SAFER TRUCK FRONT DESIGN FOR PEDESTRIAN IMPACTS

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ABSTRACT

Truck and bus frontal impacts account for a major proportion of pedestrian fatalities in many less motorized countries. To understand this phenomenon, we have collected injury data on pedestrian impacts with buses and trucks and performed computer simulations to identify critical design parameters at 15-45 km/hr impact velocities for further investigation. A male dummy which was scaled to 50 percentile Indian dimensions has been used for simulations using MADYMO 5.2. Bumper height, bumper offset and grille inclination affect the pelvis and thorax forces and HIC values critically. Bumper width has less effect. An exhaustive set of simulations was performed to optimize for the above-mentioned three parameters. Changes in front geometric parameters reduce injury to the upper body and head below safety limits for the existing force-deflection properties but do not affect leg injuries significantly. Hence bumpers need to be made less stiff. Injury data show that pedestrians also sustain tibia fractures in bus/truck impacts in apparent low velocity impacts. The computer Modeling does not offer adequate explanation for this phenomenon. These simulations confirm that it is theoretically possible to make truck/bus fronts safer for pedestrians in impacts up to 35 km/hr.

VULNERABLE ROAD USERS (VRUs) in Delhi comprise about 75% of all fatalities and trucks and buses are involved in 60-70% of the known fatal crashes. This pattern is very different from that obtained in the highly motorized nations where buses and trucks are not involved in such a high proportion of fatalities. Since most of those killed in impacts with buses and trucks are VRUs, we must give much more attention to designing safer front structures for these vehicles.

Safer truck fronts developed for pedestrians would also be of benefit to bicyclists since impact forces are not likely to be very different in the two cases. As use of bicycles and walking becomes more popular in the highly motorized nations, safer truck front designs would be beneficial there also. In addition, similar designs could be incorporated on buses and trams also.

In this work we have modeled truck pedestrian impacts using the MADYMO 5.2 simulation program and developed optimized design criterion for safer truck fronts at different impact velocities in order to minimize injuries to the pedestrian by varying height, width and offset (from front panel) of bumper, angle of bus front with vertical, and force deflection properties of truck front above the bumper.

METHODOLOGY

Injury data for truck - pedestrian impacts was collected from Delhi hospitals to understand the epidemiology of these crashes. A pedestrian model representing fifty percentile Indian male (1.65m height and 57 kg weight) and models of truck types existing in India for use in MADYMO 5.2 software were prepared for analyzing of truck- pedestrian impacts. The force -deflection properties of the front panels of trucks were determined using quasi-static test. These models were then further used to optimize the truck front properties in order to minimize the injuries caused to pedestrians.

DATA COLLECTION - Four major hospitals in Delhi were contacted to obtain details of injuries sustained by pedestrians in impacts with buses and trucks and case files examined to assess the quality of data available. Most of the case files in hospitals contained very little epidemiological information regarding the crash. We included only those files where description of both the type of road user and the type of vehicle impacting the victim was available. However, this limits the representative nature of the data available. We could not access the details of pedestrians brought dead to the hospital owing to legal reasons. Therefore, the data collected in this project represents less severe crashes. Also, the data obtained include road crash victims mostly from the Delhi metropolitan area and hence has an urban bias and represents impacts at lower velocities.

Hospital records were examined to extract files of those cases where the victim was suspected to be a pedestrian and the impacting vehicle a bus or a truck (In India buses and trucks are

Figure 1: The flat front truck

built on the same chassis and have similar fronts). 350 cases were identified for the period 1 January 1997 - 31 October 1997. An examination of the identified case files showed that only 94 out of the 350 cases were actually pedestrians, 68 were victims of bus impacts and 26 of trucks.

THE PEDESTRIAN MODEL - The basic pedestrian dummy used in this project is based on the work done by Yang et al.(1997). The body segment size, mass and inertia for fifty percentile Indian male (height 1.65 m and weight 57 kg) (Mohan et al., 1997) are estimated using GEBOD (Generator of Body data). The joint angle characteristics for pedestrian are based on the model by Ishikawa (1993).

The Part 572 crash dummy used in MADYMO 5.2 does not give results compatible with tests on biological specimens (Wijk et al., 1983; Janssen et al, 1986; Yang et al., 1994). This provided the impetus for the development of a detailed pedestrian lower extremity model. The model of the human knee used in this project is based on the work done by Yang and Kajzer (1992). This model uses planes and ellipsoids to model the skeletal components of the knee joint. The lateral femur condyle and the medial femur condyle have been represented by one ellipsoid each. The femur condyle is modeled by a plane. This Modeling takes into account the geometric shape of these bones. The soft tissue structures as major ligaments and the joint capsule are modeled by spring type elements.

