Trucks with Different External Frontal Frames: Comparing Vulnerable Road User's Injury Severities Using MADYMO

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ABSTRACT
Each year thousands of pedestrians and bicyclists are killed or injured in road traffic accidents around the world. Highway crashes involving pedestrians include a high percentage of hit and run accidents where accused vehicles are trucks and victims are pedestrians and bicyclists. This along with the high exposure of vulnerable road users (VRU) on high speed freight corridors requires an in-depth analysis of impact of trucks with VRUs. While a variety of such analysis can be performed, in this study, focus has been given to carry out analysis of vulnerable road users (VRU) with trucks using simulation software MADYMO. External frontal frames of trucks composed of energy absorbing materials are used in this study as a means of impact injury reduction of VRUs in the event of side and/or rear collision at speeds between 15 and 60 km/h.
The direct contact of the VRUs with hard metal surface is prevented by using these energy absorbing materials attached externally to the truck front. The spatial configuration of energy absorbing materials has been determined without negatively influencing either headlights or the direct sight and the air circulation of the engine parts. Injury criteria results obtained for all body segments reduced significantly for both pedestrians and bicyclists when the truck is attached with energy absorbing frontal system.
Keywords: Vulnerable road users, pedestrian, bicyclist, energy absorbing materials

INTRODUCTION

Road transport is one of the major surface transport systems in the world serving transportation needs of millions of people as well as million tonnes of freight to their respective destinations. It has been observed that road transportation collisions occur on a frequent basis in comparison to other modes of transport. Even though the cause of these road transport collisions are a result of either human error, mechanical failure and/or due to the forces of nature; these collisions results in loss of life, property and pose a huge economic burden to the society. The problem of deaths and injury as a result of road accidents is now acknowledged to be a global phenomenon with authorities in virtually all countries of the world concerned about the growth in the number of people killed and seriously injured while in transportation on roads.

The World Report on Road Traffic Injury Prevention of the World Bank and World Health Organization (WHO) in the year 2004 stated that road traffic injuries are *a major but neglected global public health problem* requiring concerted efforts for effective and sustainable prevention. The World Health Organization has estimated that in 2002 almost 1.2 million people died in road crashes worldwide and as many as 50 million were injured. Unless action is taken, global road deaths are forecast to double by 2020 even though it is a known fact that many of these deaths and injuries could have been prevented. As per reports by WHO, it has been observed that more than eighty five per cent of road traffic deaths and injuries occur in low income and middle income countries. The majority of these deaths are of vulnerable road users (VRU) such as pedestrians, pedal cyclists and motorcyclists. In high-income countries, deaths among car occupants continue to be predominant but risk per capita that vulnerable road users face are significantly high. The major contributing factors leading to road crashes and injury include drinking and driving, lack of helmet use, seat belt non compliance, excessive speed, and poor infrastructure design and management. To avoid the increasing human loss and injury on the roads and thereby prevent a large economic cost to society, road traffic injury prevention and mitigation should be given the same attention and scale of resources that are currently being channeled towards other predominant health issues. The World Report recommends practical actions to mitigate these factors is an integrated 'safety systems approach' to road safety improvements, using a lead agency to coordinate the development of national road safety strategies and plans.

Apart from the humanitarian aspect of reducing road deaths and injuries in developing countries, a strong case can be made for reducing road accident deaths on economic grounds alone, as they consume massive financial resources that the countries can ill afford to lose. Road traffic deaths and injuries impose huge economic costs on developing economies in low and middle income countries. These economic costs are estimated at US$65 billion in developing and transitional countries, and US$453 billion in highly motorized countries, making a crude estimated total of US$518 billion worldwide.

The road traffic deaths in India are also increasing every year - in 2004 the number of deaths had increased to 92,618 in comparison to 84,674 of 2002. Official road traffic crash data do not include fatalities by road user category in India. Such data are only available from a few cities and research studies done on selected locations on rural highways. Figure 1 shows traffic fatalities by category of road users on selected locations on national highways (NH- 4, 6). These data show that car occupants were a small proportion of the total fatalities - 15% on rural highways whereas VRUs accounted for 67% on rural highways (Mohan, 2009). The low proportion of car occupants can be explained by the low level of car ownership at 7 per 100 persons as compared to more than 50 per 100 persons in most high income countries. At present levels of growth in vehicle ownership in India, vulnerable road users are likely to remain the dominant mode for the next few decades. Majority of such victims in road crashes are males in 30-44 years age group. However, it is to be noted that detailed data is not available at the national or state level for crashes on national highways

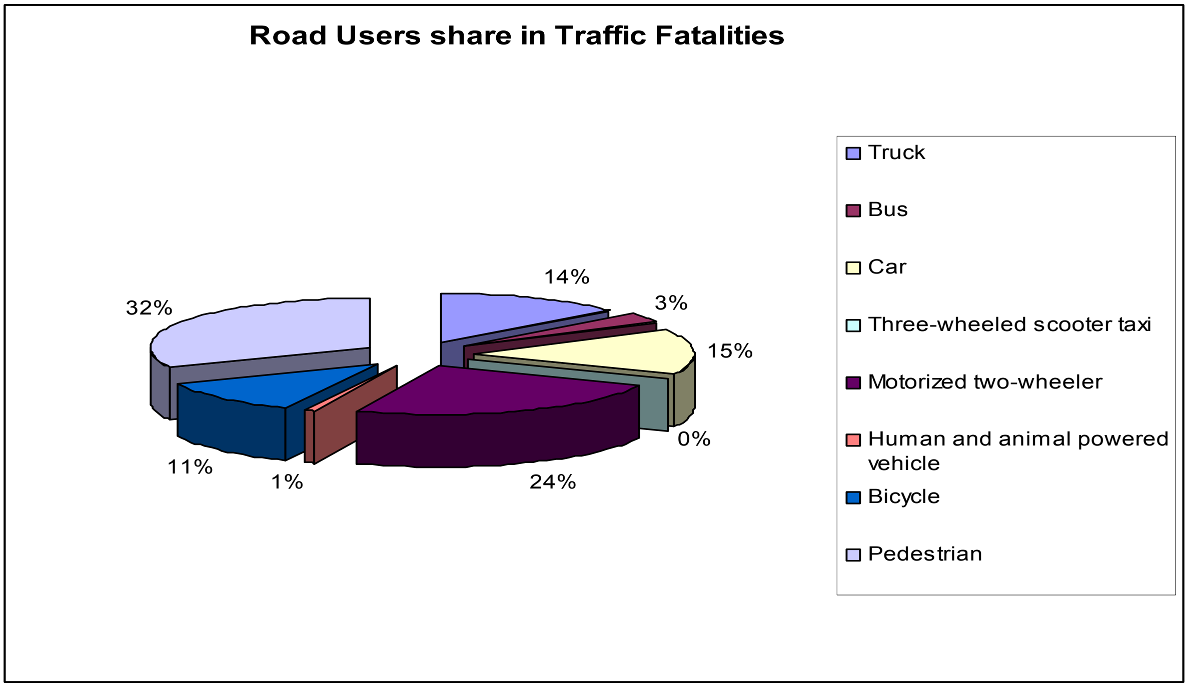


Figure 1 Traffic fatalities by category of road user on selected locations of national highways (India) 1999

Main Objectives are:

1. To carry out the analysis of vulnerable road users accidents with trucks using MADYMO simulation software and determine the injuries sustained by Pelvis, Head, Thorax and lower body parts
2. To find the most important factors influencing the VRU injury severities, like speed and impact type (side, rear, etc)
3. To analyze the injury severity during first and secondary impacts
4. To find the differences and similarities between pedestrian and bicycle accidents in terms of injury severity, contact points of various body segments with truck
5. To develop a novel Deformable Energy Absorbing (DEA) system simulation models and evaluate the performance of these novel system in VRU's injury severity reduction

LITERATURE REVIEW

Several research studies have focused on numerical simulation of the collision event of a pedestrian and/or a bicycle with a cars and light vehicles. The impact severities of a VRU are measured based on accelerations sustained by different parts of the body in the event of the collision. Most of the research in this area of simulation of the collision event considers a parameterisable multi-body vehicle model and a numerical human pedestrian model. Feist et al. (2008) concluded that head injuries are the most frequent injuries sustained by pedestrians involved in a collision with a flat-fronted vehicle (such as truck) and rotational accelerations are responsible for around 70% of head injuries. Parametric studies were also performed as part of this research for different vehicle geometry, vehicle speed, friction coefficients, gait and orientation of the pedestrian. Mukherjee et al. (2007) studied the effect of vehicle design on head

injury severity and throw distance variations in bicycle crashes with different categories of vehicles such as small cars, sports utility vehicles and buses. It was observed through parametric studies that variation in angle of approach and/or point of contact causes significant change in accident severity. It was also observed from the study that the HIC values were higher in the case of bus as compared to the SUV and the small car. Fiesta et al. (2008) introduced the concept of retrofittable energy absorbing front end for heavy goods vehicles for protection and injury severity reduction of VRUs. Different types of these energy absorbing front end devices were utilized such as adaptive deformable front (ADF), multi-chambered net of tubes (MCNT), Segmented energy-absorbing front, Safety bar (foam–steel structure) to simulate the event of collision of pedestrian and bicyclist with heavy goods vehicles at speeds of 30, 40 kmph for three different impact types (side, rear and front). A coordinated experimental and numerical research revealed a reduction of 90% for HIC injuries on using these energy absorbing front end devices. Fremgen et al. (2005) identified that foam panels can be used as a possibility of reducing impulse transfer between the foam and the impact body.
The major share of vulnerable road users (VRU's) fatalities and serious injuries occurs in collision with trucks rather than in comparison to other vehicles like cars, jeeps, two and three wheelers. The main reasons for these severe fatalities for trucks include geometry, stiffness and shape of trucks which are much higher than other vehicles. As the number of trucks (Light, Medium, Heavy) population on highways continues to increase, a new area of concern regarding VRU'S safety has emerged.

MODEL SELECTION AND DEVELOPMENT OF MODEL IN MADYMO FOR IMPACT ANALYSIS BETWEEN VRU'S AND TRUCK

The major share of vulnerable road users (VRU's) fatalities and serious injuries occurs in collision with trucks rather than in comparison to other vehicles like cars, jeeps, two and three wheelers. The main reasons for these severe fatalities includes geometry, stiffness and inertia of trucks are much higher than other vehicles. As the number of trucks (Light, Medium, Heavy) population on highways continues to increase, a new area of concern regarding VRU'S safety has emerged.

