

Predicting the Influence of Windscreen Design on Pedestrian Head Injuries

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Abstract Head/windscreen impacts cause severe injuries to pedestrians, but little is known about the effect of windscreen geometry on pedestrian head injury. This study used MADYMO multi-body modelling to investigate the influence of windscreen angle, stiffness characteristics and head/windscreen friction on pedestrian head injury risk as evaluated by the head acceleration. A model of an adult pedestrian struck by a sedan at 40km/h was generated and validated against staged tests. A simulation matrix was then constructed to vary windscreen angle (20°-55°), contact friction (0.1-0.6) and contact stiffness. The results generated using a real-world contact stiffness characteristic show that an increasing windscreen angle decreases the maximum linear and angular accelerations of the head by 7% and 18% respectively. However, these trends reverse when a linear stiffness is applied, and it appears that the mass of the body plays a more significant role for steep windscreens in this case. Increasing head/windscreen contact friction increases the magnitude of head accelerations, but does not affect the trend that they reduce with increasing windscreen angle. However, scaling the real-world stiffness does affect the head injury risk trends. It is, therefore, cautiously suggested that a steeper windscreen angle is safer for pedestrian head injuries in pedestrian-vehicle impacts.

Keywords Pedestrian-vehicle accidents, windscreen angle, car front design, pedestrian head injury.

I. INTRODUCTION

It is estimated that 1.2 million people die in road accidents every year [1] and, overall, pedestrians are the most important road safety consideration [2]. Although impact speed is the most important risk predictor for pedestrians [3], the vehicle shape also has a very significant effect on pedestrian injury [3-9]. Therefore appropriately designed vehicle fronts significantly reduce the injury caused in pedestrian accidents.

The principal vehicle parameters influencing pedestrian injury risk are shape and stiffness [3]. Shape largely dictates which body structures are struck and the closing speed of the contacts, while stiffness determines the manner in which the kinetic energy is dissipated in each of these contacts [3]. Thus vehicle design (considering both shape and stiffness) is important for pedestrian injury minimisation. Much work has been done to examine bumper and bonnet leading edge design, with investigations into the effects of their shape and stiffness characteristics on mid-body and lower limb injury, e.g. [4-7]. However, for head protection, the windscreen area is the most important vehicle region, as this is where head contact on the vehicle most often occurs. Xu et al. [10] reported that, of 273 pedestrian-vehicle accidents selected from the National Traffic Accident Database of Tsinghua University, head impact with the windscreen accounted for 81% of all head-vehicle contacts. Similarly, Crandall et al. reported that around 80% of serious injuries sustained by pedestrians are to the head and that 15.6% of all pedestrian injuries are caused by the windscreen, the highest proportion of all car structures [4]. Nonetheless, research to examine the effect of windscreen design on pedestrian head injury has been limited. Otte [8] performed an investigation into over 190 pedestrian and cyclist accidents from a German national database and concluded that a shallower windscreen is safer for pedestrians. However, these findings were based solely on

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accident data, with no further analysis. As with all accident data, there was significant variation in pedestrian size, position and orientation at impact and uncertainty about the circumstances surrounding the accidents. Variability in windscreen angle would be accompanied by other geometrical changes and the individual effect of windscreen angle on pedestrian injury would be difficult to quantify. There appear to have been no further evaluation of pedestrian accidents to assess windscreen design nor has there been a biomechanical analysis of the influence of windscreen angle and stiffness on pedestrian injury risk. This paper aims to develop a preliminary understanding of the effect of windscreen design on pedestrian head injury. In particular, the effect of windscreen angle on head injury risk is investigated, and this is followed by an analysis of the effects of windscreen stiffness and the coefficient of friction in the head/windscreen contact. The analysis does not consider the metal windscreen frame which is an inherently stiffer structure and is known to cause significant pedestrian injuries [3]. The stiffness characteristics used are intended to replicate those of a tempered glass windscreen.

II. METHODS

The MADYMO (MATHematical DYnamic MOdel, TNO Automotive Safety Solutions, Rijswijk) version 7.0 simulation environment was used to investigate the influence of windscreen angle, the coefficient of friction in the head/windscreen contact and the windscreen stiffness in vehicle-pedestrian accidents.

A. Model Set-Up

Vehicle-pedestrian impact simulations were run using the MADYMO pedestrian model [11] and a model of a small sedan based on the tests by Kerrigan et al. [12, 13] (Fig. 1). Force/deformation curves for the bumper and bonnet leading edge were sourced from Liu et al. [14] while the windscreen stiffness was extracted from the impactor tests of Mizuno and Kajzer [15], (Fig. 2). Separate unloading curves based on 10% of the loading curves for bumper, bonnet and windscreen and 1% of the loading curves for the BLE from the same sources were used to apply effective damping in the impact. In all simulations the pedestrian was struck from the side by the vehicle as this is the most frequent collision scenario [3]. The positive X axis was the direction of motion of the car and the positive Z axis was vertically upwards. The Y axis was then defined using the right hand rule (Fig. 3).

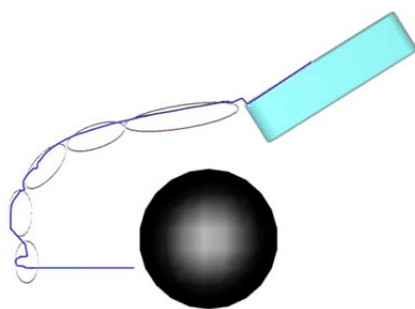


Fig. 1 - Madymo car compared with actual shape outline [12, 13].

