

Simulation of motorcyclist's kinematics during impact with W-Beam guardrail

A.B. Ibitoye, A.M.S. Hamouda*, S.V. Wong, R.S. Radin

Road Safety Research Center, Faculty of Engineering, University Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia

Received 23 March 2004; received in revised form 24 November 2004; accepted 24 November 2004
Available online 20 June 2005

Abstract

W-Beam guardrail system has been in use as a standard for roadside safety barrier since 1950s. Recently, its safety performance standard has been upgraded to absorb impact from large vehicles. This performance standard requires guardrail system to be capable of capturing and redirecting a large range of vehicle types and sizes but its effects on safety of motorcyclists are not yet understood.

The paper describes a three-dimensional computer simulation of the kinematics impact of motorcycle and dummy rider with W-Beam guardrail inclined at angles 45 and 90° to the initial direction of travel. The simulation is based on the test procedure recommended by ISO 13232 on the configurations for motorcycle–car impact. The focus of this study is not on the motorcycle change in velocity, but on the rider's kinematics and acceleration vs. time history.

Multibody model of motorcycle and finite element model of guardrail were developed in commercially available software. The simulation results are presented in this paper in form of kinematics and acceleration vs. time history.

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Keywords: Kinematics; Impact; Acceleration–time history; Motorcycle; Guardrail

1. Introduction

Guardrails are highway appurtenances that provide a relative degree of protection to vehicle occupants from hazardous roadside features and from errant vehicles encroaching across a median. Although guardrails are expected to perform satisfactorily for a wider range of vehicles under a wider range of impact conditions, the existing guardrail is not designed for motorcycles impacts. Therefore, many factors used in the design of highway safety structures should be reconsidered to include motorcycles impacts and riders.

A review of literature indicates that the existing guardrails appear too stiff for motorcycle impacts [1]. Speeding and wrong manoeuvring may cause motorcyclist to loose control and this may eventually lead to off-road accident. Speeding increases the severity of the crash since the force

of impact sustained by motorcyclists increases by the square of the velocity [2]. On losing control motorcyclists may either involve in side collision with other vehicles, hit objects like trees, poles or lamp posts or even fall on roadway and slide along the roadway. Roadway is the second most frequently struck object by motorcycle [3]. The motorcycle hitting the guardrail will cause the rider to be ejected to either slide under the guardrail, hit the posts or rollover the guardrail to hit more hazardous object. Impacts with guardrail posts are especially harmful to motorcyclists as they cause injuries that are five times more severe than an average motorcycle accident [4,5]. Rollover accident is found to be the most dangerous type of accident in terms of fatalities and serious injuries per occupant [6].

The design of guardrail under vehicle impact is initially performed experimentally through an iterative process of design, build, test, redesign and retest, until the product meets its design criteria [6]. Since it is becoming economically impossible to perform full-scale field-testing in wide range of parameters, impact simulation is thus an effective tool for design and evaluation of guardrail system

* Corresponding author.

E-mail address: hamouda@eng.edu.upm.my (A.M.S. Hamouda).

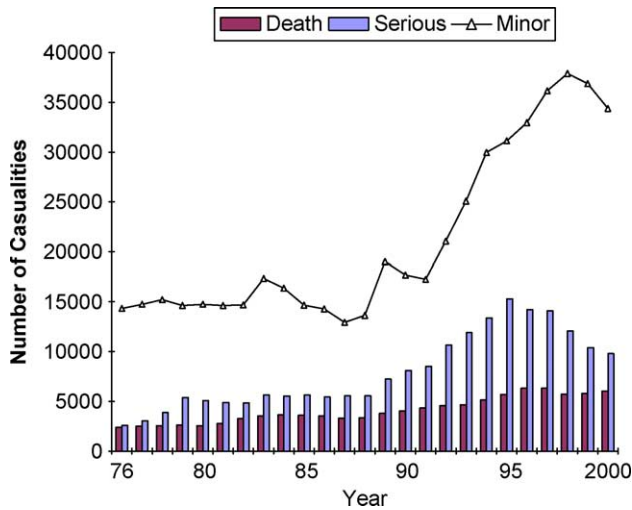


Fig. 1. Motorcycle accident and casualties in Malaysia.

[7]. The design of guardrails and their consequences for motorcyclists has been given little consideration by many researchers. In the International testing standards for the evaluation of safety barriers, motorcyclists have not been explicitly considered as test vehicles [8]. This may be as a result of non-recognition of dangers involving motorcyclists and low priority perceived in motorized vehicle dominating countries like Europe and America. These were the main motivation factors behind this current study.

