Chapter 95
Auto Rickshaw—Pedestrian Head and Neck Impact Injury Mitigation—An Analysis of Impact Material Alternatives, Their Costs and Their Benefits

A. J. Al-Graitti, T. Smith, R. Prabhu and M. D. Jones

Abstract Rapid motorisation of developing nations has led to road traffic accidents being the leading cause of fatal injuries in low- and middle-income countries. Auto-rickshaws act as a popular low-cost alternative to four-wheel-vehicles in developing countries, however, they are relatively unsafe, particularly during pedestrian impacts, since their structures and materials provide poor impact energy absorption. Passive safety systems can improve pedestrian-vehicle impact safety by increasing energy absorbtion within the vehicle structures. An investigation was conducted of the commonly impacted auto-rickshaw windscreen frame and windscreen, to develop easily implementable, improved, impact absorbing structural alternatives. Aluminium and magnesium, were compared as an alternative to the high carbon steel windscreen frame and polycarbonate, for the glass windscreen. Finite-element analysis (LS-DYNA) was applied to assessing head and neck injury risks by impacting a 50% percentile adult male anthropomorphic-test-device, at the front, side and rear. Impacts were simulated at, and offset of, the vehicle centreline at velocities between 10 and 40 km/h and the corresponding Head Injury Criterion (HIC_{15}) and Neck Injury criterion, (N_{ij} and N_{km}), investigated. Aluminium-6016-T4 and magnesium-AZ31B windscreen frame materials and the polycarbonate (PC) windscreen produced the lowest injury risk of all the materials investigated, particulary those head injuries associated with upper frame impacts. The PC windscreen produced higher HIC values for centreline impacts than glass, since it caused impact at the upper windscreen frame. Of the materials investigated, the aluminium (6016-T4) frame and PC windscreen produced the greatest safety at the lowest cost; establishing that material alternatives can assist in impact injury mitigation.

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95.1 Introduction

Road accidents are considered one of the most important global challenges and various strategies are being pursued to achieve a significant reduction in the number and severity of accidents that occur worldwide. The head and neck are the most frequently injured regions of the body during pedestrian-vehicle impacts [1–6]. A number of countermeasures, such as improved traffic management, speed limits [7–9], speed cameras [10, 11] and education [12], are assisting in reducing pedestrian casualties. However, engineering enhancements to the vehicle can make a significant contribution to the mitigation of pedestrian injuries. The bonnet (hood) and windscreen (windshield) are the most frequently impacted components of four-wheeled vehicles, with vehicles often constructed of materials that are stiff during impact and produce severe pedestrian head injuries [3, 5, 13, 14]. It has been recognised that making improvements to a vehicles frontal design, such as altering front-end geometry, materials and component thicknesses, could increase a vehicle's ability to absorb and dissipate impact energy [18] and lead to a reduction in injury risk and fatality [15]. An analysis of vehicle-pedestrian impacts in the German In-Depth Accident Study (GIDAS) and International Harmonized Research Activities (IHRA) databases demonstrate that serious injuries, corresponding to an Abbreviated Injury Scale value of AIS3+, could be reduced by between 18 and 27%, after improving current automobile designs [16].

Vehicle safety countermeasures can be split into two classes: active safety systems and passive safety systems. Active safety systems intervene before an accident occurs, whereas passive safety systems are those components that protect occupants and pedestrians during an impact. Automotive companies focus on minimising pedestrian harm during impact by using specific materials that exhibit excellent energy absorption capabilities, with this being one of the most important passive safety systems adopted. The main purpose of using high energy absorbing materials is to reduce the kinetic energy transmitted to the pedestrian during an impact by preventing the peak reaction force [17]. Therefore, the suggested engineering enhancements to the vehicle, to improve its energy absorbing capabilities, could have a potential influence on reducing pedestrian injury risk.

When attempting to make improvements to pedestrian safety, the most important aspects are to either modify the shape at the front of the vehicle, or to alter the material response of those components that account for the highest number of impacts with the pedestrian (i.e. windscreen and windscreen frame). The structural stiffness and impact energy absorption capacity of the vehicles frontal design are the crucial factors that affect pedestrian safety enhancement. It was pointed out that FE simulation technique can be consistently used in material selection and design enhancement of energy absorbers as a passive means of pedestrian protection [18].

Traditionally, automobile bodies have been made of low carbon steels, mainly due to its low cost and malleable nature, thus, making it the most common form of steel. Recently there has been a change from low carbon steels to a combination of steels, light alloys and polymer matrix composites [19]. One of the reasons the automobile industry has been targeting these new materials is for their reduced weight, which allows for an improved fuel economy of the vehicle, but most importantly, lower environmental pollution [19]. Furthermore, these materials have not been selected solely on their weight reduction potential but also for factors including safety, durability and cost.

The two materials currently considered the best alternatives to steel are aluminium and magnesium, especially for use in automotive applications [20–26]. Although the two materials are both more expensive than carbon steel, they are more cost effective alternatives than composite materials, which are mostly used in high-performance vehicles. Regarding the windscreen, polycarbonate has emerged as an excellent replacement for glass. It is less expensive, has a lower density, is lighter and a better absorber of energy during impact. While these materials provide safer alternatives to pedestrians and other vulnerable road users, they must also be sufficiently safe for vehicle occupants. Thus, it is important to keep the stiffness at least equal to the original material so that the vehicle retains its rigidity and bending is not increased during load transfer. This can be achieved by increasing the thickness of the alternative material used in a component, therefore, suitable thickness must be a consideration.

The auto rickshaw is a common mode of transport in developing countries that has a detrimental effect on the safety of pedestrians in urban areas. Impacts with the windscreen and windscreen frame are the most frequent injury causing events [27–30]. Therefore, engineering modifications focusing on the windscreen and windscreen frame are needed to reduce injury risk. Such modifications are going to come at a cost and since the economies of developing countries are relatively weak, cost must be a consideration. Thus, a cost-benefit analysis is essential when assessing the viability of vehicle modifications. An Indonesian study of road traffic injuries estimated that average total costs for slight injuries are around $464 (US) per crash, $1400 for serious injuries and approximately $37168 for fatal injuries [31]. A similar study in India found minor injuries in 2013 cost approximately $628, major injuries $6047 and fatal injuries $114487 [32]. These studies highlight the economic disparity between road traffic injury costs of two Asian countries, where auto rickshaws are popular, however, they do not differentiate between the costs of injuries to different areas of the body or the actual AIS level of those injuries.

Nguyen et al. [33] provided a more in depth analysis of how costs differ between AIS level injuries and body regions for pedestrian road traffic injuries in the Thai Binh province of Vietnam. Auto rickshaw injured pedestrians had the highest direct medical costs; higher than bicyclists, motorcyclists and car occupants [33]. The study estimated the mean costs to pedestrians whilst hospitalised could be as high as $2700 for severe head injuries (AIS4+) [33]. In addition, it was noted that injuries to the spine, which includes the neck and chest, had no significant cost difference and often had the lowest costs of all body regions, being approximately 38% lower than head injuries [33]. Neck and chest injuries were estimated to cost as high as $1520 for serious injuries (AIS3+) [33], the average annual income in the Thai Binh province is just $695 [34]. The costs only consider those incurred during the patients stay at one particular hospital, so does not consider transfer of the patient to a higher level hospital or loss of work due to injuries, thus, actual costs are likely to far exceed these estimates [33].