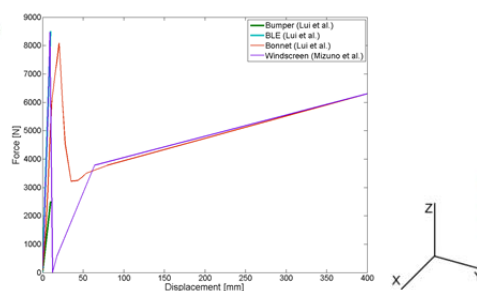


Fig. 2 - Force/Displacement curves for car parts

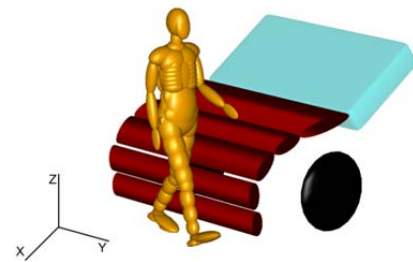


Fig. 3 - Typical simulation set up and coordinate system

B. Model Validation

To validate the model, Polar pedestrian dummy tests and Post-Mortem Human Specimen (PMHS) tests conducted by Kerrigan et al. [12, 13] were simulated, see [16]. The principal aspect of the validation relevant to this study was the ability of the model to predict the head impact speed

against the windscreen. Three different stances were used by Kerrigan et al. and these were replicated approximately in the simulations by comparing the photographs supplied by Kerrigan et al. to images of the MADYMO pedestrian model and matching the stance (Fig. 4). The MADYMO scaling tool was used to scale the pedestrian model based on mass and height.



Fig. 4 – Sample of replicated stances, shown here for D1 (left), DA1 (middle) and P3 (right).

Eight different tests were replicated in total. The three nominally identical dummy tests (D1, D2 and D3) were used to create a corridor to compare to a single set of model results. Table 1 shows the physical characteristics of the subjects. DA1 and DA2 are altered dummy tests: in DA1, the dummy was given the same stance as the PMHS subject and in DA2 the dummy had the same stance as DA1 but was raised off the ground by 5cm. Thus there were six validation simulations in total. Tests P1, P2 and P3 used three different Post-Mortem Human Specimens (PMHS) with the subjects’ wrists tied to the front. This was modelled using a spring damper joint constraint element at the wrist joints.

Kerrigan et al. [12, 13] determined the resultant head impact velocity by analysing high speed video camera footage at 1000Hz so the time of head impact could only be determined to an accuracy of 1ms. To account for this, the head velocity just before and after head impact and the average are reported and compared to the predicted head impact velocity from the MADYMO simulations in Table 3. Head impact in the MADYMO simulations was defined as the instant that the head/windscreen contact force became non-zero. MADYMO output parameters were written at a time resolution of 0.1ms. The integration time step was 1e-5s, but a check was performed at 1e-6s to ensure convergence.

Table 1 - Physical Characteristics of Test Subjects, from [13]

Test	Subject	Age/Gender	Mass (kg)	Stature (cm)	Stance	Ground Level (cm)
D1	Dummy	-	75	173	Dummy	0
D2	Dummy	-	75	174	Dummy	0
D3	Dummy	-	75	174	Dummy	0
DA1	Altered Dummy	-	75	174	PMHS	0
DA2	Altered Dummy	-	75	179	PMHS	+5
P1	PMHS	61/F	80.7	187	PMHS	0
P2	PMHS	70/M	54.4	179	PMHS	0
P3	PMHS	62/M	81.6	186	PMHS	0

C. Injury Criteria

There is much debate over the most effective and conclusive way to quantify and predict head injury, and there are several methods at the level of multibody modelling to relate accelerations and forces to head injuries. Linear acceleration as a result of blunt trauma is well correlated with focal brain injury and skull fracture and this has led to the popularity of the Head Injury Criterion (HIC) [17]. However, diffuse brain injuries are more strongly correlated with angular accelerations which cause shearing of the soft brain tissue and subsequent neurological injuries [18]. Detailed finite element models of the head and brain are currently the best way to predict brain injuries [19], but their complexity is not justified for studying the generalised influence of windscreen angle and

stiffness on pedestrian head injury risk. Furthermore, there are indications that the correlation between simpler metrics such as the acceleration based Head Injury Criterion and more detailed strain based criteria is high [19]. Accordingly, in this paper the head angular and linear accelerations are used to evaluate trends in head injury risk.

D. Simulation Matrix

Following validation, the scaled pedestrian models replicating the Kerrigan et al. subjects were replaced with the MADYMO 50th percentile adult male pedestrian model. In all cases, the pedestrian model was stationary when struck from his left side with the struck leg back (at 10% of the gait cycle) (Fig. 5) [20]. The vehicle impact speed was chosen as 40km/h (11.11m/s) since this a critical speed for the onset of serious/fatal injuries [3]. No braking was applied as it has been reported that a driver’s reaction time can be up to 1.2 seconds, with the average being 0.9 seconds [21]. The simulations were terminated after 300ms to allow sufficient time for the pedestrian’s head to strike the windscreen and disengage.

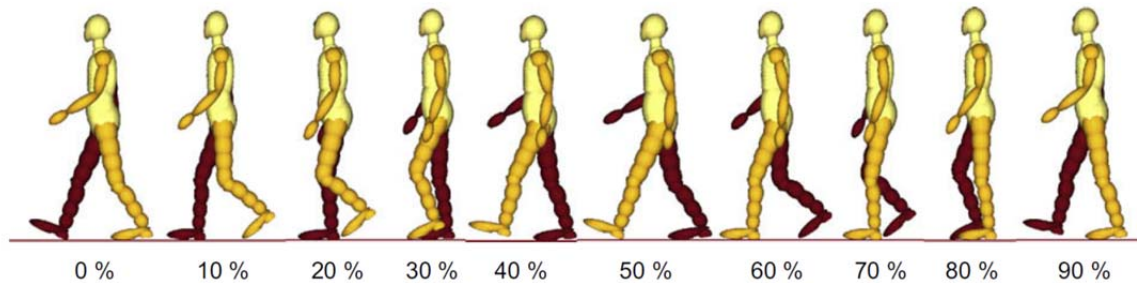


Fig. 5 - The pedestrian gait cycle, adapted from [20].

The main parameter under investigation was the windscreen angle which was defined with respect to the horizontal. Fig. 6 shows the tested variation in windscreen angle. The contributing effects of the coefficient of friction in the head-windscreen contact and the force deformation characteristic of the head/windscreen contact were also examined and the matrix of simulations is summarised in

Table 2.

