Analysis of structural crash worthiness of a conventional three wheeler incorporating a passenger restrain system.

B S Jurangpathy[1], S D Rasika Perera[1*]

[1]Department of Mechanical Engineering, The Open University of Sri Lanka, Nawala, Nugeoda, Sri Lanka.

*Corresponding Author: email: sdper@ou.ac.lk, Tele: +714421887

Abstract –*Automotive structures are required to be able to maintain the passenger compartment intact while absorbing the crash energy by a crumple zone in a controllable manner within a short period of time during a crash. The safety of three-wheelers has been a crucial issue when it comes to public transport in developing countries. Being less protected is one of the main reasons for fatalities from two and three-wheelers.*

An analysis was carried out using FEA on full Width Frontal Impact Collision without Occupants and full Width Frontal Impact Collision with Occupants. A barrier was modelled as a rigid object along with a floor to support the motion of the Three-Wheeler. The human crash dummy model created was based on dimensions and mass specifications of a 50th Male Hybrid III Anthropometric Test Device. The analysis of the existing structure revealed that the passenger compartment is not rigid enough to provide a protective shell to occupants. The structure experienced a severe plastic deformation in the mid-section, crashing into the passenger compartment. Further, the front face of the three-wheeler intrudes into the driver compartment, virtually crushing the driver against the driver's seat. The results of the FEM analysis were confirmed by the analysis of real world accidents.

The analysis revealed a comparatively lower acceleration for passengers compared to that of the driver. The higher acceleration of the driver can be attributed to the space limitation for the driver due to intrusion of the front face and the comparatively lower acceleration can be attributed to the plastic deformation occurred in the mid-section which absorbed part of the crash energy.

During the collision of a conventional three-wheeler, the passengers experienced a 47G force and the driver experienced a maximum of 81 G force. As per the literature review, both magnitudes exceed the tolerable limit for humans. However, the analysis revealed that had there been a restrain system, the acceleration of passengers could have been brought to 20G and the acceleration of the driver to 25G.

The availability of a restrain system may decrease the severity of injuries to occupants of three wheelers. The main reason for fatal injuries during a head on collision of a three wheeler is due to deficiencies of basic structural features such as lack of a crumple zone, rigid passenger compartment and restrain systems.

Keywords: *car design, crash safety, full width frontal impact, passenger safety, three-wheeler*

Nomenclature

FEA	-Finite Element Analysis
G force	-Gravitational Force Equivalent
CAD	-Computer Aided Design
NCAP	-New Car Assessment Programme

1. INTRODUCTION

The safety of three-wheelers has been a crucial issue when it comes to public transport in developing countries. Being less protected is one of the main reasons for fatalities from two and three-wheelers (WHO 2018).

The low cost of the vehicle itself and the fuel economy due to its simple lightweight structure are the driving forces behind the popularity of three-wheelers. In current research, the structural safety of conventional three-wheelers is analyzed using the Finite Element method.

Conventionally, engineering structures are being designed using elastic analysis to ensure the ability of the structure to withstand service loads without yielding or collapsing. In contrast to conventional structural design, automotive structures are required to be able to plastically deform and absorb energy in a short period of time to absorb crash energy in a controllable manner during a crash (Bois, et al., 2004). Another important aspect of enhancing passenger safety of road vehicles is by introducing seat belts. An effective seat belt can ensure efficient deceleration of occupants with respect to that of the automobile. The objective of the research was to investigate the effectiveness and improve the structural crash-worthiness of conventional three-wheel vehicles, with a particular focus on enhancing passenger safety. This is achieved by utilizing Finite Element Analysis (FEA) to assess the performance of the vehicle's structure during crash scenarios and to understand how the current design could be contributing to potential injuries during collisions.

The ultimate goal is to use these findings to suggest modifications that could make three-wheelers safer for use, especially in developing countries where they are commonly used for public transportation. The paper highlights the need for basic structural features like a crumple zone, a more rigid passenger compartment, and a restrain system to enhance the safety of such vehicles.

2. LITERATURE REVIEW

It is understood that relatively little research has been conducted on Three-Wheelers as compared to conventional vehicles, especially in the area of crashworthiness. However, notable works include that of Srikanth & Prakash (2009), who studied the behavior of a TVS Three-Wheeler in collaboration with TVS Motor Company Ltd under frontal and rear impact at 20 km/h and 48 km/h speed variations.

Other studies include that of Doshi (2017), where a static structural analysis of a frame of a commercial Three-Wheeler was conducted.

