

PREDICTING THROW DISTANCE VARIATIONS IN BICYCLE CRASHES

MUKHERJEE S, CHAWLA A, MOHAN D, CHANDRAWAT S, AGARWAL V
TRANSPORTATION RESEARCH AND INJURY PREVENTION PROGRAMME
INDIAN INSTITUTE OF TECHNOLOGY NEW DELHI

S Mukherjee
Department of Mechanical Engineering
Indian Institute of Technology, New Delhi INDIA
Tel No.: 011-26591138 (O)
Email : sudipto@mech.iitd.ernet.in

A Chawla¹
Department of Mechanical Engineering
Indian Institute of Technology, New Delhi INDIA
Tel No. : 011-26591058 (O)
Fax No. : 011-26582053 (O)
Email: achawla@mech.iitd.ernet.in

D Mohan
Transportation Research & Injury Prevention Programme
Indian Institute of Technology, New Delhi INDIA
Tel No. : 011-26591147 (O)
Email: dmohan@cbme.iitd.ernet.in

S Chandrawat
Department of Mechanical Engineering
Indian Institute of Technology, New Delhi INDIA
Tel No. : 011-26591058 (O)
Fax No. : 011-26582053 (O)

V Agarwal
Department of Mechanical Engineering
Indian Institute of Technology, New Delhi INDIA
Tel No. : 011-26591058 (O)
Fax No. : 011-26582053 (O)

ABSTRACT

This paper investigates correlation between throwing distance and impact speed / point of impact / angle of approach for varying bicycle-car crash configurations. Crashes between a bicycle and a car were simulated using multi body models developed in MADYMO™. The Hybrid III 50th percentile male dummy model, available from MADYMO library has been used. Crash configurations reported in literature have been used and parametric variations

¹ Communicating Author

have been done in speed, angle of approach and point of impact. It is observed that only some configurations show a monotonic dependence of the throwing distance on the car speed.

Keywords: Bicycle, Car, MADYMO, Crash simulation, throwing distance, impact speed

INTRODUCTION

In the last two decades, there has been a considerable emphasis on the use of computer simulations for vehicle and vehicle riders' safety. Cyclists and pedestrians are the most vulnerable group in traffic crashes [Carsten et al., 1992]. In the past, studies and developments in the field of crash modeling were mainly directed towards protecting the occupants in motor vehicle crash. We see very few studies regarding bicycle-motor vehicle crashes. Bicycles generally do not have a standardized structure and there is no conformity criterion for the material used, design and construction methods. Hence generic safety standard for bicycle riders have been very difficult to formulate and are not standardized yet. Reconstruction of accidents involving vulnerable road users in general and bicycles in particular, has been gaining importance. Accident reconstruction techniques use post-crash data to estimate the pre-crash situation. The fact that the collection of data starts at the scene of accident post facto, leads to indirect determination of parameters leading to the crash. Some useful correlations are provided by the laws of physics governing momentum conservation, energy dissipation from plastic folding and friction, measurement of skid marks etc. These are however not specific to the bicycle-car interaction. To aid reconstruction, correlations specific to the type of impacts are desirable. The vehicle motion is analyzed through tire marks, vehicle damage patterns and debris scattering. For pedestrian impacts, two such correlations are wrap distance and throw distances. For bicycle crashes also throw distances have been used in the past [Otte, 1980, 1989, 2002]. This paper investigates variations in the throw distance of bicycle riders with the impact parameters to aid bicycle accident reconstruction efforts through simulations. We have first established bicycle crash configurations for analysis, and have then developed rigid body models in MadymoTM and observed throwing distances in varying impact conditions. Attempts were made to establish variations in the throwing distance with the vehicle velocity for various crash configurations. Based on the position of the vehicle, the point of impact between the car and bicycle and the distance to which the cyclist is thrown, these variations would help predict the car speed. It is hoped that this data, once calibrated, will be useful for reconstruction of crashes involving bicycles. Similar data is presently used extensively for pedestrian crashes.