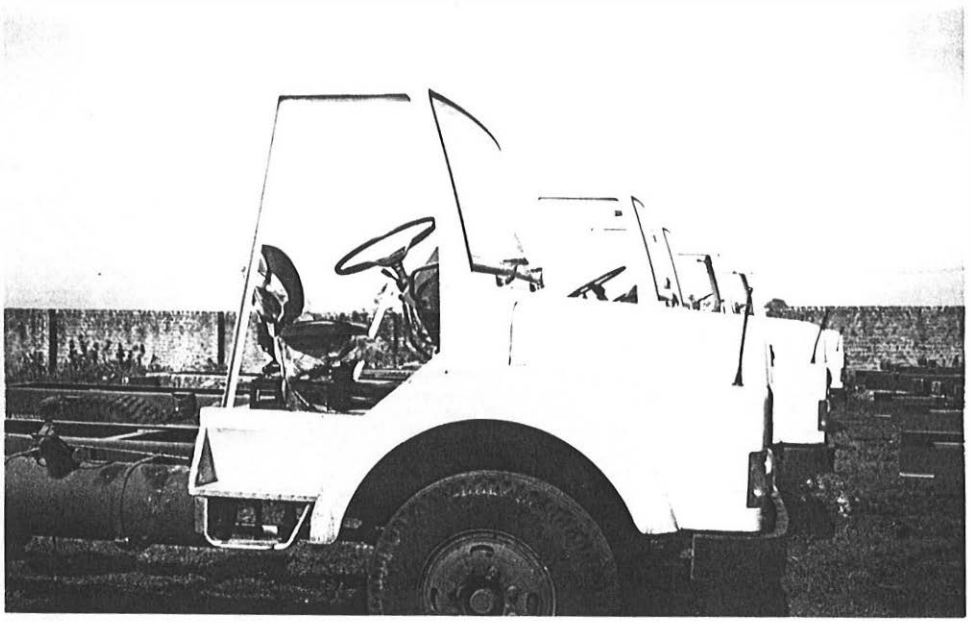

Figure 2: The bonnet front truck

We have used the Head Injury Criterion (HIC) for estimating severity of head injury. Values greater than 1000 have been considered unacceptable. Thorax deceleration was used as an indicator of severity of thoracic injury. A tolerance level of 588 m/s^2 (60g) sustained for 3 ms or longer by the center of gravity of thorax was used to indicate a severe chest injury (AIS >= 4). We have chosen to use 4 kN as upper limit for bumper impact force on tibia (Hoefs et al., 1987). Although the truck pedestrian collisions are not directly comparable to this study because of different direction of impact force, this was the best estimate we could get in absence of relevant data. In case of femur, the maximum allowable value of 7.5 kN was used (Gibson et al., 1986). A value of 10 kN was used as the upper allowable limit of force on pelvis (Mohan et al.,1997).

TRUCK MODELS - Two truck shapes are use in India : with a flat front (Figure 1) and with a bonnet front (Figure 2). Both types of trucks were chosen for analysis. Dimensions of parts of fronts of these trucks critical for pedestrian impacts such as bumper height, width and offset and dimensions of front panels were measured. The distance between the radiator and the front panel was measured and included in the model. The truck fronts were approximated by planes

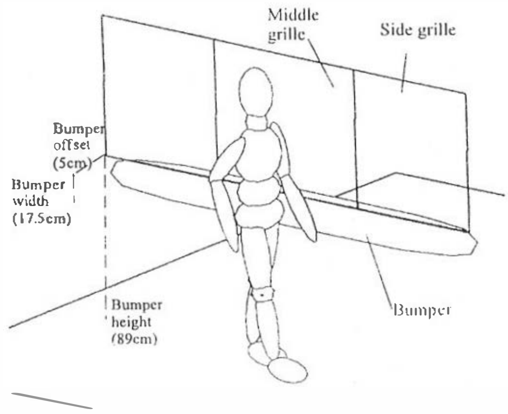

Figure 3: The MADYMO model of the flat front truck

and ellipsoids. In this paper, we present results for only two models due to space constraints but they are sufficient to cover all the essential findings. Figures 3-4 show these models.

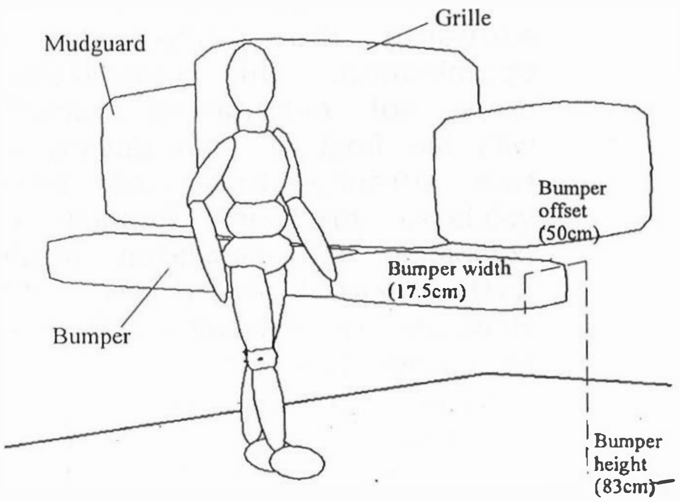

Figure 4: The MADYMO model of the bonnet front truck

Preliminary simulations were performed using assumed force-deflection properties of truck parts in order to determine the front contact points with the dummy. We determined these points both for pedestrian collisions with the truck at the middle of front panels as well as at an offset. The force - deflection properties of front panels at these locations were determined in quasi-static tests. Since bumpers are very stiff compared to the human body, they were assumed to be rigid. Hence their force-deflection properties were not determined. Injuries to legs and pelvis were calculated assuming worst case scenario. The legs of the pedestrian were so oriented that only one leg suffered initial impact. If both the legs contact the bumper simultaneously, then the force on each leg will be less.

