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Analysis and Design Optimization of Heavy Goods Vehicle for Pedestrian Safety −For Adult and Child Safety -

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1. Abstract

This paper addresses the analysis and design optimization of a new passive safety concepts for Heavy Goods Vehicle (HGV) by the installation of additional component under a bumper called “lower bumper stiffener” and “airbag” on the front panel of HGV to minimize the adult and child injuries. The HGV-to-child and HGV-to-adult collisions were simulated by the MADYMO crash analysis solver, in which the HGV collision at the speed of 25km/h against the child and adult models with several variations of working postures and facing directions were simulated. The scope of the analysis is limited to the duration of impact between the HGV and the child/adult models, so this will ignore all the post impact cases after collision. The design parameters of this concept were varied by the adoption of the Response Surface Method techniques with the use of Latin Hypercube Sampling (LHS) and the child/adult body injuries of Head Injury Criterion (*HIC*), thorax Cumulative acceleration (C_{3ms}), and peak femur loads were taken as the objective functions. Due to the diverse parameters and constraints of the initial conditions and the injury thresholds, the design problems were solved by multi-objective optimization by the Weighted Injury Criterion (*WIC*) that combined all these injuries. Based on the results of the design optimization, the potential of these child/adult pedestrian safety design concepts were discussed. Based on the two kinds of design concepts of “lower bumper stiffener” and “airbag” on the front panel of HGV, the airbag has shown better results in reducing pedestrian injuries, especially the head injury of child. The information provided for the pedestrian protection in this study could be used to assist the understanding towards designing a better HGV front bumper, particularly relating to the child pedestrian safety.

2. Keywords: Heavy Goods Vehicle (HGV), Pedestrian Safety, Collision Damage Estimation, Multi-objective Optimization, MADYMO.

3. Introduction

Research on vehicle structures to protect pedestrian injury at the collision is one of a highly important issue in vehicle safety design. Vehicle manufacturers have to meet the safety legislations and regulations in order to sell vehicles to the public. An early design stage planning with consideration of pedestrian safety is an inevitable demand and the use of computer simulation techniques such as the multi-body simulation and the finite element simulation is vital to evaluate the behavior of a real accident. According to the type of vehicle safety system, it can mainly be divided into passive and active systems. The active system is a system that assists a driver to avoid collision such as antilock brake system (ABS), while the passive system is a vehicle component that prevents or reduces injury when a collision happens such as between an airbag and bumper. Both systems have already led to high standard protection system, but the defense for pedestrians is quite poor. Moreover, little improvement can be found in the interaction between Heavy Goods Vehicle (HGV) and pedestrians.

The HGV which can be defined as a truck or a lorry that has gross combination mass of over 3,500 kgw is not heavily approach in pedestrian safety. This is because of its problematic nature of having aggressive front geometry and a higher risk of pedestrian run over. So far only few passive system improvements of HGV were studied to reduce pedestrian fatality and serious injury. Chawla et al. [1] used MADYMO (Mathematical Dynamic Models) simulations to investigate critical design parameters of HGV front geometry in HGV-pedestrian impact. They identified that the reduction of head injury, thorax and upper leg hit laterally by the HGV can be reduced by altering bumper height, bumper offset from front and by force-displacement characteristics of the HGV front panels. Shen et al. [2] performed numerical simulations tests on flat front vehicles against pedestrian and concluded that the additional frontal components such as bumper bar can greatly influence the pedestrian injuries, especially the head injuries. In addition, studies by Advanced Protection Group (APROSYS) have proposed a few possible designs of HGV passive system. Feist et al. [3] have suggested a retrofittable and energy absorbing design made by EPP foam for energy absorption in front of the HGV to minimize the pedestrian injury. They claimed that the injuries to head and lower extremities may be reduced up to 90% at impact velocities of up to 40 km/h by this concept design. Moreover, Hamacher et al. [4] suggested a change to the front of truck from flat front to tapered shape to improved pedestrian kinematics. This design had been proved numerically and experimentally that it would be able to reduce injuries and would be able to deflect pedestrian to the sideways in order to prevent the risk of a run over.

On the other hands, in pedestrian safety involving automobiles, there are a few recent ingenious solution of automobile. One system is the utilization of additional component below the bumper called lower stiffener. The stiffener was intended to reduce the bending angle of leg and the tibia acceleration so that the pedestrian kinematics after collision is improved. The idea of installing this kind of bumper to the HGV has been preliminary analyzed in [5] and from the findings, varying bumper height and bumper protrusion would influence the lower leg injuries, but gave a minimal improvement to the pedestrian's head injuries. In addition, a pedestrian airbag for automobiles to protect pedestrian head injury has also been invented in automotive safety. In this system, the car`s hood will be push upward and an airbag under the base of the windshield will be deployed to protect head injuries. The system uses high sensitivity radar and infrared technology to pre-detect a collision and inflates quickly enough to cushion the impact. The system had been claimed to be fully worked at the lower speed of less than 25 km/h. The aim of this research is to reduce the adult and child injuries when the pedestrians are collided against the HGV in the MADYMO multi-body environments. Two suggested design concepts of HGV for pedestrian safety, in which a lower stiffener structure and an add-in airbag in front of front panel, respectively, were adopted.