CRASH CONFIGURATIONS

The throwing distance and injury level vary with crash configurations. Simulations are generally carried out for configurations identified as likely or common. For example, in car-motorcycle crashes, such configurations have been standardized in [ISO 13232, 1996]. Similar standards are not available for car-bicycle crashes, but the 1996 study by the Federal Highway Administration (FHWA) [Tan, 1996] that applied the basic National Highway Traffic Safety Administration (NHTSA) bicycle topologies to a sample of 3,000 bicycle-motor vehicle crashes from six states can be a starting point. In that study particular attention was given to roadway and location of vehicles in order to identify situations where engineering, educational, and/or regulatory countermeasures could have been effectively implemented to reduce the frequency of crashes. The basic bicycle-motor vehicle crash patterns reported by [Tan, 1996] are still relevant and intersections, driveways, and other junctions continue to be locations where about three-fourths of the crashes occur. In the study bicycle-motor vehicle crashes were divided into three main categories, Parallel Path Events (36 %), Crossing Path Events (57 %) and Specific Circumstances (7 %). The most frequent parallel-path crashes were motorist turn/merge into bicyclist's path (12.2%), motorist overtaking the bicyclist (8.6%), and bicyclist turn/merge into motorist's path (7.3 %). The most frequent crossing path crashes were motorist failed to yield to bicyclist (21.7 %), bicyclist failed to yield at an intersection (16.8 %), and bicyclist failed to yield mid block (11.8 %). These six individual crash types accounted for almost 80 % of all bicycle-motor vehicle crashes. In our study we have used two of these configurations corresponding to the front-to-side impact, which is one of the most prevalent crossing path crashes. Specifically the front-to-side and the frontal oblique configurations have been considered (Figure 3). When an adult pedestrian is struck by a car front, the first contact occurs between the bumper and either the leg or the knee joint area. For the case of a bicycle, the initial impact is with the bicycle tyre or the leg. The final position of cyclist post crash is a primary measure and hence is an important parameter to ascertain the collision speed within the framework of accident reconstruction. The distance from the collision point to the first point of contact with the ground is indicated as "throwing distance". Figure 1 (reproduced from [Otte, 2002]) shows the only available correlation for throwing distance in relation to the collision speed for bicycle crashes. A large variation in the throwing distance can be seen. This paper reports the results of variation in throwing distance in front-to-side crashes between car and bicycles with variation of car / bicycle speeds and the point of initial impact between the car and the bicycle. There is significant dependence on these parameters, and the trends in the throw

distance follow those in reconstructed data reported in literature. Further, the throwing distance is predicted to have non-monotonic dependence on the impact configuration, which could complicate reconstruction attempts.

MODEL DEVELOPMENT

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

Bicycle model

The bicycle is modeled as a system of four rigid bodies: the frame, the front fork, and the two wheels. The frame and the front fork are connected by a revolute joint; for which the rotation axis is in the plane of symmetry of the bicycle. Front and rear wheel are connected by revolute joints to front fork and the frame, respectively. Rotation axes are perpendicular to the plane of symmetry. A sketch of the bicycle with key dimensions is shown in Figure 2. The rider has been modeled using the Hybrid III model from the Madymo library. Initial simulation of the crash between the car and bicycle indicated that the bicycle tyre characteristic plays an important role in defining the impact and consequently the initial motion provided to the rider. The results reported from various tests and analysis ([Burgoyne and Dilmaghanjan, 1993], [Gavin, 1996]) have been used to extract 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 [Gavin, 1996].

Contacts between the road and the tyres of the car were defined using the tyre model in Madymo and available internal tyre pressure, wheel diameter and wheel thickness. In practice, after the impact the bicycle front handle turns freely up to approximately 135° before being restrained due to the brake wires tightening against the bicycle frame. We found that it was important to model this effect for a realistic simulation. This was implemented in simulation by keeping the handle joint free till the limiting angle and incorporating a high stiffness beyond it.

Car model

The car has been chosen as the Mruti ZEN model, a common car on Indian roads. Its overall dimensions are as shown in Figure 4. 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. Each tree originates at the vehicle body, where the vehicle motion is prescribed. The front suspension linkages form a double wishbone configuration, with an upper control arm, steering linkage, wheel, and lower control arm bodies. The rear suspension consists of a body to model each of the rear axle and the wheel/tire areas, and represents a simplified suspension configuration. It was found necessary to include the lateral part of car hood, rear door, side and rear windows as the cyclist impacted the lateral part of the car in some post impact situations. These parts are approximated as ellipsoids based on the geometry of the vehicle.