Simulations were done for each model at velocities of 15 km/h, 25 km/h, 35km/h and 45 km/h. The flat front model was chosen for optimization of the truck front parameters for the simplicity of its design. MADYMO 5.2 includes an optimization program called Madimizer. This program searches for an optimum solution in a prescribed domain by approximating objective function and constraints by linear functions. However, due to the nature of the optimization problem and also the high sensitivity of HIC for changes in head acceleration, this optimization method did not give consistent results in different runs. Hence we chose to do an exhaustive evaluation by dividing the design parameter domain into equally spaced points and running a simulation at each point.

The optimization was done for impact of pedestrian side with middle of the truck front. But these results are valid for impact at an offset also, as only force-deflection curve and bumper extensions are different and these aspects are anyway being considered in optimization. Although force deflection characteristics are different

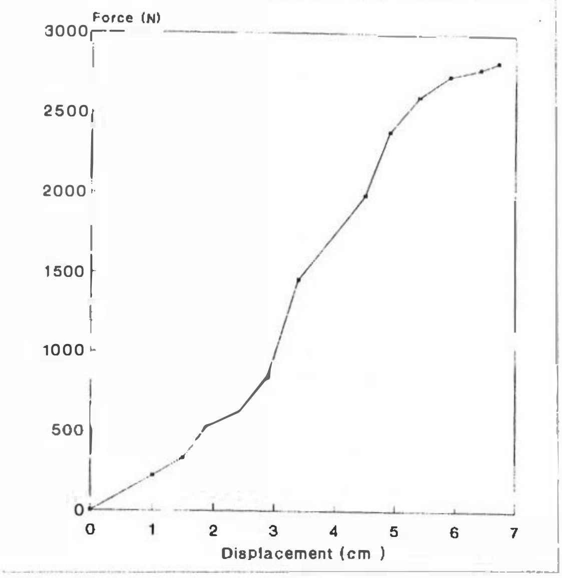

Figure 5: Force - deflection curve for the front panel of the flat front truck

at the top and the middle of grille, the worst case force deflection curve (which is at the center of middle grille) was assumed for the whole grille for reducing the complexity of optimization. This optimization does not encompass impacts with the front of the dummy as this dummy has not been validated for such impacts by comparing the simulation results with experimental results. However we simulated this kind of impact also for the optimized designs to get an idea of their performance. The optimization was done for a truck velocity of 35 km/h and a constant deceleration of 0.5g as HIC and 3ms criterion for chest are within tolerance limits up to 25 km/h. The force-deflection curve for grille was kept constant because being the most important parameter influencing the injury criteria, it could easily subdue the effect of variation in the geometric parameters. We evaluated the effect of varying each parameter individually before a full scale optimization starting from the existing parameters values, so that less important design parameters could be eliminated in order to reduce number of simulations. The results for unmodified and optimized truck fronts are discussed in the next sections.

RESULTS AND DISCUSSION

The injury data showed that only 7% of the 350 crashes involving trucks and buses included victims who were occupants of cars, 55% were vulnerable road users, 21% bus commuters, 8% other truck occupants, and 10% unknown. These data show that in India, even in urban areas, trucks have a significant involvement with pedestrians and motorcycle and bicycle riders. Therefore, truck/bus fronts would have to

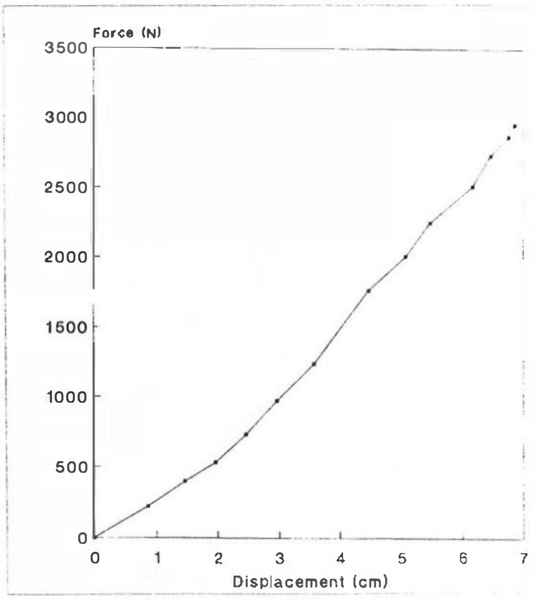

Figure 6: Force - deflection curve for the front panel of the bonnet front truck

optimized for crashes with all kinds of road users. Out of 94 pedestrians 67% were in 15-44 years of age, 20% above 45 years and 13 % between 0-14 years of age. In India the proportion of population in the age group 0-14 years is estimated to be 40%. The data indicates that children are under-represented as a proportion of their population in the pedestrian-truck/bus impacts. The distribution of injury by body part and severity is shown in Table 1. 71% of the severe injuries (AIS≥ 3) are recorded for pelvis and lower extremities. This is probably because the impacts are at lower velocities and also because the front panels of trucks and buses at head and chest level are made of relatively soft sheet metal. Only 4 out of the 94 cases were fatal. There were 17 injuries to the lower extremities at the level of the knee and lower with severity AIS≥2. This is interesting as the height of the bumper in buses and trucks on the roads in India is higher than the knee level. The mechanism of these injuries needs further investigation. It is possible that data sources which include impacts at higher velocities would involve a higher proportion of head and chest injuries.

