

EFFECT OF VEHICLE DESIGN ON HEAD INJURY SEVERITY AND THROW DISTANCE VARIATIONS IN BICYCLE CRASHES

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ABSTRACT

The variation of the throwing distance and Head Injury Criterion with car velocity, point of impact and angle of approach has been studied for bicycle impact with three different categories of vehicles- small cars, sports utility vehicles and buses. Crashes between a bicycle and the vehicles were simulated using multi body models developed in MADYMO™ with parametric variations in speed, angle of approach and point of impact. The variation in the angle of approach or point of contact causes significant changes. From the simulations, the large spread in the data reported by reconstruction is predicted to originate from variation in the impact configuration. The changes in the trends can be associated with key changes in the nature of the impact visible in the simulations (head impacting car, no impact of rider with car etc.). The kinematics of impact has significant differences in case of the bus and this leads to differences in the nature of correlations. The HIC values were found to be higher in the case of bus as compared to the SUV and the small car. The paper reinforces the hypothesis that for bicycle accident reconstruction should take into account variations in the impact configuration in addition to the throw distance recorded. The paper also gives data which when populated further could form a basis of such reconstructions.

INTRODUCTION

On an average, there are about 100,000 fatalities in road accidents each year [1]. More than a million sustain serious injuries. Cyclists and pedestrians are the most vulnerable group in traffic crashes [2] and the actual number of injured cyclists and total number of crashes may be underreported. In a heterogeneous traffic situation, as it exists in India, the safety of these most vulnerable sections should be given due importance while designing motorized vehicles. Computer simulations can play an important role in understanding the phenomena of crashes. Attempts have been made to simulate impacts between cars and bicycles at different standard configurations [3]. To initiate measures to protect the vulnerable road users, it is necessary to understand the important factors and variation in phenomena for a range of vehicles. Computer simulations of crashes are through finite element analysis or multi-body dynamic simulations. Though the accuracy of finite element analysis is much higher, they are computationally expensive. Hence, multi-body simulations are often carried out for such cases using software packages such as MADYMO™ (TNO Automotive, Netherlands) have been accepted for crash safety analysis throughout the world.

The study the kinematics of impact in simulations, we redefine 'throwing distance' as the distance between the point of impact and the point at which the body first hits the ground. The car speeds were correlated with throw distance from MADYMO simulations in Mukherjee [3]. The results were then compared with experimental data in [5]. They were able to attribute the spread obtained in [5] for

frontal side impacts to the point of impact on the bicycle with the car. This paper extends their work to cover other vehicles in the traffic stream. In addition, Head Injury Criterion values calculated by MADYMO™ were compared for the cases of impacts of bicyclists with the Car, the SUV and the bus in impact of the vehicle-front with bicycle-side configuration.

MODEL DEVELOPMENT

We need to build models for the rider, bicycle and the vehicles for these simulations and define interactions between them

Bicycle model

The bicycle model in Mukherjee [3] and has a system of four rigid bodies: the frame, the front fork, and the two wheels. The frame and the front fork were connected by a revolute joint; for which the rotation axis is in the plane of symmetry of the bicycle. Front and rear wheel were connected by revolute joints to the front fork and the frame, respectively. Rotation axes are perpendicular to the plane of symmetry. A sketch of the bicycle with key dimensions is as shown below in Figure 1. The results reported from tests and analysis [[6], [7]] have been used to determine the mechanical properties of the wheel reproduced in Table 1. The radial stiffness of the tyre has been obtained from the stress – strain curve for the bicycle tyres [[7]]. Contacts between the road and the tyres of the car were defined using the tyre model in MADYMO™ and using internal tyre pressure, wheel diameter and wheel thickness.