An HGV design with attached lower stiffener was varied depending on the impact speed, and the HGV was collided against different pedestrian walking conditions with several pedestrian gaits and different facing conditions with respect to the HGV position. The application for both of these lower stiffener and airbag concepts of HGV to reduce the pedestrian injuries were attained by the design optimization techniques. Both of these two suggested design concepts of HGV are parameters of the design and by adoption of the Response Surface Method (RSM) techniques with the Latin Hypercube Sampling (LHS) and the quadratic regression. These design problems were solved by multi-objective optimization to obtain the optimized lower stiffener parameters and the airbag parameters, where the pedestrian injuries such as Head Injury Criterion (*HIC*), Thorax Cumulative 3 ms Acceleration (C_{3ms}) and peak force value acted on both of femurs are taken as the objective functions. The scope of this study is only focused on the duration of impact between adult and child pedestrian models and the HGV model, respectively. Therefore, the results of this study will ignore all the post impact cases such as impact of child with road or vehicle run-over onto the pedestrian after collision.

4. Design Model Description

4.1 Injury Criteria of Pedestrian and between Pedestrian Walking Model

Pedestrian body can sustain a limited impact load before undergoing mechanical and physiological changes. Standard injury parameters have been recommended by recognized bodies such as EuroNCAP to identify the limitation of injury mechanism. For head injury, usually the Head Injury Criterion (*HIC*), which is a measure of the possibility of head injury occurred from an impact, is utilized. The *HIC* equation is stated as follows;

$$HIC_{15} = \left\{ \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a dt \right]^{2.5} (t_2 - t_1) \right\}_{max} \tag{1}$$

where t_1 and t_2 are the initial and final times (in seconds) of the interval during which the *HIC* attains a maximum value, and acceleration a of head is measured in g. The maximum time duration of $HIC_{t2 - t1}$, is usually limited to 15 ms. The maximum value for *HIC* is less than 1,000 for an adult. While the thorax, which is the next most critical organs after the head is measured by a common criterion, the Thorax Cumulative 3 ms Acceleration (C_{3ms}). C_{3ms} can be defined as the highest acceleration level that is exceeded during at least 3 ms. The maximum linear acceleration of 60 g is measured at upper thorax[6]. For upper leg injuries, a peak force value acted on left femur, F_L and right femur, F_R must be less than 10 kN[6] for adults.

In order to reduce the whole bodies injuries of pedestrian, one effective solution is to implement crash simulation of nonlinear explicit Finite Element Analysis (FEA) in high performance computer with acceptable accuracy and efficiency. Nonlinear explicit FEA such as MADYMO (Mathematical Dynamical Model) has been widely utilized for the design of vehicle but the implicit relation could affect the possibility to imply to the real application. The pedestrian in the simulations were realized by two MADYMO pedestrian adult models and a 6-year old child pedestrian model, i.e. a male model, a female model and a child model. The MADYMO pedestrian model is an ellipsoid human model developed by TNO automotive and the model was built based on the data of Western European population aged 18-70 years. The height and weight of the pedestrian models are tabulated in Table 1, which are constructed by 52 rigid bodies and are described by 64 ellipsoids to replicate the human bodies. The ellipsoids of the model act as several individual body parts such as head, torso or upper leg, where the stiffness, shape, size, mass and inertia are predefined based on the study by MADYMO. Several joints exists such as shoulder joints and elbow joints to connect these ellipsoids together. In addition, the pedestrian model can measure the injuries loads acted on the bodies if any external impact force acted on it. The MADYMO pedestrian models have been validated extensively in various studies which can be referred in the MADYMO Human Models Manual [5]. In order to used the MADYMO pedestrian model, the initial position and orientation of pedestrian of the study need to be established first. Then in the MADYMO simulations, the joints of the pedestrian model are changed in the ways to mimic the pedestrian conditions. For example, if the pedestrian is running before colliding with a vehicle, the pedestrian leg joint angles and hand joint angles before the collision need to be identified at first. Then the same angle values are applied to the joints of MADYMO pedestrian model.