1. *Windscreen Angle*

Otte [8] reported windscreen angles ranging between 29° and 55°, while Mizuno and Kajzer reported windscreen angles ranging from 29° to 40° [22]. Accordingly, a range between 20° and 55° was chosen in steps of 1° to allow for trends to be analysed, with the initial expectation of lower windscreen angles being safer based on Otte’s work [8] (hence a 20° lowest angle, which is here effectively an extension of the bonnet of the car).



Fig. 6 - Variation of Windscreen Angle, shown in 5° steps, from 20° to 55°.

2. *Coefficient of Friction*

The coefficient of friction between the pedestrian’s head and vehicle has been estimated as 0.3 [22, 23]. However, to evaluate the effect of friction on the head injury versus windscreen angle relationship, 3 different coefficients of friction were investigated: $\mu = 0.1, 0.3$ and 0.6 .

3. *Windscreen Force Characteristic*

Given that the force, and thus the acceleration, experienced by the head depends on the force/deformation properties of the windscreen, the effect of the contact characteristic on the head acceleration versus windscreen angle relationship was investigated for windscreen angles between 20° and 55° . As stated, the baseline force/deformation characteristics for the windscreen were extracted from a single trace presented by [15]. Precise stiffness values for windscreens are poorly reported. In order to test the sensitivity of the results, this force characteristic was first doubled and then halved. The force deformation characteristic of laminated glass is inherently non-linear. It includes a linear portion up to the breaking of the glass; the force then falls off before increasing again gradually as the laminate stretches. To investigate the influence of the non-linearity of the characteristic on the results, a mock windscreen stiffness was generated which used only the initial linear part of the Mizuno characteristic. Again, for sensitivity analysis, the effect of halving and doubling the magnitude of the force in this characteristic was investigated. A plot of the various force characteristics is shown in Fig. 7.

Table 2 - Simulations

Simulations	Windscreen angles	Windscreen force characteristic	Coefficient of Friction
Windscreen Angle	$20^\circ - 55^\circ$ in steps of 1°	Mizuno and Kajzer [15]	0.3
Coefficient of Friction	$20^\circ - 55^\circ$ in steps of 1°	Mizuno and Kajzer [15]	0.1, 0.3 and 0.6
Force Characteristic	$20^\circ - 55^\circ$ in steps of 5°	Mizuno and Kajzer [15] and Linear stiffness.	0.3

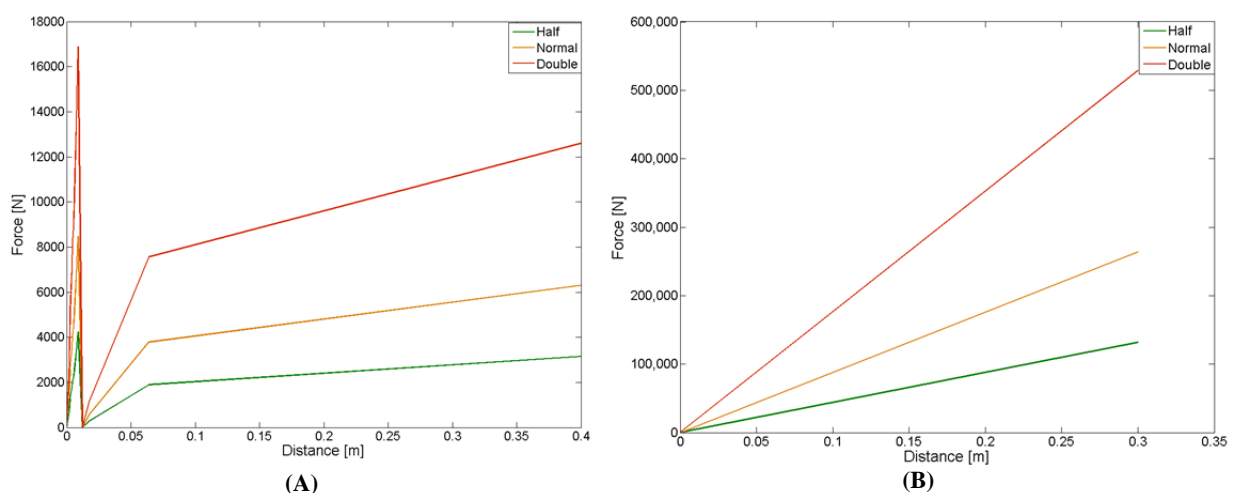


Fig. 7 - Stiffness Characteristics: (A) Mizuno and Kajzer and (B) Linear Stiffness

III. RESULTS

A. Validation

A comparison of the recorded head impact velocities and the associated errors is given in Table 3. Fig. 8 to Fig. 13 below show the time histories of the relative velocity of the pedestrian’s head with respect to the vehicle for each of the six simulations superimposed with the relevant plots from Kerrigan et al. [12, 13].

Table 3 - Results of validation simulations

Test ID	Kerrigan			MADYMO	Errors		
	V_{h1} (m/s)	V_{h2} (m/s)	$V_{h, avg}$ (m/s)	V_h (m/s)	Error V_{h1} (%)	Error V_{h2} (%)	Error $V_{h, avg}$ (%)
P1	13.70	13.18	13.44	13.66	-0.29	3.64	1.64
P2	14.70	14.14	14.42	13.30	-9.52	-5.94	-7.77
P3	12.00	11.00	11.50	13.37	11.42	21.55	16.26
D1	14.85	14.26	14.56	11.73	-21.01	-17.74	-19.41
D2	13.77	12.84	13.31	11.73	-14.81	-8.64	-11.84
D3	14.47	13.28	13.88	11.73	-18.94	-11.67	-15.46
DA1	16.00	15.77	15.89	12.24	-23.50	-22.38	-22.95
DA2	15.42	15.10	15.26	12.09	-21.60	-19.93	-20.77

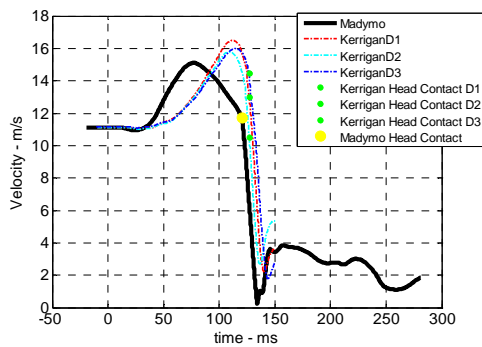


Fig. 8 - Validation Plots for Kerrigan et al. D1, D2 & D3 [13].