In Asian countries such as Malaysia where motorcycles dominate the road traffic, 53% of vehicle registration is motorcycle [2]. The tremendous increase in the number of motorized two wheelers has been causing dramatic increase in the annual motorcycle fatalities in Malaysia (Fig. 1). A quarter of these fatalities are reported to be associated with roadside structures [2]. Since this accident record does not specify the extent of direct motorcyclist's impact with guardrail, the study simulates the rider's kinematics impact so as to evaluate the safety of guardrail to motorcyclists. The following sections of the paper discuss the development of the virtual model, system model and crash scenarios for the simulation. The results were then discussed to conclude that the existing guardrail is not suitable to protect motorcyclists as it protects the occupants of other vehicles.

2. Development of virtual model

The following procedures were involved in developing the model algorithm:

- Modelling of KRIS 110 Modenas Motorcycle model with Company's specifications [9].
- Modelling of W-Beam guardrail according to JKR (Ministry of Public Works) specifications [10].
- Creating input file using XML-Spy editor and Hyper-mesh 5.0 as pre-processor.

Table 1
Input parameters for modelling of motorcycle and guardrail

<i>Motorcycle</i>	
Size	Small
Overall length (mm)	1910
Overall width (mm)	670
Overall height (mm)	1050
Dry weight (kg)	100
Bodies	5
Joints	5
Ellipsoid	12
Cylinder	2
<i>W-Beam guardrail (material properties)</i>	
Density (kg/m^3)	7.860000×10^3
Young's modulus (N/m^2)	2.000000×10^{11}
Poisson ratio	0.28
Thickness (m)	0.00267
Yield stress (N/m^2)	3.4500000×10^8

- Regular debugging of input file using parser and editor.
- Post-processing using MadView.

The commercially available Madymo software (mathematical dynamic model) is used in this study. MADYMO combines in one simulation program the capabilities offered by multibody and finite element techniques. Input file was written as ASCII text file in accordance with Reference Manual [11]. XML-Spy editor was used to edit and validate the text file before running Madymo to solve the simulation and give back the output requested in the input file. MadView graphical post processor was used to animate kinematic data and plot time history data. Table 1 shows the input parameters used for the modelling of motorcycle and guardrail.

The finite element method of approach used in the modelling of W-Beam guardrail consists of:

- (1) Model discretization
- (2) Material properties specification
- (3) Specification of boundaries and constraint conditions
- (4) Load time history
- (5) Mesh convergence studies, and
- (6) Computational analysis phase.

2.1. Model discretization

Finite element method was used to reduce a continuum to a discrete numerical model. Finite elements are interconnected at a discrete number of nodes. The nodes and elements are fixed to the material and move through space with the material. The model is discretized by interpolating the displacement, velocity and acceleration of any point in an element in terms of the same quantities at the nodes connected to this element [12].

The material properties of steel were defined according to the manufacturer's specification, which are based on the guideline of Ministry of public Works (JKR).

2.2. Load time history

The time element for the simulation was specified to run from 0 to 1.5 s, with a time step of 0.0001 s, and using the modified EULER integration method [12]. Modified Euler method was used because model stability is a determinant for the step size of the simulation and that the finite element model was supported on a rigid body.

Starting point for time integration of the equations of motion are the second order differential equations given by:

$$q_n'' = h(q, q', t) \text{ with initial values } q_0 \text{ and } q_0' \quad (1)$$

h defines the equations of motion; q is a column matrix with the generalised coordinates, the joint position degrees of freedom; q' and q'' are the joint velocity degrees of freedom and their first time derivatives. The column matrix q contains m elements, corresponding with the m degrees of freedom of the model.

These acceleration equations are integrated using explicit Euler method which gives the solution for the velocity variables at time point $t_{n+1} = t_n + t_s$

$$q'_{n+1} = q'_n + t_s q''_n \quad (2)$$

2.3. Specification of boundaries and constraint conditions

The initial position of the models was defined in relation to road and direction of travel. Initial linear velocity of motorcycle and rider was also defined to be 50 and 30 km/h for each crash scenario.

2.4. Mesh convergence studies

Preliminary investigations were carried out on several models and comparable between the acceptability of the computational results and excessive CPU's demand had to be made. The mesh shown in Fig. 2 has an acceptable number of elements and reasonable mesh density distribution.