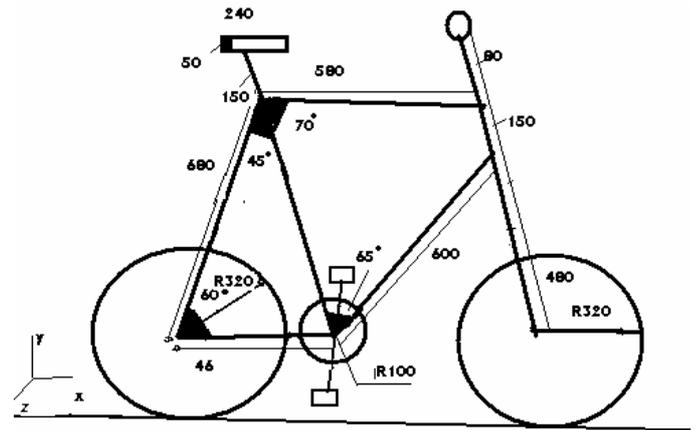


Figure 1 Dimensions of a Bicycle

Table 1 Bicycle tyre mechanical properties

Quantity	Value
Outer rim radius (to centroid of rim)	309.4 mm
Inner hub radius (to centre of spoke holes)	18.0 mm
Spoke diameter	2.10 mm
Area of spokes in one plane	62.34 mm ²
Elastic modulus of rim	70 kN/mm ²
Elastic modulus of spokes	210 kN/mm ²
Area of rim	138.4 mm ²
2 nd moment of area of rim (for bending in the plane of wheel)	1469 mm ²

Car Model

For carrying out the simulations of car-bicycle impacts, the model developed in [3] was used. For the MADYMO input file, the car frame has been modelled as a single rigid body i.e. all ellipsoids are rigidly connected to each other. The vehicle model consists of 4 multi body tree structures, representing the front left, front right, rear left, and rear right vehicle suspension.

SUV Model

A model of a SUV was developed in a manner similar to that of the car. The vehicle was modelled as one single body, consisting of a combination of cylinders and ellipsoids. It consisted of five rigid bodies- the vehicle body and the four tyres. All the surfaces in the body of the vehicle were rigidly locked against each other. The only movable joint was between the road and the centre of gravity of the vehicle. Thus, there is only one movable part and that is the vehicle body. There is no relative movement possible between the parts. In total the model consists of 59 surfaces and 5 rigid bodies. Out of these 59 surfaces, 54 are ellipsoids while 5 are cylinders. Since from the perspective of a bicyclist, the vehicle is a very large mass, the dynamic loading effects on the SUV velocity were neglected. This allowed the usage of the same tyre properties as for the small car. The windscreen was defined using two ellipsoids while the front hood using a single ellipsoid of degree 8. The bumper was defined using 4 different ellipsoids. Due, to their size, the front headlights were modelled using two separate ellipsoids. Second degree ellipsoids were used to model the A, B C and D pillars. The suspension was also not modelled as it is sufficient to model the tyres and the centre of gravity of the vehicle.

Bus Model

The model of the bus was developed in a manner similar to that of the SUV. The vehicle was modelled as one single body, consisting of a combination of cylinders and ellipsoids. In total the model contains 31 surfaces and 5 rigid bodies. To further analyze impacts between buses and bicycles, an alternative bus design slanting hood type of front instead of a flat-fronted design was considered.

Contact Interactions

Multi body contact interactions were defined using the force penetration functions for the dummy with the bicycle, vehicle, pavement and road, for the bicycle with the vehicle and the road, the vehicle with the road and between dummy body parts. Head form impact test data reported in [8] for the WAGON R FX, which is similar to the WAGON R car prevalent in India was used to generate load deformation characteristics. By averaging over the bonnet and windscreen respectively, separate force – deformation characteristics were defined for the car bonnet and the windscreen. For sake of simplicity, the same deformation characteristics were used for all vehicles.

SIMULATIONS OF CAR-BICYCLE IMPACTS

Simulations for frontal-side impacts between cars and bicycles were reported in [3] for car speeds ranging from 15 km/hr to 65 km/hr. This was extended to lower speeds of upto 2.5 km/hr. The bicycle speed was kept constant at 10km/hr. The throw distances for these simulations are plotted in Figure 2. It was observed that that for very low speeds (<10 km/hr) the spread was high and this can be expected because at such low values of throw distance, there is a significant dependence on the body part which impacts the ground. As this speed increases, the throw distances start to increase as expected.