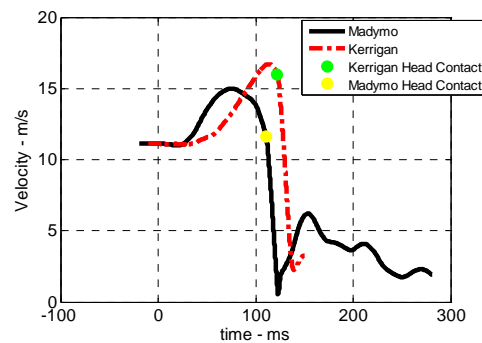


Fig. 9 - Validation Plots for Kerrigan et al. DA1 [13].

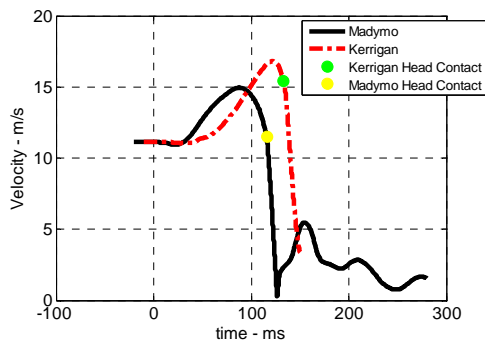


Fig. 10 - Validation Plots for Kerrigan et al. DA2 [13].

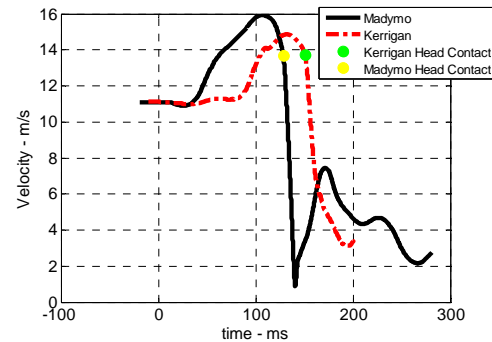


Fig. 11 - Validation Plots for Kerrigan et al. P1 [13].

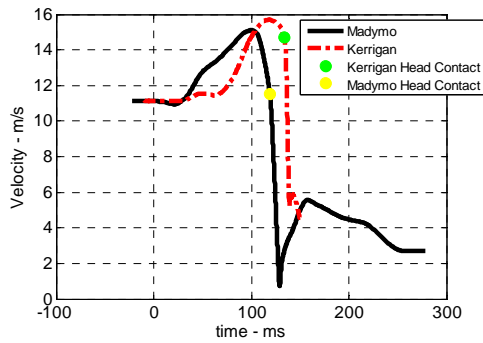


Fig. 12 - Validation Plots for Kerrigan et al. P2 [13].

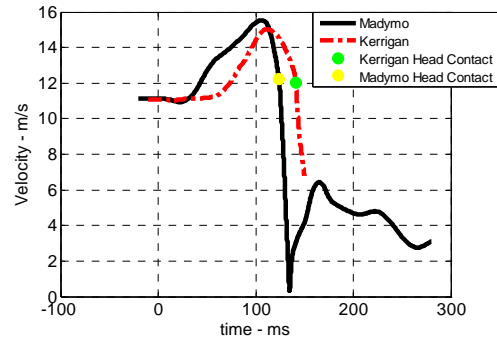


Fig. 13 - Validation Plots for Kerrigan et al. P3 [13].

B. Windscreen Angle

The effect of windscreen angle on peak head angular and linear acceleration for the non-linear Mizuno characteristic is shown in Fig. 14 and Fig. 15.

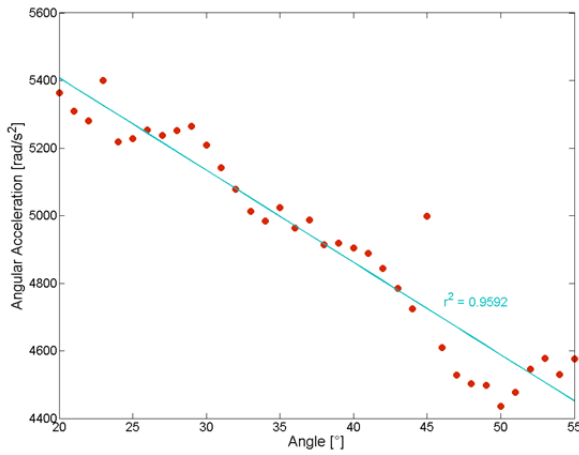


Fig. 14 - Variation of Maximum Head Angular Acceleration with Windscreen Angle for Mizuno Windscreen Stiffness.

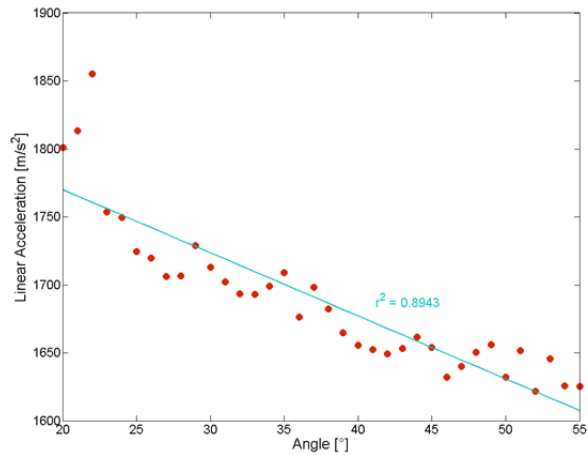


Fig. 15 - Variation of Maximum Head Linear Acceleration with Windscreen Angle for Mizuno Windscreen Stiffness.