The average price for steel, which is currently used in structural elements, is approximately $0.93/kg [35]. Both aluminium and magnesium are more expensive than steel, with aluminium having an average price of $2.29/kg and magnesium higher again at an average price of $5.36/kg [35]. Moreover, the current glass windscreen has an average price of $1.70/kg [36], whereas polycarbonate has a price nearly double that of glass per kg, with approximate cost of $3.08/kg [37].

Therefore, if it can be established that engineering modifications have the ability to reduce injury risk to pedestrians and reduce medical costs incurred by injuries a modest investment in retrofitting/fitting key components can result in significant societal and environmental gains. The impact attenuation of magnesium and five grades of aluminium were compared with high carbon steel and polycarbonate was compared with glass, to determine whether material changes could improve pedestrian safety and injury reduction. Two important assessment criteria were established: that the design changes must provide potential to reduce pedestrian-auto rickshaw impact injuries. Secondly, that the materials be economically justifiable in terms of cost-benefit applying the cost of severe head injury (AIS4+) and serious upper neck injury (AIS3+) for the modified materials based on previous literatures [33, 34] to assess whether they are practical within their environment. Therefore, a cost-benefit analysis will be utilised to briefly estimate whether the material modifications are economically justifiable, given these vehicles are mainly used in developing countries.

95.2 Methodology

95.2.1 Simulation Setup

Auto rickshaw-pedestrian impact simulations and analyses were performed with a 50% Hybrid III adult male dummy in LS-DYNA software-Livermore Software Technology Corporation (LSTC). Auto-rickshaw-pedestrian impact simulations were conducted with a model from AL-Graitti et al. [30], at two vehicle contact regions, the vehicle centreline and 42 cm offset from the centreline. Three impact positions were investigated, frontal (facing the vehicle), rear (back to the vehicle) and laterally in a walking posture with the right leg forward (without a walking speed) and the left arm positioned backward, (see Fig. 95.1). Impacts were simulated at velocities of 10, 15, 20, 25, 30, 35 and 40 km/h.

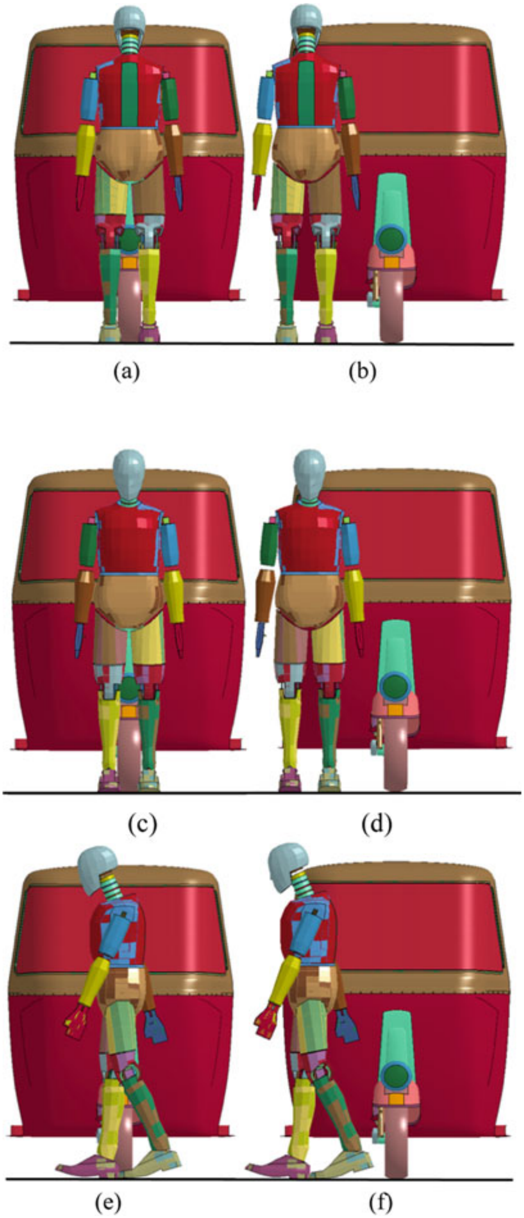

Fig. 95.1 Auto rickshaw–adult pedestrian impact simulations at different positions; **a** frontal impact to front of head at the vehicle centreline; **b** frontal impact to front of head, 42 cm offset from the vehicle centreline; **c** rear impact to back of head at the vehicle centreline; **d** rear impact to back of head, 42 cm offset from the vehicle centreline; **e** side impact during walking to side of head at the vehicle centreline; **f** side impact during walking to side of head, 42 cm offset from the vehicle centerline

95.2.2 Material Properties and Thicknesses

Magnesium-AZ31B alloy and Aluminum alloys (6016-T4, 6061-T6, 6111-T4, 5182-O, and 5754-O) comprised the windscreen frame and Polycarbonate (PC) the windscreen. The materials were tested for passive pedestrian safety improvement, as shown in Table 95.1. The materials were chosen because of their availability, high resistance to corrosion and that they are easily formable [38]. Past studies have concluded that decreasing the thickness of the component permits a decrease in both the Head Injury Criterion (HIC) value and the product weight, yet the thickness cannot be simply reduced to any value for structural parts, since it requires a sufficient stiffness [39].

Consequently, improving the stiffness of magnesium and aluminium alloys can be achieved by increasing the component thickness by a specific factor, such that it has the same stiffness as steel. The factor by which the thickness has to be increased for equal stiffness can be calculated using the following formula [38, 40]:

$$\frac{t_B}{t_A} = \sqrt[3]{\frac{E_A}{E_B}} \tag{95.1}$$

where t_A is the thickness for the original material (that is steel part), and t_B is the thickness of the new material (aluminium/magnesium components). E_A and E_B are Young's modulus for the original and new materials, respectively. For body-structure sheets, the thickness of aluminium alloys should be increased by a factor of approximately 1.45 to have the same stiffness as the original steel panel [38, 41]. While

Table 95.1 Materials mechanical properties and thicknesses of the modified vehicle components

Materials	Mass density (Kg/mm^3)	Young's modulus (Gpa)	Poisson's ratio	Yield Stress (Gpa)	Thicknesses (mm)	References
Steel (original)	7.890e–006	210	0.30	0.25	2	[43, 44]
AL-6016-T4	2.700e–006	70	0.33	0.147	3	[22, 41]
AL-6061-T6	2.700e–006	71.1	0.33	0.25	3	[24, 41]
AL-6111-T4	2.700e–006	70	0.33	0.16	3	[18, 38, 41]
AL-5182-O	2.710e–006	70	0.33	0.119	3	[18, 41, 45, 46]
AL-5754-O	2.710e–006	70	0.33	0.102	3	[18, 41, 47]
AZ-31B	1.780e–006	45	0.35	0.165	3.34	[40, 48]
Windscreen (original)	2.500e–006	76	0.30	0.13	5.8	[43, 49, 50, 51]
Polycarbonate (PC)	1.200e–006	1.5	0.37	0.62	5	[42, 52, 53]

the thickness of magnesium alloys should be multiplied by a factor of nearly 1.67 [40]. For the windscreen, it was suggested that the frontal (PC) windscreen should have a thickness of at least 4.5 mm [42]. Hence, the alternative thicknesses of the windscreen and windscreen frame materials were assumed, as shown in Table 95.1. The of injury metrics and injury risk levels were compared with that reported by AL-Graitti et al. [30] to assess the pedestrian safety improvement made by the new materials.