From the medical reports of road accident cases it was found that when VRU's impact with trucks, the head, thorax, pelvis, and lower extremities (Upper leg, Lower leg) of the VRU are subjected to serious injuries. The major cause of these severe injuries includes collision of the VRU with different parts of the truck such as the bumper part, front grill, and the windscreen. In order to estimate the injury severity levels during different collision types and collision speeds, to correlate the injury severity of real crashes and to reconstruct the event with in short time computer simulation softwares are required. In this research commercial software MADYMO has been used to simulate vehicle crashes and information regarding the injury criteria of human body along with its tolerable limits are also discussed.

As most of the trucks hit the pedestrians and bicyclists either sidewise (laterally) and from rear, modeling of side impact and rear end impacts are performed in this study. To model the VRU accident with truck the first step is to select a standard truck, a bicycle and pedestrians. After selection of such prototypes from the real world, the next step will be to develop similar multibody model in MADYMO. For developing the model in MADYMO, in general various properties of the system such as appropriate dimensions of various parts, mass and stiffness of various parts are needed. At this point it is important to mention that pedestrian models used in the simulation were chosen from existing models in the MADYMO 7.2. Before developing the various system models in the MADYMO reference space, ground plane (road way) should be developed as a surface plane and the properties like stiffness, dimensions, and unevenness of the surface, if applicable for this ground plane, should be provided.

Development of Truck Model

For the purpose of modeling for simulation, **Tata SE 1613 Turbo EX BS II** was selected which is generally used for carrying heavy goods (otherwise referred to as a heavy commercial vehicle, HCV). The geometry, gross weight of the vehicle, front and rear axles weights are obtained from the vehicle broachers supplied by manufacturers. Material properties of various truck frame parts are represented in terms of stiffness of each member by assuming that all parts are made up of mild steel, table 1 shows the dimension and weights of the truck parts. In the following table GVW represents Gross Vehicle weight, GCW represents Gross Combined, FAW and RAW represents Front and Rear Axle Weights. From the information provided in the table, the truck was modeled in MADYMO as a multibody system.

Max.Permissible GVW/GCW(kg)	16200
Kerb weight with cabin (kg)	4230
Max Permissible FAW(kg)	6000
Max Permissible RAW(kg)	10200
Wheel base (mm)	4225
Max. width (mm)	2316
Max.height (mm)	2704

Table 1 Weight and Dimensions of Tata Truck

Multi-body framework of truck – The truck model consists of eight major rigid bodies: truck, bumper, front axle, rear axle, front left wheel, front right wheel, rear left wheel, rear right wheel. Truck rigid body was attached to the reference space with a free joint in which none of the six degrees of freedom are restrained. Bumper of the truck attached to the truck body by one directional translational joint (in which apart from one translational dof, all the other 5 dof are restrained). Figure 2 shows Tata SE 1613 Turbo EX BS II truck and the finished truck model in MADYMO.

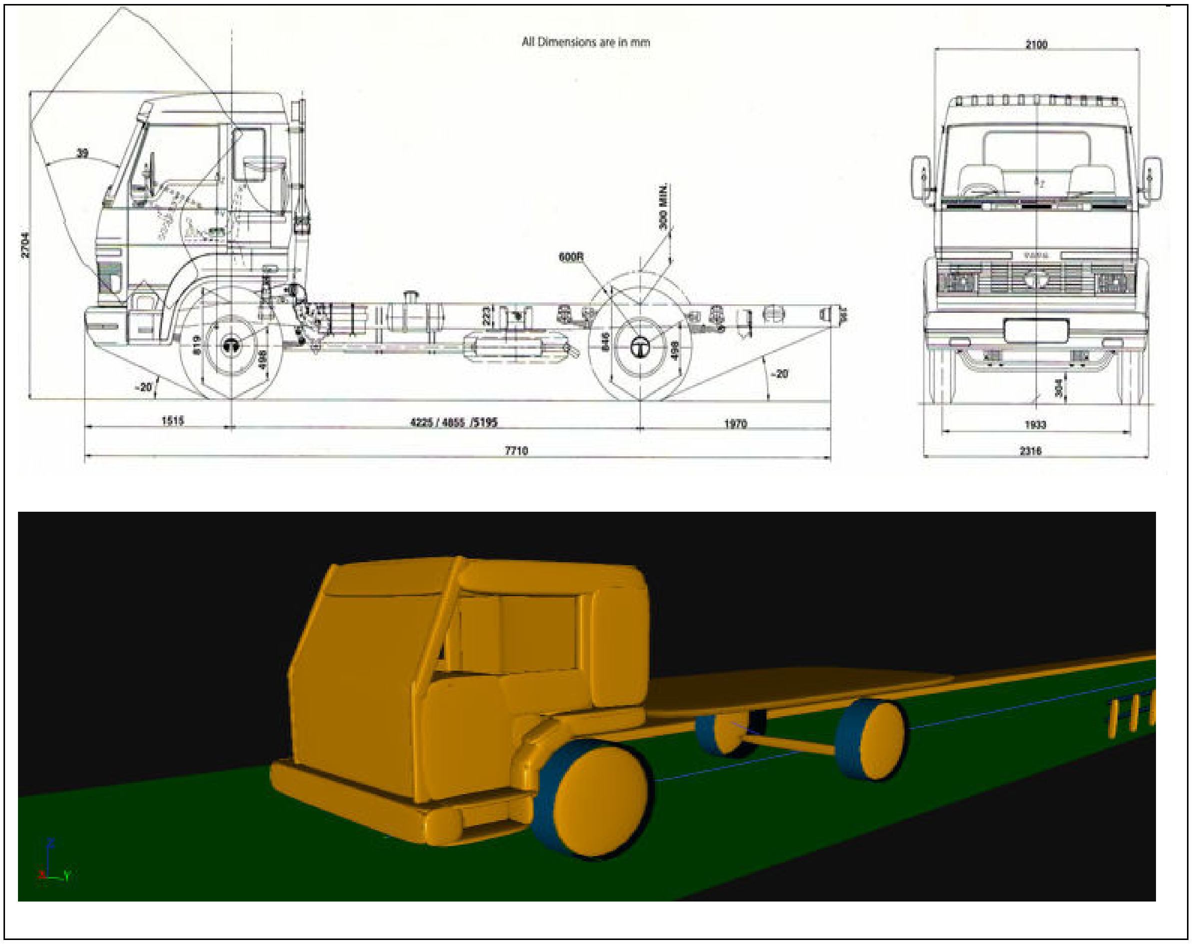


Figure 2 Tata SE 1613 Turbo EX BS II Truck & Truck Model Developed in MADYMO

Development of Bicycle Model

Bicycle model was developed from Hero Jet cycle whose dimensions and weights were found by physical measurements. The radial stiffness of the wheels was obtained from the force-deflection curve for the bicycle wheels (Gavin, 1996). The bicycle model was represented with a system of five rigid bodies: Center of Gravity of cycle, handle bar, front wheel, rear wheel, and a dummy body.

Generation of DEA frontal system for the Truck

In order to design a passive safety system which will reduce injury severity of the VRU's during accidents, it is essential to use some material which will absorb energy at the time of impact. For this purpose energy absorbing properties of materials and the deformation mechanism of such energy absorbing systems should be known. Generally foam materials satisfy such requirements and have been used in mine-counter-measure naval vessels to absorb the impact load generated due to blast. Thereby foam materials are chosen as a possible candidate material in this research to reduce the injury severity of a VRU in the event of a collision with a heavy commercial vehicle

Concept of Deformable Energy Absorbing (DEA) system:

- This system is modeled as FE model structure in LS-DYNA software program to facilitate specification of foam materials characteristics as a constitutive relationship. The system consists of upper grill and bumper parts and sufficient gap space is left for the head lights and engine grill for air circulation and lighting.
- The FE model was then transformed from LS-DYNA to MADYMO and material properties and contact interactions were given in MADYMO. Figure-4 shows the developed truck model attached with Deformable Energy Absorbing (DEA).
- The DEA frontal system is attached to the bumper of the truck by a unidirectional translational joint in order to give an initial displacement during impact.
- DEA frontal system made from semi-rigid poly-vinyl-chloride foam having a density of 100 kg/m^3, cell size of approximately 400μm and stress strain characteristics as shown in figure 3.

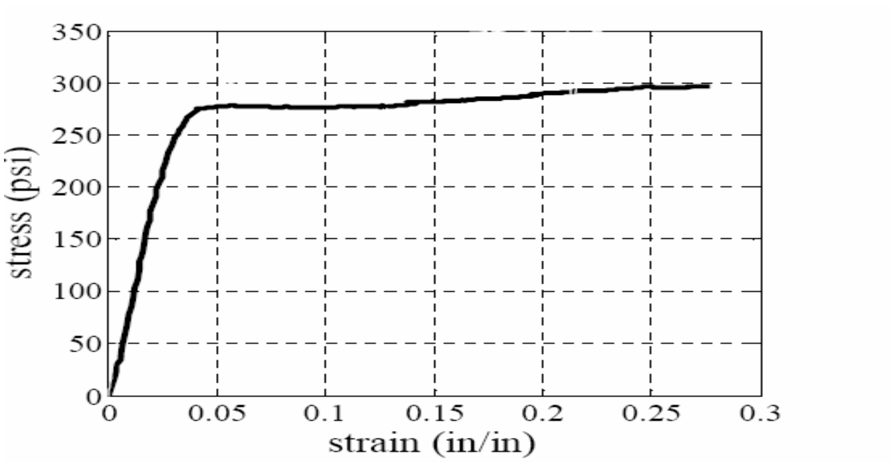


Figure 3 Stress-strain curve of PVC Foam Material

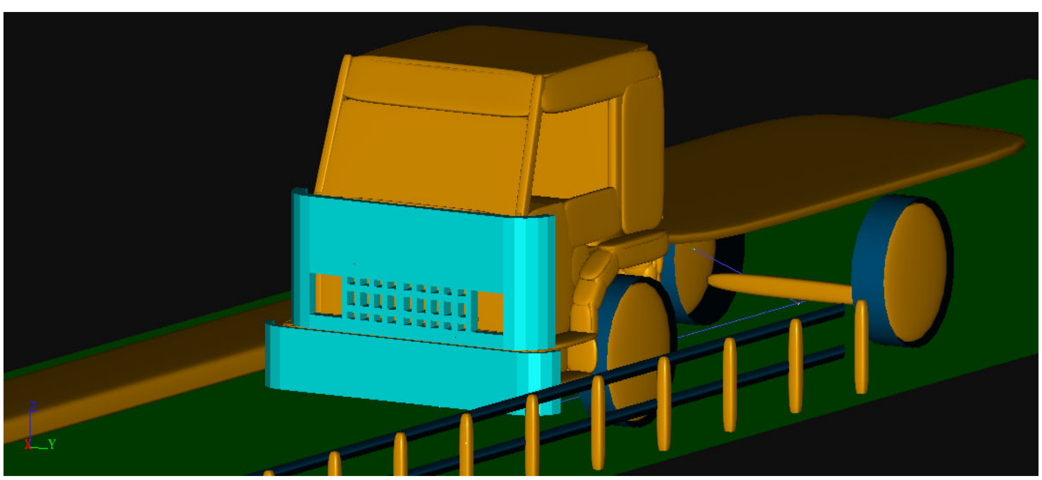


Figure 4 Truck attached with DEA frontal system

The DEA foam system was supported by PVC frame channels which are connected to the truck front grill by means of springs or simple jack system to give a 100mm initial displacement during impacts. Thickness of entire bar system is taken as 100mm. Figure 4 shows truck attached with DEA frontal system developed in MADYMO.