Table -1 Distribution of injury by body part and severity

	Severity of Injury by AIS				
Body part	1	2	3	4	5
Head/neck	8	4	1	0	1
Face	17	0	2	0	0
Chest	2	2	2	0	0
Abdomen	0	4	0	0	0
Shoulder/arm	7	6	0	0	0
Forearm	5	5	0	0	0
Wrist/hand	8	1	0	0	0
Elbow	3	1	0	0	0
Pelvis	2	8	3	0	0
Thigh	5	6	9	0	0
Knee	6	1	0	0	0
Leg	5	4	3	0	0
Ankle	0	1	0	0	0
Foot	7	8	0	0	0

Unknown 8

The experimental force - deflection curves for the grilles of the flat and the bonnet front truck are given in Figure 5-6. Bumpers have been assumed to be rigid. In the next section we describe the results for the flat and bonnet type trucks for impacts with the front as well as the side of the dummy.

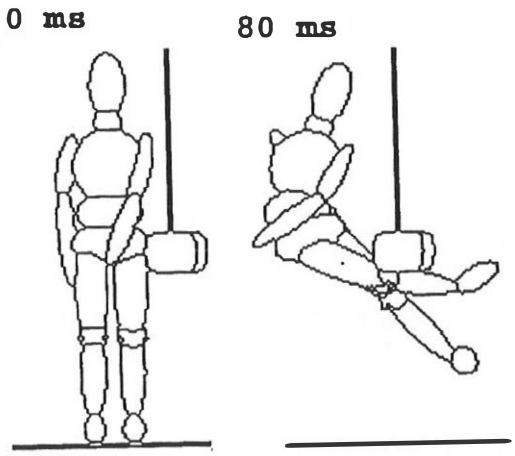

Figure 7: The Kinematics of impact between the flat front truck and the side of dummy

FRONTAL IMPACT WITH THE SIDE OF THE DUMMY

<u>Flat Front Truck</u> - The kinematics of impact of the side of dummy at middle of the truck front is shown in Figure 7 and maximum values of injury parameters are given in Table 2.

The left upper leg hit by the bumper sustains force greater than 7.5 kN at velocities 25-45 km/h. This can cause severe injuries to the leg. The other leg suffers forces an order of magnitude less than the leg hit directly. As the bumper height is high at 89 cms, the pelvis (lower torso) is hit directly by the bumper. Even at a low impact velocity of 15km/h, the pelvis experiences a force of 9.4 kN. Hence bumper height has to be reduced to avoid the pelvis region. Only the right lower leg suffers a high force. This forces increases with increase in velocity and becomes very high at 45 km/h. This force is not caused by a direct impact with bumper but when the pedestrian is thrown away at a high speed after collision and the lower legs impact the truck. This is shown by the kinematics in Figure 7. The hospital injury data also show fractures to the tibia. However, at present we are not very confident about this result due to two reasons. The cumulative due to rounding off errors in numerical integration becomes large in later steps of simulations when this collisions occurs. Secondly, the behavior of lower extremity depends strongly on the joint properties which have

Table 2 - Injury parameters for frontal impact at middle of flat truck model with side of dummy.

Velocity (Km/h)	Left upper leg-bumper force (kN)	Right upper leg-bumper force (kN)	Right lower leg-bumper force (KN)	Left lower leg - bumper force (kN)	Pelvis - bumper force (kN)	Pelvis - midgrille force (kN)	Left upper arm - bumper force (kN)**	HIC	Upper torso 3ms acc. (m/s²)
15	2.7	0.0	0.0	0.0	9.4	0.0	2.4	80.4	247
25	10.8*	0.0	4.5*	.01	15.0*	0.00	4.2	316.9	515
35	17.4*	0.4	11.6*	0.4	19.4*	0.00	5.8	755.2*	776*
45	21.1*	2.0	17.3*	0.2	24.2*	0.0	7.4	1451*	1023.7*

** parameters exceeding the safety limits.*

*** Not critical for safety of the pedestrian but high value will result in shoulder injury.*

to be determined very accurately.

Head, thorax and upper left arm experience low severities at 15 km/h impact. HIC is below 1000 for impact velocities below 35 km/h but exceeds the limit at 45 km/h. 3ms criterion for thorax (upper torso) is below the safely limit of 60g at impact velocities less than 25km/h but exceeds the limit at 35 and 45 km/h. This is in conformance with the hospital based observations that injuries to head and chest were less severe compared to lower extremities at low impact velocities. The upper arm force is low only at 15 km/h and is high for 25-45 km/h.