3. Overall system model development

Four systems were involved with road taken as inertial system, motorcycle model as multibody system and guard-rail model as Finite element model while Hybrid III ellipsoid 50-percentile dummy was used. Road was defined as a plane surface with three points representing the inertial

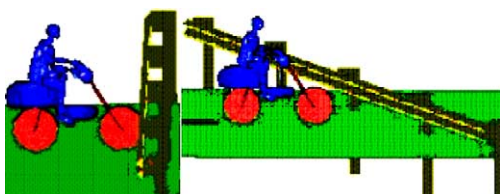


Fig. 2. Simulation Model set up for 45 and 90 degree.

coordinate system, termed global coordinate system or the reference space. The coordinate of the inertial system remained fixed throughout the duration of simulation while the coordinate and orientation of other systems were defined in relation with the inertial coordinate system.

3.1. Modelling of motorcycle

Multibody motorcycle model was represented with five rigid bodies as: Seat-frame, Driver, Front fork, Rear and Front wheel-spokes. Seat-frame was selected as a parent body to which all other bodies were connected in a chain. Body inertia properties with mass, m and moment of inertia (I_{xx} , I_{yy} and I_{zz}) were specified with respect to center of mass. Ellipsoids were considered for the bodies' shapes and cylinder for both front and rear wheels. Planar and revolute joints were defined as kinematics joints to constrain the relative motion of a pair of bodies. Kelvin restraint element was used to represent both rear and front wheels absorber system. This restraint calculates the forces produced by a spring parallel with a damper as in the case of motorcycle wheels. The spring and damper forces act on the bodies at the Kelvin restraint's attachment points.

3.2. Modelling of guardrail

W-Beam guardrail is modelled as finite elements using a central difference method with constant time step. The relations for the central difference method with a constant time step are:

$$\begin{aligned} v_{n+\frac{1}{2}} &= v_{n-\frac{1}{2}} + \Delta t a_n \\ u_{n+1} &= u_n + \Delta t v_{n+\frac{1}{2}} \end{aligned} \quad (3)$$

Subscripts $n - \frac{1}{2}$, n , $n + \frac{1}{2}$, and $n + 1$ correspond with time points $t - \Delta t/2$, t , $t + \Delta t/2$, $wt + \Delta t$, respectively, where t is the current time point.

Guardrail geometry was defined in terms of nodal coordinates and element connectivity.

About 2700 elements and 4000 nodes were defined for W-Beam rail and 166 elements with 240 nodes for each post with block-out. Isotropic material and geometrical properties of the elements were specified in terms of Young's modulus, Poisson's ratio and shear modulus. The relationship between these constants is:

$$G = \frac{1}{2} E / (1 + \nu) \quad (4)$$

The model was positioned at angles 90 and 45° such that the centre initially coincides with the origin of the inertial coordinate system. Supports were defined to connect rail to block-out and from block-out to the posts while the posts are rigidly fixed to the ground with defined contacts. Kinematics contact model was defined for the interaction between motorcycle wheels cylinders and W-Beam rail elements. Nodes displacement in x -direction was defined to

represent the deformation of W-Beam rail elements when impacted by motorcycle.

3.3. Contact interaction model

Contact interactions were defined between the master surface and a slave surface based on specified group of surfaces for interactions. Groups of ellipsoid surfaces were defined to represent Hybrid III dummy while ellipsoids and cylinders surfaces represent motorcycle model. Elastic contact model was specified between dummy ellipsoids and motorcycle ellipsoids with Hybrid III dummy ellipsoid defined as slaves and motorcycles ellipsoid as masters. Similarly, contact between motorcycle cylinders and the road was defined with motorcycle cylinders as slaves while road as masters. The elastic force generated during contact depends on the penetration and the force penetration characteristics. The contact point between contact points of the surfaces are calculated from:

$$P = P_1 + [x_e, el / (x_e, el + x_e, pl)] (P_2 - P_1) \tag{5}$$

where,

- x_e, el penetration into ellipsoid
- x_e, pl penetration into plane
- P_1 contact point on ellipsoid
- P_2 contact point on plane.

The combined contact characteristic of the interacting plane and ellipsoid or cylinder was specified in the input file. The force-penetration characteristics were specified for each contact with loading and unloading function as:

Pen (m)	Force (N)
0.00	0.0
0.001	1000
0.002	10,000
0.003	100,000

The longitudinal slip for tyre contact was defined as:

Pen (m)	Force (N)
0.00	0.0
0.01	1.5
0.02	1.0
0.03	1.0

Element of W-Beam guardrail was defined as slave surface and that of motorcycle wheels cylinders defined as the master surfaces. Kinematic contact model was defined between these surfaces because neither elements nor nodes of the finite element model are expected to penetrate the master surface of the wheel cylinders. The contact force was based on an inelastic impact between the elements and the front wheel cylinder surfaces.

