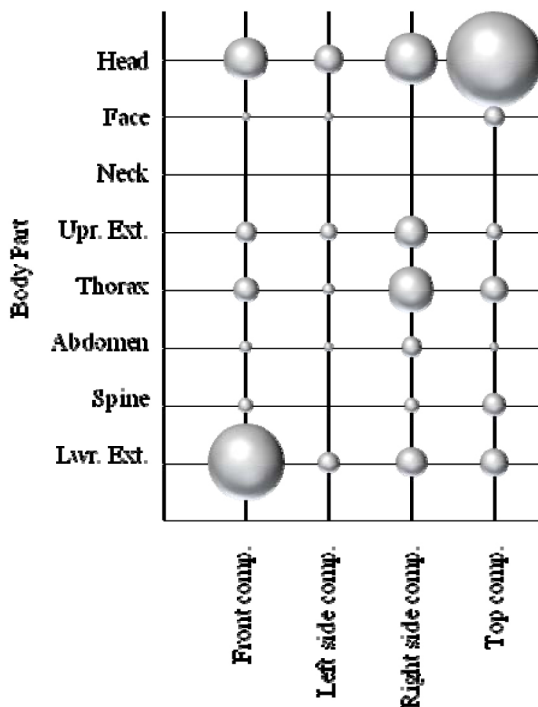


Figure 3. Source of injury vs. injured body region (AIS 3+)

This study focuses on the leading factors affecting post-crash pedestrian movement and the injury mechanisms in relation to impact speed. Human FE model simulations were carried out to reconfirm and endorse the findings and the trends in accident analyses.

NASS-PCDS ANALYSIS

The NASS-PCDS, a pedestrian crash case database project, was implemented by the National Highway Traffic Safety Administration (NHTSA) in the '90s. The database contains data on 552 pedestrian crashes and 4499 injuries during 1994-1998. It is not a statistically weighted sample. The database consists of cases that satisfy the following criteria [13]:

- Bicyclists and others on non-motor conveyances are not included.
- A 1990+ model vehicle moving forward must be involved.
- The pedestrian must be the only thing the vehicle impacts.
- The vehicle portion striking the pedestrian must be in its original condition with no previous damage.
- The first vehicle-pedestrian contact must be forward of the vehicle A pillar.
- Crash investigations must be initiated on-scene.

These criteria, however, eliminate cases with secondary pedestrian collisions.

Statistical inferences of this study are limited in the NASS-PCDS database and do not necessarily represent the

overall US pedestrian crash statistics relating to the frequencies of types of pedestrian accidents and the percentage of related injuries.

One of the NASS-PCDS variables, 'Vehicle pedestrian interaction (variable 524)', indicates the post-crash pedestrian kinematics. There are 17 codes to describe the types of interaction. Four of those codes are picked out in accordance with frequencies of occurrences. They are categorized as following the four main types (Table 1).

The numbers of cases for each type are indicated in the fourth row of the table, the next two rows show the average pedestrian height, the average impact speed and its standard deviation. On the basis of this basic statistical information, a human FE model simulation, as shown in the last row, was carried out to verify the kinematics for corresponding types of impact. From the simulation results, corresponding to four different (Type A-D) kinematic modes, it is observed that:

- Type A differs from the other three types in the relative velocity after impact. The Type A pedestrian is accelerated in the same direction in which the vehicle is traveling. The pedestrian's body is thrown forward in front of the vehicle.
- In the other three types, Types B, C and D, the pedestrians are accelerated by the impact, up to a speed not more than the traveling speed of the vehicle. The torso of the pedestrian travels relatively backward with respect to the front end of the vehicle.