Table 1 Sizes of pedestrian models

	Large male	Small female	Child
Height (m)	1.74	1.53	1.23
Weight (kg)	75.5	49.8	23.0
Knee height (m)	0.54	0.47	0.35

A successful alternative is to apply metamodel techniques such as the Response Surface Method (RSM). Redhe and Nilsson[7] found that the RSM performs well if the design variables are fewer and could be useful in vehicle frontal structure optimization. Fang et al.[8] found that conventional quadratic polynomials do provide a good approximation to the RSM model of the energy absorption. In addition, vehicle crashworthiness involves various design variables that might conflict each other and some problems arise when a great number of design variables are involved. Hence, a multi-objective optimization could be used to solve the problem simultaneously. In the frontal impact protection, Hong et al.[9] solved *HIC*, chest acceleration, chest deflection, and peak loads of femurs, where the quadratic response surfaces were used.

With the purpose of minimizing pedestrian injuries during collision with the HGV, a multi-objective optimization using the RSM can be conducted by computer simulation. In the simulation setup, the HGV front model and three kinds of pedestrian models, i.e., male and female adult models and a child model, are used for the estimation of collision injury of pedestrians as shown in Fig.1. Firstly, for the HGV model, the design parameters and the design constraints that might influence the minimization of pedestrian injuries need to be identified and modeled. Furthermore, initial conditions of HGV such as mass and speed should also been applied to the model. On the other hand, for the pedestrian model, the pedestrian gaits and the initial pedestrian position before the collision with HGV also need to be recognized. After that, the computer simulations need to be performed by using Design Of Experiments (DOE) techniques and as a result, the estimation values of pedestrian injuries are obtained. The pedestrian injuries from the results of computer simulation are presented by different body region of pedestrian bodies such as *HIC*, C_{3ms} or leg injuries. In order to obtain the minimal value to the overall pedestrian injuries, significance weight is given to each of pedestrian injuries body region. Hence, a multi-objective optimization based on the weighted sum of the body injuries can be performed mathematically and the best design parameters for the HGV can be obtained.

4.2 Concept of Pedestrian Protection from HGV Collision

Two design concepts of passive pedestrian protection against collision of HGV are considered in this research. These designs were intended to minimize the injuries of pedestrian in the multi-body MADYMO environment by the adoption of the RSM techniques with the Latin Hypercube Sampling (LHS) and the quadratic regression. The design problems were solved by multi-objective optimization to obtain the optimized lower bumper stiffener parameters and the airbag parameters, where the pedestrian injury criterion such as *HIC*, C_{3ms}, F_L and F_R are taken as the objective functions. The scope of this study is only focused on the duration of impact between pedestrian model of male, female and child with a vehicle model, respectively.

Figure 2(a) shows Design Concept 1, which is the concept of lower bumper stiffener that has been used in some car to keep pedestrian's leg bending angle lower and also to reduce tibia acceleration. However, comparing to the collision of an automobile with a pedestrian, the time duration of HGV impact with the pedestrian upper bodies are generally shorter than the passenger's automobile. In order to delay the impact time, the bumper of HGV is equipped to project forward. In this concept, a HGV has a bumper and lower bumper stiffener mounted to the front end of the vehicle front body. During a collision, the bumper and the lower bumper stiffener of HGV will hit the pedestrian legs first, before the HGV front panel will hit the pedestrian upper bodies. By varying the setup positions of the bumper and the lower bumper stiffener far and closer to the ground, and the bumper and the lower bumper stiffener projected forward and back, reducing effect of leg injuries and upper body injuries were considered.

Whereas, in the Design Concept 2 in Fig.2(b), an airbag is equipped on the HGV front panel to expect the reduction of upper bodies injuries. In this concept, a pedestrian sensor and an inflator are also equipped with the airbag to work punctually. The bumper is mounted to the front end of the vehicle front body while the airbag is located in the front end of the front panel of HGV. The sensor detects a collision between a pedestrian and the HGV. When the inflator receives the signal, and it responds by producing and supplying gas in order to expand the airbag. The airbag expands forward to cover the front area of the front panel and protect the upper injuries of pedestrian. Finding the combination of best airbag parameters is necessary in this design concept.