95.2.3 Selected Injury Parameters and Injury Risk Level

In terms of selected injury parameters and tolerance levels, the Head Injury Criterion (HIC_{15}), Neck Injury Criterion (N_{ij} and N_{km}), and (AIS) were used to assess pedestrian head and upper neck injury risk.

95.3 Results

95.3.1 Head Injury and Injury Risk Level

Impact at the vehicle centreline.
The HIC values for an adult male pedestrian impacted by the auto rickshaw at the vehicle centreline in front, rear and side impact positions at impact velocities between 10 and 40 km/h, for the original vehicle materials and the modified materials are shown in (Fig. 95.2). All iterations of the modified auto rickshaw include a polycarbonate windscreen with differing windscreen frame material.

Comparing HIC values for the original materials of the windscreen and windscreen frame, reported by AL-Graitti et al. [30], to the modified materials shows a significant improvement has been made to HIC values and head injury risk for frontal and rear impacts at the vehicle centreline for all windscreen frame materials with PC windscreen. However, Aluminium 6016-T4 and Magnesium AZ31B show a remarkable decrease in HIC values and injury risk level at all impact velocities. Despite this, the HIC values and head injury risk in the side impact position produce by far the worst results, with large increases in HIC at all velocities through implementation of the PC windscreen and modified windscreen frame materials.

Impact at 42 cm from the vehicle centreline.
The HIC values for an adult male pedestrian impacted by the auto rickshaw at 42 cm offset from the vehicle centreline in front and rear impact positions at impact velocities between 10 and 40 km/h, for the original vehicle materials and modified materials are shown in (Fig. 95.3). The iterations of the modified auto rickshaw all include a polycarbonate windscreen with differing windscreen frame material.

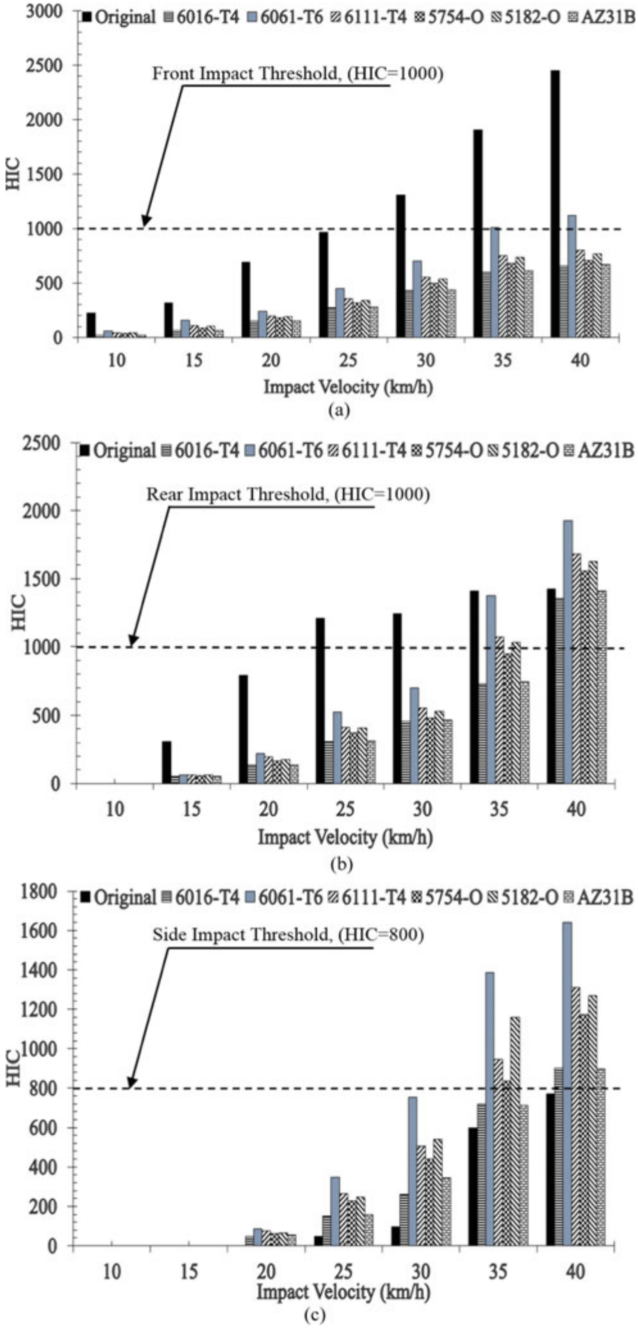

Fig. 95.2 HIC values for adult pedestrian impacts at the vehicle centreline for all simulations run with a polycarbonate windscreen and modified windscreen frame materials. Includes HIC threshold lines (HIC = 1000 for front and rear impacts and HIC = 800 for side impacts)