Contact Interactions

Multi body contact interactions are defined using the force penetration functions for the dummy with the bicycle, car, pavement and road, for the bicycle with the car and the road, the car with the road and between dummy body parts. Head form impact test data reported in [JNCAP DATA, 2004] 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. The characteristics used for the bonnet and the windscreen are shown in

Figure 5.

SIMULATIONS OF THE FRONT-TO-SIDE COLLISION

Simulations for the impact when the car front hits the bicycle side have been performed. Figure 6 shows a series of snapshots for the case when the centre of the car moving at 25 km/hr hits the bicycle moving at 10 km/h at the saddle. The snapshots in Figure 6 show the basic characteristics of the bicycle-car crash phenomenon. The rider impacts the hood, and then proceeds to roll up the windscreen towards the roof of the car. With respect to the car, a lateral movement is also present causing the rider to roll off the side of the car in this case. For higher velocities, the rider may clear the roof, landing at the back of the car. For lower velocities, the rider may be carried on the front end of the car for longer time duration before rolling off. The behavior is qualitatively different at varying speeds, initial impact locations and bicycle speeds. The simulations were carried out with the speed of the cycle as 10 km/h and the impact speed of car varying between 15 km/h to 65 km/h (4.17 m/s to 18.06 m/s). The distance of point of impact of bicycle saddle from the car centre was also varied, and is measured positive in the direction of bicycle motion shown in Figure 7 below.

Variations in the offset

The offset of the bicycle centre with respect to the car longitudinal plane (as shown in Figure 7) was varied from 0 to 0.6 m. Figure 8 shows the change in throwing distance for different car velocities at these offsets. 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. In bulk of the simulations, the rider impacted the bonnet or the windscreen. At higher speeds (above about 13 m/s) however, the cyclist is thrown to a greater height and goes above the roof of the car. This qualitative change causes the throwing distance curve to change slope. At very low velocities (below about 5 m/s) the bicycle hits the car but the cyclist does not.

Variation with point of impact at constant speed

The point of impact on the car has a strong influence of the throwing distance. The point of impact has been varied from -0.9 m to 0.75 m with the car speed constant at 10 m/s. Figure 9 shows variation in throwing distance for bicycle speed of 10km/h and car speed of 30 km/h in front-to-side impact with change in point of contact. The throwing distance changed significantly, and obviously went down to zero when there is no contact.

Comparison with accident data

The throwing distance for all impact positions has been plotted in Figure 8. If all the offset configurations are considered, there is a significant spread of data, especially at higher velocities. The spread of the throwing distance at 18 m/s (64 km/hr) between 5 and 35 m is similar to the spread between 8 and 35 m seen in the data reported by Figure 1. We may conclude that the large spread in the data reported by [Otte, 2002] is predicted in the simulations and can be attributed to changing contact points on the car. It is hence suggested that in reconstruction, a single throwing distance correlation may not be very useful and the contact point with the car be identified for good correlation.

Variation in bicycle speed

Though the bicycle velocity is small compared to the car velocity, variation in the bicycle velocity does affect the throwing distance. This was investigated by simulating with the car velocity constant at 50 km/h (13.89 m/s) with bicycle speed varying from 5 km/h to 20 km/h (1.39 m/s to 5.56 m/s). The variations in the throwing distance are plotted in Figure 10 for two different impact offsets (-0.3 and -0.6 m). It was observed that the throwing distance variation with the bicycle velocity has a peak, instead of a monotonic variation. For lower bicycle speeds, post impact the rider gains lesser height, impacting lower on the car

windscreen. The rider then tends to roll off the front or side of the car, leading to lower throwing distance. For higher cyclist velocities the cyclist crosses the car (due to a velocity perpendicular to car) earlier, thereby its motion was not significantly influenced by the car impact leading to lower throwing distances. This analysis suggests that the bicycle velocity at which the throwing distance is maximum will change with the distance of impact from the car centre. From the above figures, the variation in throwing distance with bicycle velocity is estimated to be of the order of 15 m at a car velocity of 50 km/h. The variation due to change of impact position on the car for the same car velocity is of the order of 10 m from Figure 9. So we conclude that the variation in throwing distances due to impact position variation is of the same order as the variation due to bicycle speed. The variation becomes more prominent for higher offset in the impact point.