Hybrid III 50th percentile Male was utilized as pedestrian model and Hybrid III 50th percentile Q Dummy 2 was used as Bicycle rider model in the present study.

Analysis and Simulation of VRU Accidents with Truck

After selection and development of models in MADYMO the next step is to run the simulation analysis and study the kinematics in a particular impact with truck. In this study side and rear-end impacts with trucks were analyzed at various truck speeds. For each type of impact, severity of injury was computed and compared with trucks attached by DEA frontal system. The injury criterion is based on acceptance levels of EEVC proposal and from European Passive Safety Network.

The analysis part includes the following four cases

1. Truck , Pedestrian Side Impact Analysis
2. Truck , Pedestrian Rear Impact Analysis
3. Truck , Bicyclist Side Impact Analysis
4. Truck , Bicyclist Rear Impact Analysis

Analysis of Truck Pedestrian Impacts

Pedestrian side and rear-end impacts were modeled at 10 different truck speeds starting from 15 kmph to 60 kmph at an increment of 5 kmph speeds. Initial velocity of the pedestrian walking was taken as 2 m/s (7.2kmph) and was placed initially at 0.5m from the center of the truck. All the pedestrian body segment was selected as slave surfaces and truck body parts was selected as master surfaces. The coefficient of friction between master and slave surfaces was taken as 0.15 (Feist et al. 2008). The various contact interactions for the truck-pedestrian impact simulations were defined as follows: head/chest, abdomen pelvis, shoulder with the front grill part of the truck, upper and lower leg with bumper of the truck, for the secondary impact with ground plane pedestrian body parts were selected as slave surfaces and ground plane as master surface and coefficient of friction between master and slave surfaces was taken as 0.55 (Fiest et al. 2008). For the case with DEA frontal system, simulations were done at same conditions except the slave surfaces in this case was finite element DEA frontal system and the pedestrian body parts were selected as master surfaces during first impact. The head resultant acceleration, pelvis forces, forces on upper and lower leg were found during first and secondary impacts and performance of DEA frontal system was evaluated.

Truck, Pedestrian Side Impact Analysis

The most common type of impact scenario is lateral or side impact in which pedestrian moves perpendicular to the motion of the truck. Simulation analysis done for both the cases of trucks attached with DEA frontal system and without DEA frontal system.

Results:-

Figure 5 shows the variation of pedestrian HIC value with the impact speed during first and secondary impacts for both cases of truck with and without DEA frontal.

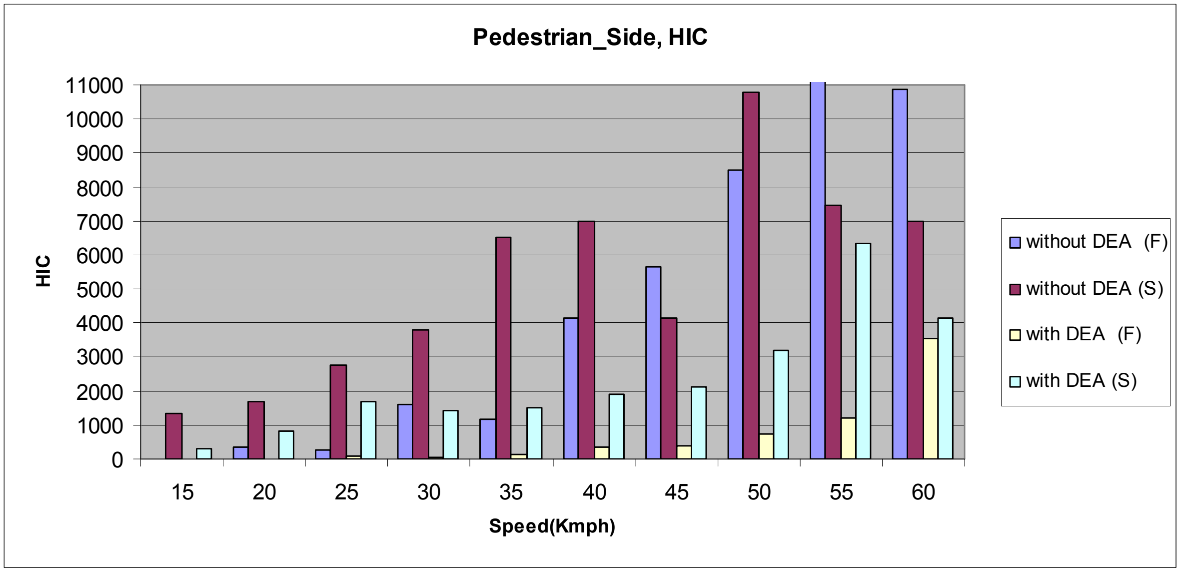
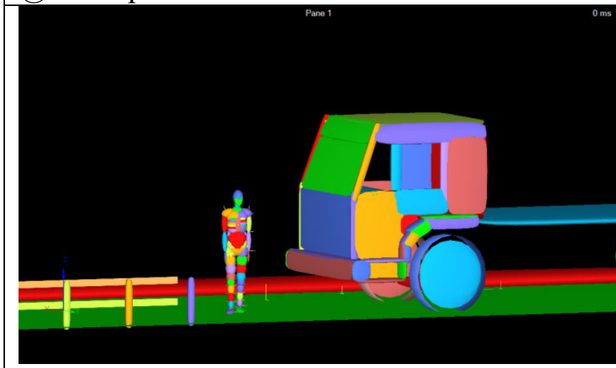
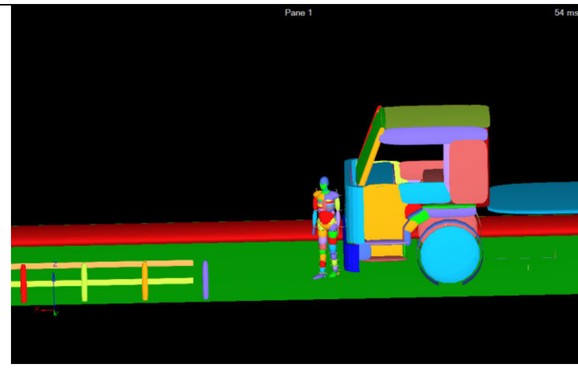


Figure 5 Plot for HIC at different speeds during first and secondary impacts for pedestrian side impacts

Figure 6 shows the kinematic variation of pedestrian during side collisions at 30 kmph impact speed. It is observed that time duration for pedestrian to touch the ground from its initial contact point is higher in case of truck attached with DEA frontal system. This is due to energy absorption of the DEA frontal system at the time of impact. It can also be explained from first principles in physics that in a contact between two bodies, as the time of contact increases the energy transfer is decreased and energy absorption is higher.

<table>
<tr><td colspan="2">Kinematics of Truck_Pedestrian Side Impacts with and without DEA frontal System @30Kmph</td></tr>
<tr><td>

0 ms</td><td>

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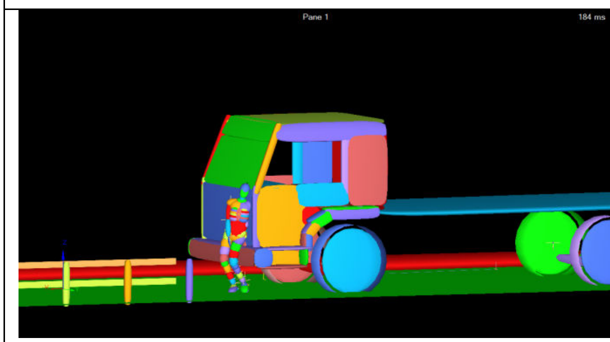
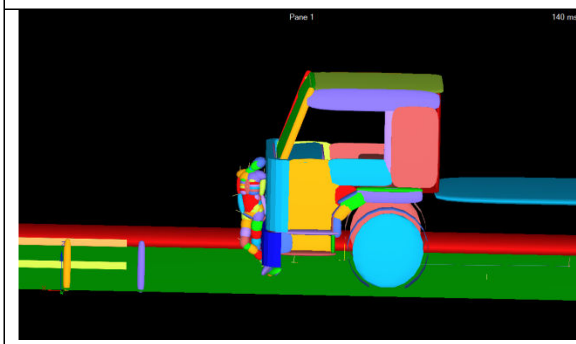
<tr><td>

184 ms</td><td>

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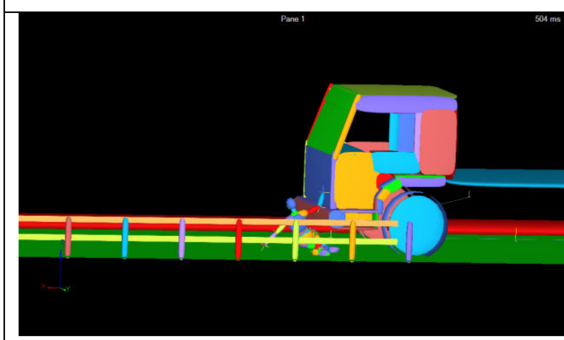
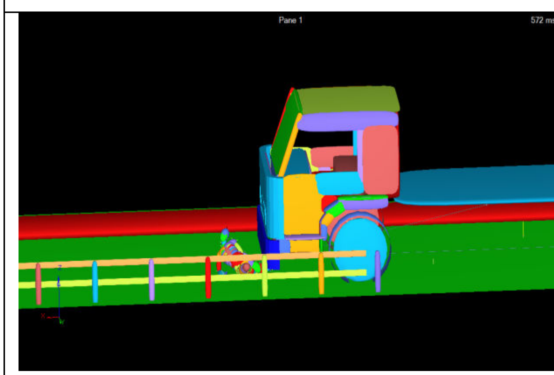
<tr><td>