The pelvis does not collide with the grille in the unmodified design of this truck model so this force is zero at all speeds. However the force on pelvis due to bumper impact is very high as discussed earlier.

Bonnet Front Truck - The kinematics of impact at middle position on the truck front is shown in Figure 8 and the maximum values of injury parameters are given in Table 3.
Table 3 - Injury parameters for frontal impact at middle of the bonnet type truck model with side of dummy.

Left upper leg sustains a high force even in impacts at 15 km/h. This is different from the flat front model. Force on right upper leg is higher compared to the flat front but still is one order of magnitude less than that on left upper leg. Right lower leg also suffers higher forces except at 25 km/h. However, pelvis suffers a lower force compared to the flat front model. This effect is due to a lower bumper height. This indicates the possibility of changing the magnitudes of forces on lower extremities by varying bumper height. In this model, the pelvis does not hit the grille.

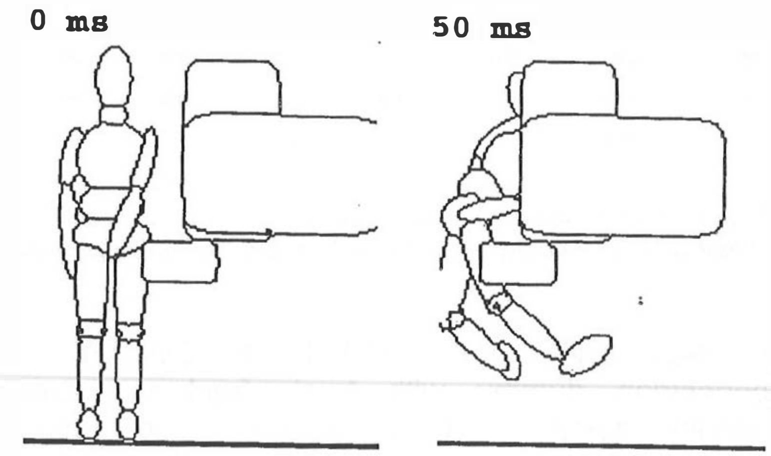

Figure 8: The Kinematics of impact between the bonnet front truck and the side of dummy

The left upper arm suffers little force. It is only 1.5 kN even at 45 km/h. This is because the grille is quite soft.

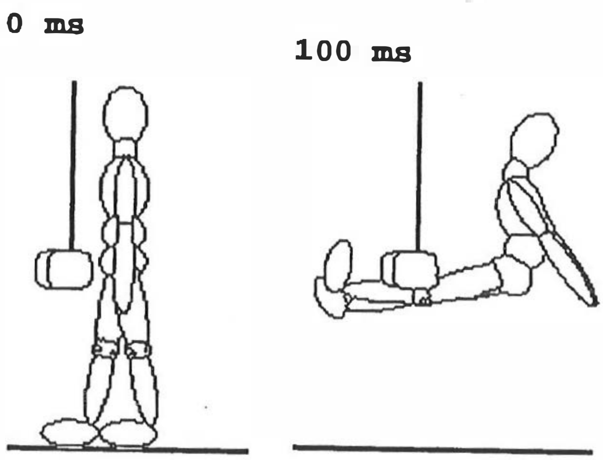

Figure 9: The kinematics of impact between the flat front truck and the front of dummy

This is also the reason for a lower 3ms value for upper torso even at 45 km/h compared to the flat front model although it is still beyond the safety limit. However, HIC is higher compared to the flat front model because the head is colliding with the leading edge of the bonnet. Since the bonnet is stiffer at the corner (where the head collides) and comparatively softer (where the upper torso hits), the impact force is mostly shared by the head. This can also result in severe injuries even at 15 km/h as evident form the kinematics given in Figure 8. These kinds of trucks (with a bonnet in front) are not recommended.

We changed force - deflection properties of the upper part of front panel where the head impacts and inferred that maximum forces on upper legs and lower legs do not depend on these force-deflection properties. Hence during design, force-deflection properties of the upper portion of grille and bumper can possibly be treated separately.

Velocity (Km/h)	Left upper leg-bumper force (kN)	Right upper leg-bumper force (kN)	Right lower leg-bumper force (kN)	Left lower leg-bumper force (kN)	Pelvis - bumper force (kN)	Pelvis - midgrille force (kN)	Left upper arm force (kN)**	HIC	Upper torso 3ms acc. (m/s^2)
15	8.6*	0.0	0.0	0.0	6.0	0.0	0.7	146.0	136.3
25	16.2*	2.7	0.2	0.0	8.9	0.0	1.0	389.6	269.8
35	21.3*	5.1	13.0*	0.0	11.1*	0.0	1.2	828.1	401.9
45	25.9*	8.5*	24.4*	0.6	12.4*	0.3	1.5	1664*	558.1*

** parameters exceeding the safety limits.*

*** Not critical for safety of the pedestrian but high value will result in shoulder injury.*

IMPACT WITH THE FRONT OF DUMMY - Impact of the front of pedestrian dummy with truck front was analyzed for the flat and bonnet types of truck models. The results obtained have been discussed in following sections. These results should be accepted with caution as the dummy used in simulations has not been validated by experiments for such impacts.