C. Coefficient of Friction

The effect of the head/windscreen contact friction on peak head angular and linear acceleration for the non-linear Mizuno characteristic is shown in Fig. 16 and Fig. 17.

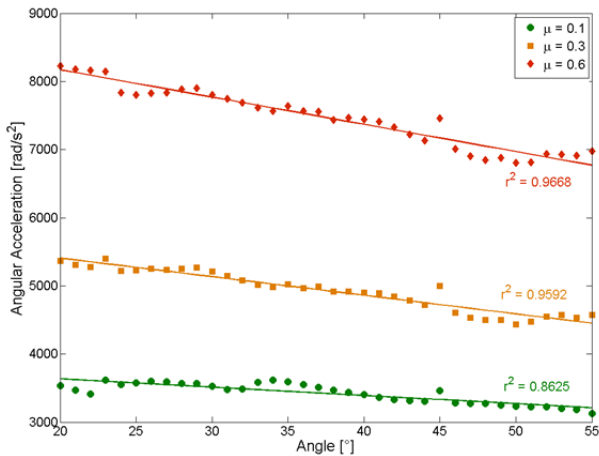


Fig. 16 - Variation of Peak Angular Acceleration with Angle over 3 different Coefficients of Friction for non-linear Mizuno Windscreen Stiffness.

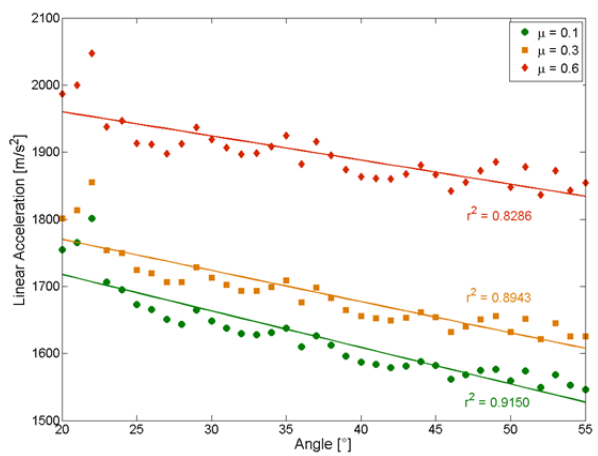


Fig. 17 - Variation of Peak Linear Acceleration with Angle over 3 different Coefficients of Friction for non-linear Mizuno Windscreen Stiffness.

D. Force Characteristic

The effect of doubling and halving the non-linear Mizuno head windscreen contact characteristic on peak head angular and linear acceleration is shown in Fig. 18 and Fig. 19.

1. Mizuno and Kajzer contact characteristics

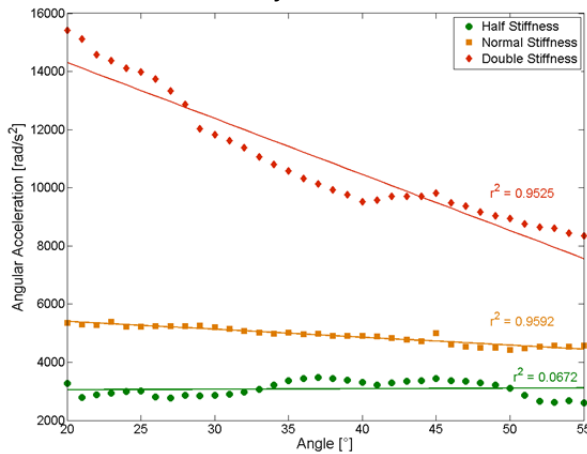


Fig. 18 - Effect on Peak Angular Acceleration of scaling the non-linear Mizuno Windscreen Stiffness Curve.

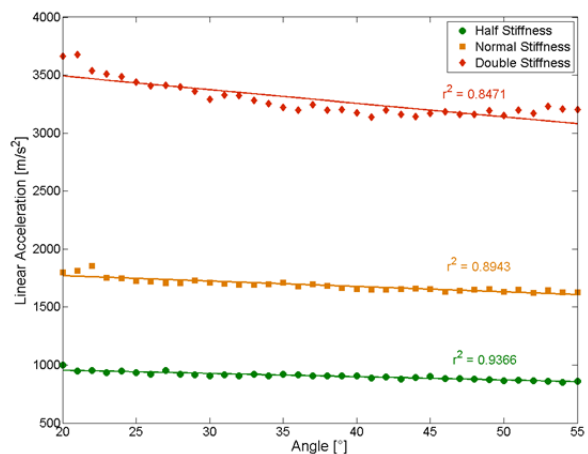


Fig. 19 - Effect on Peak Linear Acceleration of scaling the non-linear Mizuno Windscreen Stiffness Curve.

2. Linear contact characteristics

The peak linear and angular accelerations of the head for the linear windscreen stiffness are shown in Fig. 20 and Fig. 21.

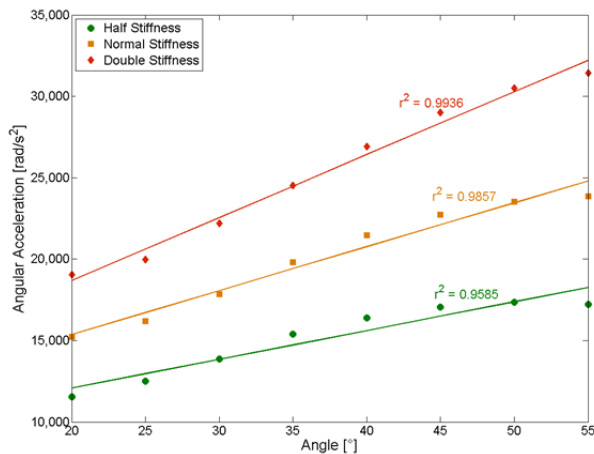


Fig. 20 - Effect on Peak Angular Acceleration of scaling the Linear Windscreen Stiffness Curve