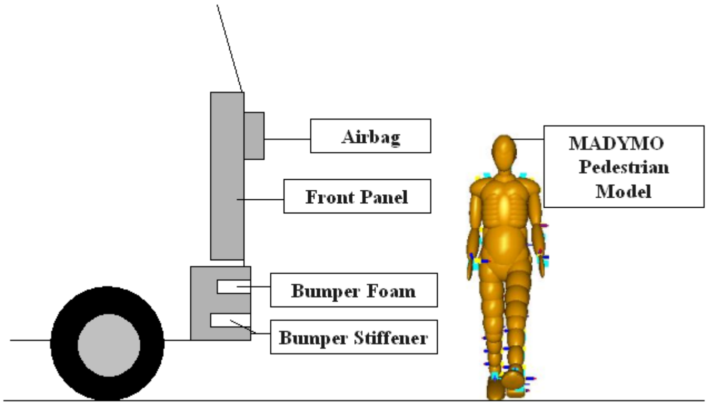
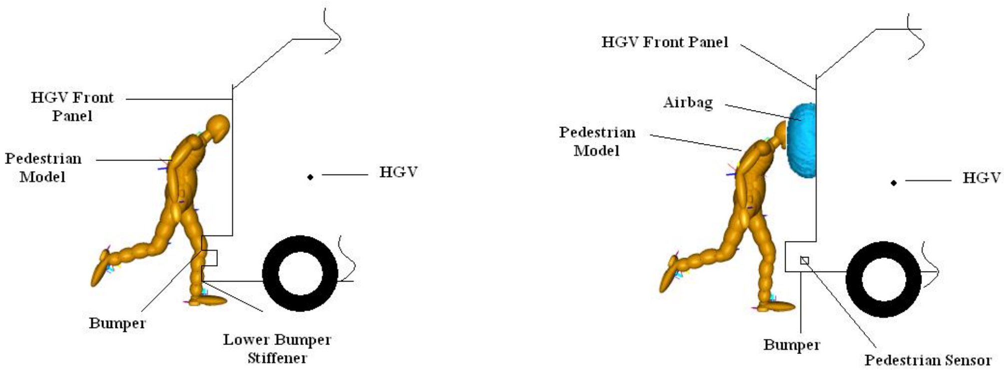


Figure 1: Setup of MADYMO simulation model with a pedestrian and the HGV.



(a) Concept 1 - Lower-bumper stiffener (b) Concept 2 - Attached airbag

Figure 2: Design concepts for pedestrian protection against HGV

4.3 Crash Simulation in MADYMO Environment

At first, adult pedestrians of male and female were intended to survive at a frontal impact crash of HGV at the maximum speed of less than 20 km/h. In order to achieve this target, two kinds of design concepts stated in the previous section were considered as case studies and treated independently. The first design concept was to see how the variation parameters of bumpers and lower bumper stiffener influence the pedestrian injuries. While the next, second design concept was considered in which the airbag attached to the front panel of HGV is effective. All crash simulations were implemented by using MADYMO solver. Most serious collision between vehicles and pedestrians occurs when pedestrian is facing sideways with the front surface of HGV. Because of this reason, only lateral impact of HGV-pedestrian was selected in this study.

For the first design concept, the frontal enhancement of HGV by means of equipping lower bumper stiffener to the front panel and without an airbag shown in Fig.2(a). The front of HGV was developed as three rigid bodies of ellipsoids of front panel, bumper foam and lower bumper stiffener. The front panel ellipsoid was assumed to perform as HGV front components such as grille and hood, where the front panel was simplified and treated to have the same stiffness so that the impact between the HGV and the upper bodies of pedestrian are the same throughout the study. The force-displacement curve for the HGV front structure from Ref.[2] was implemented, where a car bumper and lower bumper stiffener from Ref.[10] are used in this study. The EPP foam (20 g/l in density) shown in Table 2 was selected as the materials of lower bumper stiffener. In addition, the location of bumper is positioned at 500mm above the ground and 100mm in front of the front panel surface, while the position of lower bumper stiffener is maintained at a distant of 250 mm under the bumper as the baseline model.

On the other hand, for the second design concept, the same HGV model setup such as Fig.2(b) was implemented but added an airbag positioned at the front panel of HGV. Furthermore, the reason to use the same bumper and lower bumper stiffener to the second design concept was to observe the effect of airbag to pedestrian upper body injuries under same conditions. A front passenger's MADYMO airbag model was implemented to the setup which was designed by the finite elements model. The initial location of airbag had been estimated which was by positioning it in front mid-center line of HGV front panel and locating it at 1.5 m above the ground. The airbag model setup and theory can be referred in the MADYMO Theory Manual[5]. Practically, the idea of inserting an airbag to the HGV front is quite difficult to accomplish because of the needs of a shorter airbag firing time. However, this study assumed that a short firing time could be achieved in the near future. Furthermore, a total mass of 5,000 kg was also assigned to these bodies of HGV and the vehicle speed was set to 20 km/h. Since the pedestrian models were ellipsoid models, a multi-body to multi-body contact between the front of HGV and the pedestrian model was used. In contrast, the multi-body to the finite element contact was applied between the airbag component and the pedestrian model.

A study by Anderson et al.[11] demonstrated that the walking posture of the pedestrian before collision with vehicle front influences the pedestrian kinematics and the pedestrian injuries after the impact. However, because of the highly scattered data that it might generate, the kinematics of pedestrian model was kept the same throughout the experiments in this study. The pedestrian's initial posture from Ref.[12] was assumed to be in walking pattern with speed of 2.2 km/h and at 50% period of gait cycle. Furthermore, the pedestrian position with respect to the HGV location would be assumed to be facing the vehicle laterally in two conditions, i.e. facing left and facing right, and it was positioned exactly in the middle of the front vehicle. Due to the unsymmetrical gait of pedestrian, it is worthy noting that the pedestrians' gaits were different between both the facing directions and this would result in different value of injuries response between both pedestrian positions.