To maximize the survivability of occupants in a crash, it is important to have an understanding of the tolerance of human individuals to abrupt accelerations. In general, human tolerance to acceleration is a function of five extrinsic factors given in Table 1 (Shanahan, 2004). Other intrinsic factors include age, health, sex, physical condition, and personal tolerance. Some documented Human Tolerance Limits as per the work by (Shanahan, 2004) and (Coltman, et al., 1989) are shown in Table 2, each within the timeframe of 0.1s.

3. METHODOLOGY

With the advent of Finite Element Analysis (FEA) and increasing software capabilities and computing power, it became easier to model complex simulations. Thus, the FEA method was adopted to study the crashworthiness of Three-Wheelers. This involved the modelling of a Three-Wheeler using a CAD modeler and simulating it in simulation software that can model high velocity impacts.

As per the requirements extracted from the NCAP [Safety of Quadricycles], the analysis was carried out mainly on following aspects.

1. Full Width Frontal Impact Collision without Occupants
2. Full Width Frontal Impact Collision with Occupants
3. Full width Frontal Impact Collision with seat belt for occupants

Table 1. Extrinsic Factors to Human Tolerance

No	Factor	Description
1	Magnitude	The larger the acceleration, the greater the injury.
2	Direction	Humans are more capable of withstanding G-forces perpendicular to the spine with a higher tolerance when the acceleration is in the forward direction, also known as 'eyeballs in' than when experiencing an acceleration in the vertical axis.
3	Duration	Humans can withstand high magnitudes of acceleration given that it occurs in a small period of time. The values ranged from 20 G for less than 10 seconds, 10 G for around 1 minute, and 6 G for 10 minutes
4	Rate of onset of acceleration	Refers to how rapidly the acceleration is applied. The greater the onset, the less tolerable the acceleration will be.
5	Position/Restraint/Support	Refers to how well the occupant is supported by the seat and is restrained by the restraint system and how the loads experienced in the crash are distributed over the body.

Table 2. Human Tolerance Limits to G forces

The direction of Accelerative Force	Occupant's Inertial Response	Tolerance Level
Headwords (+Gz)	Eyeballs Down	20-25 G
Tail ward (-Gz)	Eyeballs Up	15 G
Lateral Right (+Gy)	Eyeballs Left	20 G
Lateral Left (-Gy)	Eyeballs Right	20 G
Back to Chest (+Gx)	Eyeballs Out	45 G
Chest to Back (-Gy)	Eyeballs In	45 G

The simulation of collisions and high velocity impacts require the simulator to be capable of analyzing the events that take place under short time durations in great detail. What makes these events unique is that materials do not behave in their normal manner due to undergoing shock loading where the stress wave propagation carries a significant impact on the material properties. Ansys Explicit STR was selected as the program to be used for analyzing the Three-Wheeler for crashworthiness. All impact tests were carried out at an initial velocity of 50 km/h.

4. EXPERIMENTAL INVESTIGATION AND RESULTS

The investigation was carried out by using Ansys Explicit STR module. The velocity during the test was set to 50 km/h. The investigation consisted of three major sections as Full Width Frontal Impact Collision without Occupants, Full Width Frontal Impact Collision with Occupants and Full width Frontal Impact Collision with seat belt for occupants. The experimental procedure and results are given below.

4.1Full Width Frontal Impact Collision test without Occupants

The Full Width Frontal Impact Test was conducted for adult protection. The barrier, as per the standards was 3 m wide and 1.5 m tall. It was modeled as a rigid object along with a floor to support the motion of the Three-Wheeler. The set-up is shown in Fig. 1.