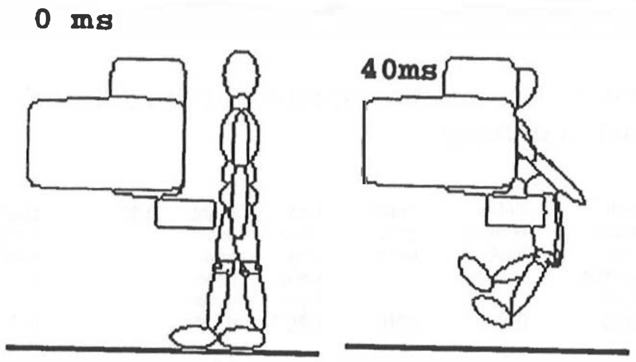

Figure 10: The kinematics of impact between the bonnet front truck and the front of dummy

<u>Flat Front Truck</u> - The kinematics of impact of the front of dummy at middle of the truck front at is shown in Figure 9 and the maximum values of injury parameters are shown in Table 4.

Both upper legs suffer high forces - left upper leg at 45 km/h and right upper leg at 35 and 45 km/h. This is different from impact with the side of dummy where only the leg directly hit by bumper (upper left leg) sustains high impact forces and the forces on the other leg are low. However the maximum magnitude of this force is lower. This is also true for lower legs. This indicates that in impact involving the front of dummy, both legs are equally vulnerable to injury although possibly the injuries will be less severe. Magnitude of force on pelvis remains same for both types of impacts but force on upper arms is lower.

Table 4 - Injury parameters for frontal impact at middle of the flat front truck model with front of dummy.

Velocity (km/h)	Left upper leg-bumper force (kN)	Right upper leg-bumper force (kN)	Right lower leg-bumper force (kN)	Left lower leg-bumper force (kN)	Pelvis-bumper force (kN)	Pelvis grille force (kN)	Left upper arm-grille force (kN)**	Right upper arm-grille force (kN)**	HIC	Upper torso 3ms acc. (m/s^2)
15	0.2	0.9	0	0	8.9	0	0.5	0.4	108.7	186.5
25	0.8	8.2*	0.07	4.8*	15.1*	0	2.0	1.8	511.1	431.5
35	6.0	14.3*	3.0	8.5*	19.5*	0	3.7	3.6	1389.8*	766.7*
45	12.8*	19.1*	12.7*	15.2*	24.0*	0	4.9	4.9	2751.6*	1130.2*

** parameters exceeding the safety limits.*

*** upper arm forces are not critical for the safety of pedestrian but high value will result in shoulder injury*

HIC is higher at all speeds compared to impacts with the side of the dummy. The difference is more at 35 and 45 km/h and HIC is much greater than 1000. 3ms acceleration is higher for side impacts except at 45 km/hr and the difference decreases with velocity. Impact with this truck model can cause severe injuries to neck as is evident from the kinematics given in Figure 9.

Bonnet Front Truck - The kinematics of impact of the front of dummy at middle of the truck is shown in Figure 10 and the maximum values of injury parameters are shown in Table 5.

Table 5 : Injury parameters for frontal impact at middle of the bonnet type truck model with front of dummy.

Velocity (km/h)	Left upper leg-bumper force (kN)	Right upper leg-bumper (kN)	Right lower leg-bumper (kN)	Left lower leg-bumper force (kN)	Pelvis-bumper force (kN)	Pelvis-grille force (kN)	Left upper arm-grille force (kN)**	Right upper arm-grille force (kN)**	HIC	Upper torso 3ms acc. (m/s^2)
15	0.5	5.5	0	0	7.2	0	0.3	0.1	212.6	149.6
25	6.3	12.6*	0	0	10.9*	0	0.7	0.6	523.3	296.9
35	14.4*	18.6*	0	0	13.4*	0	0.9	0.8	1149.6*	477.7
45	20.3*	21.8*	0	0	14.0*	0.09	1.0	1.0	2055.5*	652.2*

** parameters exceeding the safety limits.*
*** upper arm forces are not critical for the safety of pedestrian but high value will result in shoulder injury*

Both upper legs sustain high forces. Right upper leg has a force greater than the prescribed safety limit above 25 km/h and left upper leg above 35 km/h. However, the maximum of these forces is lower compared to that in impact with the side of the dummy. As mentioned earlier, this indicates the vulnerability of injury to both legs. These simulations were performed only for 100 ms at 15 km/h and 40 ms at 45 km/h because due to high force sustained by the head, the dummy restraints during simulation are violated beyond this duration. Hence forces on lower legs could not be ascertained as bumper hits them at a later time in simulations. Forces on upper arm and pelvis are same for both types of impacts and are quite low. Compared to the flat front model, forces on legs are higher but force on pelvis is lower. This is due to reduction in bumper height.

HIC is higher for impact with dummy front especially at 45 km/h where it has a very high value of 2055. This is due to impact with the sharp edge of bonnet. 3ms for chest is also higher for these impacts. Such impacts may result in severe injury to neck as the head collides against the hard corner of bonnet and chest against a much softer grille as is evident from kinematics.