302 ms</td><td>

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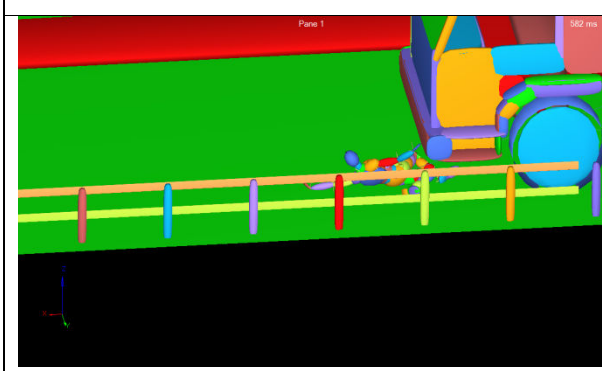
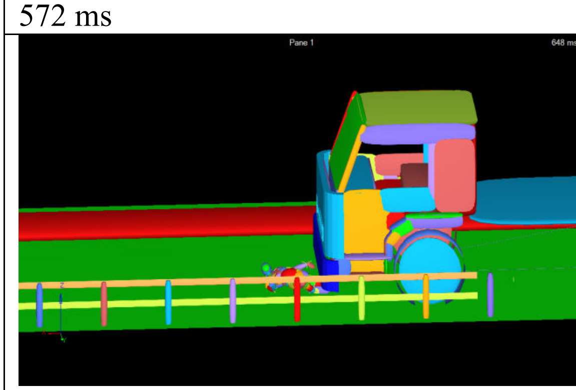
<tr><td>

582 ms</td><td>

648 ms</td></tr>
</table>

Figure 6 Comparison of kinematics for truck pedestrian side impacts

Comparison of the results

Table 2 shows the injury suffered by pedestrian in side impacts. Injury severity was compared in both the cases of truck attached with and without DEA frontal system.

Impact Speed	Without DEA frontal system		With DEA frontal system	
	First impact	Secondary impact	First impact	Secondary impact
15 kmph	None	Head	None	None
20 kmph	None	Head	None	None
25 kmph	None	Head	None	Head
30 kmph	Head	Head	None	Head
35 kmph	Head	Head	None	Head
40 kmph	Head	Head	None	Head
45 kmph	Head, Pelvis	Head	None	Head
50 kmph	Head, Pelvis	Head	None	Head
55 kmph	Head, Pelvis	Head	Head, left Leg low	Head
60 kmph	Head, Pelvis	Head	Head, left Leg low	Head

Table 2 Injury suffered by pedestrian during first and second impacts with trucks in side impact

Discussion on Pedestrian Side Impact Results

It is observed from the results, truck without any DEA frontal system causes increase in head and pelvis injuries from impact speeds of 30 and 40 kmph respectively whereas in case of truck with DEA frontal system head injuries increases from 55 kmph impact speed and pelvis forces are within the tolerable limits during first impact at speed level lower than 60 kmph. Left lower leg injury exceeds the tolerable values at speeds exceeding 55 kmph for the case of truck attached with DEA frontal system. The reason for this may be traced to increased bumper height. Head injuries are more during secondary impacts in both the cases except for 15 kmph, 20 kmph in case of truck attached with DEA frontal system. It is observed from the above results that injury severity of pedestrians can be reduced considerable in first impacts by providing the DEA frontal system to the truck front.

Truck, Pedestrian Rear Impact Analysis

Rear-end collisions are also frequently occurring cases on road ways because of lack of sidewalks and pedestrians are forced to use the road way sections instead of road shoulders. Here the pedestrian direction of travel is same as the truck direction. Simulations are done for both the cases of truck with and without DEA frontal system.

Results:-

Figure 7 shows the variation of pedestrian HIC value with the impact speed during first and secondary impacts for both cases of truck attached with and without any DEA frontal system.

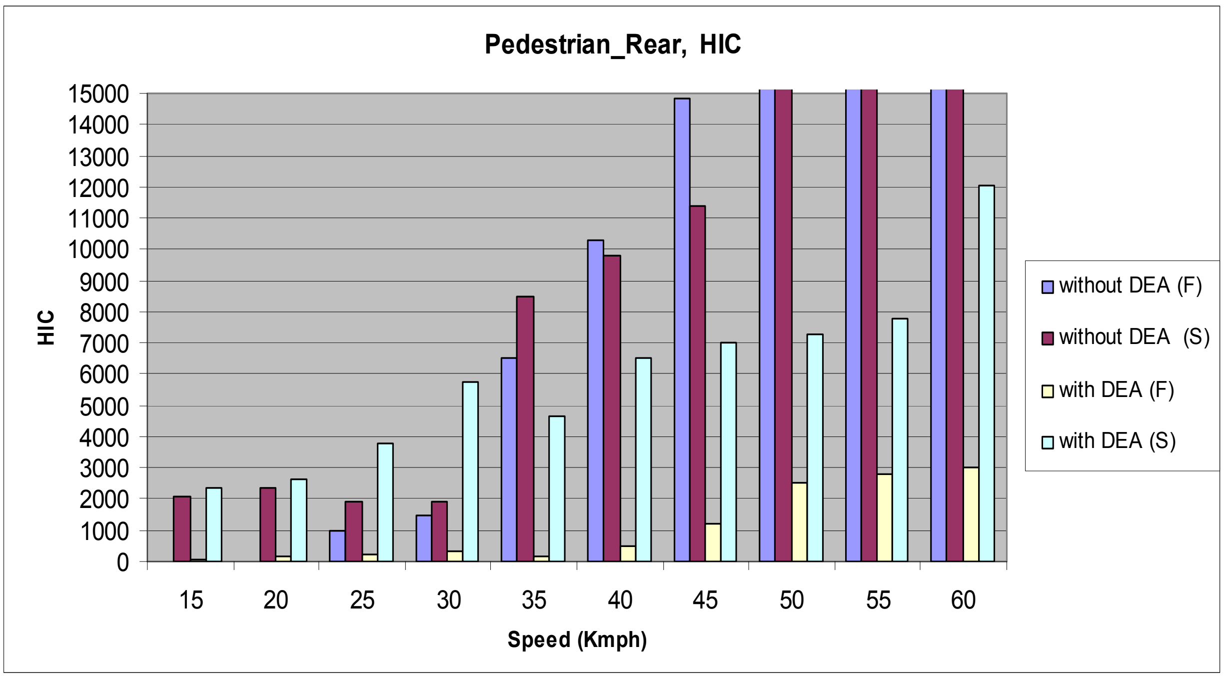


Figure 7 Plot for HIC at different speeds during first and secondary impacts for pedestrian rear impacts

Figure 8 shows the kinematic variation of pedestrian during rear-end collisions at 30 kmph impact speed. It is observed that time duration for pedestrian to touch the ground from its initial contact point is higher in case of truck attached with DEA frontal system. This is due to energy absorption of the DEA frontal system at the time of impact.

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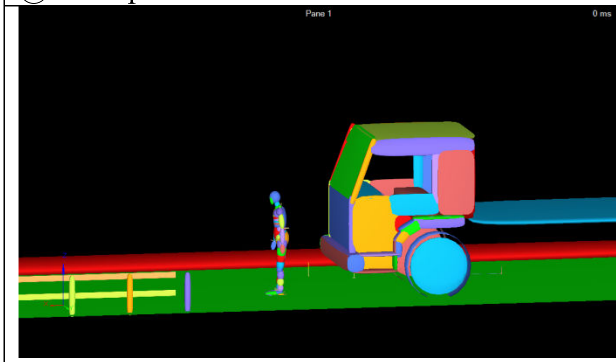
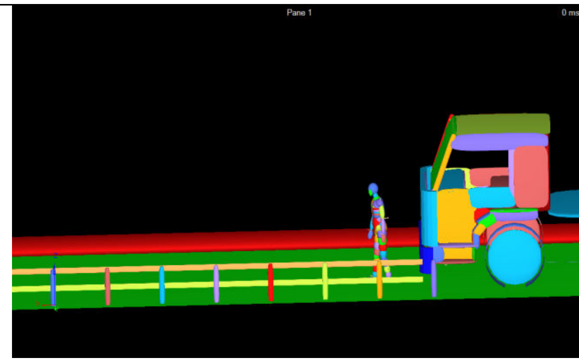
<tr><td>
0 ms</td><td>
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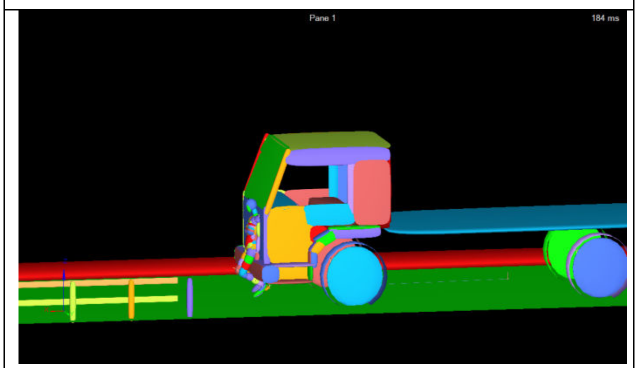
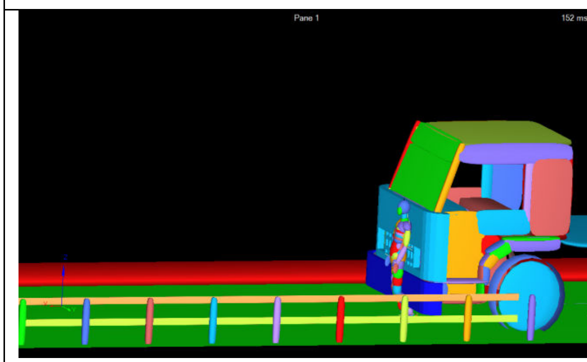
<tr><td>
184 ms</td><td>
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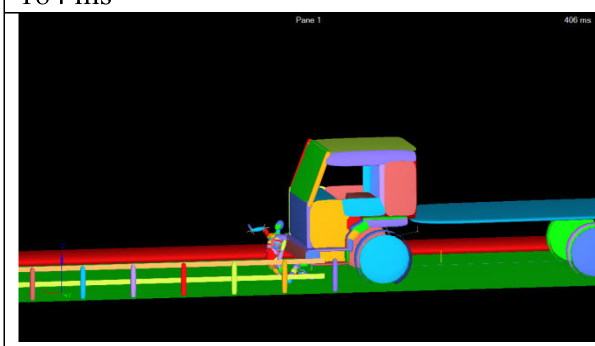
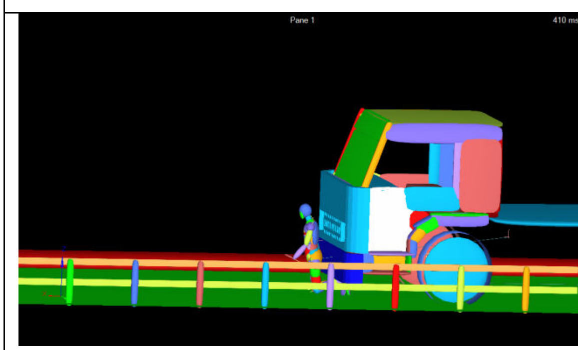
<tr><td>
530 ms</td><td>
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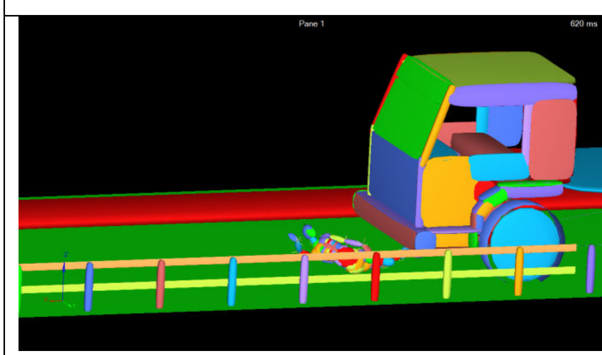
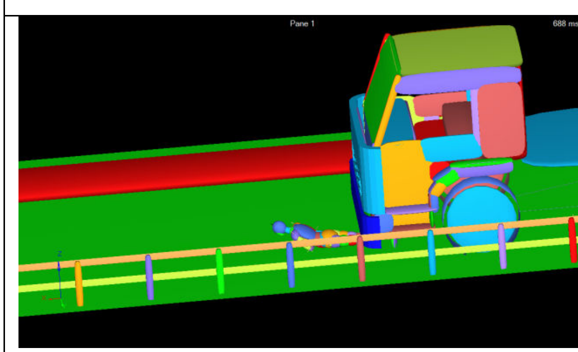
<tr><td>
624 ms</td><td>
688 ms</td></tr>
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Figure 8 Comparison of kinematics for truck pedestrian rear impacts