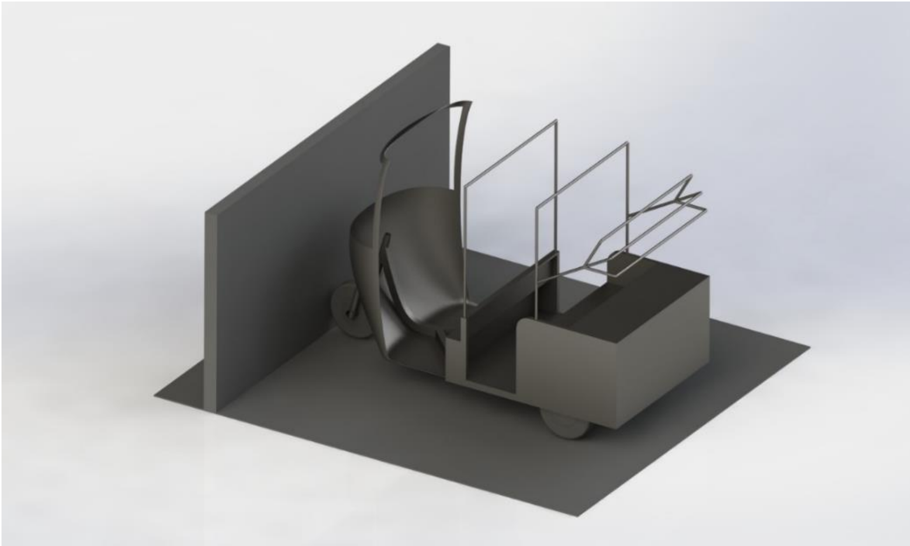

Fig. 1. Full Width Frontal Impact Test - Full Assembly

4.3.1 Results of the Full Width Frontal Impact Collision test without Occupants

Following multiple tests and refinements, a full body test was conducted for the three-wheeler without occupants. The mesh Type used was “Fine” with a total of 125,014 elements.

It was noticed that severe plastic deformation occurred at the base of the front face of the Three-Wheeler, the steering column and its support as well as multiple areas of the base structure as seen in Fig.2 and Fig. 3. As observed, it can be deduced that the bulk of the crash energy is absorbed by the steering column as well as the base structure.

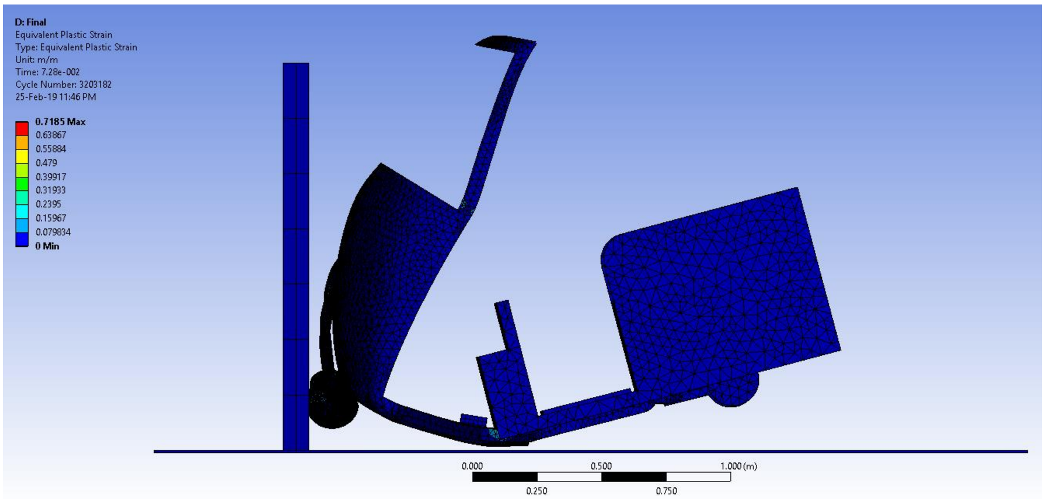

Fig. 2. Plastic Strain of the front face

The severe plastic failure in the mid-section of the base structure as seen in Fig. 3 drastically reduces the gap between the driver's seat and the front face, greatly increasing the risk of severe injury to the driver. The Total Mass Average Velocity Graph is presented in Fig. 4. On analyzing the graph and the data, the Three-Wheeler was found to decelerate after 0.012S after the collision and come to a stop at 0.0728s before rebounding. The total crash duration is 0.0608s.