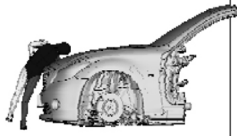
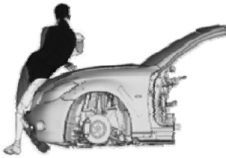
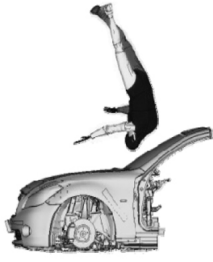
Figure 4 shows a set of histograms of severe injuries (AIS3+) at various impact speed ranges. Figure 4(a) (Type A) has the lowest frequencies (10) of severe injuries MAIS 3+. However, note that there are some MAIS-4 and MAIS-5 injuries even in the lowest impact speed range ($V=11-20$ km/h) in Type A cases. Type A cases typically include pedestrians with low height or a relatively high front-end on the vehicles. Figure 4(b), (c) and (d) correspond to Types B, C and D, respectively. No Type B case (Figure 4(b)) exceeds 60 km/h. Type C (Figure 4(c)) has the highest frequency in the 31-40 km/h impact speed range. Type C accounts for the largest ratio of the severe injuries under 40 km/h. Type D (Figure 4(d)) does not appear in the speed range of 40 km/h and under. Type D has the smallest number of injuries among the four types, but also has the largest ratio of MAIS3+ injuries, i.e., 80.0% (Table 1).

The four types in the NASS-PCDS database have different trends with respect to vehicle types, pedestrian size and impact speed. Factors that determine these types are discussed in the following sections.

PRINCIPAL COMPONENT ANALYSIS

Four types of post-crash pedestrian kinematics are defined in the previous section. The pedestrian and vehicle sizes have a significant effect on pedestrian kinematics, as does the impact speed. Prior to the evaluation of the influences of such factors, the Principal Component Analysis (PCA) was applied to select independent variables from the NASS-PCDS codes. The main aim of this PCA was to reduce the number of non-

Table 1. Classification of vehicle-pedestrian interaction (Type A - D) in frontal crash.

	Type A	Type B	Type C	Type D
Variable 524	5	1	2	4
Description in NASS-PCDS manual	Thrown straight forward	Carried by vehicle, wrapped position	Carried by vehicle, slid to windshield	Passed over vehicle top
Numerical fact		Variable 428 (ground to front head contact) value is no more than variable 426 (Ground to base of windshield)		Variable 428 (ground to front head contact) value is no less than variable 426 (Ground to base of windshield)
(a): No. of pedestrian (total 275cases)	35	82	138	20
Average pedestrian height [cm]	158	163	168	172
Average impact speed [km/h] (standard deviation)	19.8 (12.2)	21.9 (11.2)	41.0 (19.6)	66.7 (10.5)
(b) MAIS 2-	25	67	60	4
(c):MAIS 3+	10	16	78	16
Ratio of MAIS 3+ (c)/(a)	28.6 %	19.5 %	56.5 %	80.0%
FE verification with adult male and 6-year-old child based on JAMA model				

relevant variables, without omitting the necessary information and the characteristics of the overall dataset.

Table 2 is a list of NASS-PCDS variables. Eleven variables shown in bold case on the list were chosen for the PCA. The other 16 variables were eliminated for the following reasons:

- NA: Variables without sufficient data (e.g. Ground clearance)
- PDI: Measurements or dimensions perpendicular to the direction of impact (e.g. Original track width)

- NNV: Non-numerical variables (e.g. Hood material)
- CV: Composite variables (e.g. Ground to base of windshield)
- SDV: Secondary or subjective parameters such as pedestrian partial length (e.g. Ground to knee height)

Only primary parameters such as 'Height' and 'Weight' are included as human factors. Pedestrian age is a decisive factor for injury level due to biomechanical tolerance [14], but it has less influence on kinematics. Hence, a set of 11 main variables out of a total of 27 variables was chosen for the PCA.