Overall, four different cases of situation were conducted for Design Concept 1 of added lower bumper stiffener and another four different cases of situation were conducted for Design Concept 2 of an added airbag. To discuss easily the results in the following section, Table 3 summarizes the different cases and different pedestrian conditions, from which the Design Concept 1 and Design Concept 2 depend on the adult and child models and their facing direction.

Table 2 EPP foam properties

Physical Properties	Value
Density (gw/l)	20
Tensile strength (MPa)	0.26
Tensile elongation (%)	14.0
Tear strength (kN/m)	1.74
Flexural strength (MPa)	0.21
Flexural modulus (MPa)	9.8

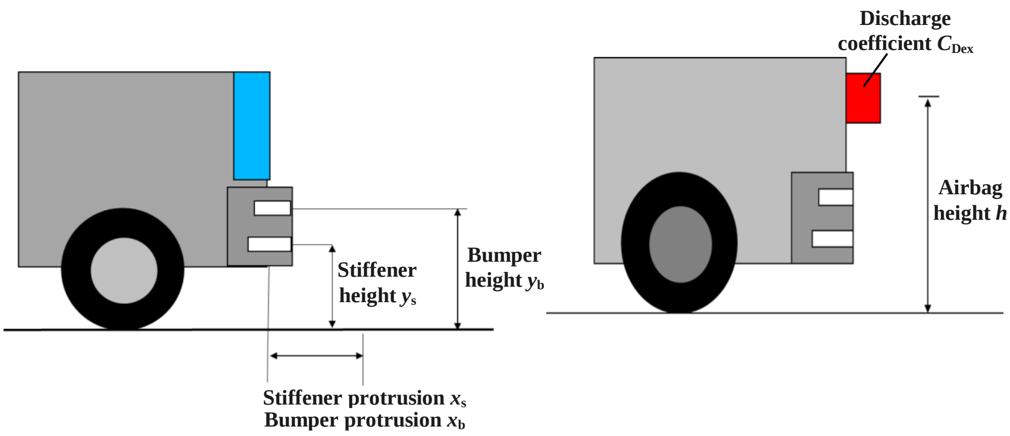
Table 3 Summarized parameters of simulation

Parameters	Test Scope
HGV Model	Baseline model
HGV initial speed (km/h)	15, 20, 25 and 30
Pedestrian models	Male, female, and 6 year child
Facing directions (°)	0, 45, 90, 135,180, 215, 270, 315, 360
Pedestrian gaits (%)	0 - 90

5. Design Optimization

Two cases of HGV front optimization were considered and treated independently. The first optimization case was to investigate how the variation parameters of bumper and lower stiffener influence the pedestrian injuries. While the next case considered was an airbag attached to the front of HGV panel**.** Figure 3 illustrates the locations of these parameters study, while the summarizations of parameters adopted in the simulation are listed in Table 3. The pedestrian's initial 80% period of gait cycle, which is facing to the right of the HGV, was chosen as the pedestrian parameters of studies. Based on the baseline HGV model, the design variables for lower stiffener concept can be shown in Table 4. In this optimization study, the lower stiffener protrusion x_s and bumper protrusion x_b were varied their positions forward and back between -100 mm and 100 mm. While the lower stiffener height y_s and bumper height y_b were moved downwards and upwards from the initial position -100 mm and 100 mm.

Whereas, for the second case, the same HGV baseline model but with an added airbag was positioned in the front and mid-center line of HGV front panel. The MADYMO finite elements airbag model [5] that was used to protect car passenger, was implemented in this setup. For the parameters of airbag, two design variables were considered for the design optimization study and presented in Table 5. The airbag's discharge coefficient C_{Dex}, which can be defined as a scale factor area of airbag vent hole, were changed its value by increased and decreased the scale factor value between 0.9 and 1.1. Next, the location of airbag in the *z*-direction was adjusted based on the height of the adult and child models. The maximum height of airbag is based on the height of child where the distance of 1.0m from the ground was chosen. The parameters were varied by ± 200mm in order to observe the effect of airbag impact with pedestrian upper injuries. The other airbag parameters were maintained from the basic MADYMO model.