Effect of Car Braking

At the time of impact, it is expected that driver of the car would have engaged brakes. Simulations were carried out to find the effect of braking on the throwing distance. Front-to-side impacts were simulated with the point of impact on the car at a distance of 0.30 m from car centre. The bicycle velocity was 10 km/h (2.78 m/s) and the car velocity was varied from 15 km/h to 65 km/h (4.1 m/s to 18.06 m/s). The braking rate is 0.5 g (4.9 m/s^2). The variation in the throwing distance for the two cases can be seen in Figure 11Figure 10. It is predicted that the throwing distance would reduce when the brakes are applied. At around 13 m/s, there is a sudden drop in the throwing distance for the crash involving car motion without brakes. For this case, after the impact with car windscreen, the bicycle rider gained enough height to pass over the top of the car and fall behind the car. This reduced the distance to which the bicycle rider was carried away by the car thereby reducing the throwing distance. We can also observe that there is no sharp change in the throwing distance curve for the case when brakes are applied. For this case, the bicycle rider does not rise high enough on the car to pass over the top. The overall pattern of the curve for the two cases remains the same with small difference in the magnitudes of throwing distance for a given car velocity.

FRONTAL OBLIQUE IMPACT

The frontal oblique collision is when the bicycle front tier hits the front of the car at an angle off the normal. This class of collision takes place when one of the vehicles is taking a turn while the other vehicle is moving in the wrong direction. For the simulation, the angle of approach is taken as 45° and point of impact as car centre (Figure 3). The car velocity is varied and the change in the throwing distance is shown in Figure 12. The bicycle rider

impacts the car bonnet and the windscreen after the crash. The rider ends up in front of the car for low velocities (up to 20 km/h or 5.5 m/s) or at the side of the car (up to 30 km/h or 8.5 m/s) or gets thrown over the car. Consequently, this also changes the range of throwing distance. Consequently over the range of velocities between 8-10 m/s the throwing distance decreases with increase of car velocity.

CONCLUSION

The variation of the throwing distance with car velocity, point of impact and angle of approach has been studied through simulation and over 200 simulations for bicycle-car crash have been carried out for two crash configurations derived from the Carol Tan configurations [Tan, 1996]. The obvious conclusion that the throwing distance generally increases as the car velocity increases, was reinforced. 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 Otte (2002) is predicted to originate from variation in the impact configuration. The trends in the front-to-side impact follow reconstructed data reported by Otte (2002). 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.). One significant limit of the study is that it is currently based on only one car model. Real life data, for example of the type reported by Otte include a larger range of vehicles. The change in throwing distance for other vehicles is yet to be studied. Further, variation in the bumper and bonnet height could also affect the throwing distance. These effects can also be studied.

REFERENCES

1. Carsten, O.M.J. et al (1992), Drive Project V1031, An Intelligent Traffic System for Vulnerable Road Users. Institute for Transport Studies, University of Leeds.
2. ISO13232, (1996), Motorcycles – test and analysis procedures for research evaluation of rider crash protective devices fitted to motor cycles, International Organization of Standardization, Reference Number ISO 13232-1 to 7: 1996(E).
3. Tan, C. (1996), “Crash Type Manual for Bicyclists”, Pub. No. FHWA–RD–96–104
4. Otte D., Possibilities and Limitation for protective measures for injury reduction of vulnerable road users, IJCrash 2002, Vol 7 No.4, pp. 441-461.
5. Burgoyne, C.J. and Dilmaghanian, R. (1993) “Bicycle Wheel as Prestressed Structure.” Journal of Engineering Mechanics, 119(3), pp. 439-455.