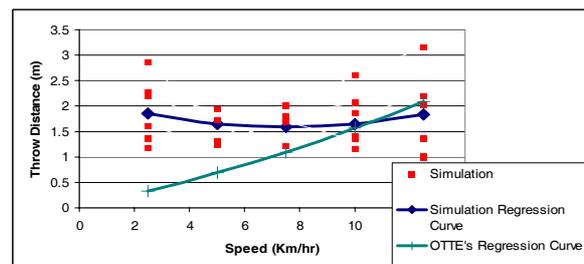


Figure 2: Throw distances for car-bicycle impacts at low speeds.

SIMULATIONS OF SUV-BICYCLE IMPACTS

Simulations have been performed for the SUV front impacting the bicycle Figure 3 shows a series of snapshots for the case where the SUV moving at a speed of 20 km/hr impacts with a 0.3m offset of

the bicycle pedal. Due to the characteristics of the shape of the SUV such as height and angle of inclination of the hood the phenomenon observed

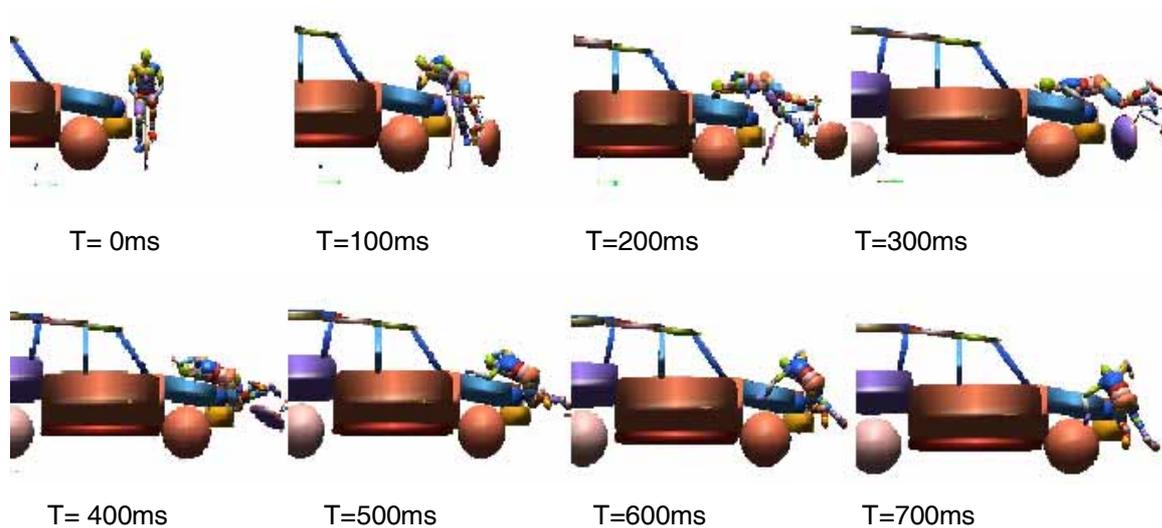


Figure 3 Motion of bicycle rider in frontal-side crash (SUV velocity = 20 km/hr, Point of impact at offset -0.3 m)

during crashes are qualitatively different. The riders do not roll up the windscreen towards the roof of the vehicle. The simulations were carried out with the speed of the cycle as 10 km/h with the impact speed of the SUV varying between 5 km/h to 65 km/h. The distance of point of impact of bicycle saddle from the vehicle centre was also varied, and is measured positive in the direction of bicycle motion as shown in Figure 4 below

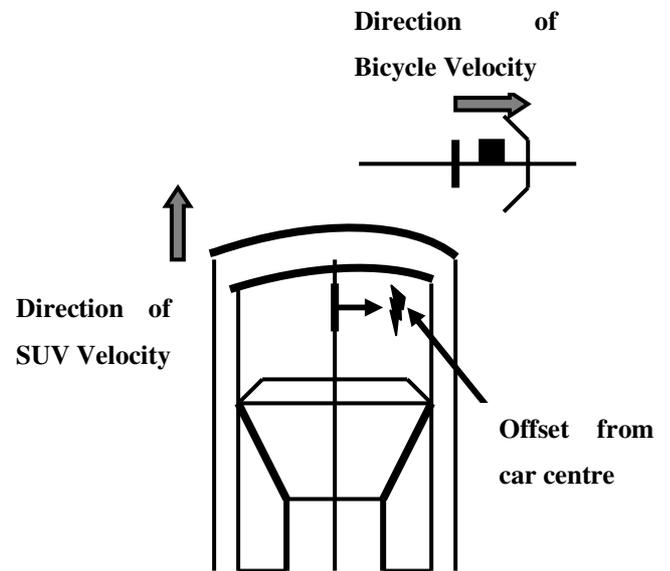


Figure 4 Frontal Side impact orientation

Variation of throw distances with vehicle speed

The throw distances for various speeds of the SUV are plotted in Figure 5. The results reinforce the