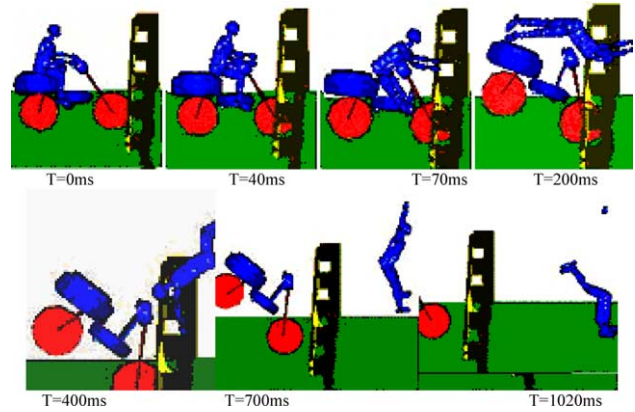


Fig. 3. Rider's kinematics view for MC impact speed of 50 km/h at impact angle of 90°.

4. Crash scenarios

The four scenarios similar to four different configurations of car motorcycle impact recommended in the ISO 13232 [13] were considered. They are:

- Case I: Inclination of guardrail at 90° with impact speed of 50 km/h
- Case II: Inclination of guardrail at 90° with impact speed of 30 km/h
- Case III: Inclination of guardrail at 45° with impact speed of 50 km/h
- Case IV: Inclination of guardrail at 45° with impact speed of 30 km/h

In all the configurations motorcycle was subjected to impact the guardrail within the span of the beam rail. The simulation results for the two inclinations of guardrail were compared for each impact angle. There is no similar crash test data to compare with since no simulation or full-scale crash test has been carried out under the same conditions and parameters. For instance, most motorcycle–car impact test concentrates more on the initial trajectory of rider;

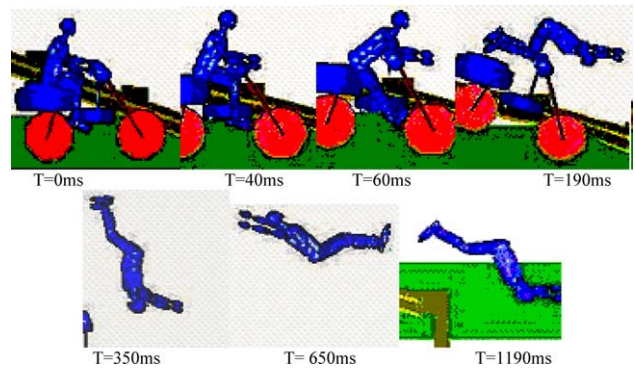


Fig. 4. Rider's kinematics view for MC impact speed of 50 km/h at impact angle of 45°.