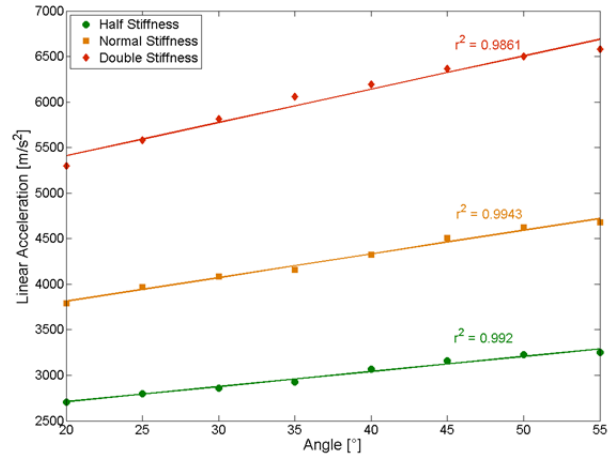


Fig. 21 - Effect on Peak Linear Acceleration of Scaling the Linear Windscreen Stiffness Curve

IV. DISCUSSION

A. Validation

Figures 8-13 show that the overall MADYMO simulation time history response is good when reconstructing the Kerrigan et al. [12, 13] experiments. Table 3 shows the maximum error (based on the average resultant cadaver head impact velocity) to be 16%. The maximum error for the dummy cases was 23%, and there are some contributing factors that might explain this. Firstly, the MADYMO pedestrian model is not designed to replicate the crash test dummy used in the experimental tests. Secondly, analysis reveals that head impact occurs at a period of high head acceleration even before windscreen contact occurs, meaning that a small error in the predicted time to head impact results in a large error in predicted head impact velocity. Finally, the stiffness characteristics used for the vehicle surfaces were not directly derived from the car used by Kerrigan et al. as these were not available, and this would again slightly affect the kinematics of the pedestrian. However, overall, the MADYMO time history graphs of the head velocity replicate dummy and cadaver tests of Kerrigan et al. reasonably well and the model is suitable for the kind of parametric analysis applied in this study.

B. Windscreen Angle

It is evident from Fig. 14 and Fig. 15 that increasing windscreen angle reduces both the angular and linear accelerations of the head and is thus important for considering pedestrian head injuries. The relationships appear mainly linear, with linear regression yielding r^2 values of 0.96 and 0.89 for angular and linear acceleration respectively. The scatter can be partially attributed to shoulder contact occurring before head contact in very shallow windscreen angles, and the arm contact is the cause of the unusual peak in the head angular acceleration at 45 degrees in Fig. 14. A change in windscreen angle from 20° to 55° results in about an 18% change in peak angular acceleration and about a 7% change in peak linear acceleration. The shoulder impact occurred before head impact in windscreen angles up to 25°, but the minimum windscreen angle for small sedan and sports cars has been reported as 29° [8, 22]. These results indicate that steeper windscreens cause lower peak linear *and* angular acceleration of the head. The time histories of the head velocity in the global X and Z directions are shown for 20° and 55° windscreens in Fig. 22 and Fig. 24 respectively. The largest component of head velocity at the instant of windscreen contact is vertically downwards due to whole body rotation, see Fig. 25. Since a steeper windscreen is more vertical and a steeper windscreen angle results in earlier head contact (see Fig. 22 and Fig. 24), the perpendicular head impact velocity on the windscreen reduces and the velocity parallel to the windscreen increases with increased windscreen angle, see Fig. 23.

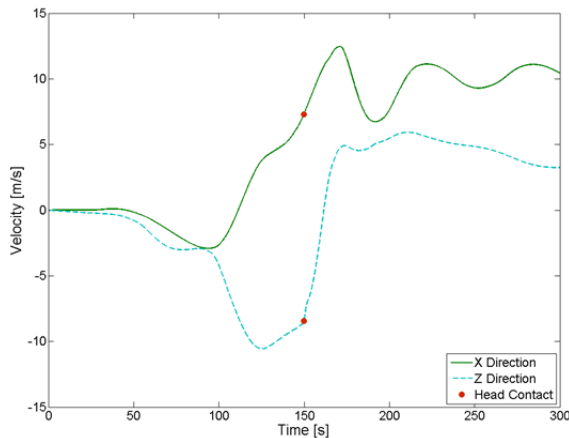


Fig. 22 - Time History of the Linear Velocity of the head for a windscreen at 20° with the Mizuno windscreen stiffness curve

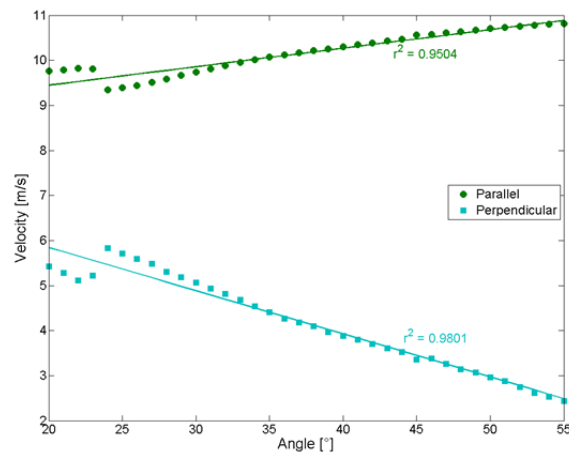


Fig. 23 - Velocity of the Head Perpendicular and Parallel to the Windscreen vs. Angle at instant of head contact with windscreen

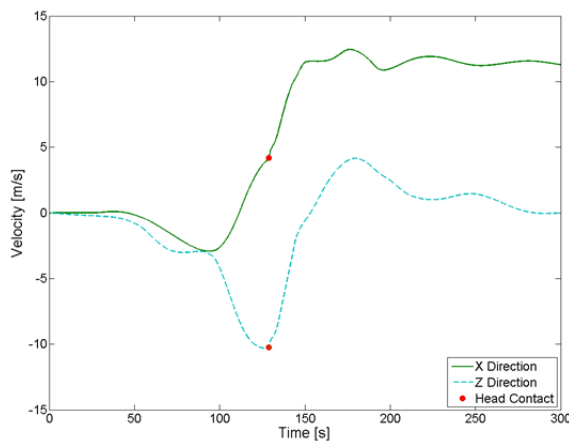


Fig. 24 - Time History of the Linear Velocity of the head for a windscreen at 55° with the Mizuno windscreen stiffness curve