obvious conclusion that the throwing distance is predicted to increase as the car speed increases. The sudden changes in slopes of these otherwise monotonically varying curves can be associated with significant qualitative change in the kinematics of the bicycle rider at certain points. A qualitative change is for example the cyclist landing on the hood in the centre and instead of tumbling off, he may continue riding on the hood before rolling either in front of the vehicle or on the side. In case, the bicyclist lands in front of the vehicle, the probability of the vehicle running over is high.

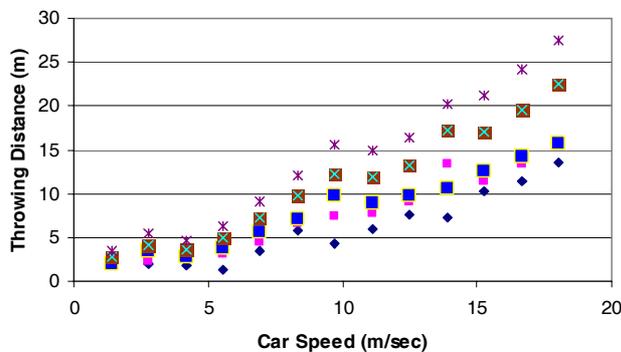


Figure 5: SUV throwing distance variation for frontal side impact

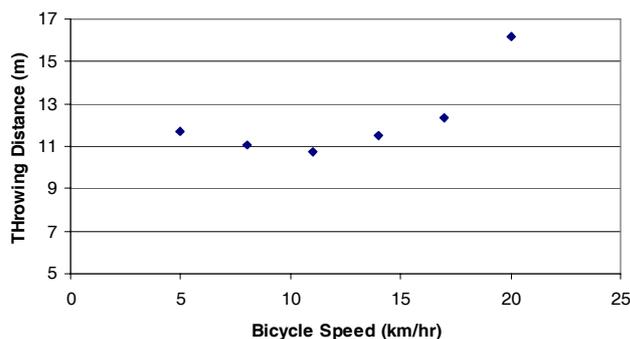


Figure 6 : Variation in throwing distance with bicycle speed at 0m offset

Variation of throw distances with bicycle speed

The throw distances for different bicycle speeds have been plotted in Figure 6. The variation in throw distances is between 11 and 16 m for bicycle

speed variation between 5 and 25 m/s with the magnitude first decreasing then increasing. This can be attributed to the fact that as bicycle speed decreases, the drag in the direction of the bicycle motion will decrease leading to higher distances, whereas the impulse in the direction of the vehicle will decrease as the vehicle comes in contact for a lesser duration and length thus decreasing the distance.

Variation of throw distances with vehicle speed in frontal-oblique impacts

The frontal oblique collision occurs when the bicycle front tyre hits the front of the car at an angle as shown in Figure 7. This could occur in real life when one of the vehicles turning into the path of the other vehicle. For the simulation, the angle of approach is taken as 45° and point of impact as car centre. The throw distances for this configuration are plotted against the vehicle speed in Figure 8. The sudden increase in throwing distance at low car speeds is attributed the change in kinematics of the bicyclist. In this situation due to low speeds, the impact does not impart a large momentum but instead the rider travels on top of the hood before rolling down in front of the vehicle. However, we again see the general trend of increase in throw distance with speed. The behavior as seen for the SUV frontal oblique crashes taking place at an angle of 45° is similar to those as seen in frontal crashes. The major difference is that the bicyclists rises to a higher distance and can reach the roof of the vehicle