6. Gavin, H.P., "Bicycle Wheel Spoke Patterns and Spoke Fatigue," *Journal of Engineering Mechanics*, vol. 112, no. 8, (1996) pp. 736-742.
7. JNCAP DATA, New Car Assessment Program Japan, Choosing a safer car, March 2004, Ministry of Land Infra Structure and Transport and Natinal Agency for Automotive Safety and Vixtim's Aid, Japan.
8. Otte, D. (1980), A review of different kinematics forms in two-wheel accidents—their influence on effectiveness of protective measures, Stapp Car Crash Conference, SAE Paper No. 801314.
9. Otte, D. (1989), Injury mechanism and crash kinematics of cyclists in accidents—an analysis of real accidents, Stapp Car Crash Conference, SAE Paper No. 892425.

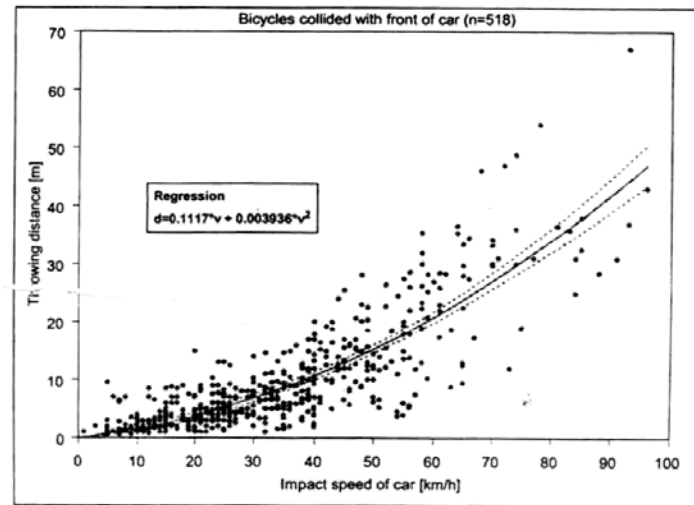


Figure 1 Throwing distance of bicycles in relation to impact speed of car for front-to-side impact [Otte, 2002]

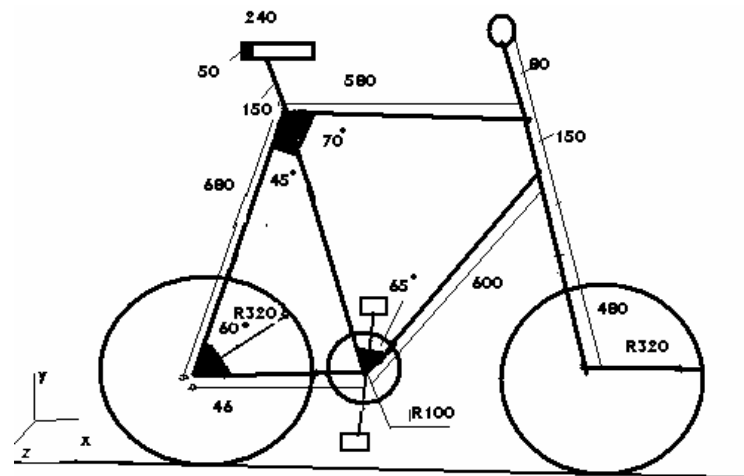


Figure 2 Dimensions of a Bicycle

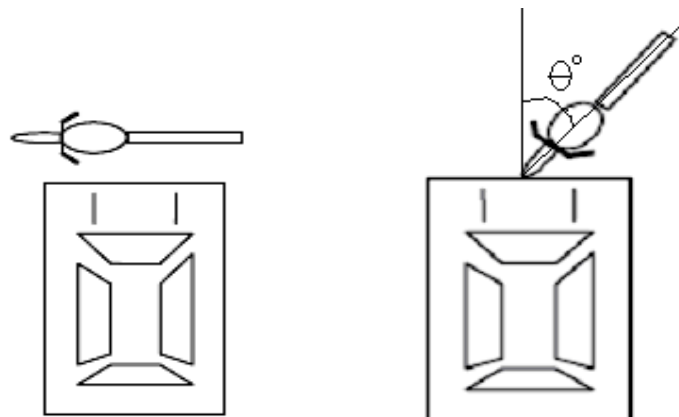


Figure 3 The front-to-side and the frontal oblique configurations used in the current study.