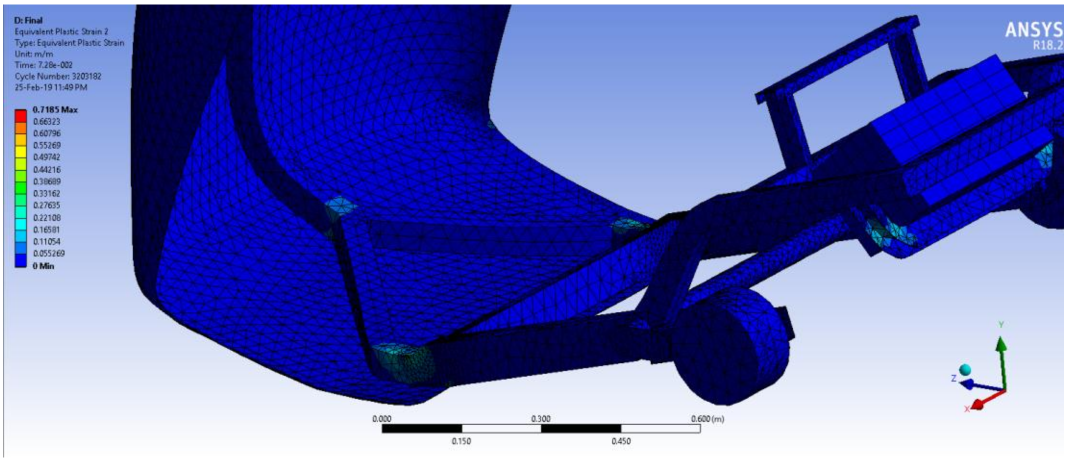

Fig. 3. Plastic Strain of the Base Structure without occupants

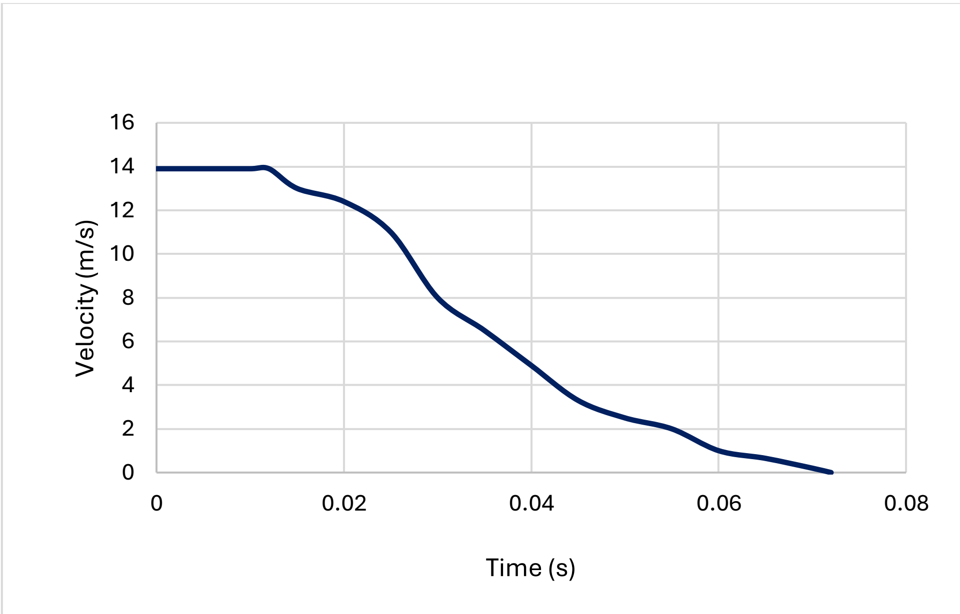

Fig. 4. Mass Average Velocity signature without passengers

4.2 Full Width Frontal Impact Collision test with Occupants

A simulation was set up and carried out to study the behavior of the Three-Wheeler whilst fully loaded with a driver and three passengers. The importance of the simulation is to study the dynamic behavior of the human models under frontal impact which could carry on to further research in developing restraint systems. Parameters such as average velocity, force and momentum amongst others were measured.

The human crash dummy model created was based on dimensions and mass specifications of a 50th Male Hybrid III Anthropometric Test Device [Hybrid III 50th percentile male]. The CAD model of the crash test dummy is shown in Fig. 5. The material model assigned was a modified Steel 1006 to bring the total mass to 88kg. The motion and forces acting on the dummy were recorded as well, notably the acceleration at the back of the neck, from which data related to possible whiplash can be obtained. The final setup with all occupants is seen in Fig. 6.