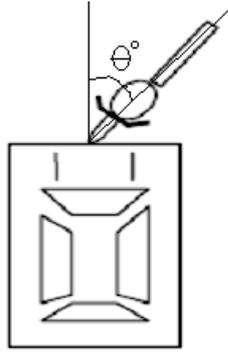


Figure 7: The frontal oblique impact configuration

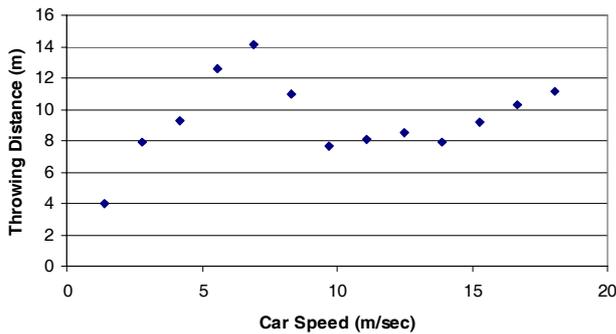


Figure 8: Variation in throwing distance with car speed in frontal oblique crashes (angle =45 degree)

SIMULATIONS OF BUS-BICYCLE IMPACTS

Simulations of the a flat-fronted bus front impacting a bicycle were carried out and Figure 9 shows a series of snapshots for the case where the bus moving at a speed of 50 km/hr impacts with a 0.3m offset of the bicycle pedal. The kinematics of impact of the bicyclist with the bus is quite different from that in case of the SUV and the Car. The first impact usually takes place with the leg or the saddle which is followed by the rest of the body impacting the bus front. However, due to the flat shape of the bus, bicyclist is not launched very high in the air, as was the case with SUV and the car. The flatter trajectory leads to lower throw distances.

Variation of throw distances with vehicle speed

The throw distances for various speeds of the bus are plotted in Figure 10. The spread in the case of the buses is much less and this can attributed to the fact the bus front is similar along its length and the impacting surface does not vary much with offset. The expected trend of monotonically increasing throw distances is observed. The magnitude of the

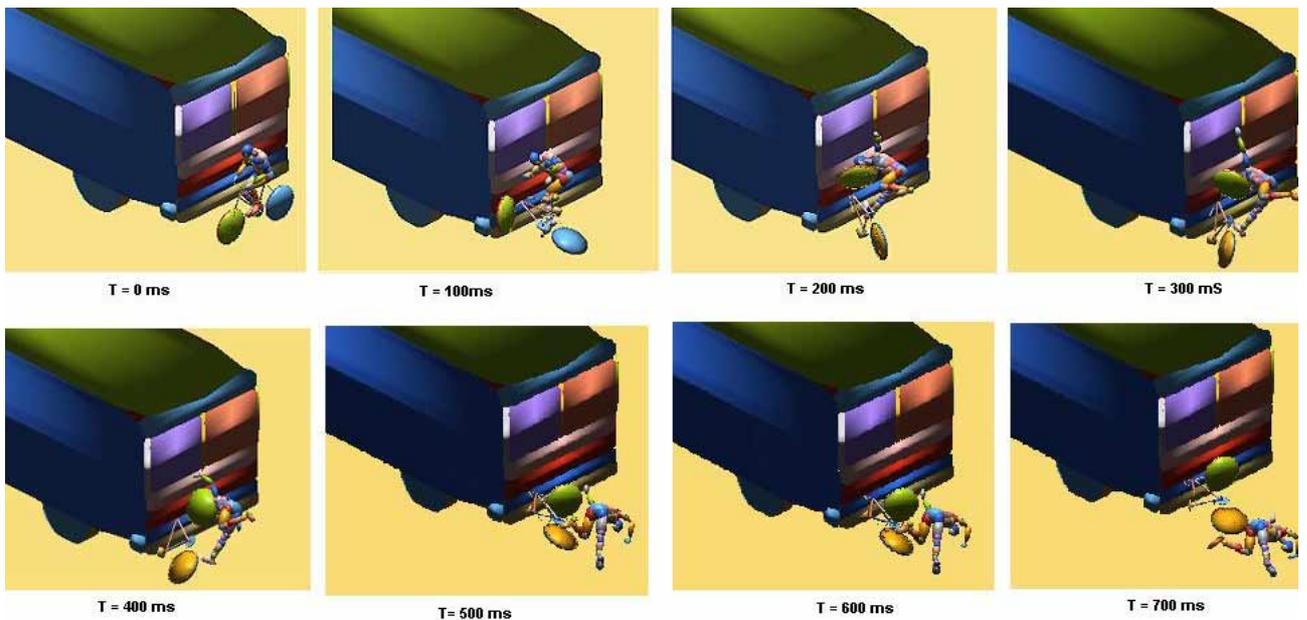


Figure 9: Motion of bicycle rider in frontal-side crash (Bus velocity = 50 km/hr, Point of impact at offset 0.0 m)

throw distances at high speeds is lower than the SUV and the car due to the difference in the crash phenomena as explained earlier. The variation in throwing distance with bicycle speed observed in simulation is not significant.