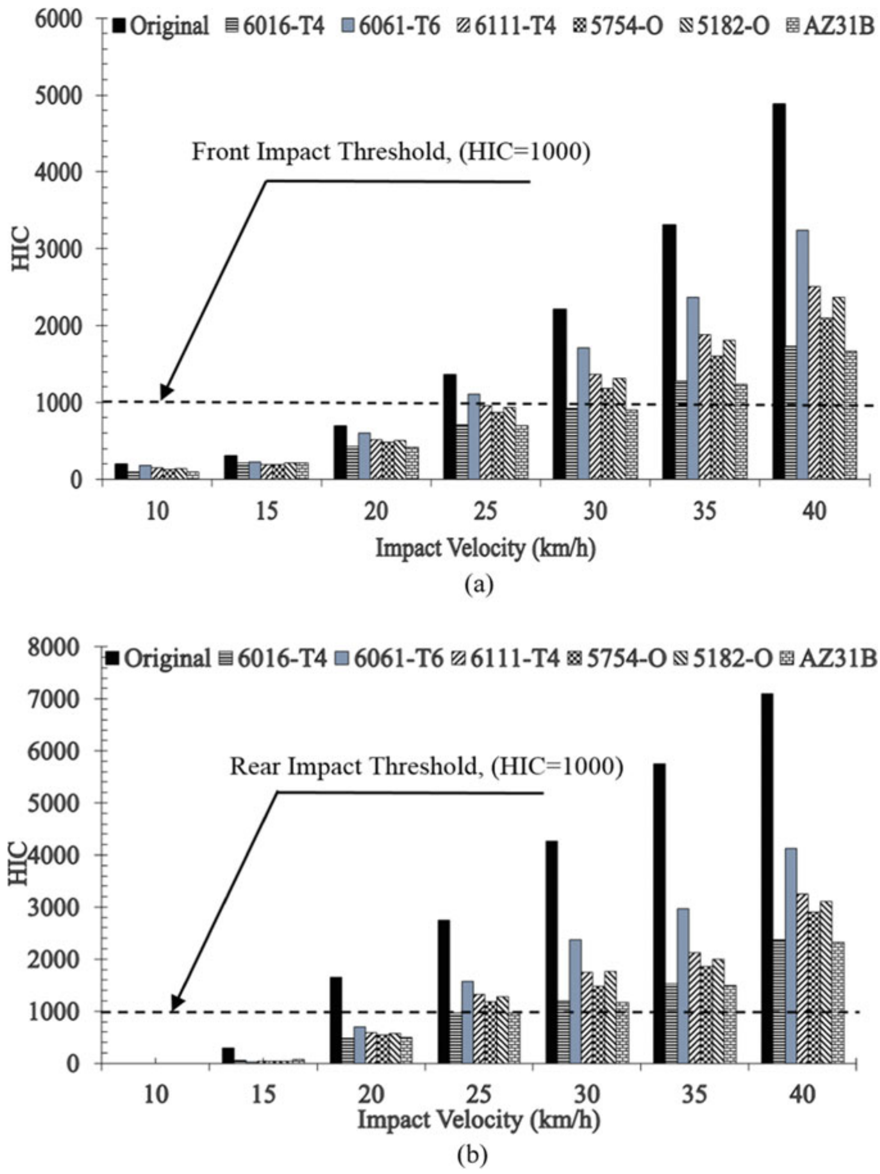

Fig. 95.3 HIC values for front and rear impacts at 42 cm offset from the vehicle centreline for all simulations run with a polycarbonate windscreen and modified windscreen frame materials. Includes HIC threshold line (HIC = 1000)

It can be observed that pedestrian safety improved significantly as the HIC values and head injury risk reduced at all impact velocities for the front and rear impact positions at the 42 cm offset. Although the modified materials show a greater reduction in head injury risk for the offset positions, the HIC values and head injury risk produced in offset positions are significantly greater than those at the vehicle centreline. In addition, side offset impacts are not included in this study, as there was no adult pedestrian head contact with the vehicle at impact velocities of between 10 and 40 km/h.

95.3.2 Upper Neck Injury and Injury Risk Level

Neck injury risk for both front and rear impacts is represented by the Neck Injury Criteria (N_{ij}) and (N_{km}) respectively. Both upper neck injury values were determined by selecting the worst load condition from each individual simulation.

Impact at the vehicle centreline.
The upper neck injury values at the vehicle centreline in frontal (N_{ij}) and rear (N_{km}) impact positions at velocities between 10 and 40 km/h, for the original auto rickshaw materials and the modified materials are shown in (Fig. 95.4). As above, the modified auto rickshaw iterations all include a polycarbonate windscreen with differing windscreen frame material.

Comparing upper neck injury values for the original materials of the windscreen and windscreen frame, reported by AL-Graitti et al. [30], with the modified materials, indicates that remarkable reductions to upper neck injury risk were attained for all simulations in frontal impacts to the vehicle centreline. Overall, the greatest improvements were observed for the simulations with a PC windscreen and either Aluminium 6016-T4 or Magnesium AZ31B windscreen frame materials, which exhibited notable decreases in Nij values at all impact velocities. Alternatively, the material modifications only show slight improvements for rear impacts and still have high N_{km} values, which would produce great upper neck injury risk.

Impact at 42 cm from the vehicle centreline.
The upper neck injury values for an adult male pedestrian impacted by the auto rickshaw at 42 cm offset from the vehicle centreline in frontal (N_{ij}) and rear (N_{km}) impact positions at velocities between 10 and 40 km/h, for the original auto rickshaw materials and the modified materials are shown in (Fig. 95.5). The modified auto rickshaw iterations all include a polycarbonate windscreen with differing windscreen frame material.

Comparing upper neck injury values for the original materials of the windscreen and windscreen frame, reported by AL-Graitti et al. [30], with the modified materials shows that adult pedestrian safety associated with upper neck injury was improved significantly for frontal impacts in all simulations. Once again, the simulations run with a PC windscreen and either Aluminium 6016-T4 or Magnesium AZ31B showed the most notable decrease in N_{ij} values at all impact velocities. Similar to rear impacts