Fig. 5. Custom Human Hybrid III 50th Male Model

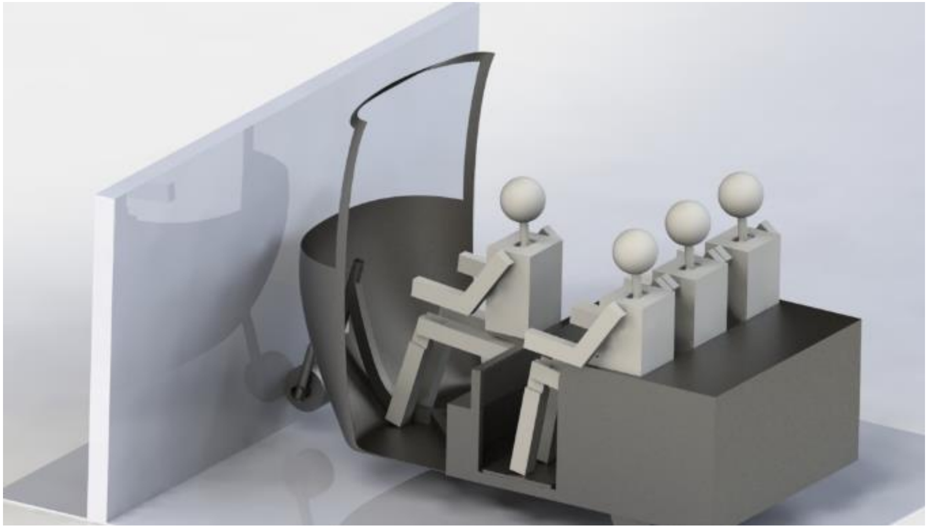

Fig. 6. Final Setup with Occupants

4.2.1 Results of Full Width Frontal Impact Collision with Occupants test

.It was noted that the inclusion of the occupants affected mesh generation properties, notably on the steering column which underwent severe fracture and breakage. The mesh Type used was “Fine” with 179,414 No. of Elements.   The results of the simulation are presented in Fig. 7.

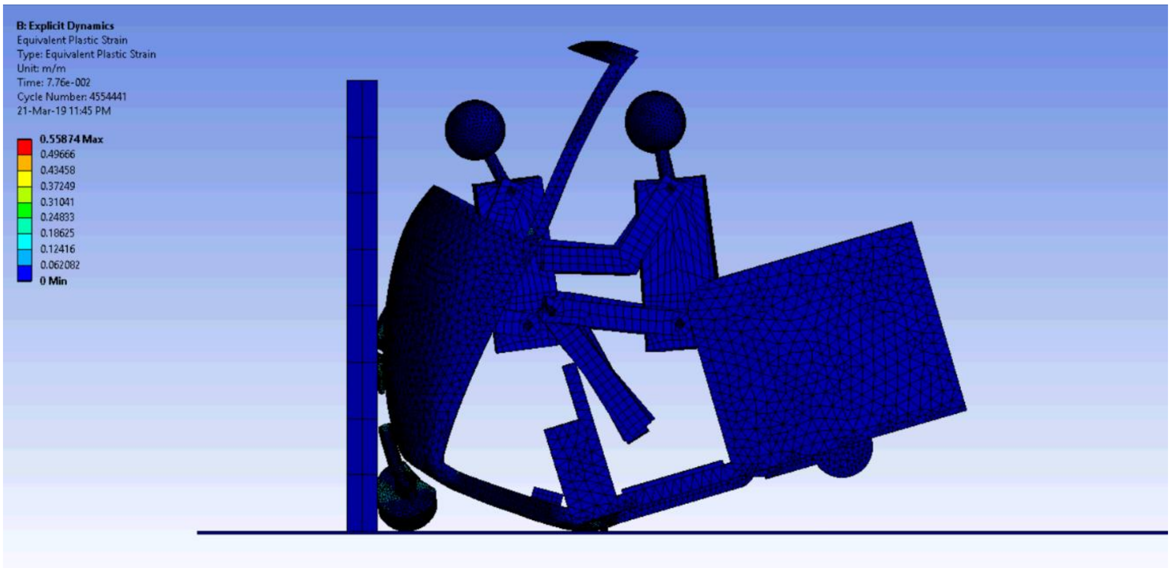

Fig. 7. Plastic Strain of the Three-Wheeler with Occupants

As observed during the simulation without passengers, the model underwent deformation at the same locations as for the test carried out without passengers shown in Fig. 7.