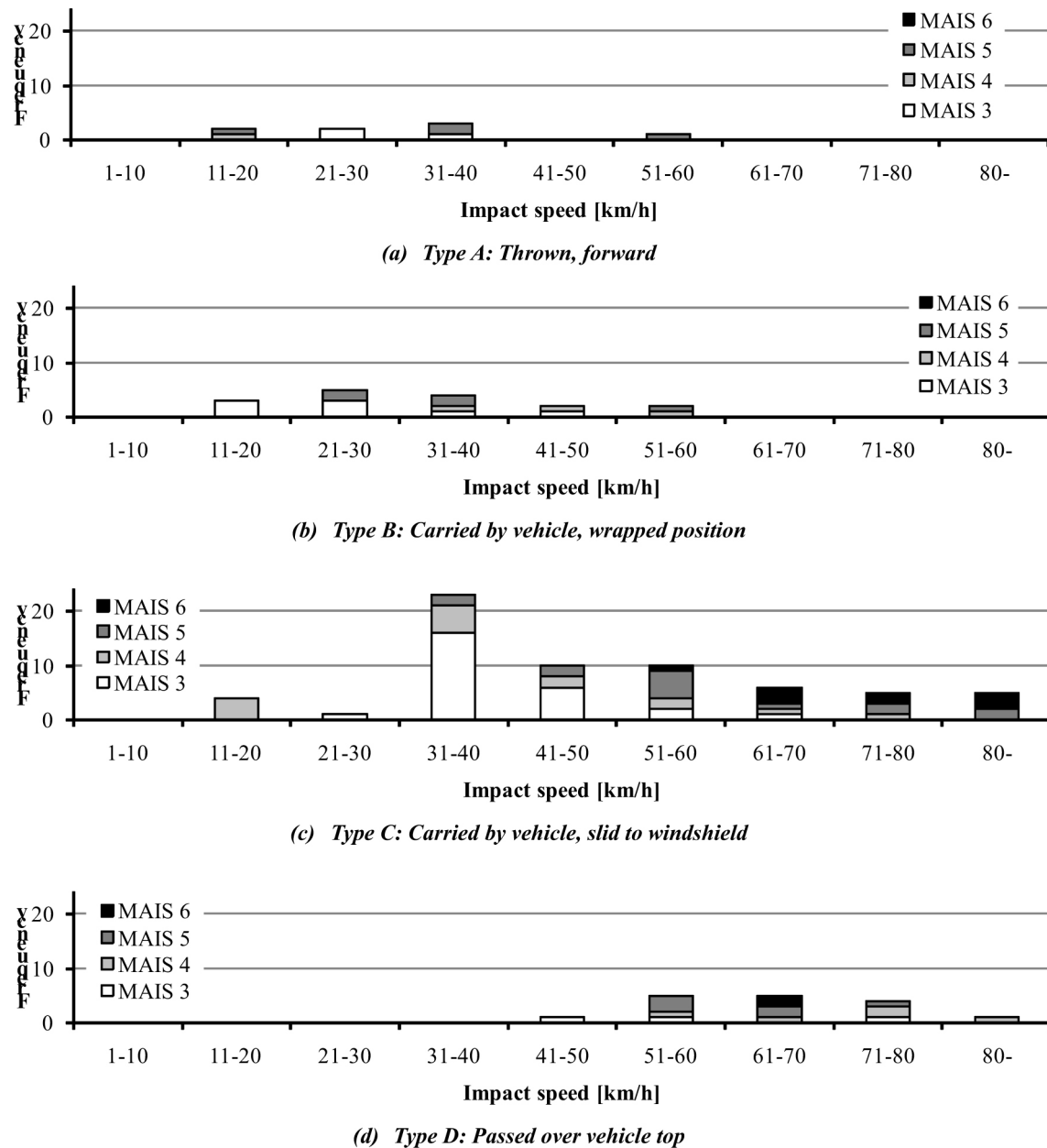


Figure 4. Variation injury level related to different vehicle-pedestrian interaction and impact speed ranges