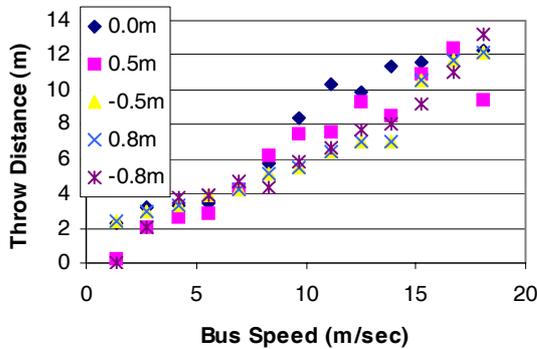


Figure 10 Throw distances in bus-bicycle impacts for different offsets

THROW DISTANCE REGRESSION CURVES

For all the impact configurations, the nature of the curves obtained for throwing distance is similar to that seen in simulations of small cars. A comparison between the regression curves obtained from the SUV and Car simulations for frontal side impact shows similar behavior in comparison to Otte's accident reconstruction data. These regression curves were obtained by assuming a quadratic fit similar in nature to Otte's curve. The point of intersection in the case of the SUV shifts to the right as shown in Figure 12. For the frontal side impact with the SUV different kinematic situations were observed. At low speeds and negative offsets, the bicyclist lands on top of the bonnet of the vehicle and continues riding before impacting the windscreen and slowly rolling off. In some high velocity cases it was observed that the bicyclist impacts the region of the bonnet closer to the edge, thus bouncing off it without colliding with the windscreen. A completely different kinematic phenomenon is seen in case of bus-

bicycle impacts. In this case, the bicyclist is not pushed higher into the air as he impacts with a flat surface. Hence, throw distances in case of the bus-bicycle impacts are expected to be lower as compared to the SUV and the car. Looking at the coefficients of the regression curves, it can be seen that the quadratic coefficient is much smaller in case of the buses. The throw distances would thus increase slowly at higher speeds. It can be seen that at higher speeds the throw distances for the buses are less than those of the car and the SUV.