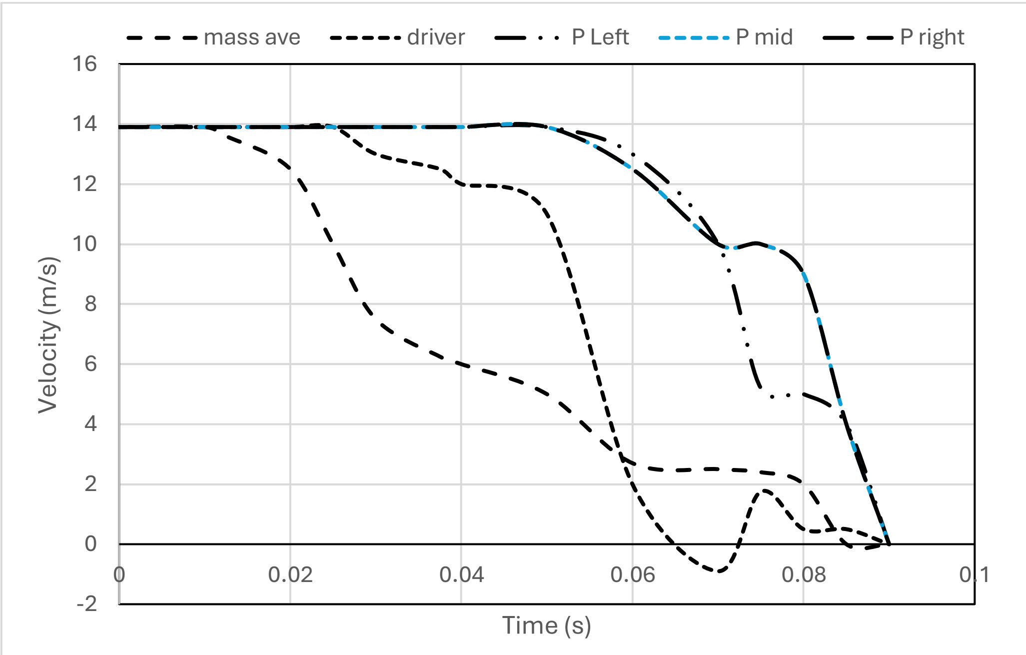

Fig. 8. Mass Average Velocity signature with occupants

The mass average velocity graph for the analysis with passengers and the driver is shown in Fig. 8. The analysis revealed that the front face of the three-wheeler is intruding into the driver's compartment.

Due to the sudden acceleration, the driver is moving frontward colliding with the front panel. At high speed, there is a possibility that the driver gets crushed in between the driver's seat and the front panel. Even after the collision, the passengers continue to move at the initial velocity before the collision for some time and abruptly come to a stop creating a magnificent deceleration.

4.3 Full Width Frontal Impact Collision with restrained Occupants

Further, the analysis was extended to the case of restrained occupants. The restraining system was such that the system is fully tensioned at a distance of 0.15 m movement of the passenger with respect to the vehcle.