Comparison of the results

Table 3 shows the injury suffered by pedestrian in rear impacts. Injury severity was compared in both cases of truck attached with and without any DEA frontal system.

Impact Speed	Without DEA frontal system		With DEA frontal system	
	First impact	Secondary impact	First impact	Secondary impact
15 kmph	None	Head	None	Head
20 kmph	None	Head	None	Head
25 kmph	Head	Head	None	Head
30 kmph	Head	Head	None	Head
35 kmph	Head	Head	None	Head
40 kmph	Head	Head	None	Head
45 kmph	Head,	Head	Head	Head
50 kmph	Head, Pelvis, left Leg up, left Leg low, right Leg low	Head,	Head, left Leg up	Head
55 kmph	Head, Pelvis, left Leg up, left Leg low, right Leg low	Head,	Head, left Leg low	Head
60 kmph	Head, Pelvis, left Leg up, right Leg up, left Leg low, right Leg low	Head, Pelvis,	Head, left Leg low	Head

Table 3 Injury suffered by pedestrian during first and second impacts with trucks in rear impact

Discussion on Pedestrian Rear Impact Results

It is observed from the results, truck without any DEA frontal system causes increase in head and pelvis injuries from impact speeds of 25 and 50 kmph respectively where as incase of truck with DEA frontal system head injuries increases from 45 kmph impact speed and pelvis forces are within tolerable limits during first impact for speeds lower than 60 kmph. Left lower leg injury exceeds the tolerable values at higher impact speeds (50 kmph) when truck attached with DEA frontal system which might be a result of increased bumper height. Head injuries are more during secondary impacts in both the cases. Hence, from the above results injury severity of pedestrians can be reduced significantly in first impacts by providing the DEA frontal system to the truck front.

Analysis of Truck Bicycle Impacts

Bicycle side and rear-end impacts were modeled at 10 different truck speeds starting from 15 kmph to 60 kmph at an increment of 5kmph. Hybrid III 50th percentile Q 2dummy male model was seated on the bicycle for simulation. Hybrid III dummy body segments selected as slave surfaces and truck body parts selected as master surfaces. The coefficient of friction between master and slave surfaces was taken as 0.15. The various contact interactions for the truck-pedestrian impact simulations were defined as follows: head/chest, abdomen, pelvis, shoulder with the front grill part of the truck, upper and lower leg with the bumper of the truck, for the secondary impact with ground plane dummy body parts selected as slave surfaces and ground plane as master surface, slave surface contact characteristics were selected and coefficient of friction between master and slave surfaces taken as 0.55. Contact between truck and various bicycle parts also defined by selecting truck parts as master and bicycle parts as slave surfaces. While on the other hand the when truck was attached with DEA frontal system simulations were done at same conditions except the slave surfaces in this case was finite element DEA frontal system and pedestrian body parts selected as master surfaces during first impact. The head, thorax, pelvis resultant acceleration, neck forces, forces on upper and lower leg were founded during first and secondary impacts and performance of DEA frontal system was evaluated.

Truck , Bicycle Side Impact Analysis

Bicycle side collisions occurring on the roads in which bicycle faces perpendicular to the motion of the truck. This type of impacts usually occurred on road ways while bicyclist crossing the road laterally. Simulation analysis done for both the cases of trucks attached with DEA frontal system and without DEA frontal system.

Results:-

Figure 9 shows the variation of bicyclist HIC value with the impact speed during first and secondary impacts for both cases of truck with and without DEA frontal system.

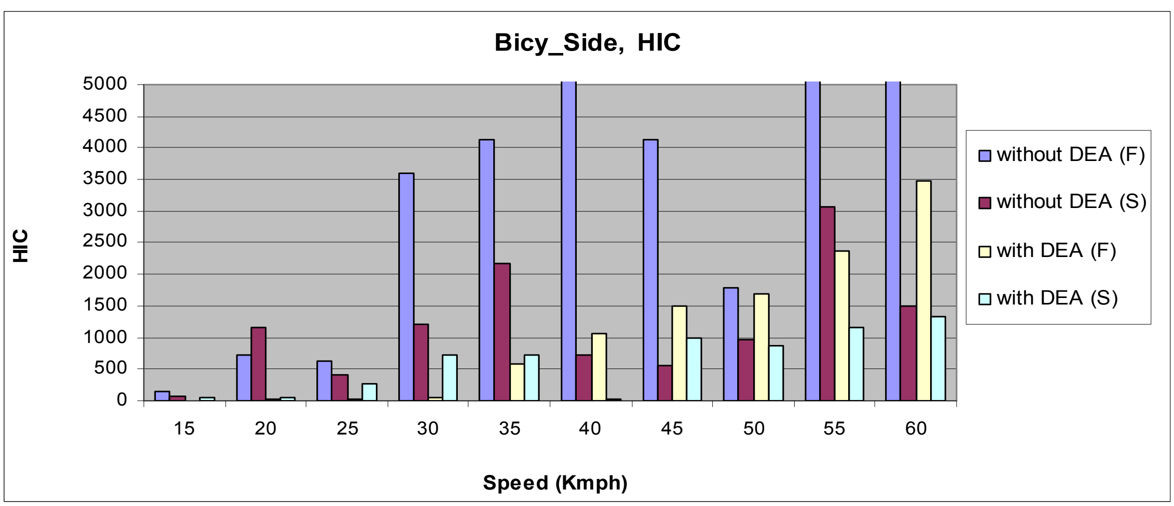


Figure 9 Plot for HIC at different speeds during First and secondary impacts (Bicycle side)