OPTIMIZATION OF THE FLAT FRONT TRUCK MODEL - It was found that variation in bumper width does not cause as much changes in the various injury criteria compared to the other factors. It does not affect forces on right upper leg, pelvis and left upper arm and causes small changes in 3ms acceleration for the chest. Change in HIC and force on right lower leg is less compared to changes caused by the other factors. Hence the bumper width was eliminated from consideration in full scale optimization. Also, increase in bumper width decreases all injury criteria unlike other parameters. After optimizing the rest of the parameters, a convenient value of bumper width can be chosen. Moreover, change in bumper width leads to change in effective bumper height, so that bumper width cannot be increased beyond a certain value. In the final optimization, we chose to vary bumper offset, bumper height and front panel slant only. We used 5 values for bumper height measured from the upper edge (85 cm, 80 cm, 75 cm, 70 cm and 65 cm), three values for grille slant angle (0°, 10° and 20°) slant and five values for bumper offset (5 cm, 10 cm, 15 cm, 20 cm and 25 cm). Simulations were performed for each combination of the aforementioned values of the parameters. Thus a total of 75 simulations were performed.

It is interesting to note that the bumper impact forces on left upper leg and pelvis are affected mainly by bumper height. The effects of bumper offset and grille slant can be neglected for optimizing impact forces on the upper leg . This is so because these forces arise due to initial impact with bumper which is not influenced by bumper offset and grille height.

The optimum design parameters are different for different safety criteria. We rejected all the designs where HIC values were greater than 900 and 3ms acceleration values for chest greater than 500. We did not consider designs where bumper height is 80 cm or above in order to reduce high forces on pelvis, upper right leg and lower legs due to impact with bumper and grille. However, bumper at this lower height can still cause injuries to smaller people. It will also have to be reduced, if the bumpers of cars and trucks have to be made at the same height in future. Thus the issue of bumper heights for trucks has to be further investigated in detail. We further eliminated all designs with offset less than10 cm from consideration as other configurations give lower injury severity values. It was found that the effect of a larger bumper offset is similar to that of a greater front panel slant. It is advisable to use larger bumper offsets rather than giving front panel slant for safety of smaller people. We

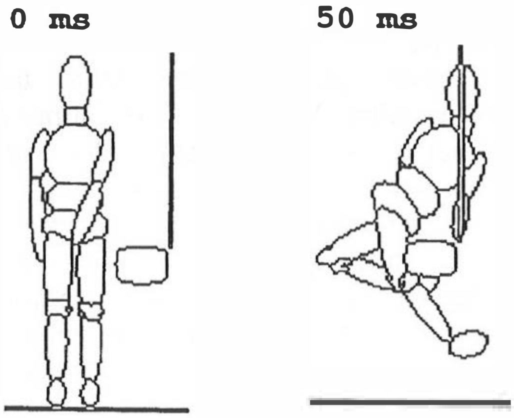

Figure11: The kinematics of impact between the optimized flat front truck and the side of the dummy

have not considered designs which provided for a front panel slant. This leaves only two configurations which are given in Table 6 along with values of injury criteria.

The forces on the upper left leg are same for all short-listed configurations and are higher than prescribed limit. One way to reduce injuries to the leg which is directly hit by bumper is to make the bumper less stiff. However, a compliant bumper changes the effective bumper offset. This effect of using a compliant bumper requires further investigation. The force on the right upper leg also remains same for all configurations and is quite low. The left lower leg is not directly hit by the bumper in all cases. The force on right lower leg does not vary more than 1.8 kN.

The kinematics of impact of the side of dummy at the middle of the second optimized truck front is shown in Figure 11. Results of impact between the front of dummy and the truck for these optimized configurations are shown in Table 7. Although HIC and 3ms acceleration values for the chest are below the safety limits for theses two design configurations in case of impact with the side of dummy, they are very high for impact with the front of dummy. The forces on the legs are also very high. However, the direct impact between pelvis with bumper and grille has been avoided. This indicates that the injury criterion is different for the impacts of the truck front is with the pedestrian side and front. Hence, it is necessary to consider impact with both the side and the front of dummy before deciding the final design configuration.

CONCLUSION

In this project we have evaluated the injury producing characteristics of the most commonly used trucks in India. The field studies show that there are two basic shapes we have to be concerned with : flat front and front with bonnet. The simulations show that it would be easier to provide a safer front with the flat front type rather than the bonnet type. The designs of the latter trucks make it very difficult to provide surfaces which reduce head and neck injury. This is because the leading edge of the bonnet occurs at head height or just below it. Therefore, we recommend that truck fronts should be almost vertical and flat so that their properties can be designed to optimize for minimum head and neck injury.