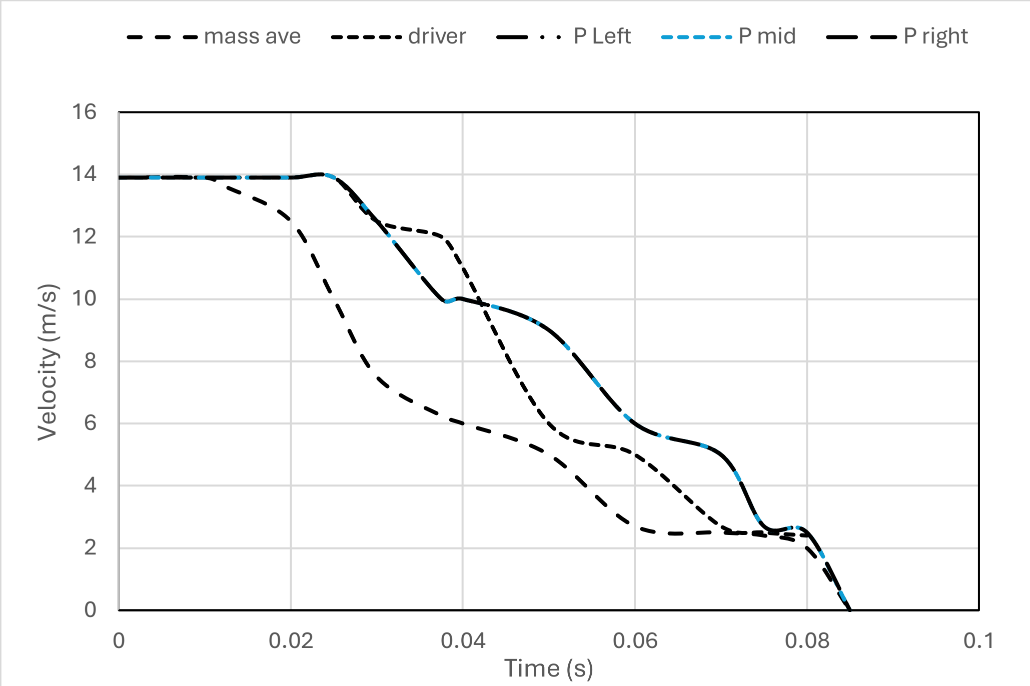

Fig. 9. Mass Average Velocity signature with restrained passengers and driver

As depicted in Fig. 9, as soon as the three-wheeler collides with the rigid barrier, the occupants move at the same initial velocity of the three-wheeler for 0.15m which accounts for a period of 0.12 seconds with respect to the ground. After moving 0.15m, the restrain system tightens. As now the passenger is restrained to the vehicle, the passenger's velocity with respect to the vehicle becomes zero. This action eventually brings the velocity of the occupants to zero with respect to the ground.

5. ANALYSIS OF RESULTS

5.3 Analysis of the Full Width Frontal Impact Collision without Occupants

It should be noted that severe front face deformation in any vehicle is observed in Frontal Offset Collisions. These types of collisions are stated to be the most dangerous with the likelihood of structural failure very high.
Taking the region between 0.012s and 0.0728s from Fig. 4 where the simulation was carried out without passengers; the acceleration is 23.3G.
The G-Force experienced is slightly lower than the average Human Tolerance limit of 27.5 G. While this may be an indicator for suitability of the vehicle to a certain degree, relying on this calculation alone is not sufficient. However, the three wheeler alone is not sufficient to obtain an accurate account of the vehicle, when it is fully loaded with passengers.

5.2 Analysis of the Full Width Frontal Impact Collision with Occupants

The deformation of the Three-Wheeler at the center allowed it to fold in half absorbing crash energy considerably. The driver is the first to impact with the front face and faces the largest deceleration after traveling 0.173 meters within the three-wheeler with respect to the ground after the collision. The initial low deceleration is due to the fact that the occupants are not restrained, and they move at the initial velocity of the vehicle. The passengers travel 0.52 meters within the three-wheeler with respect to the ground after the collision. In addition to this, the motion puts the head of the driver in direct collision with the windscreen. It was noted that the abrupt motion generated high stress at the back of the neck as seen in Fig. 10 which increases the risk of injuries related to whiplash.

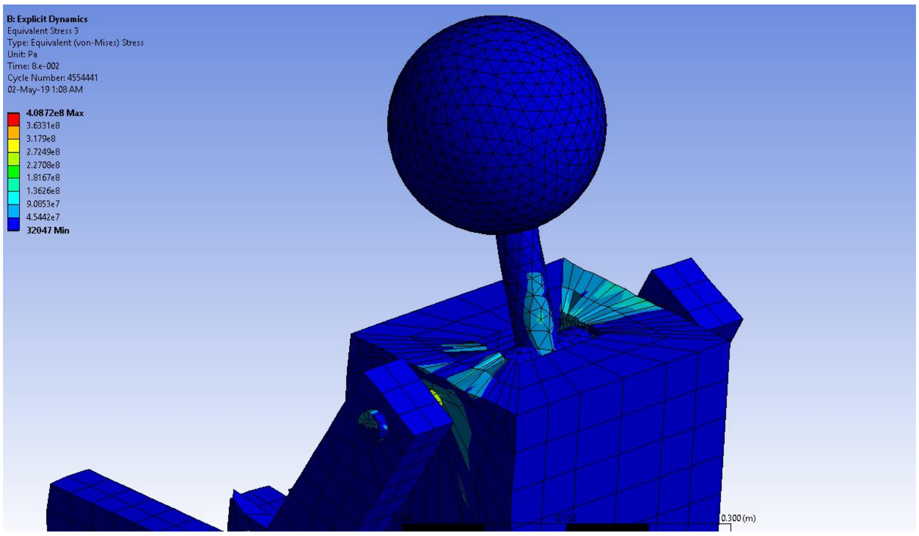

Fig. 10. Whiplash of the Driver

The motion is such that the shins of each passenger impact against the passenger compartment, which leads to heavy injury and possible fracture of the shin bone. Only the center passenger collides directly with the back of the driver due to being placed right behind him. The probable motion could lead to spinal injury for the driver due to the high momentum of the center passenger. The trajectory of the remaining passengers is directed to the driver space with a possible forward tilt of the torso, causing the passengers to move headfirst towards the front face and windscreen. This motion itself could increase the likelihood of fatalities in passengers. The acceleration data for each occupant is tabulated in Table 3

Table 3 Occupant Dynamic Motion Data

Occupant	Maximum G Force
Driver	81 G
Passenger (Left)	47 G
Passenger (Mid)	47 G
Passenger (Right)	47 G

The table values indicate that the driver experiences loads of up to 81 G, which drastically exceeds the Human Tolerance limits given in Table 1 and Table 2.