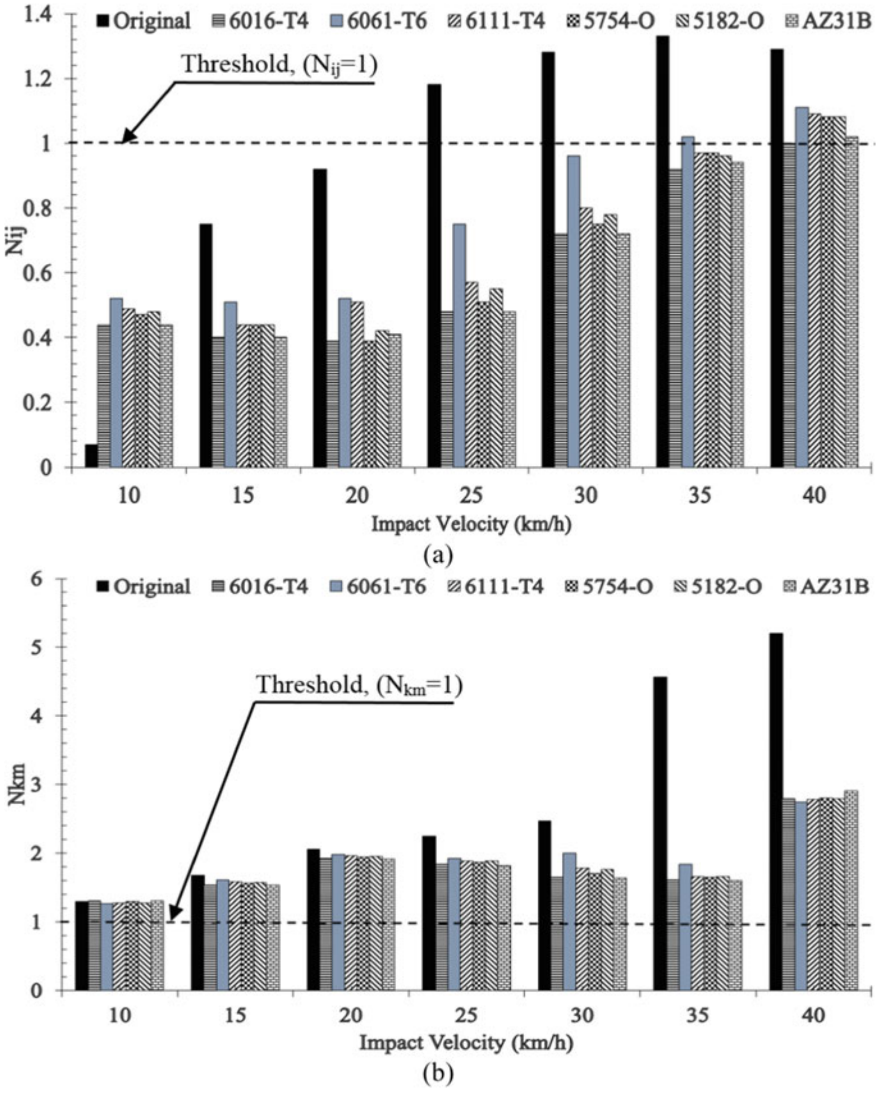

Fig. 95.4 Upper neck injury values at the vehicle centreline for all simulations run with a polycarbonate windscreen and modified windscreen frame materials; **a** N_{ij} for frontal impact and N_{ij} threshold line ($N_{ij} = 1$); **b** N_{km} for rear impact and N_{km} threshold line ($N_{km} = 1$)

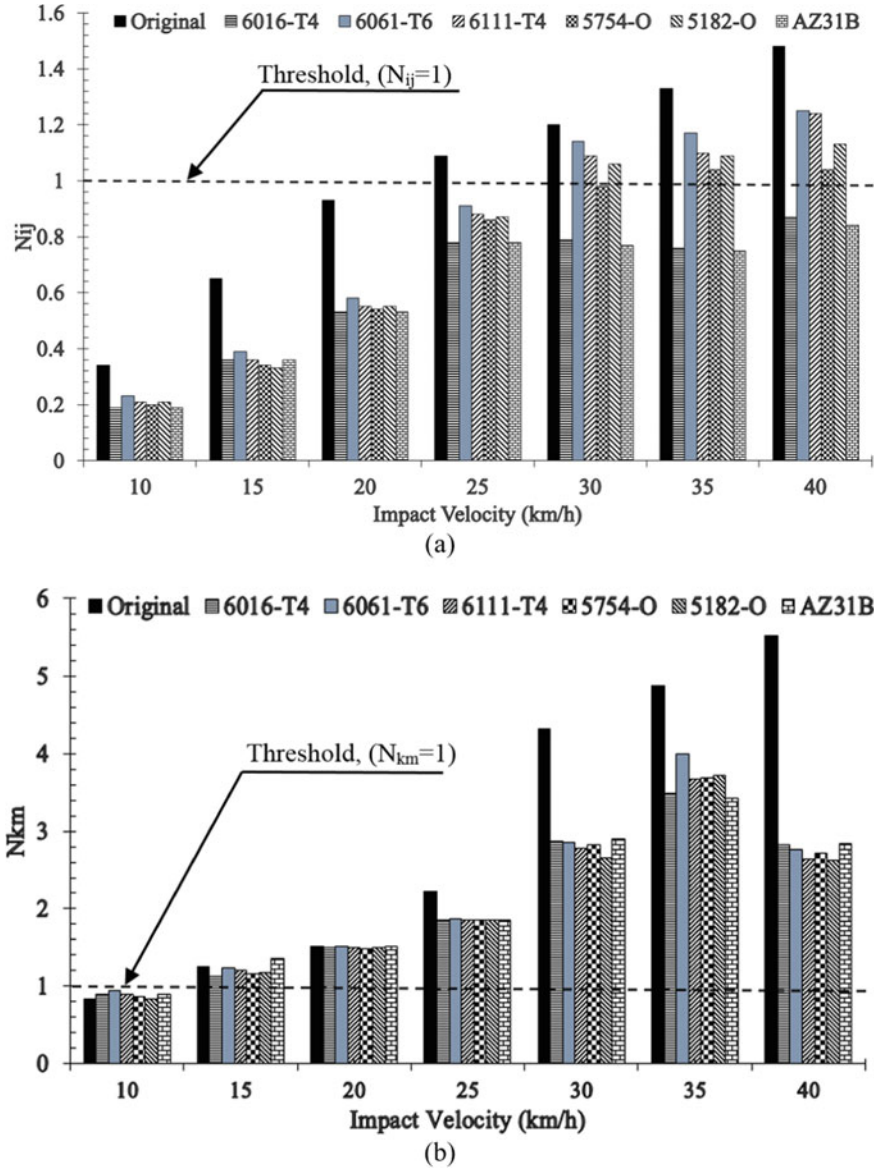

Fig. 95.5 Upper neck injury values at 42 cm from the vehicle centreline for all simulations run with a polycarbonate windscreen and modified windscreen frame materials; **a** N_{ij} for frontal impact and N_{ij} threshold line ($N_{ij} = 1$); **b** N_{km} for rear impact and N_{km} threshold line ($N_{km} = 1$)

at the vehicle centreline, rear impacts at a 42 cm offset show the material modifications provided only minor safety improvements, with N_{km} values still producing a high upper neck injury risk. There was also little difference between the N_{km} values of the modified materials for all impact velocities.

95.4 Discussion

95.4.1 Head Injury and Injury Risk Level

Changes in pedestrian impact position and vehicle contact region produced variations in HIC values and head injury risk. Additionally, increasing the impact velocity resulted in a significant increase in head injury risk. HIC values exceeding the injury risk threshold ($HIC_{15} = 1000$ for front and rear impacts and 800 for side impacts) for an adult pedestrian correspond with a risk of severe head injury (AIS4+) between 16 and 18% and are associated with bone structure deformation, soft tissue injury, skull fractures, brain contusions, lacerations and/or brain bleeding [54–57]. Increasing injury severity can be used to predict whether a skull fracture may be linear, depressed or comminuted, which can be pushed into the cranial cavity and cause damage to the brain [58]. One study by Nguyen et al. [33] provided a more in depth look at how costs differ between AIS level injuries and body region for pedestrian road traffic injuries in Thai Binh province, Vietnam. This study estimated the mean costs to pedestrians, whilst hospitalised could be as high as $2700 for AIS4+ head injuries. These are very considerable costs given that the average annual income in the Thai Binh province is just $695 [34]. In addition, the costs only represent those incurred during the patient's stay at one particular hospital, so does not consider transfer of the patient to a higher level hospital or loss of work due to injuries, thus, the actual costs are likely to far exceed these estimates [33]. Regardless of the country in question, it is clear that if the severity of an injury was to be reduced then so would the associated in medical expenses. When accrued, these cost savings would have a hugely beneficial impact on developing countries. Therefore, the results of this study will concentrate on the likelihood of an adult male pedestrian suffering severe head injuries (AIS4+) in an impact with an auto rickshaw made of the original materials and an auto rickshaw containing the modified materials.