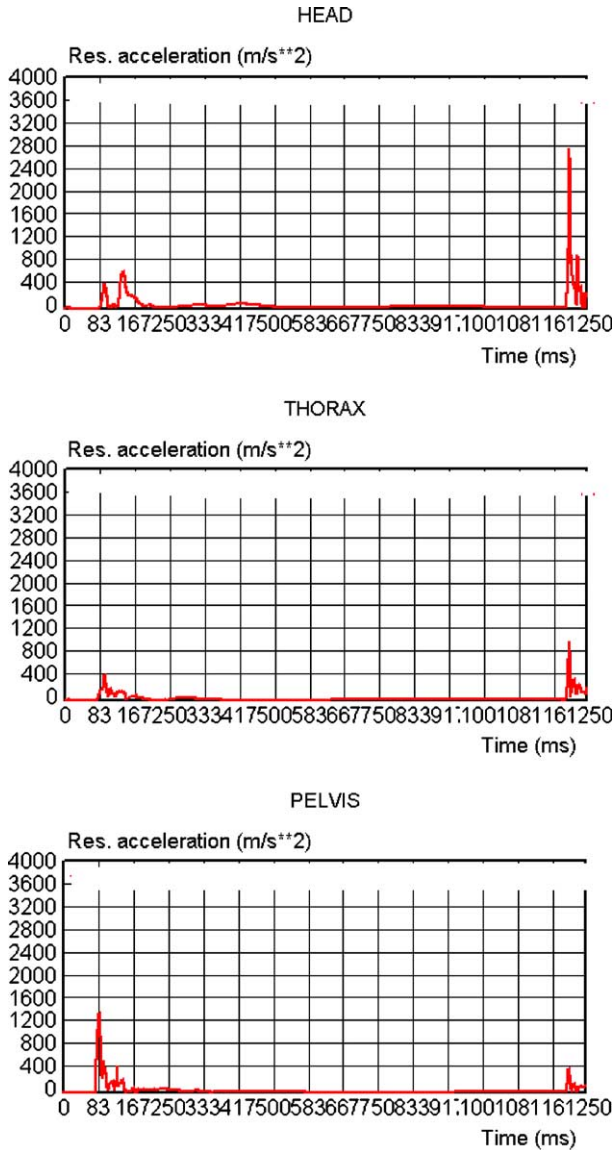


Fig. 5. Resultants acceleration of head, pelvis and thorax for 90° impact angle.

the head impact on the window frame or sill of car rather than the final fall of the rider. Thus, there are ongoing efforts to validate the result through a full-scale crash test of motorcycle and W-Beam guardrail. Figs. 3–6 present the kinematics and time history results of the rider at 90° in comparison to 45° inclination (Table 2).

5. Computational result and discussion

The case I and case III scenarios were considered critical and were thus compared for the period when the dummy was airborne until when the dummy reached the ground. The kinematics of the dummy was evaluated based on major body contact to the ground as shown in Figs. 3–5.

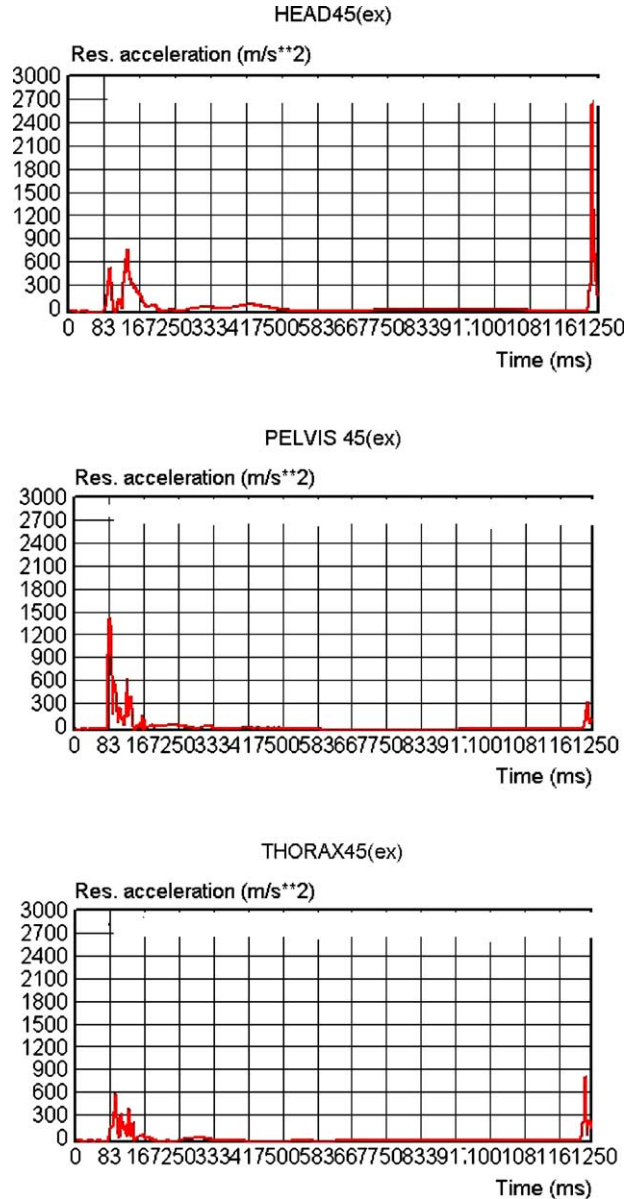


Fig. 6. Resultants acceleration of head, pelvis and thorax for 45° impact angle.

Table 2
Comparison of maximum value of injury parameters at different impact angles for impact speed of 50 km/h with biomechanical limits (tolerance levels)

Injury parameters	Impact angles		Biomechanical limits
	90°	45°	
HIC	17,742	3509.7	1000
3 MS (chest) (g)	58.43	61.92	60
FNIC_tension (KN)	40.15	3.61	3.3
FNIC_shear (KN)	21.61	5.25	3.1
FNIC_bending (Nm)	2189	511	57
FFCL (KN)	3.98	6.19	10
FFCR (KN)	3.98	6.20	10

In the case I, the dummy first touched the ground with the arm and head slanting downward while in case III it was the wrist joint with the head vertically downward. This result agrees with the studies by Fildes and Vulcan [14], which put injury frequency on head as 63%. The distance from the guardrail position to point of first contact is shorter for case III compared to case I. Also the final fall of dummy for case I was in the direction of travel with face and knee in contact with ground while in case III dummy was contacting by the back with head pointing against the travel direction.