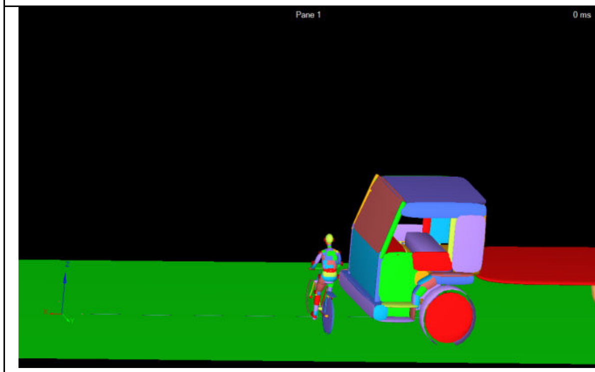
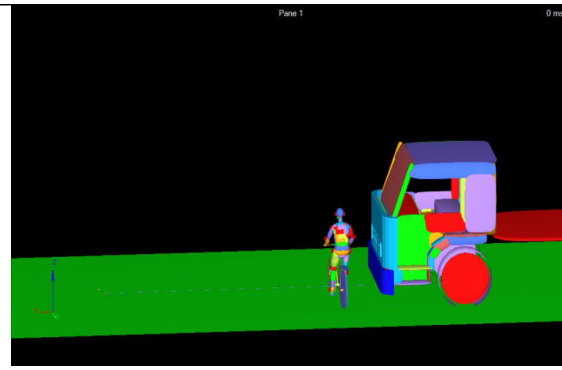
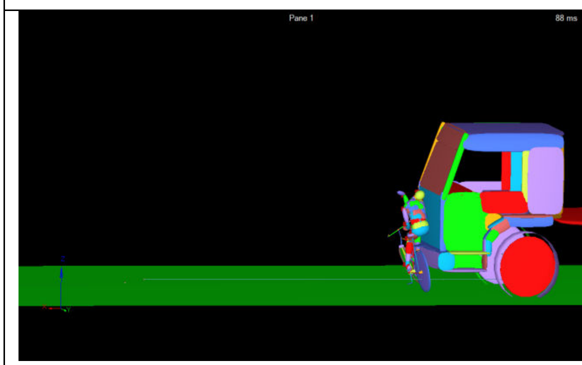
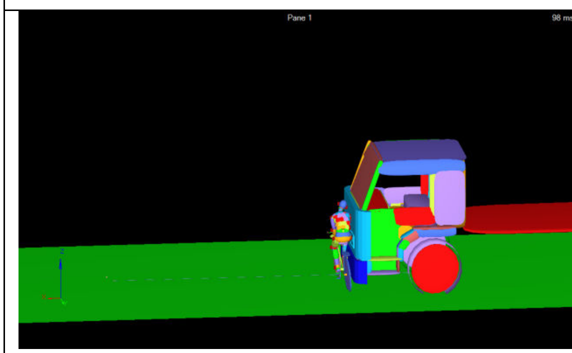
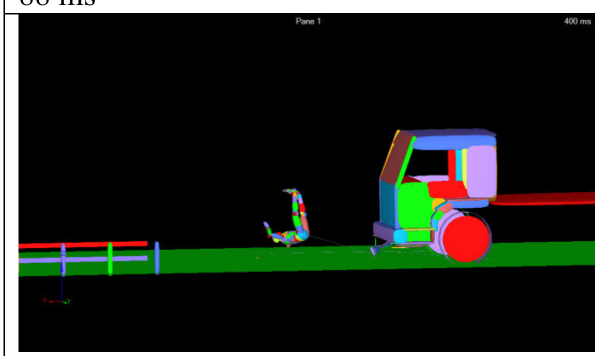
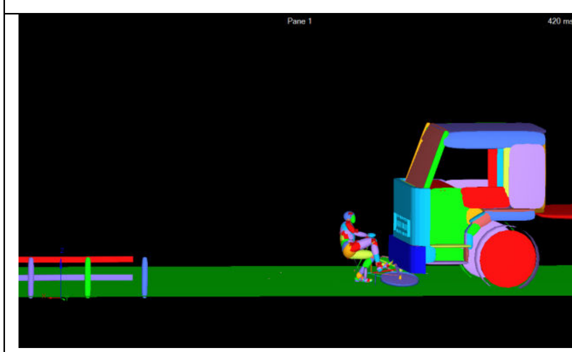
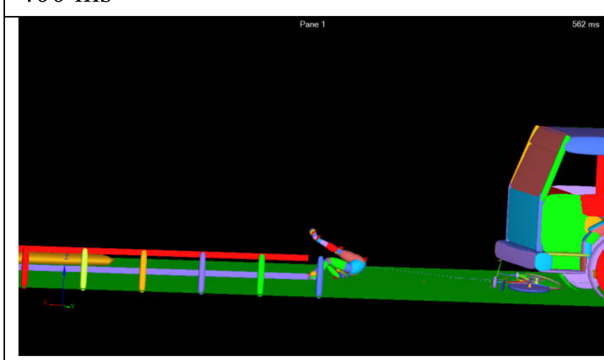
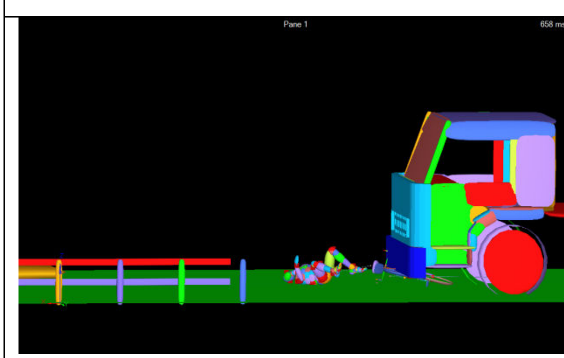
Kinematics of Truck_Bicycle Side Impacts with and without DEA frontal System @30Kmph	
 0 ms	 0 ms
 88 ms	 98 ms
 400 ms	 420 ms
 560 ms	 658 ms

Figure 10 Comparison of truck bicycle side impact kinematics

Figure 11 shows the variation of bicyclist thorax resultant acceleration value with the impact speed during first and secondary impacts for both cases of truck attached with and without DEA frontal system.

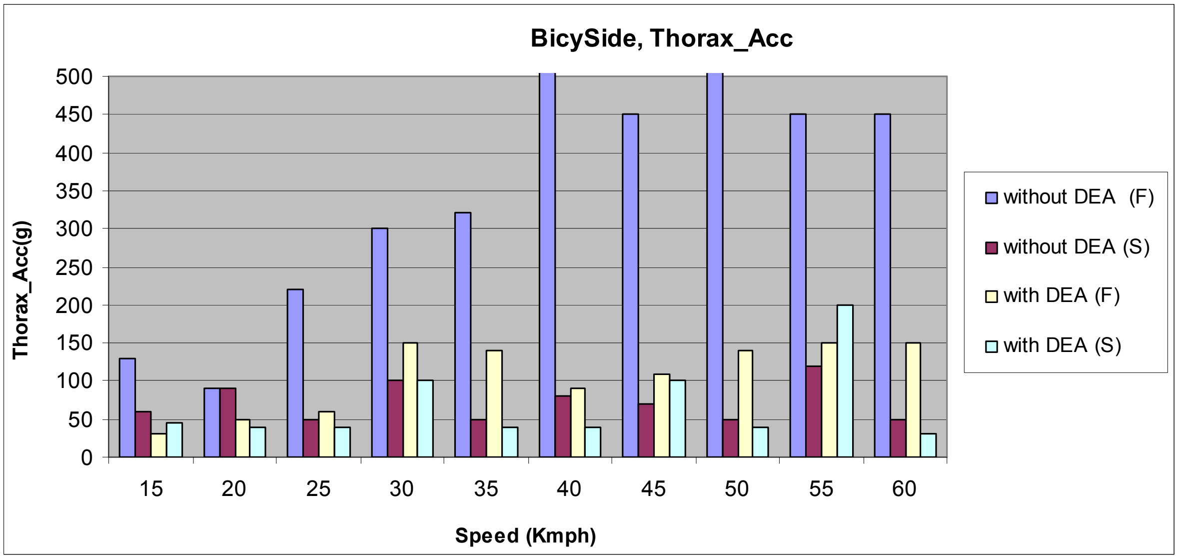


Figure 11 Plot for thorax acceleration at different speeds during first and secondary impacts

Figure 12 shows the variation of bicyclist pelvis resultant acceleration value with the impact speed during first and secondary impacts for both cases of truck attached with and without DEA frontal system.

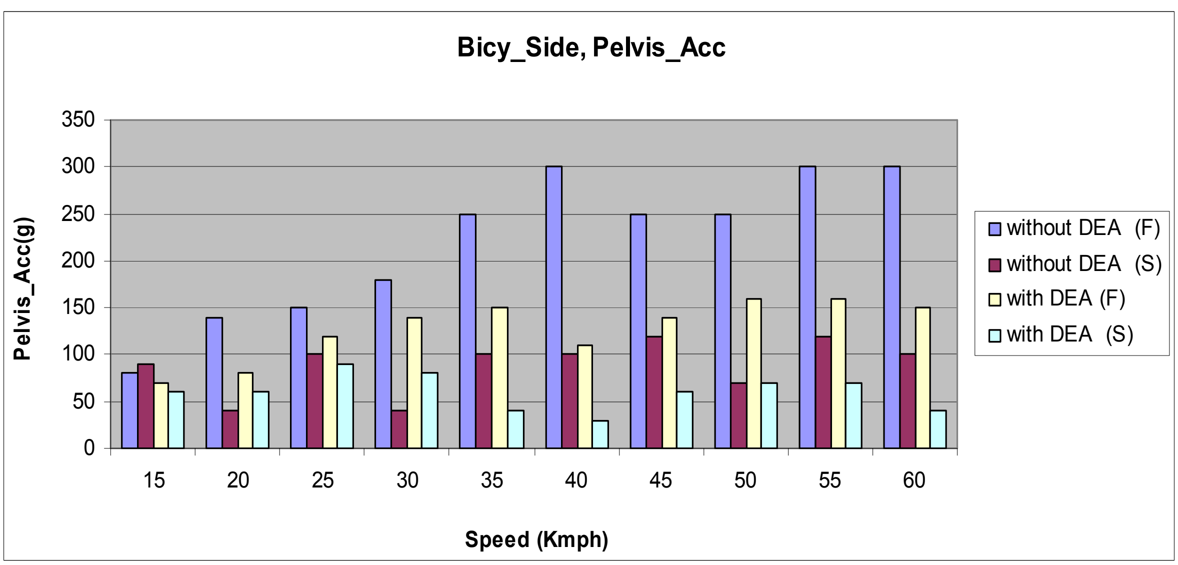


Figure 12 Plot for Pelvis acceleration at different speeds during first and secondary impacts

Table 4 shows the injury severity levels of various body segments during first and secondary impacts and also shows the effectiveness of DEA frontal system in injury severity reduction

Impact Speed Kmph	Without DEA frontal system		With DEA frontal system	
	First impact	Secondary impact	First impact	Secondary impact
15	Thorax, Pelvis, NIC_Tension	Pelvis	Pelvis	None
20	Thorax, Pelvis, NIC_Tension	Pelvis	Pelvis	None
25	Thorax, Pelvis, NIC_Tension	Pelvis	Pelvis	None
30	Head, Thorax, Pelvis, NIC_Tension, NIC _Shear	Head, Thorax, Pelvis	Thorax, Pelvis	None
35	Head, Thorax, Pelvis, NIC_ Bending, NIC_Tension, NIC _Shear	Head, Thorax, Pelvis	Thorax, Pelvis	None
40	Head, Thorax, Pelvis, NIC_ Bending, NIC_Tension, NIC _Shear	Head, Thorax, Pelvis	Head, Thorax, Pelvis	None
45	Head, Thorax, Pelvis, NIC_ Bending, NIC_Tension, NIC _Shear, Right Femur force	Head, Thorax, Pelvis, NIC _Shear, Right Femur force	Head, Thorax, Pelvis, NIC_Tension	Thorax,
50	Head, Thorax, Pelvis, NIC_ Bending, NIC_Tension, NIC _Shear, Right Femur force	Head, Thorax, Pelvis, NIC_Tension, NIC _Shear, Right Femur force	Head, Thorax, Pelvis, NIC_Tension	Thorax,
55	Head, Thorax, Pelvis, NIC_ Bending, NIC_Tension, NIC _Shear, Right Femur force	Head, Thorax, Pelvis, NIC_Tension, NIC _Shear, Right Femur force	Head, Thorax, Pelvis, NIC_Tension	Head, Thorax, left Femur force
60	Head, Thorax, Pelvis, NIC_ Bending, NIC_Tension, NIC _Shear, Right Femur force	Head, Thorax, Pelvis , NIC_Tension, NIC _Shear, Right Femur force	Head, Thorax, Pelvis, NIC_Tension	Head, Thorax, left Femur force

Table 4 Injury suffered by bicyclist during first and second impacts with trucks in side impact

Discussion on bicycle side collisions results

From the results truck without DEA frontal system causes increase in head injury severity from 30 kmph and also neck tension, pelvis and thorax accelerations exceeds the tolerable limits at all impact speeds except the right femur force which exceeds the tolerable limit at 45 kmph speed during first impact. The same scenario is also observed in secondary impact as well.