Impact at the vehicle centreline.
For frontal impacts, HIC values for the adult pedestrian impacted by the original auto rickshaw exceeded the threshold ($HIC_{15} = 1000$) at 30 km/h, as reported by AL-Graitti et al. [30], shown in (Fig. 95.2a). All modified auto rickshaw designs showed significantly lower HIC values, with almost all failing to exceed the head injury threshold at all impact velocities (10–40 km/h). The exception to this was aluminium 6016-T6, where the HIC value exceeded the threshold ($HIC_{15} = 1000$) at 35 km/h and above. However, it still indicates improvements have been made, as the

threshold was exceeded at an impact velocity 5 km/h higher than that for the original materials.

The results indicate an average AIS4+ reduction at impact velocities between 10 and 40 km/h of 33, 32, 32, 32 and 33% for 6016-T4, 6111-T4, 5754-O, 5182-O and AZ31B materials, respectively. This was considerably lower for the 6061-T6 material which produced an average AIS4+ reduction of 27%. Due to the reduction in severe head injury, these results estimate that the modified materials might provide an average medical cost saving for a pedestrian hit by an auto rickshaw in Vietnam of $882, 847, 868, 853 and 881 for 6016-T4, 6111-T4, 5754-O, 5182-O and AZ31B, respectively [33]. Whilst, for the 6061-T6 material, this average cost saving was estimated to be $732 [33].

For rear impacts, HIC values for the adult pedestrian impacted by the original auto rickshaw exceeded the threshold ($HIC_{15} = 1000$) at 25 km/h, as reported by AL-Graitti et al. [30], shown in (Fig. 95.2b). All auto rickshaw simulations containing the modified materials produced considerably lower HIC values than the original vehicle design. In addition, aluminium 6061-T6, 6111-T4 and 5182-O produced HIC values that exceeded the HIC threshold at 35 km/h. While, aluminium 6016-T4 and 5754-O and magnesium AZ31B, produced HIC values that exceeded the HIC threshold at 40 km/h. This indicates excellent improvements to pedestrian safety have been produced, as the modified materials allowed for the HIC threshold to be exceeded at impact velocities at least 10 km/h or 15 km/h greater than the original auto rickshaw.

In addition, these results indicate an average AIS4+ reduction at impact velocities between 10 and 40 km/h of 19, 5, 12, 15, 13 and 19% for 6016-T4, 6061-T6, 6111-T4, 5754-O, 5182-O and AZ31B, respectively. Due to the reduction in severe head injury observed for rear impacts, these results estimate that the modified materials may provide an average medical cost saving for a pedestrian impacted by an auto rickshaw in Vietnam of $524, 139, 327, 406, 358 and 502 for 6016-T4, 6061-T6, 6111-T4, 5754-O, 5182-O and AZ31B, respectively [33].

For side impacts, HIC values for the adult pedestrian impacted by the original auto rickshaw did not exceeded the threshold ($HIC = 800$) at all impact velocities between 10 and 40 km/h, as reported by AL-Graitti et al. [30], shown in (Fig. 95.2c). However, all simulations for the modified auto rickshaw design showed a large increase in HIC value compared to that of the original materials for all impact velocities. Thus, side impacts to the centreline of the auto rickshaw exhibited by far the most negative HIC results, as no improvement was made after altering the windscreen and windscreen frame materials. The simulations also surpassed the HIC threshold at 35 km/h for aluminium 6061-T6, 6111-T4, 5754-O and 5182-O with an average AIS4+ increase of 27%, 11%, 7% and 13%, respectively.

Moreover, aluminium 6016-T4 and AZ31B exceeded the HIC threshold at 40 km/h with an average AIS4+ increase of 2%. Due to the reduction in severe head injury observed for rear impacts, these results estimate that the modified materials might provide an average medical cost increase for a pedestrian hit by an auto rickshaw in Vietnam of $54, 735, 301, 192, 364 and 56 for 6016-T4, 6061-T6, 6111-T4, 5754-O, 5182-O and AZ31B, respectively [33].

Contact between the auto rickshaw and torso of the pedestrian may be the reason for this rise in HIC for the PC windscreen, especially at higher velocities, where more of the torso makes contact with the PC windscreen than at lower velocities, where the torso also contacts with the stiffer lower windscreen frame. When the torso impacts with the stiff glass windscreen or the lower section of the metal windscreen frame, less energy is absorbed by the material than it would be for a material that exhibits large amounts of deformation. This leads to more kinetic energy being transferred to the torso of the pedestrian, potentially pushing the body away from the vehicle after impact. Although this would result in a high risk of injury to the upper torso (chest), it may push the body away enough such that the head contact is actually minimised as it accelerates back towards the vehicle during neck extension. However, when the polycarbonate windscreen impacts with the torso it deforms significantly. Less energy is transferred to the torso, meaning the body is not pushed away as much as it is with the stiffer materials. This may lead to the head of the pedestrian having a more significant impact with the vehicle, causing a higher HIC than the glass windscreen.

The materials that absorbed greater amounts of energy, subsequently had lower head accelerations due to longer contact times between the head and the windscreen frame. HIC is proportional to the resultant acceleration of the head, so a longer contact time between the head and the upper windscreen frame will lead to higher head accelerations, hence higher HIC values. The 6016-T4 and AZ31B windscreen frames had the longest contact times between the metals, across all simulations. For a frontal impact to the vehicle centreline at 40 km/h, the 6016-T4 and AZ31B windscreen frames had head contact times of 40 ms. All other windscreen frames had shorter head contact times than this, with the original mild steel windscreen frame having the shortest at 27.5 ms for a frontal impact to the vehicle centreline at 40 km/h. The results here were mirrored for all impact positions, although the actual contact times do differ between impact positions and velocities.

Impact at 42 cm from the vehicle centreline.
For frontal impacts, HIC values for the adult pedestrian impacted by the original auto rickshaw exceeded the threshold ($HIC_{15} = 1000$) at 25 km/h, as reported by AL-Graitti et al. [30], shown in (Fig. 95.3a). Similar that for the original materials, the HIC produced by aluminium 6061-T6 also exceeded the head injury threshold at 25 km/h. The modified vehicle designs that include the aluminium 6111-T4, 5754-O and 5182-O windscreen frame materials exhibited HIC values that were considerably reduced, exceeding the threshold at 30 km/h. Aluminium 6016-T4 and Magnesium AZ31B produced the most promising results, with HIC values that exceeded the threshold at 35 km/h. The results indicate that pedestrian safety was improved for the modified designs as the HIC threshold was exceeded at impact velocities at least 5–10 km/h higher than the original materials.

In addition, the results indicate an average AIS4+ reduction at impact velocities between 10 and 40 km/h of 30%, 7%, 14%, 21%, 16% and 31% for 6016-T4, 6061-T6, 6111-T4, 5754-O, 5182-O and AZ31B, respectively. Due to the reduction observed in severe head injury, the results estimate that the modified materials may equate to an average medical saving cost for a pedestrian hit by an auto rickshaw in Vietnam of

$810, 179, 389, 557, 432 and 845 for 6016-T4, 6061-T6, 6111-T4, 5754-O, 5182-O and AZ31B, respectively [33].