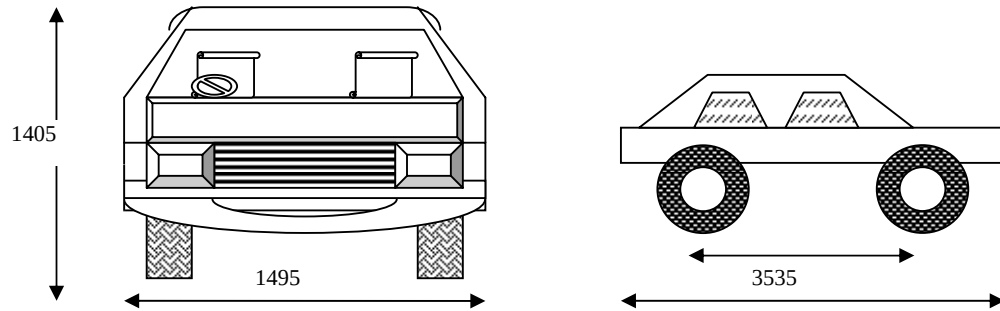


Figure 4 Dimensions of Car (Maruti Zen)

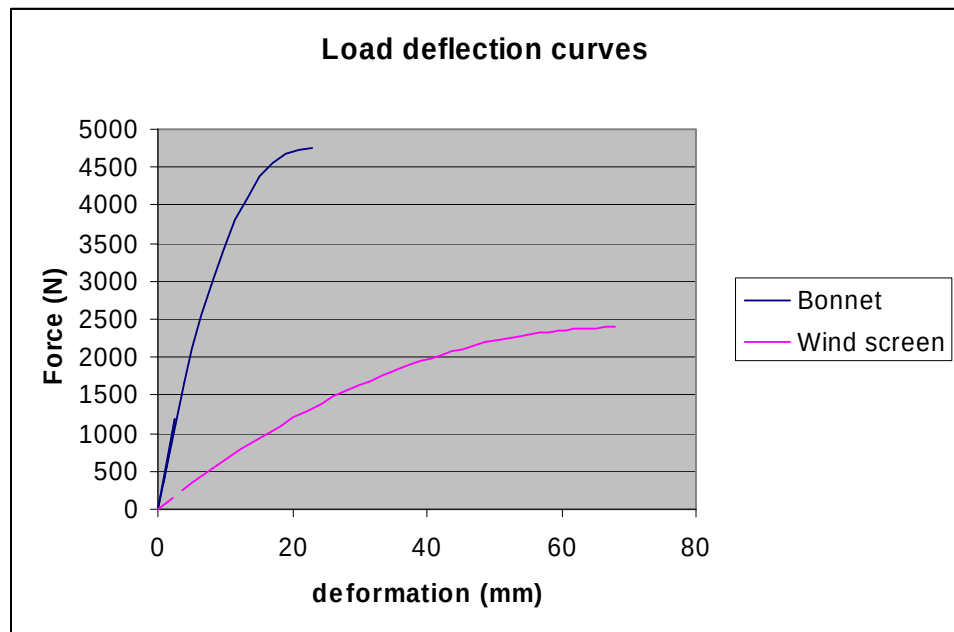


Figure 5 Load – deformation curve for car bonnet and windscreen.



Figure 6 Motion of bicycle rider in front-to-side-side crash (Car velocity = 25 km/hr, Point of impact at car centre)