However, the FEM analysis revealed the fact that the driver is suffering severe injuries due to the intrusion of the front face towards the driver. A typical example of such an accident is depicted in Fig. 11

Fig. 11. An accident with the front face intrusion killing the driver. [Daily News 2016]

5.3 Analysis of Full Width Frontal Impact Collision with Restrain system

The G force acting upon each restrained occupant of the three-wheeler is given in Table 4. From Table 4, it is clear that the G force acting on each occupant has drastically reduced.

Table 4 Occupant Dynamic Motion Data with restrain system

Occupant	Maximum G Force
Driver	25 G
Passenger (Left)	20 G
Passenger (Mid)	20 G
Passenger (Right)	20 G

6. DISCUSSION AND CONCLUSIONS.

The behavior of a three wheeler during a head on collision was investigated using Finite Element Analysis. The collision without passengers, with passengers and with the restrain system were analyzed. Analysis revealed that the predicted damage pattern is in conformity with real world accident records.

First, Full Width Frontal Impact Collision without Occupants was carried out. The mass average acceleration of the three-wheeler was 23.3G. The G-Force experienced is slightly lower than the average Human Tolerance limit of 27.5 G.

The analysis of the existing structure revealed that the passenger compartment is not rigid enough to provide a protective shell to occupants. The structure experienced a severe plastic deformation in the mid-section, crashing into the passenger compartment. Further, the front face of the three-wheeler intrudes in to the driver compartment, virtually crushing the driver against the driver's seat. The results of the FEM analysis were confirmed by the analysis of real-world accidents.

The analysis revealed a comparatively lower acceleration for passengers compared to that of the driver. The higher acceleration of the driver can be attributed to the space limitation for the driver due to intrusion of the front face and the comparatively lower acceleration can be attributed to the plastic deformation occurred in the mid-section which absorbed part of the crash energy.

During the collision of a conventional three-wheeler, the passengers experienced a 47G force and the driver experienced a maximum of 81 G force. As per the literature review, both magnitudes exceed the tolerable limit for humans. However, the analysis revealed that had there been a restrain system, the acceleration of passengers could have been brought to 20G and the acceleration of the driver to 25G.

The availability of a restrain system may decrease the severity of injuries to occupants of three wheelers. The main reason for fatal injuries during a head on collision of a three-wheeler is due to deficiencies of basic structural features such as lack of a crumple zone, rigid passenger compartment and restrain systems.

It is necessary to re-design the structure of the three wheeler to safeguard the occupants. In doing so, the designers have to take into consideration the intrusion of the front face and plastic deformation of the mid-section.

REFERENCES:

Bois, P. D. et al., 2004. Vehicle Crashworthiness and Occupant Protection. Michigan: American Iron and Steel Institute.

Coltman, J. W., Ingen, C. V., Johnson, N. B. & Zimmermann, R. E., 1989. Aircraft Crash Survival Design Guide, s.l.: U.S. Army Aviation Research & Technology Activity.

Daily News e paper [Online] Available at https://dailynews.lk/2016/10/12/law-order/95662?page=17 [Accessed 5 March 2018].

Doshi, H., 2017. Static Structural Analysis of Frame of an Commercial Autorickshaw to Reduce Accidental Damage Using Ansys. International Journal on Recent and Innovation Trends in Computing and Communication, 5(4), pp. 234-237.

Hybrid III 50th percentile male [online] Available at: https://unece.org/fileadmin/DAM/trans/doc/2009/wp29/HIII_50th_Male_Drawings.pdf [accessed 10 March 2018].

Shanahan, D. F., 2004. Human Tolerance and Crash Survivability. s.l., North Atlantic Treaty Organisation.

Srikanth, K. M. & Prakash, R. V., 2009. Assessing the Structural Crashworthiness of a Three Wheeler Passenger Vehicle. Bangalore, India, s.n.

Safety of Quadricycles [online] Available at: https://www.euroncap.com/en/vehicle-safety/safety-campaigns/2014-quadricycles-tests/[accessed 10 March 2018].

WHO, 2018. World Health Organization. [Online] Available at: https://www.who.int/news-room/fact-sheets/detail/the-top-10-causes-of-death [Accessed 5 March 2018].