For rear impacts, HIC values for the adult pedestrian impacted by the original auto rickshaw exceeded the threshold (HIC_{15} = 1000) at 20 km/h, as reported by AL-Graitti et al. [30], shown in (Fig. 95.3b). The HIC value produced by the modified vehicle designs that included aluminium 6061-T6, 6111-T4, 5754-O and 5182-O, exceeded the head injury threshold at 25 km/h. For the modified designs, that included aluminium 6016-T4 and magnesium AZ31B, HIC values were considerably reduced and exceeded the threshold at 30 km/h. Therefore, these results indicate that there were good improvements made to pedestrian safety as the HIC threshold was exceeded at impact velocities at least 5 km/h or 10 km/h higher than the original materials.

Furthermore, the results indicate an average AIS4+ reduction at impact velocities between 10 and 40 km/h of 44%, 17%, 26%, 33%, 27% and 45% for 6016-T4, 6061-T6, 6111-T4, 5754-O, 5182-O and AZ31B, respectively. Due to these reductions in severe head injuries, the results produced an estimated average medical cost saving for a pedestrian hit by an auto rickshaw in Vietnam of $1183, 461, 698, 810, 735 and 1208 for 6016-T4, 6061-T6, 6111-T4, 5754-O, 5182-O and AZ31B, respectively.

No head contact occurred in the side offset impact position for both the original vehicle materials or the modified materials. Therefore, it can be concluded that the two stand out performers that provide the greatest HIC reduction in an auto rickshaw-pedestrian impact are aluminium 6016-T4 and magnesium AZ31B for the windscreen frame material and PC for the windscreen. These materials produced the largest amounts of deformation for all velocities, hence, they absorbed the most energy during impact and produced the lowest pedestrian HIC values. These results show a good agreement with [18], which concluded that the Mg AZ31-O had the lowest and, hence, most favourable HIC score relative to other automotive materials, such as AZ61-O, ZEK100, 6111-T4 and 5182-O, when considering pedestrian safety improvements by a series of experimental and numerical tests. The materials that absorbed greater amounts of energy subsequently had lower head accelerations, due to longer contact times between the head and the windscreen frame.

In addition, this conforms with [59], which stated that energy absorption is a significant design factor for pedestrian safety and stated that aluminium alloys have excellent energy absorption. Consequently, if greater amounts of energy are absorbed by vehicle components, then the kinetic energy of the vehicle is controlled during the crash, while preventing or reducing the peak reaction force transfer to the pedestrian [17].

HIC is proportional to the resultant acceleration of the head, so a longer contact time between the head and the upper windscreen frame will lead to higher head accelerations, therefore, higher HIC values. The 6016-T4 and AZ31B windscreen frames had the longest contact times between the metals across all simulations. For a front-centre impact at 40 km/h, the 6016-T4 and AZ31B windscreen frames had head contact times of 40 ms. All other windscreen frames had shorter head contact times than this, with the mild steel windscreen frame having the shortest at 27.5 ms for a front-centre impact at 40 km/h. The results here were mirrored for all impact positions, although the actual contact times do differ between impact positions and velocities.

As a result, the HIC values produced during impacts at the vehicle offset are significantly higher than that produced at the vehicle centreline, which produced a greater injury risk. Reasons for centreline impacts generally having lower HIC values than offset impacts may be that the initial contact is made by the front mudguard to the lower extremities of the pedestrian, which pushes the legs away from the vehicle. Offset impacts produce initial impacts at the frontal leading edge of the windscreen frame to the torso area of the pedestrian, which arches the pedestrian's body around the vehicle and appears to lead to a more energetic head contact.

95.4.2 Upper Neck Injury and Injury Risk Level

The upper neck is a vulnerable region to injury and is strongly influenced by head movement. Upper neck injury risk is represented by the Neck Injury Criterion for front (N_{ij}) and rear (N_{km}) impacts and is produced by considering a combination of forces and moments, measured at the occipital condyles. The neck injury criterion is applied using neck injury thresholds, which are $N_{ij} = 1$ and $N_{km} = 1$, reported in [60, 61]. This threshold indicates a 22% risk of serious neck injury (AIS3+) [60], which is associated with the rupture of small blood vessels of the occipital condylar joints, alar ligament rupture, damage to spinal cord (disc rupture and nerve root damage) and brainstem and even death [60–63].

Impact at the vehicle centreline.
Pedestrian impacts at the centreline of the vehicle were assessed for frontal impacts by the N_{ij}. It was reported by AL-Graitti et al. [30] that the N_{ij} of the original auto rickshaw design exceeded the upper neck injury threshold ($N_{ij} = 1$) at 25 km/h, shown in (Fig. 95.4a). It also indicates that N_{ij} values were considerably reduced for all modified materials. In addition, aluminium 6061-T6 produced the greatest N_{ij} values and exceeded the threshold at velocities of 35 km/h, while aluminium 6111-T4, 5754-O and 5182-O, and Magnesium AZ31B, produced N_{ij} values that exceeded the threshold at 40 km/h. Furthermore, aluminium 6016-T4 produced remarkable N_{ij} values, that did not exceeded the threshold ($N_{ij} = 1$) at all impact velocities between 10 and 40 km/h. The results indicate that pedestrian upper neck safety was improved as the threshold was exceeded at impact velocities 10 km/h or 15 km/h greater than the original materials. However, in the case of aluminium 6016-T4, the auto rickshaw would have exceeded the threshold at an impact velocity over 15 km/h higher than the original auto rickshaw design.

Additionally, the results indicate an average AIS3+ reduction at impact velocities between 10 and 40 km/h of 11%, 8%, 10%, 10% and 10% and 11% for 6016-T4, 6061-T6, 6111-T4, 5754-O, 5182-O and AZ31B, respectively. Due to the reductions observed to serious upper neck injury, the results for the modified materials are estimated to provide an average medical cost saving for a pedestrian hit by an auto rickshaw in Vietnam of $173, 120, 148, 159, 155 and 179 for 6016-T4, 6061-T6, 6111-T4, 5754-O, 5182-O and AZ31B, respectively [33].

Pedestrian impacts at the centreline of the vehicle were assessed for rear impacts by the N_{km}. It was reported by AL-Graitti et al. [30] that N_{km} of the original auto rickshaw design exceeded the upper neck injury threshold ($N_{km} = 1$) at 10 km/h, shown in (Fig. 95.4b). The figure also showed N_{km} values for the modified materials reduced only marginally compared to that seen for frontal impacts. However, all N_{km} values still exceeded the upper neck injury threshold at 10 km/h, which was the same velocity as the original materials.