(a) Concept 1 - Lower-bumper stiffener (b) Concept 2 - Attached airbag

Figure 3 HGV bumper variables and the airbag parameters

Table 4 Lower stiffener concept parameters

Concept	Design variable	Minimum	Baseline	Maximum
Lower Stiffener	Lower stiffener protrusion (mm)	0	100	200
	Bumper protrusion x_b (mm)	0	100	200
	Lower stiffener height y_l (mm)	100	200	300
	Bumper height y_b (mm)	400	500	600

Table 5 Airbag concept parameters

Concept	Design variable	Minimum	Baseline	Maximum
Airbag	Airbag height h (mm)	900	1,000	1,100
	Discharge coefficient C_{Dex}	0.9	1	1.1

5.1. Design Problem Description

For the safety consideration, the head injury criterion HIC, thorax acceleration C_{3ms}, and left and right femur peak loads (F_L and F_R) should be less than the values decided in the safety regulation. A general optimization problem for both of design cases stated in the previous sub-section can be express as follows;

$$\text{Minimize injury} \qquad F(\mathbf{x}) = [HIC, C_{3ms}, F_L, F_R] \tag{2}$$

$$\text{Subject to} \qquad HIC \leq 1{,}000, \quad C_{3ms} \leq 60\ (g), \quad F_L \leq 10\ (kN), \quad F_R \leq 10\ (kN) \tag{3}$$

For the lower stiffener Concept,

$$\begin{aligned} x_{smin} \leq x_s \leq x_{smax}, \quad x_{bmin} \leq x_b \leq x_{bmax} \\ y_{smin} \leq y_s \leq y_{smax}, \quad y_{bmin} \leq y_b \leq y_{bmax} \end{aligned} \tag{4}$$

For the airbag concept,

$$C_{Dexmin} \leq C_{Dex} \leq C_{Dexmax}, \quad h_{min} \leq h \leq h_{max} \tag{5}$$

where, the design variable x_s, y_s, x_b and y_b denote the bumper and lower stiffener position in the longitudinal direction and the height from the ground. On the other hand, the airbag parameters C_{Dex} and h denote the airbag parameters for discharge coeficient of air flow from vent hole and the setting height of airbag from the ground. The suffixes “max” and “min” are the upper and lower bounds of each design variables.

5.2. Solving Method

A set of sample points was then selected based on the LHS in conducting the computer simulations of HGV-Pedestrian collision. The responses for the pedestrian injuries of *HIC*, C_{3ms}, F_L and F_R obtained were used to construct quadratic regression models to approximate the solutions. Afterwards, the fitting accuracy of the models is validated by statistical analysis techniques. The coefficient of determination, the R_2, which is the statistical measure of how well a regression approximates real data values, was used for evaluating model fitness in this study. If the accuracy is not satisfied, a new regression model should been constructed by adding new sample points. The satisfied quadratic models for each *HIC*, C_{3ms}, F_L and F_R were then solved by multi-objective optimization technique. Because of the collision involved the whole pedestrian bodies, the weight of the significance injuries such as states in Table 6 is considered. Desirability functions *WIC* [13] given by Eq.(6) for each model was made separately with the significance weights and the threshold injuries assigned to them. Then the geometric mean of the individual desirability provides the solution to the optimal parameters to minimize the pedestrian injuries.

$$WIC = 0.6\left(\frac{HIC}{1000}\right) + 0.35\left(\frac{C_{3ms}}{60\text{g}}\right) + 0.05\left(\frac{F_R + F_L}{20\text{kN}}\right) \tag{6}$$

Table 6 Significance body region injuries

Body Region	Significance	Weights
Head	60%	$W_1 = 0.6$
Chest	35%	$W_2 = 0.35$
Legs	5%	$W_3 = 0.05$

5.3. Results and Discussion

(1) Optimum design for design concept 1 for adult models

The optimum design for the adult models were implemented against the collision of front lateral impact with a speed 20 km/h, when the bumper position x_b and y_b are taken as the design variables and the upper and lower bounds are set as x_{bmin} = 0 mm, x_{bmax} = 200 mm, y_{bmin} = 550 mm and y_{bmax} = 650 mm. Table 7 represents the results of the optimization for the four cases of simulations by varying simultaneously the locations of bumper and lower bumper stiffener of Design Concept 1. The results representing all cases with the values of optimal design variables, the minimum values of *HIC*, C_{3ms}, F_L and F_R injuries and also the total value of weighted injury criterion, *WIC*.

Observing optimum injuries for each case, every injury criterion attained the safer values under the threshold and the *HIC* and C_{3ms} are more severe than the F_L and F_R values. The female model has different total injury values compared with the male one. For the female model, although both of the optimal values of x_b and y_b are same, the different values of *HIC*, C_{3ms}, F_L and F_R injuries are acquired and this has resulted to the different minimum injury values depending on the gait cycle of pedestrian model.

In general, the concept of adjusting the position of bumper and lower bumper stiffener could influence the result of pedestrian injuries. Although different cases give different optimum value of injuries, the optimum solutions for the design problems still manage to be obtained. However, from the conducted simulations and optimizations, upper injuries such as head injury and chest injury had the most influence toward the obtained result. Hence, protection to the upper part of pedestrian is more necessary in the HGV-Pedestrian collision. Because of this reason, an airbag attached to the front panel of HGV is more desirable.