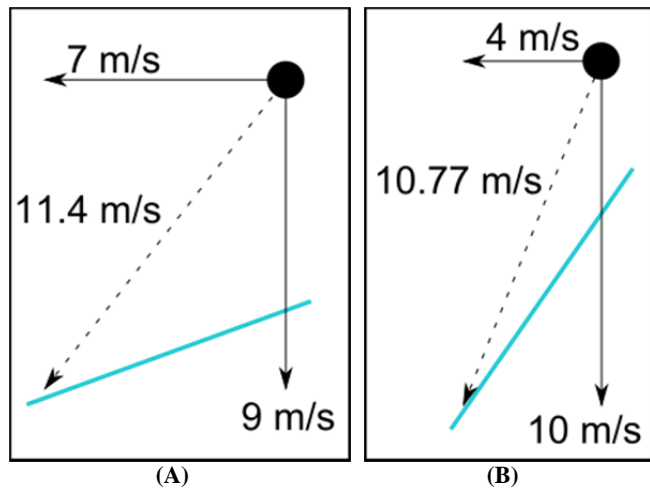


Fig. 25 - Schematics of Head Contact velocity for windscreen angles of (A) 20° and (B) 55°

This trend of decreasing linear and angular accelerations of the head (and hence injury risk) with increasing windscreen angle is not in line with the findings of Otte [8] who reported from accident data that instances of AIS3+ injuries increased with increasing windscreen angle. However, Otte’s findings may be open to re-interpretation. Firstly, only about 10% of the Otte cases involved cars with windscreen angles lower than 30°. The data also contained head impacts with the windscreen frame, a much stiffer structure than the windscreen glass. A regression plot of injury severity versus windscreen angle for Otte’s data reveals that, for the speed range studied, all of the impacts with the windscreen frame occurred in cars with windscreen angles above 34°. This artefact cannot be attributed to windscreen angle since it is largely the pedestrian kinematics *prior* to windscreen impact that determines the location of head impact on the windscreen. A reconstructed version of Otte’s regression of head injury versus windscreen angle is given in Fig. 26 and Fig. 27 with instances of impact with the windscreen frame removed. There is now a low correlation ($r^2 < 0.4$ in both cases) and the small sample size is evident. Furthermore, vehicle geometry varies considerably across the entire vehicle fleet, and thus varying windscreen angles in Otte’s dataset would also be indicative of varying bumper, bonnet leading edge and bonnet top heights, and all of these have a marked effect on pedestrian kinematics [3]. It may therefore not be appropriate to attribute changes in pedestrian head injury solely to windscreen angles in Otte’s dataset. In contrast, in the present study, the only geometrical feature changed was the windscreen angle.

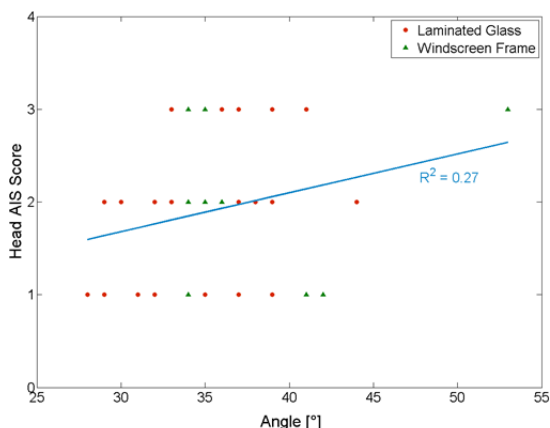


Fig. 26 - Regression Plot of Head Injury Severity as a Function of Windscreen Angle, reconstructed from [8].

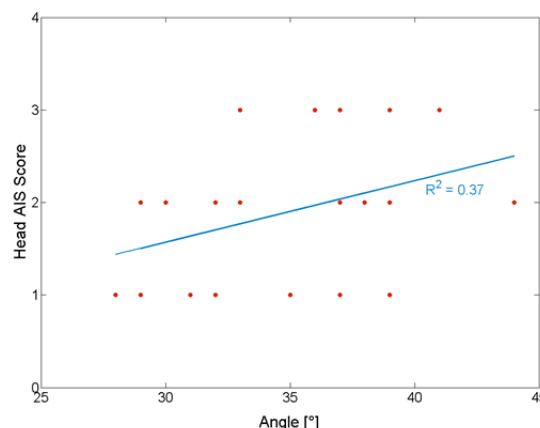


Fig. 27 - Regression Plot of only Laminated Glass Cases, reconstructed from [8].

C. Coefficient of Friction

Our literature review revealed no experimental data for the coefficient of friction for the head windscreen contact. For the baseline model, the coefficient of friction was taken as 0.3, as used by Mizuno [22], but the influence of friction on head accelerations was investigated, see Fig. 16 and Fig. 17. There were noticeable differences in the magnitude of the measured parameters, but the trends observed remained the same over the range of friction coefficients studied. A lower coefficient of friction allows more sliding of the head along the windscreen which will result in a lower linear and angular impulse to the head. These trends suggest a need for a windscreen with a low coefficient of friction to reduce linear and angular acceleration of the head. However, the coefficient of friction between the windscreen and the head is a complex quantity. The windscreen often breaks, creating a dent with a similar radius to the pedestrian’s head which probably increases the effective friction.

D. Force Characteristic

Variation of the Mizuno and Kajzer stiffness characteristic showed, not surprisingly, that stiffness has a significant influence on linear and angular head accelerations, see Fig. 18 and Fig. 19. However, the trend of decreasing head linear and angular acceleration with decreasing windscreen angle is not always maintained. At low stiffness, the angular acceleration of the head loses its trend ($r^2 = 0.07$), while at a high stiffness the trend is emphasised ($r^2 = 0.95$). The Mizuno and Kajzer stiffness characteristic appears to be the only one available in the literature for the centre of the windscreen. The observed effect of stiffness on acceleration was initially puzzling – a square root relationship between acceleration and stiffness results would result in the case of a free flying head striking a linear contact stiffness (as can be derived using a spring mass analysis), but this is not observed in Fig. 18 and Fig. 19.