The results for rear impacts to the vehicle centreline indicate an average AIS3+ reduction at impact velocities between 10 and 40 km/h of 18%, 13%, 16%, 17% and 16% and 18% for 6016-T4, 6061-T6, 6111-T4, 5754-O, 5182-O and AZ31B, respectively. Due to the reductions observed to serious upper neck injury, it is estimated that the modified materials might produce average medical cost savings for a pedestrian hit by an auto rickshaw in Vietnam of $(268.736, 191, 238, 252, 241 and 270 for 6016-T4, 6061-T6, 6111-T4, 5754-O, 5182-O and AZ31B, respectively [33]).

Impact at 42 cm from the vehicle centreline.
Pedestrian impacts at 42 cm offset from the centreline of the vehicle were assessed for frontal impacts by the N_{ij}. It was reported by AL-Graitti et al. [30] that the N_{ij} of the original auto rickshaw design exceeded the upper neck injury threshold ($N_{ij} = 1$) at 25 km/h, shown in (Fig. 95.5a). This suggests N_{ij} values were significantly reduced for all modified materials. Aluminium 6061-T6, 6111-T4 and 5182-O produced N_{ij} values that exceeded the threshold at an impact velocity of 30 km/h, whereas aluminium 5754-O produced N_{ij} values that exceeded the threshold at 35 km/h. However, following the trend of previous results, the aluminium 6061-T4 and magnesium AZ31B materials produced the lowest N_{ij} values and did not exceed the threshold ($N_{ij} = 1$) at all impact velocities between 10 and 40 km/h. Therefore, pedestrian upper neck safety was improved for all modified designs and resulted in the upper neck injury threshold being exceeded at impact velocities between 5, 10 and 15 km/h greater than the original materials. However, for both aluminium 6016-T4 and magnesium AZ31B, the threshold would be exceeded at an impact velocity over 15 km/h higher than the original materials.

Moreover, the results indicate an average AIS3+ reduction at impact velocities between 10 and 40 km/h of 12%, 6, 7%, 9%, 8% and 12% for 6016-T4, 6061-T6, 6111-T4, 5754-O, 5182-O and AZ31B, respectively. Due to the reductions observed to serious upper neck injury, these results estimate that the modified materials may produce an average medical cost saving for a pedestrian hit by an auto rickshaw in Vietnam of $183, 88, 104, 136, 118 and 187 for 6016-T4, 6061-T6, 6111-T4, 5754-O, 5182-O and AZ31B, respectively [33].

Pedestrian impacts at 42 cm offset from the centreline of the vehicle were assessed for rear impacts by the N_{km}. It was reported by AL-Graitti et al. [30] that the N_{km} of the original auto rickshaw design exceeded the upper neck injury threshold ($N_{km} = 1$) at 15 km/h, shown in (Fig. 95.5b). In addition, the figure shows the N_{km} for all modified materials also exceeded the threshold at 10 km/h and only exhibited minor improvements compared to that of the original design.

Furthermore, the results indicate an average AIS3+ reduction at impact velocities between 10 and 40 km/h of 6%, 4%, 6%, 6% and 7% and 4% for 6016-T4, 6061-T6, 6111-T4, 5754-O, 5182-O and AZ31B, respectively. Due to the reductions observed to serious upper neck injury, it is estimated that the modified materials may produce an average medical cost saving for a pedestrian hit by an auto rickshaw in Vietnam of $84, 68, 88, 90, 98 and 60 for 6016-T4, 6061-T6, 6111-T4, 5754-O, 5182-O and AZ31B, respectively.

Therefore, it appears as though the optimal vehicle materials are the 6016-T4 and AZ31B windscreen frames, along with the PC windscreen, with regards to the safety of a 50% adult male pedestrian and cost-effectiveness. However, mitigating potential road traffic injuries is paramount in not only improving public health but also allowing for a reduction to the high costs that burden growth in developing countries. Thus, estimating the increased cost of these suggested materials must be weighed up against the potential costs saved by mitigating injury severity.

For the windscreen of the auto rickshaw, LS-DYNA estimated a mass of 8.13 kg for the original glass design, which would produce an estimated cost of approximately $14 [36]. On the other hand, the estimated mass for the PC windscreen is just 3.74 kg, which would equate to an estimated cost of approximately $12 [37]. For the auto rickshaw windscreen frame, LS-DYNA estimated a mass of 7 kg for the original mild steel design, which would cost approximately $7 [35]. For the aluminium 6016-T4 windscreen frame, LS-DYNA estimated its mass to be 3.64 kg, which would give it an estimated cost of $8 [34]. For the magnesium AZ31B windscreen frame, LS-DYNA estimated its mass to be 1.589 kg, giving it an estimated cost of approximately $9 [35].

Subsequently, it is clear that both the aluminium 6016-T4 windscreen frame and the PC windscreen has the potential to provide the greatest reduction in the medical expenses, associated with head and upper neck injuries, whilst also showing potential to reduce material costs for the components. Regardless of the country in question, it is clear that if the severity of an injury was to be reduced, then this could save significantly in medical costs alone. When accrued, these cost savings would have a hugely beneficial impact on developing countries. Therefore, aluminium 6016-T4 and PC provides the best material combination between all modified vehicle designs tested for pedestrian head and neck injury risk reduction and safety improvement, as they show exceptional ability to absorb impact energy during pedestrian impacts. Thus, the materials have a considerable influence on head acceleration and head movement of the pedestrian, which results in a good agreement with [64, 65]. In addition, this modification would help to reduce the weight of the vehicle, allowing for the auto rickshaw to reduce from an estimated mass of 373 kg, to a mass of 365 kg, which would also influence fuel consumption and pollution. However, many other factors have to be taken into consideration before these engineering modifications can be considered, such as the manufacturability of the chosen materials and occupants safety.

95.5 Conclusion

Several aluminium and magnesium alloys were identified as possible replacements to steel in the windscreen frame, whilst polycarbonate was identified as possible replacements for the glass windscreen. Response kinematics identified the two best windscreen frame metals for mitigating potential pedestrian injuries were the aluminium 6016-T4 and magnesium AZ31B, which showed excellent reductions in HIC and upper neck injury criterion in frontal impacts (N_{ij}). Combining these changes to the windscreen and windscreen frame allowed the auto rickshaw to produce lower injury criteria at most impact positions, although offset head injury risk remained high with high probability of AIS4+ head injuries and rear impact neck injuries also proved high risk, with a high probability of AIS3+ neck injuries. After taking into consideration economic factors, the 6016-T4 windscreen frame with a PC windscreen was identified as the most suitable vehicle design, showing potential to keep costs relatively similar to the current design, although a more in depth analysis of additional manufacturing costs will also need to be evaluated. Results indicate the proposed auto rickshaw design may have the ability to reduce the severity of certain injuries, which in turn demonstrates great potential to decrease medical costs in low- and middle-income countries.

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Limitation and Future Work Simply changing the material composition of the vehicle will not optimally alleviate pedestrian injuries; future studies are anticipated of the frontal geometry and retrofitting impact attenuation technologies to the front of the vehicle.

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