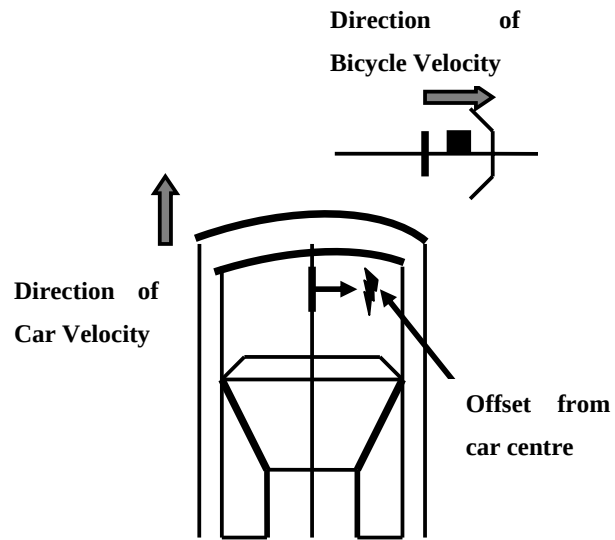


Figure 7 Front-to-side impact orientation

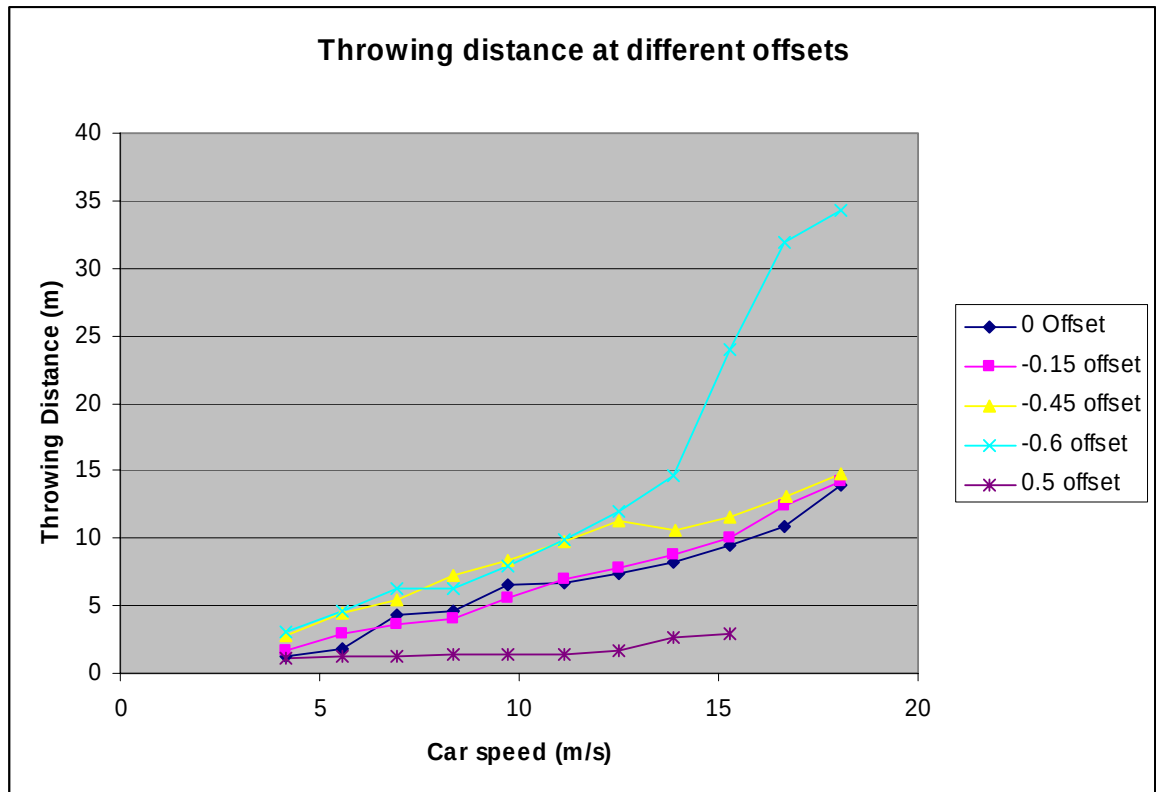


Figure 8 Variation of throwing distance of cyclist with car velocity for different offsets of the bicycle saddle with respect to the car centre

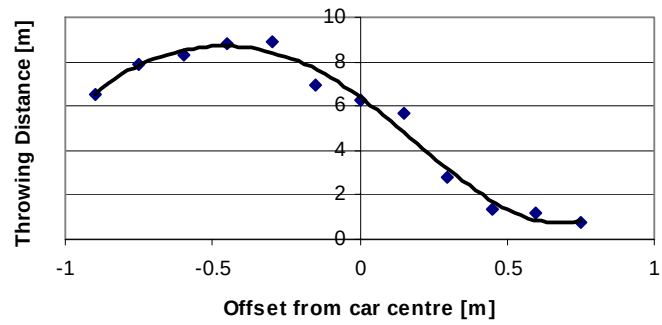


Figure 9 Variation of throwing distance of bicycle rider with change of offset (for a car speed of 30 km/h and the bicycle speed of 10 km/h)