Table 2. List of numerical variables of NASS-PCDS codes

	Variable number (total 27)	Variable name	Omitted
Vehicle specifications	328	Vehicle curb weight	
	329	Vehicle cargo weight	NA.
	407	Original wheelbase	
	408	Original track width	PDI
	409	Hood material	NNV
Horizontal measurement	411	Hood length	
	412	Hood width-forward opening	PDI
	413	Hood width-midway	PDI
	414	Hood width-rear opening	PDI
Vertical measurement	421	Forward hood opening	
	429	Ground clearance	NA.
Bumper	419	Front bumper-bottom height	
	420	Front bumper-top height	
	422	Front bumper lead	
	445	Front bumper lead angle	
Wrap distances	423	Ground to forward hood opening	CV
	424	Ground to front/top transition point	CV
	425	Ground to rear hood opening	CV
	426	Ground to base of windshield	CV
	427	Ground to top of windshield	CV
Crash case	331	Impact speed	
Pedestrian	508	Age	NNV
	510	Height	
	511	Ground to knee height	SDV
	512	Ground to hip height	SDV
	513	Ground to shoulder height	SDV
	514	Weight	

The followings are the actual steps followed in the process of PCA:

1. Filter the NASS-PCDS data to eliminate incomplete cases.
2. Standardize the values by the average and standard deviation for each variable.
3. Calculate the correlation coefficients for all of the variable combinations.
4. Double fold the triangular matrix of correlation coefficients to make a square matrix. Correct the main diagonals values to 1.
5. Calculate the eigenvalues and the eigenvectors of the previous square matrix. Those eigenvectors make the principal components.

6. Selected the most significant eigenvalues and corresponding eigenvectors. In this case it is 6.

Table 3 shows the eigenvalues and eigenvectors of the resultant six significant principal components. The third row from the bottom of the table, 'Contribution rate', indicates the percentage of the information the corresponding column have. The 'Accumulated proportion', the second row from the bottom of the table, sums up to 89%. It indicates that the selected main 6 principal components capture 89% of the information in the original 11 variables.

The major elements of the first principal component column (#1) are **Forward hood opening** (−0.47), **Vehicle curb weight** (−0.43) and **Front bumper - top height** (−0.42) which are concerned with the 'Vehicle size' as denoted in the last row of the table as 'Characteristics of the principal component' item. The corresponding contribution rate is 34%. It means that 34% of information of the selected 11 variables is related to the 'Vehicle size'.

The second principal component column (#2) is related to 'Pedestrian size'. Pedestrian **Height** (0.66) and **Weight** (0.64) are the dominant elements.

The most dominant element for the third component column (#3) is the **Bumper lead** (−0.69), for the fourth column (#4), the **Front bumper -bottom height** (−0.61), and for the fifth column (#5), the **Hood length** (0.66), respectively.

The sixth principal component is concerned with the variable 'Impact speed', with 7% of the contribution rate. This contribution rate indicates the amount of information the sixth principal component contains, and does not mean the level of influences to the pedestrian kinematics. It is to be noted that highest contribution rate is 34% for 'Vehicle size'. This is due to the fact that 'Vehicle size' set consists of 5 out of 11 parameters, not that it influences pedestrian kinematics the most.

The four types of pedestrian kinematics, previously mentioned, are re-examined in the next section according to the six chosen variables, **Impact speed**, **Hood length**, **Front bumper - bottom height**, **Forward hood opening**, **Front bumper lead** and **Pedestrian height**. However, due attention should be paid that those particular principal components that are not completely independent.

CHARACTERISTICS OF VEHICLE-PEDESTRIAN INTERACTION

The next step to analyze the NASS-PCDS database is to verify which of the previously mentioned 6 principal components characterize most of the features of the vehicle-pedestrian interactions. Figures 5 shows the average values for each of the group of four vehicle-pedestrian interaction types, related to those 6 principal factors. Figure 5(a) is for the average of the whole dataset, and Figure 5(b) is for the average of the whole data excluding the outliers, i.e., those data corresponding to higher impact speed $V > 80$ km/h. Refer