(2) Optimum design for design concept 2 for adult models

All the results of the four simulation cases of Design Concept 2 are presented in Table 8, when the upper lower bounds of airbag parameters were set as C_{Dexmin} =0.9, C_{Dexmax} = 1.1, h_{min} = 1.4 m, h_{max} = 1.6 m at the speed 20 km/h. Based on the results obtained, in general, a height increase of airbag position from the ground would decrease the value for the *WIC*. This can be explained by the height of both of pedestrian models where the male

Table 7 Optimization results of design concept 1

Conditions	x_b (mm)	y_b (mm)	*HIC*	C_{3ms} (g)	F_L (kN)	F_R (kN)	*WIC*
Male model facing right	200	583	636.9	19.06	1.593	1.376	0.5007
Male model facing left	200	583	698.8	21.74	1.193	1.037	0.5517
Female model facing right	200	583	826.6	20.63	0.762	0.770	0.6201
Female model facing left	200	583	634.3	23.36	0.404	1.285	0.5211

model height is 1.74 m, while the female model height is 1.53 m. By lowering the airbag from its initial height position, the airbag may not able to protect the pedestrian's head and for this reason will increase the values of *HIC* and *WIC*. In addition, the maximum height of 1.6 m, may good enough to protect both adult models in the similar gait position, which has the optimum *WIC* value. On the other hand, the value of discharge coefficient C_{Dex} for each case is exactly same as each other. It is concluded that a small change of the discharge coefficient does not influence the pedestrian injuries so much comparing to the location of airbag.

Table 8 Optimization results of design concept 2

Conditions	C_{Dex}	h (m)	*HIC*	C_{3ms} (g)	F_L (kN)	F_R (kN)	*WIC*
Male model facing right	0.98	1.55	40.27	17.06	0.986	1.366	0.1290
Male model facing left	0.98	1.55	186.8	15.50	0.816	1.448	0.2082
Female model facing right	0.98	1.55	150.6	15.40	0.681	1.746	0.1863
Female model facing left	0.98	1.55	107.6	17.03	0.854	1.568	0.1700

(3) Optimum design for child model

From the HGV collision at the speed 25 km/h, one of the child pedestrians that was failed due to its critical thorax injury value (Child 80% , facing left) used as the subject of optimization. The child condition was chosen because of the injuries values of the head and the thorax injury is close to the average values of the study. Furthermore, the lateral impact of the child pedestrian is considered important, because most collision between vehicles and pedestrians occurs when the pedestrian is facing sideways with respect to the front vehicles.

The result tabulated in Table 8 shows the values of optimal design variables which minimize the values of *HIC*, C_{3ms}, F_L and F_R injuries, when the positions of bumper and lower bumper stiffener and airbag height were taken as the design variables and upper and lower bounds of design variables were set as $x_{bmin} = x_{smin} = 0$ mm, $x_{bmax} = x_{sman} = 200$ mm, $y_{bmin} = 400$ mm and $y_{bmax} = 600$ mm, $y_{smin} = 100$ mm and $y_{smax} = 300$ mm, $h_{min} = 0.8$ m, $h_{max} = 1.2$, respectively. Observing the optimized results, by moving the bumper forward to 126 mm and positioning the bumper at 516 mm from the ground, the optimal protection to the head, thorax and leg injuries were attained for the child model. In addition, optimum values of injuries were also obtained when changing the position of lower stiffener near to the front panel and downward to the ground. The most improved condition was the thorax injury, where the value of C_{3ms} had improved significantly from higher than tolerance of 69 *g* to the value of 49 *g*. The thorax injury had improved because of the increased distance between the bumper and the HGV front panel. With the additional space, the child body has ample time to shift its position and avoids a direct hit of the HGV front panel. The correlation obtained from this study also confirmed that C_{3ms} had a strong relation with the bumper protrusion. Whereas, the stiffener should be located before the bumper, since the location in front of the bumper had resulted in increasing the child body acceleration towards to the HGV panel, where an increase of *HIC* values had been observed. Furthermore, both of the leg injuries were fully dependent on the position of bumper height since the measurements of upper legs were used in this study. Because of this reason, the optimal values of F_L and F_R were different from the values compared to the baseline model. However, the values of F_L and F_R is low as compared to the threshold values of 10 kN and the significance injuries of legs is only 5% as compared to the head and thorax.