Figs. 5 and 6 present the time history output in form of linear acceleration of the head, thorax and pelvis as defined in the input file. The head acceleration for 90° inclination was 10 times higher than head acceleration for 45°. Likewise the thorax acceleration is higher but pelvis acceleration for case III is twice that of case I. This implies that dummy is rotated from his normal direction of travel to fall on the back and head facing against the travel direction. This extreme higher head acceleration of case I made the dummy to fall at a greater distance from the guardrail initial position. Thus, possibility of hitting more hazardous object is higher for case I than case III. This agrees with the finding of Kuruz [15] that the probability of serious injury in fixed object collision is eight times higher compared to crash barrier collisions, regardless of the type of impact.

6. Summary

The study has examined the kinematics impact of motorcycle and injury risk to the rider. It was found that the existing guardrail is not designed to protect motorcyclist from being ejected and cannot even redirect or retain motorcycles like other vehicle. Also, the fallen motorcyclists are not protected against hitting the exposed guardrail posts or even rollover to hit more hazardous fixed objects. Thus, it can be concluded that the existing guardrail system is not safe to motorcyclists. Therefore, further studies should look into how substantial safety can be achieved through the following recommendations: (i) protection of exposed edges of guardrail posts, (ii) replacement of posts with smooth surface elements that will prevent danger of impacting sharp edge by the fallen motorcyclists, (iii) using of alternative materials to allow for better energy

dissipation, and (iv) changing of the entire design to achieve a safer barrier system.

Acknowledgements

The authors are grateful to the Ministry of Science, Technology and Environment for funding this work through an IRPA Research Grant (vot. 51543).

References

- [1] Duncan C. Motorcycle and safety barrier crash-testing: feasibility study. ISBN 0 642 25556 3. Accident Research Centre Monash University, Victoria 3800; 2000.
- [2] Pang TY, Radin Umar RS, Azahar AA, Megat AM, Mohd Nasir MT, Harwant S. Accident characteristics of injured motorcyclists in Malaysia. *Med J Malaysia* 2000;55(1):45–50.
- [3] Quincy R, Vulin D, Mounier B. Motorcycle impacts with guardrails. In: Transportation research circular: international roadside safety hardware research, No. 341; December 1988. p. 23–8.
- [4] Pieribattesti F, Lescure B. New safety barriers better adapted to the restraint of motorcyclists. *Rev Gen Routes* 1999;779:20–2.
- [5] Federated European Motorcyclists Association. Final Report on the Motorcyclists and Crash Barrier Project; 2000.
- [6] James MB, Allsop DL, Nordhagen RP, Decker RL. Injury mechanisms and field accident data analysis in rollover accidents. SAE 970396, Collision safety engineering; 1997.
- [7] Tabiei A, Wu J. Roadmap for crashworthiness finite element simulation of roadside safety structures. *Finite Elem Anal Des* 2000;34:145–57.
- [8] Gowan R. Road safety department. Wire rope safety barrier, Frankston Freeway, part 2, No. 94; 1996.
- [9] Private contact with Modernas Motorcycle Manufacturing Company in Malaysia.
- [10] Private contact with Industrial Galvanizers Corporation (M) Sdn Bhd. Malaysia and Ministry of Public Works (JKR) Malaysia.
- [11] Madymo 6.0 reference manual. TNO Automotive, Delft, Netherlands; April 2001.
- [12] Madymo 6.0 theory manual. TNO Automotive, Delft, Netherlands; April 2001.
- [13] ISO 13232 Motorcycles—test and analysis procedures for research evaluation of rider crash protective devices fitted to motorcycles—part 7: standardized procedures for performing computer simulations of motorcycle impact tests; 1996.
- [14] Fildes BN, Vulcan AP. Crash performance and occupant safety in passenger cars involved in side impacts. Proceedings of the international IRCOBI conference, Lyon, France; 1990. p. 121–40.
- [15] Kurucz CN. An analysis of the injury reduction capabilities of breakaway light standards and various guardrails. *Accid Anal Prev* 1984;16(2):105–14.