Accordingly, the MADYMO simulation was run with a linear stiffness for the windscreen contact based on the linear portion of the Mizuno windscreen characteristic, which was then doubled and halved. Table 4 shows how the magnitude of the peak angular and linear acceleration increases by a factor of approximately $\sqrt{2}$ as the stiffness is doubled. However, more importantly, the trends for linear and angular acceleration of the head as a function of windscreen angle are reversed when the linear stiffness is used instead of the more representative non-linear Mizuno characteristic. Fig. 20 and Fig. 21 show that both linear and angular acceleration increase significantly with increasing windscreen angle for the chosen linear head-windscreen stiffness. In those cases, despite the linear velocity of the head perpendicular to the windscreen decreasing with increasing windscreen angle (Fig. 23), the peak force (not shown here) experienced by the head for the linear contact cases increases with increasing windscreen angle. This can be attributed to the follow-through of the body during the impact (Fig. 28), which alters the effective mass of the head. With a shallow windscreen,

follow-through of the body does not have a big influence as the windscreen does not pose as much of an obstruction. However, for steep windscreen angles the effective mass of the head is increased by the follow-through of the body pushing the head into the windscreen. Since the force from the mass of the body and the force imparted by the windscreen are not co-linear, they have a combined effect of increasing the resultant linear and angular acceleration of the head with increasing windscreen angle, see **ig. 20** and **Fig. 21**. Thus the trends of head linear and angular accelerations with windscreen angle are highly sensitive to the nature as well as the magnitude of the stiffness of the head/windscreen contact. Though beyond the scope of this paper, this phenomenon will probably also cause higher loading of the cervical spine in cases of steeper windscreens and this should be investigated.

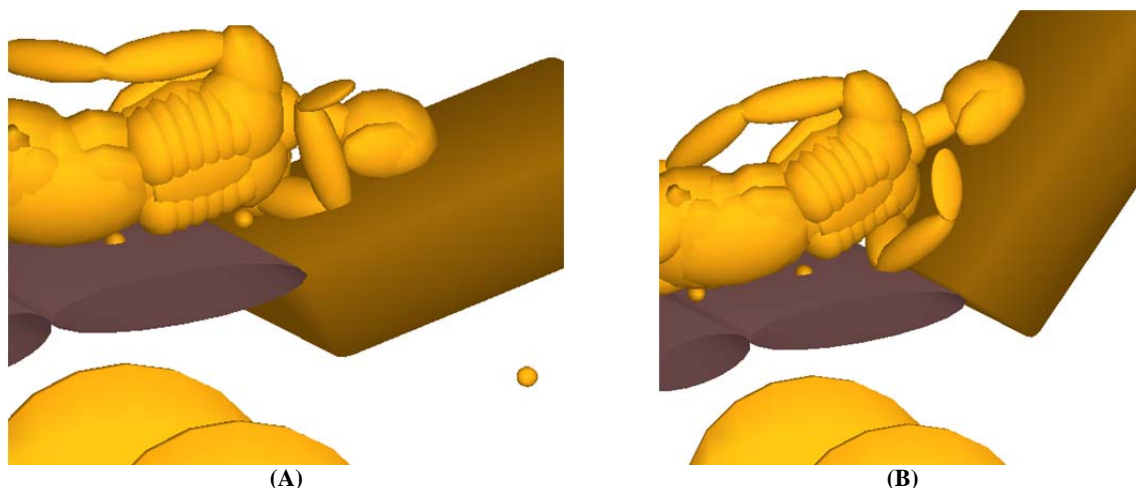


Fig. 28 – Ability of the body to follow through for (A) a shallow windscreen (20°), but not for (B) a steep windscreen (55°).

Table 4 - Maximum Values from Varying the Magnitude of Windscreen Elastic Stiffness

	Linear Acceleration	Angular Acceleration
Half Stiffness	2705	11558
Normal Stiffness	3788	15245
Double Stiffness	5300	19058

It is the non-linear nature of the force/deformation curve, as represented using the Mizuno characteristic, that causes the trends of decreasing linear and angular accelerations with increasing windscreen angle. It also causes the peak linear and angular accelerations to be more sensitive to stiffness changes (Fig. 18 and Fig. 19). Although a linear stiffness is highly unlikely at and above medium impact speeds due to breaking of the windscreen glass and loading of the plastic laminate, it is difficult to confirm these results, since there is apparently only one published stiffness curve for the windscreen. This emphasises the need for corroboration of the Mizuno windscreen stiffness data before the benefits of a steeper windscreen can be predicted with greater confidence. Furthermore, it emphasises the effect of the motion of the whole body on the resulting head injury. The mass of the body is not included in the EuroNCAP or Global Technical Regulation headform impact tests which use a simple headform impactor to measure the accelerations experienced by the head.

V. CONCLUSIONS

This simulation study showed that for impact between a side-struck adult pedestrian and a small sedan car at 40km/h, there is a decreasing trend in peak linear and angular head acceleration from the head/windscreen contact with increasing windscreen angle. A change in windscreen angle from 20° to 55° yielded a ca. 18% change in peak angular acceleration and about a 7% change in peak

linear acceleration, indicating that a steeper windscreen angle is safer for pedestrian head injuries in this impact configuration (although resultant effects on cervical spine loading have not been investigated in this study). This finding results from the non-linear nature of the head/windscreen contact stiffness and is not in line with conclusions from a previous review of accident data [8]. The coefficient of friction between the head and the windscreen has a marked effect on the magnitude of head accelerations, but over a range of friction coefficients (0.1-0.6) the trend of increasing injury severity with decreasing windscreen angle is maintained. However, an accurate knowledge of the stiffness characteristic of the windscreen is essential to understanding which windscreen angles are preferable: using a linear windscreen stiffness gave opposite head acceleration versus windscreen angle trends to those observed using the non-linear stiffness based on published impactor data. Accordingly, a new review of accident data should be performed and the stiffness characteristics of windscreens at different impact severities should be analysed.

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