In case of truck with DEA frontal system head injury increases at 40 kmph impact speed and thorax, pelvis accelerations exceeds the tolerable limits for impact speeds greater than 30 kmph during first impact. Whereas secondary injury is comparatively less when truck attached with DEA frontal system Thorax acceleration exceeds the tolerable limit from 45 kmph, head and left femur forces exceeds the tolerable values at higher speeds (55, 60 kmph). The bicyclist side injury severity levels during first and secondary impacts was considerably less compared to pedestrian side impacts in case of truck attached with DEA frontal system.

Truck, Bicyclist Rear Impact Analysis

Bicyclists rear-end collisions also often occurring on the roads in which bicycle direction of travel is same as the truck direction travel. Simulation analysis done for both the cases of truck attached with and without DEA frontal system.

Results:-

Figure 13 shows the variation of bicyclist HIC value with the impact speed during first and secondary impacts for both cases of truck attached with and without DEA frontal system.

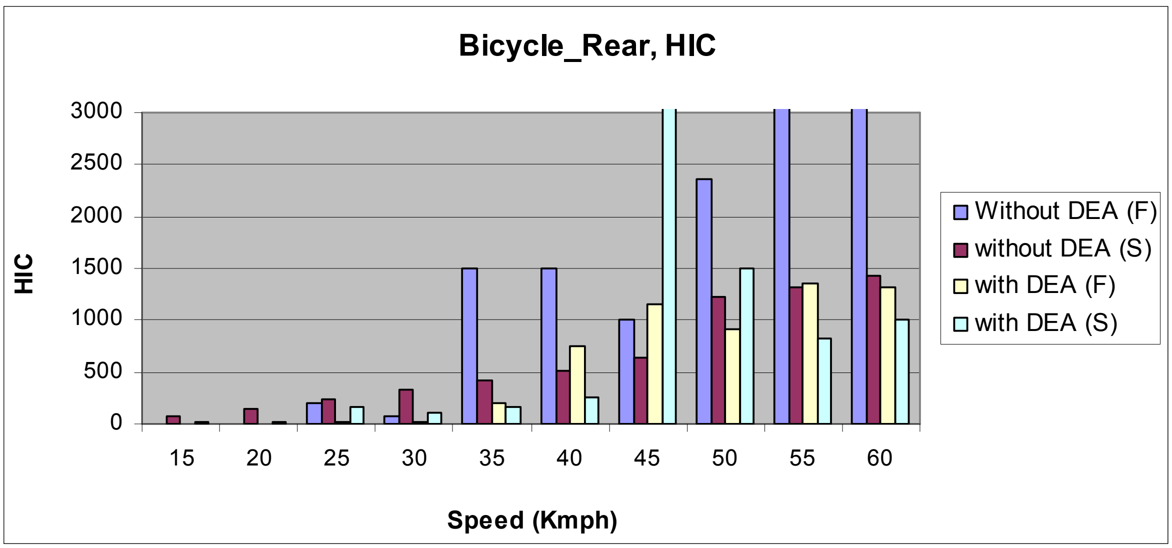


Figure 13 Plot for HIC at different speeds during first and secondary impacts for bicycle rear impacts

Figure 14 shows the kinematic variation of bicycle during rear-end collisions at 30 kmph impact speed. It is observed that time duration for pedestrian to touch the ground from its initial contact point is higher in case of truck attached with DEA frontal system. This is due to energy absorption of the DEA frontal system at the time of impact. The throwing distance of bicycle is more in case of truck not attached with DEA frontal system.

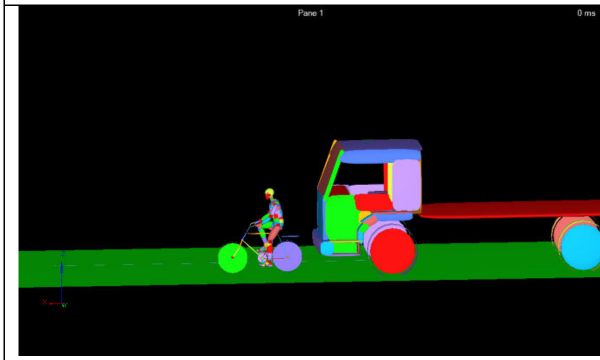
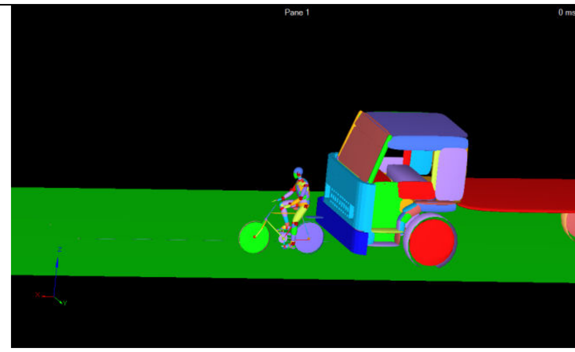
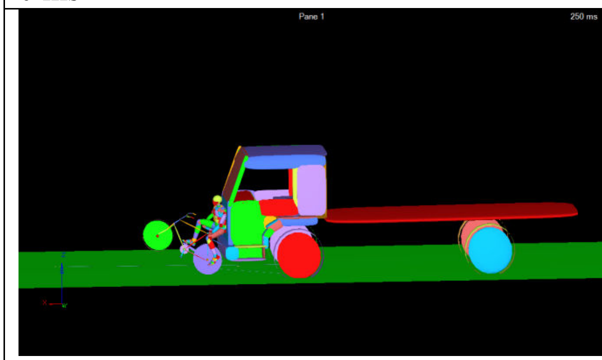
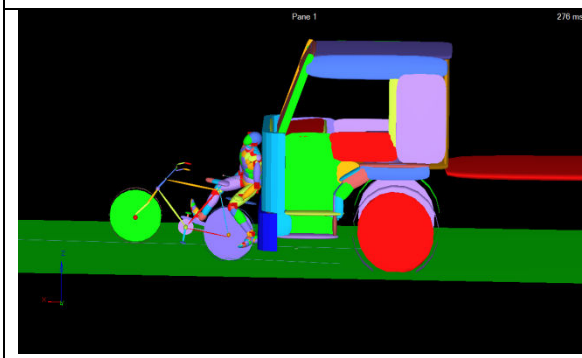
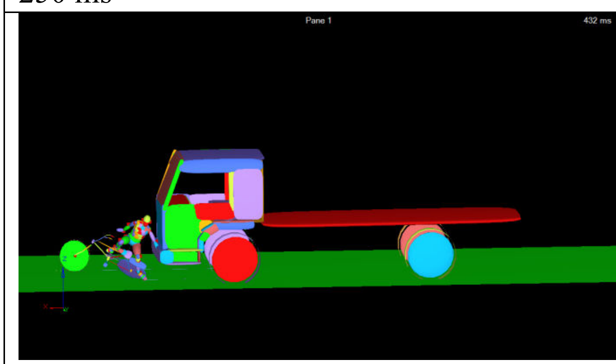
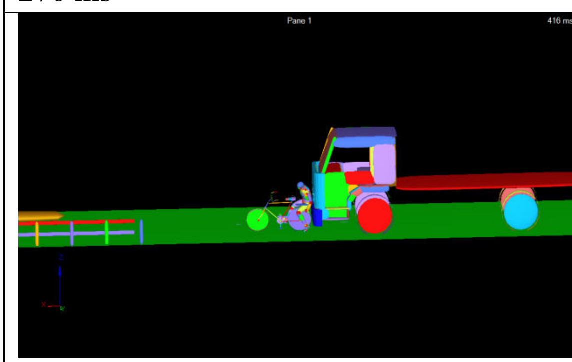
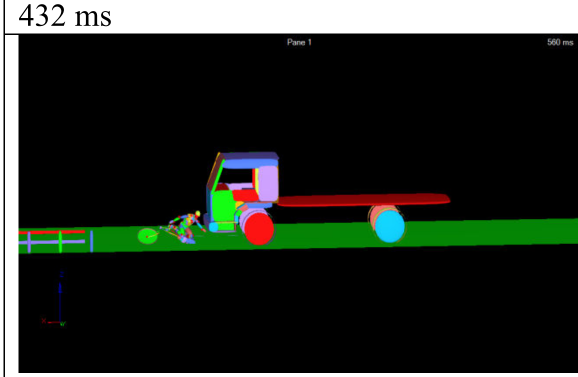
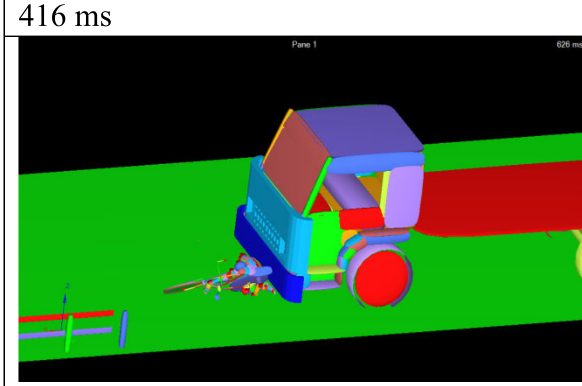
Kinematics of Truck_Bicycle Rear Impacts with and without DEA frontal System @30Kmph	
 0 ms	 0 ms
 250 ms	 276 ms
 432 ms	 416 ms
 560 ms	 648 ms

Figure 14 Comparison of truck bicycle rear impact kinematics

Figure 15 shows the variation of bicyclist thorax resultant acceleration value with the impact speed during first and secondary impacts for both cases of truck attached with and without DEA frontal system.