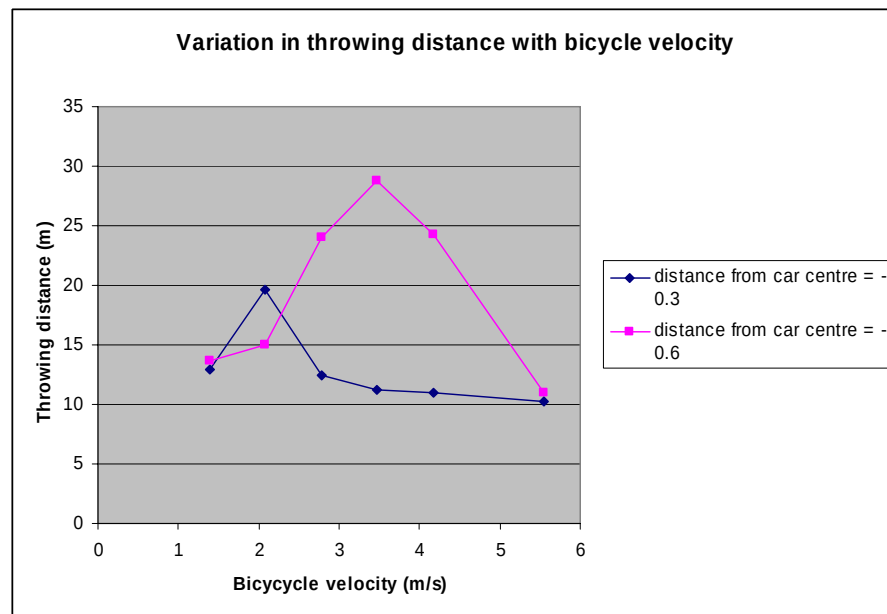


Figure 10 Variation in throwing distance with bicycle velocity when the bicycle strikes at distance of -0.3 and -0.6m from car's centre

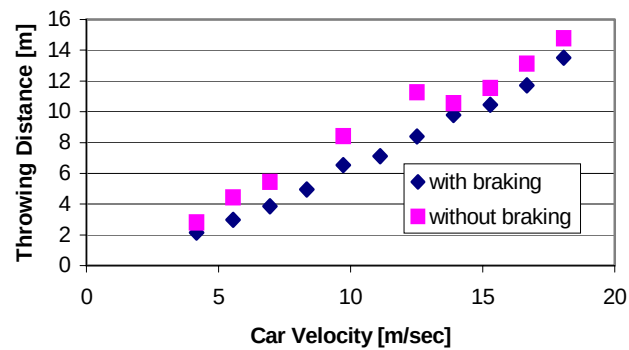


Figure 11 Variation of the throwing distance with the car velocity in the presence and absence of braking (offset = 0.3 m)

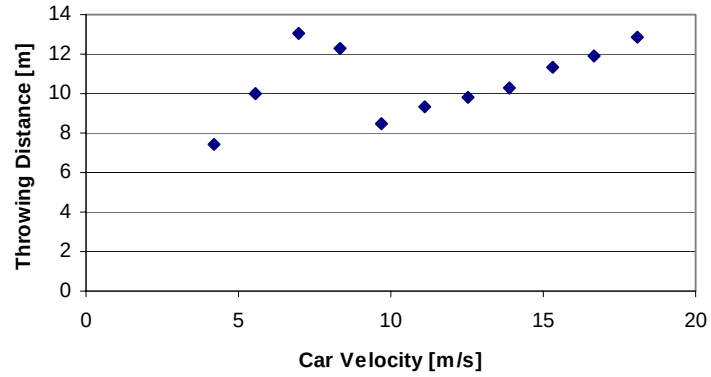


Figure 12 Variation in throwing distance with car velocity for the frontal oblique impact with an angle of approach of 45°

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 N/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