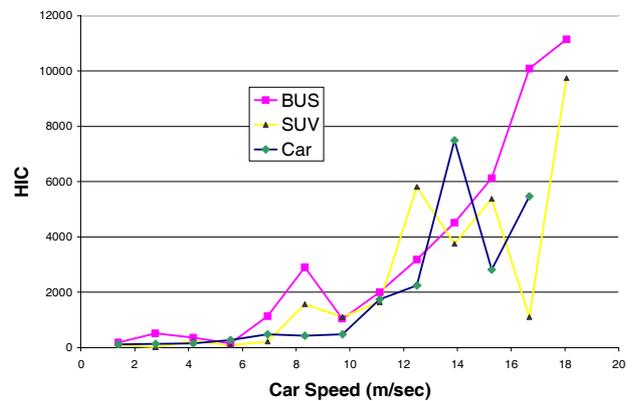


Figure 3: HIC variation with speed of vehicle

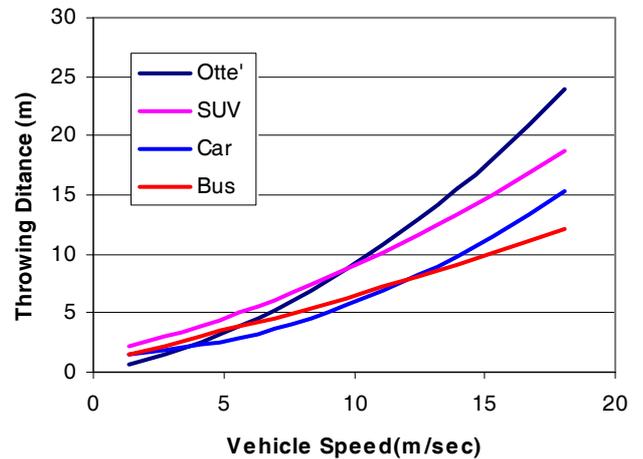


Figure 12: Throwing distance and vehicle type

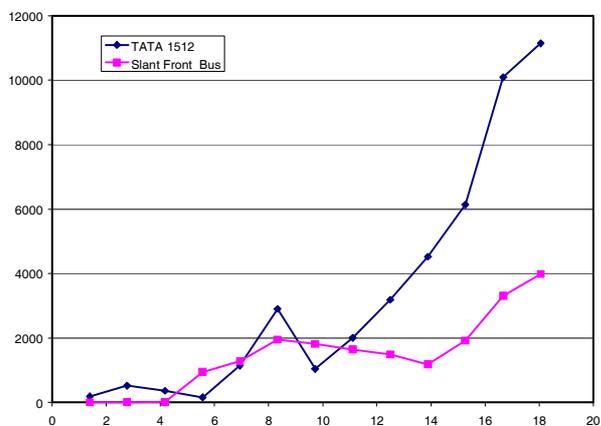
COMPARISON OF HIC VALUES

The HIC values calculated in MADYMO™ were compared for the three cases of impacts of the bicyclists with the Car, the SUV and the Bus. The

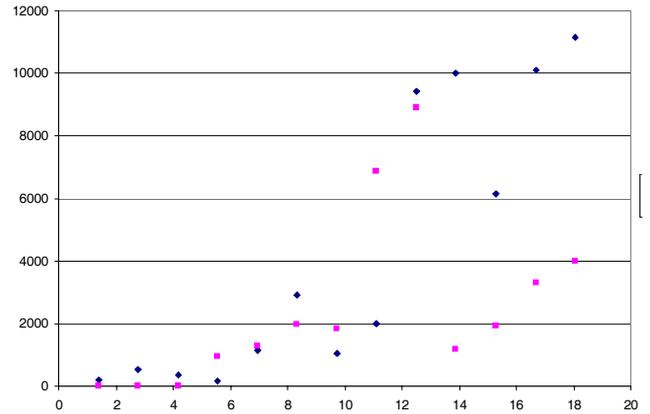
comparison was made for a central impact position in the vehicles and the variation with vehicle speed is shown in Figure 3. Unlike throw distances, the highest HIC values are generally obtained for the bus followed by the SUV. The impact of the head of the vehicle takes place immediately after the first contact in the case of the bus, leading to higher values.

HIC Values for buses with slanting hood front

The design of the bus was modified and simulations were done with the new design in which the front of the bus has a slanting hood. The HIC values corresponding to the head impact with bus are plotted with the bus speed in Figure 17 (a). The slanted design has a lower HIC value. This is attributed to the fact that in the slanted front design the head collides with hood after it has been decelerated considerably due to the impact of the bus with the lower extremity. Figure 17 (b) below reports the overall HIC value, including the contact with the ground. The rise in HIC values is not monotonic with the speed and has a local maximum at bus velocities of about 12 m/s. At certain vehicle speeds, the bicyclist rotates in the air and impacts the ground in an orientation which leads to higher energy absorbed by the head.



(a)



(b)

Figure 5: Comparison of HIC values with speed of the vehicle

CONCLUSION

Estimation of throwing distance for OV-bicycle crashes for four types of vehicles with parametric variation in OV speed and the point of impact have been carried out. The change in the nature of impact with change in vehicle front has been highlighted, qualitatively as well as quantitatively. There is qualitative change in the nature of impact with change in vehicle front. The contact point on the vehicle is not significant parameter for impacts with buses with uniform fronts. A flat front design leads to smaller throwing distances of the bicycle rider as the rider is not thrown up. The HIC due to the rider-bus impact is smaller in the slanted front bus. If the rider-ground contact is included, the trend of overall HIC is not so easily predicted. For the slant front bus, as the rider is thrown up, the ground contact could at times be with the head, leading to large HIC values. One of the limitation of this study is that experimental force-deformation relationships were not available for the contact interaction. The confidence in the results would be greater if experimental crash data were available.

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