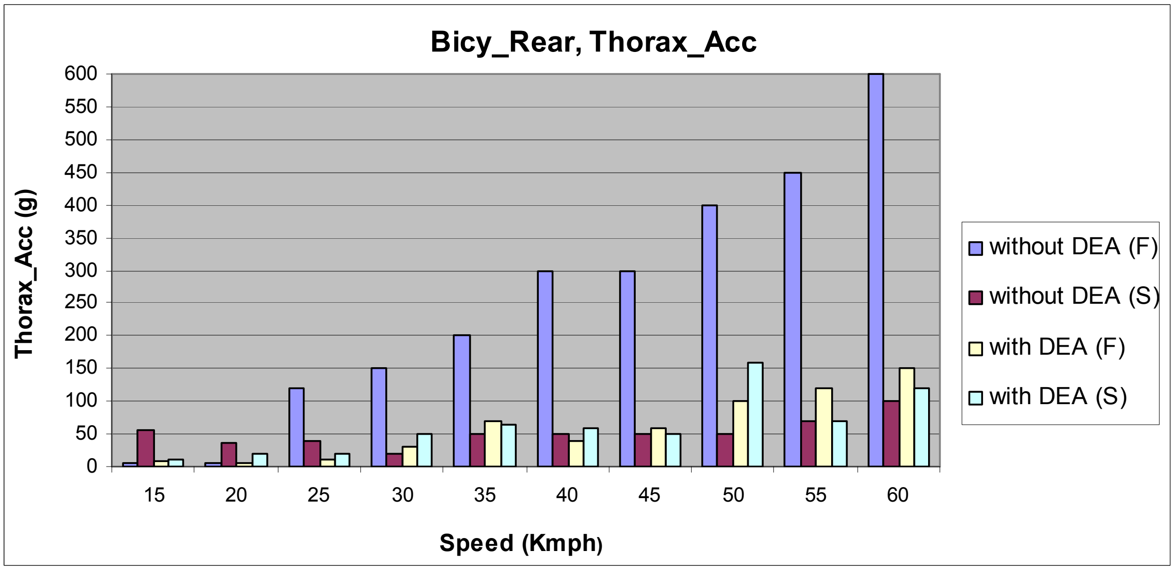


Figure 15 Plot for Thorax acceleration at different speeds during first and secondary impacts

Figure 16 shows the variation of bicyclist pelvis resultant acceleration value with the impact speed during first and secondary impacts for both cases of truck attached with and without DEA frontal system.

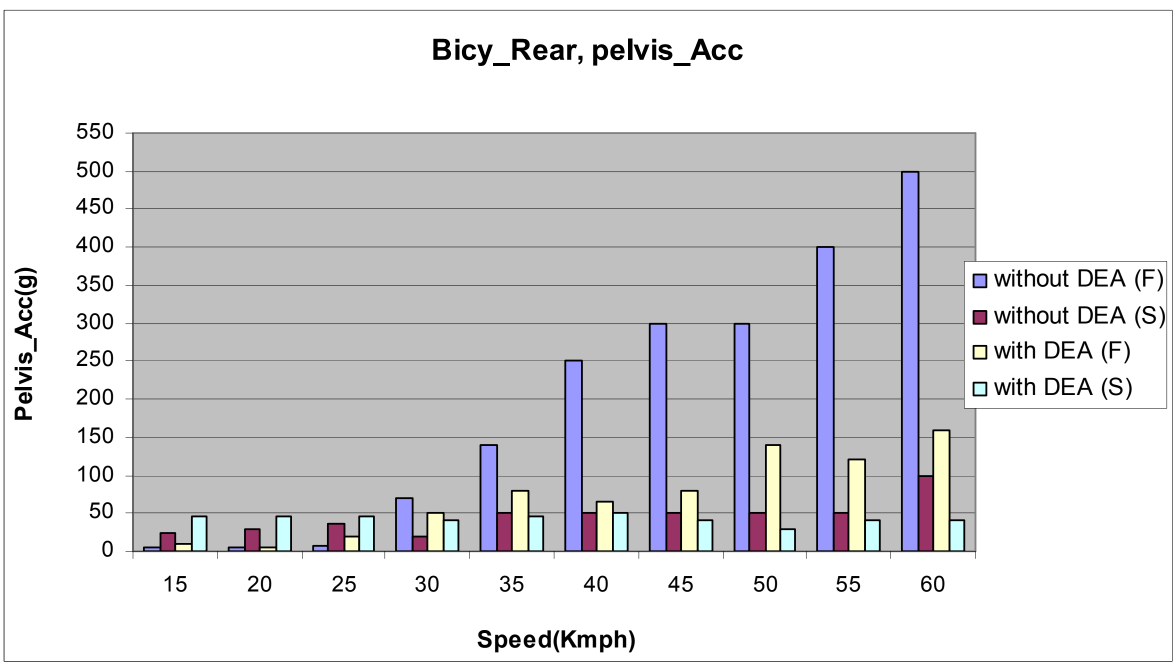


Figure 16 Plot for Pelvis acceleration at different speeds during first and secondary impacts

Table 5 shows the injury severity levels of various body segments during first and secondary impacts and also shows the effectiveness of DEA frontal system in injury severity reduction.

Impact Speed Kmph	Without DEA frontal system		With DEA frontal system	
	First impact	Secondary impact	First impact	Second impact
15	None	None	None	None
20	None	None	None	None
25	Thorax,	None	None	None
30	Thorax, Pelvis, NIC_Bending, NIC_Tension	None	None	None
35	Head, Thorax, Pelvis, NIC_Bending, NIC_Tension, NIC_Shear, right Femur force	None	None	None
40	Head, Thorax, Pelvis, NIC_Bending, NIC_Tension, NIC_Shear, right Femur force	NIC_Bending,	NIC_Tension	None
45	Head, Thorax, Pelvis, NIC_Bending, NIC_Tension, NIC_Shear, left Femur force, right Femur force	NIC_Bending,	Head, Pelvis, NIC_Tension	Head,
50	Head, Thorax, Pelvis, NIC_Bending, NIC_Tension, NIC_Shear, left Femur force, right Femur force	Head, Thorax, NIC_Bending, NIC_Shear,	Head, Thorax, Pelvis, NIC_Bending, NIC_Tension,	Head, Thorax,
55	Head, Thorax, Pelvis, NIC_Bending, NIC_Tension, NIC_Shear, left Femur force, right Femur force	Head, Thorax, NIC_Bending, NIC_Tension, NIC_Shear,	Head, Thorax, Pelvis, NIC_Bending, NIC_Tension, NIC_Shear,	Head, Thorax,
60	Head, Thorax, Pelvis, NIC_Bending, NIC_Tension, NIC_Shear, left Femur force, right Femur force	Head, Thorax, NIC_Bending, NIC_Tension, NIC_Shear,	Head, Thorax, Pelvis, NIC_Bending, NIC_Tension, NIC_Shear,	Head, Thorax,

Table 5 Injury suffered by bicyclist during first and second impacts with trucks in rear impact

Discussion on Bicycle Rear Impact results

In rear impacts head injury severity increases from 35 kmph, neck tension, neck bending, pelvis and thorax accelerations exceeds the tolerable limits at 30 kmph, also right and left femur forces exceeds the tolerable limits at 35, 45 kmph impact speeds respectively during first impact with truck. Where as in secondary impact risk of neck bending exceeds at 40 kmph, head, neck, thorax values exceeds at 50kmph in case of truck without DEA frontal system.

When truck attached with DEA frontal system head, pelvis, neck injury severity increases at 45 kmph speed where as thorax accelerations exceeds the tolerable limits for impact speeds greater than 50 kmph. The severity of secondary injury is comparatively less only head and thorax acceleration exceeds the tolerable limit at 45, 50 kmph impact speeds. Femur forces not exceeded the tolerable limits during first and second impacts for all impact speed levels. The bicyclist rear-end injury severity levels during first and secondary impacts considerable less compared to pedestrian rear-end impacts when truck attached with DEA frontal system this may be due to the higher impact energy transmitted to the pedestrian body immediately because of direct contact with truck whereas for later it is with bicycle wheels. From above results it is found that bicyclists injury severity can be reduced due to DEA frontal system up to 45 kmph impact speeds during rear-end collisions compared to truck without any DEA frontal system.

CONCLUSIONS

In this study pedestrian and bicyclist kinematics in an accident at low and high speeds during side and rear-end collisions are investigated. Truck-VRU accident reconstruction was performed by using the MADYMO version-7.2 biodynamic simulation software which widely used to perform crash simulations. Injury severity levels of various body segments in both cases of truck without any energy absorbing system and with an energy absorbing DEA frontal system was examined during first and second impact. The differences and similarities of injury severity during side and rear-end collisions for both pedestrian and bicyclist identified at various impact speeds in first and second impacts was also observed. Also, the overall kinematic behavior of pedestrian and bicyclist at all impact speeds was inspected. The following conclusions can be made from the study.

1. When HIC values are compared for pedestrian collisions, it is observed that during the primary impact in sidewise collision, head injury severity crossed the allowable limit at an impact speed of 30 kmph for the case of trucks not attached with DEA frontal system. However, the same levels of severity are observed ONLY when speed of impact is more than 50 kmph for trucks with DEA frontal system.
   When secondary impacts are compared in side collisions, it is observed that DEA frontal system did not have a significant effect in reducing impact from the view point of head injury criteria. This is due to the fact that head injuries are more during secondary impacts due to immediate contact of pedestrian's head with ground at higher speeds.

2. When HIC values are compared for pedestrian collisions, it is observed that during the primary impact in rear-end collision, head injury severity exceed the allowable limit at an impact speed of 25 kmph in case of trucks not attached with DEA frontal system. However, the same level of severity are observed ONLY when speed of impact is more than 45 kmph incase of trucks with DEA frontal system.

   When secondary impacts are compared in rear-end collisions, it is observed that DEA frontal system did not have a significant effect in reducing impact from the view point of head injury criteria— very similar to what was observed in case of side impact. Again, this is due to the fact that head injuries are more during secondary impacts due to immediate contact of pedestrian's head with ground at higher speeds as in this case pedestrians are found to be traveling at 2m/s speed along the direction of truck's movement, resulting in a higher impact speed transmitted to the pedestrian.

3. For the bicycle side collisions HIC values compared in first impact show that head injury severity exceeds the allowable limit at an impact speed of 30 kmph while neck tension, pelvis and thorax accelerations exceed the tolerable limits at all impact speeds in case of trucks not attached with DEA frontal system. However, the same level of head injury severity observed ONLY when speed of impact is more than 40 kmph where as thorax, pelvis accelerations exceeds the tolerable limits for impact speeds greater than 30 kmph incase of trucks with DEA frontal system.
   The severity of secondary injury is comparatively less as compared to the pedestrian case when trucks are attached with DEA frontal system. This is due to higher energy dissipation during initial impact with bicycle.

4. For the rear-end collisions HIC values are compared in first impact shows that head injury severity exceeds the allowable limit at an impact speed of 35 kmph. Also neck tension, neck bending, pelvis and thorax accelerations exceed the tolerable limits at impact speeds 30 kmph in case of truck with no DEA frontal system. However, the same level of injury severity for head, pelvis, neck are observed ONLY when speed of impact is more than 45kmph speed in case of truck with DEA frontal system. The injury severity level in secondary impact is considerably less than pedestrian rear-end impacts in case of truck attached with DEA frontal system. This may be due to the fact that pedestrian come in contact directly to the trucks in a pedestrian-truck accident, whereas the bicycle rather than the rider comes in direct contact with the truck in a bicycle-truck accident. This results in higher impact energy transmission to pedestrian body immediately at the contact (i.e. at the time of collision) instead of an indirect contact in bicycle-truck collisions.

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