Whereas, for the airbag concept, the parameters of C_{Dex} attained is 0.96 and the airbag height h obtained is 0.97 m. Because of the height of the child pedestrian is 1.23 m, the location of the airbag is considered sensible since the airbag is good enough to protect both of the head and thorax injuries. Whereas, the location of the bumper attained is 520 mm from the ground and the bumper protrusion obtained is 173 mm. The location of bumper protrusion influenced the result of the *HIC*, since the airbag sensor will detect the crash signal when the bumper hit the leg. From the result of the injuries, the values of *HIC* and C_{3ms} had been improved. However, minor changes were observed from the results of F_L and F_R because these leg injuries are mostly influenced by the impact of bumper and lower bumper stiffener, and not by the airbag. All of the results were under the threshold values, which mean that the airbag with lower stiffener bumper is considered effective to protect the child pedestrian.

Table 9 Results of optimal design

Conditions	Optimal design variables	*HIC*	C_{3ms} (g)	F_L (kN)	F_R (kN)
Baseline model	x_s = 100 mm, x_b = 100 mm, y_s = 200 mm, y_b = 500 mm	416.9	69.0	1.25	0.70
Lower stiffener concept	x_s = 0 mm, x_b = 126 mm, y_s = 100 mm, y_b = 516 mm	404.2	49.6	0.7	0.90
Airbag concept	C_{Dex} = 0.96 , h = 970 mm x_b = 173 mm, y_b = 520 mm	121.3	39.6	1.1	0.70

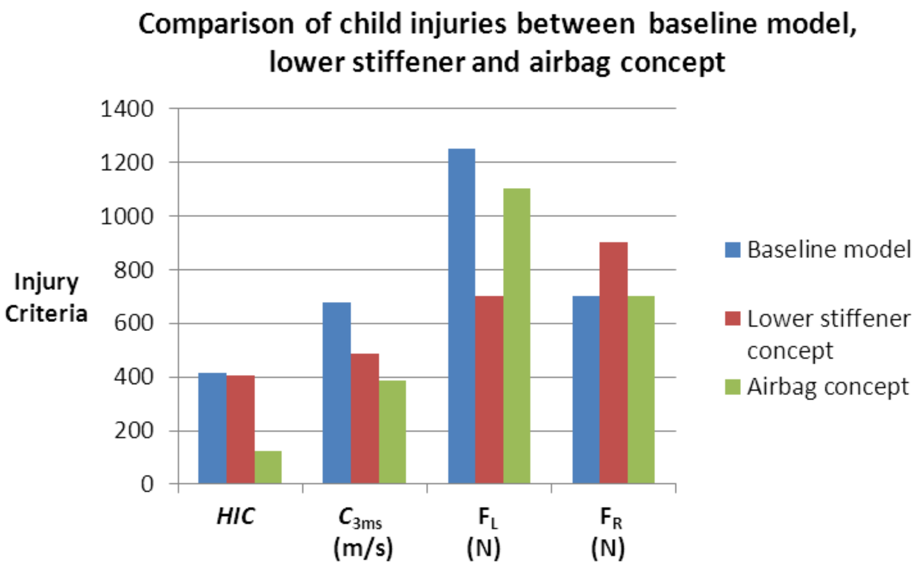


Figure 4 Comparison of child injuries between baseline model, lower stiffener and airbag concept models

Comparison between the baseline model and the two concepts such as in Figure 4 shows that the initial condition, which was failed at thorax injury, had been improved by these two concepts. The lower stiffener concept had performed well in reducing the leg injuries and also reducing the chest injuries of the pedestrian by changing the bumper and the stiffener positions. However, the best solution is to install the airbag to protect both of the head and the chest injuries. The *HIC* values had improved as much as 3 times, while the thorax injury obtained had improved only 60%. There was a slight changed of the F_L and F_R values, however they are considered non-significant because the same EPP foam material used and the values is so low as compared to the threshold injury of 10 kN.

The results of this study have considered only the collision between the HGV and the child pedestrian at lateral side (left position). Future works should be performed to investigate other child positions and child gaits, which might provide towards different optimum solutions. However, from this study it is clearly shown that both of the concepts can solve the optimum design problem of child pedestrian injuries.

6. Conclusions

In this paper, two concepts of bumper with lower bumper stiffener and airbag, which had been studied in the pedestrian safety of automobiles, had been successfully applied and optimized for the adult pedestrian models and a child pedestrian model between the HGV and pedestrian collision. The lower bumper stiffener concept is valid for the child pedestrian injuries as well as adult models to minimize the injuries by positioning the front geometries of bumper and lower bumper stiffener. Whereas, by locating the exact airbag position and the parameters of airbag had improved the pedestrian injuries. Comparing the two concepts, the airbag had shown better results in reducing pedestrian injuries, especially the head injuries. However, it is concluded that two airbags are necessary to protect the injuries of adults and child models at the same time. The information provided in this paper might be used to aid the understanding towards designing a better HGV front in the future by considering the adults and the child pedestrian safety aspects.

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