Head, thorax, pelvis, upper arms and lower and upper legs of pedestrians sustain severe injuries in case of impacts with fronts of all models of trucks at high velocities. Impacts with current models of trucks on Indian roads result in severe injury to the directly hit leg even at 25 km/h. At 35 and 45 km/h, head and chest sustain

Table 6 - Final optimum design parameters

Bumper offset (cm)	Truck front slant (degree)	Bumper height (cm)	Left upper leg- bumper force (kN)	Right upper leg- bumper force (kN)	Pelvis- bumper force (kN)	Right lower leg- bumper force (kN)	Left lower leg- bumper force (kN)	Pelvis- midgrille force (kN)	Left upper arm force (kN)**	HIC	Upper torso 3ms acc. (m/s^2)
20	0	75	22.6*	3.7	0.0	7.2*	0.0	0.0	5.6	669.8	438.8
25	0	75	22.5*	3.9	0.0	7.3*	0.0	0.0	5.2	711.0	377.8

** parameters exceeding the safety limits.*
*** upper arm forces are not critical for the safety of pedestrian but high value will result in shoulder injury*

Table 7 - Injury parameters for frontal impact of optimized flat front truck front with front of dummy at 35 km/h.

Bumper offset (cm)	Left upper leg (kN)	Right upper leg (kN)	Pelvis - bumper (kN)	Right lower leg (KN)	Left lower leg (kN)	pelvis - midgrille (kN)	Left/right upper arm (kN)**	HIC	Upper torso 3ms acc. (m/s^2)
20	19.9*	17.3*	0.0	12.4*	0.0	0.0	3.5/3.5	1635*	604*
25	19.7*	17.4*	0.0	12.3*	10.2*	0.0	3.6/2.9	1682*	522

** parameters exceeding the safety limits.*
*** upper arm forces are not critical for the safety of pedestrian but high value will result in shoulder injury*

unacceptable injuries (Table 2-5). Bumpers which are at the same height as pelvis produce severe hip injuries. Significant reduction in injuries can be achieved by altering the geometry of truck fronts as well as the force- deflection characteristics of the panels. Bumper height, bumper offset from the front and angle of truck front with vertical are the main geometric features of truck fronts influencing injuries. Bumper width influences injuries to a lesser extent but increasing bumper width leads to reduction in all injury criteria simultaneously, unlike the other geometrical parameters which reduce some injury criteria at the cost of others. However, this effect needs to be analyzed further using more sophisticated techniques including FEM analysis.

Pelvis injuries can be minimized for a fifty percentile Indian male if the top edge of bumper is below 75 cm. It is possible that it would have to be lower at 70 cm for the safety of shorter people. In this project we did not consider bumper height below the knee of fifty percentile Indian male. However, this aspect deserves attention if the truck and car bumpers have to be made at the same height. Direct bumper-knee impact is to be avoided for a majority of victims involved in crashes. For a fifty percentile Indian male, maximum bumper width can be 25 cm avoiding direct impact of bumper with both the pelvis and the knee (assuming the top bumper edge to be at 75 cm). Providing bumper offset reduces injuries to head and thorax in case of impacts with the side of dummy. Most trucks on Indian roads have small offsets including few recently launched models. Our investigations indicate that these models are not safe for pedestrians. Our simulations indicate that a bumper offset of 20-25 cm is required for a fifty percentile Indian male. Although increasing the angle of front panel reduces the injuries to head and thorax, same effect could be achieved by giving more bumper offset. Providing bumper offset is easier.

By optimizing the geometrical parameters, injuries to head and chest have been reduced below the safety limits for impacts with the side of dummy up to speeds of 35 km/h without changing the force- deflection curve. However, impact of the optimized designs with the front of dummy gives very high values of HIC and Chest at 35 km/h. The final force- deflection properties and geometrical parameters of truck panels should be decided after considering impacts with the side as well as the front of dummy for different dimensions of pedestrians.

The simulations performed in this project show that lower legs hit the bumper as the body rotates after the impact resulting in injuries. The injury data obtained from Delhi hospitals also shows fractures to lower extremities at heights of leg lower than the bumper height. However, we are not certain of the mechanism of injury as modeled with the current inputs and the magnitude of the impact force cannot be considered accurate as this impact occurs later in simulation and by that time the cumulative error in calculation becomes quite large. More detailed work would be necessary both in determining the epidemiology of leg injuries in real world crashes and in validation of simulations. Forces on upper legs are determined primarily by height of the bumper. However varying bumper height alone is not enough to reduce the forces below the safety limit. It is required to make the bumpers softer by covering them with softer material.

Since the dummy used in this project is not validated for impacts involving its front, only a few preliminary observations could be made for such impacts. Impacts with the dummy front result in higher value of HIC compared with impacts with the dummy side. Head hits the grille before the thorax. Both legs suffer high forces unlike impacts with the dummy side where only the leg directly hit by bumper undergoes a high force. Upper arm force is lower in these impacts. Further studies need to be done to evaluate details of injuries in a frontal impact with the dummy. In addition the final optimization would have to include pedestrians of different and sizes.

REFERENCES

Gibson T.J., Hinrichs R.W., Mclean A.J. *Pedestrian Head Impacts* : Development and Validation of A Mathematical Model, Proceedings of International IRBOBI Conference on The Biomechanics on Impacts, Zurich, 1986, pp. 165-176.

Hoefs R. and Heinz M. *A Bumper for Both Pedestrian and Vehicle Body Protection : A Contradiction in Terms of a Soluble Conflict.* Proceedings of the 11th International ESV Conference, Washington, 1987, pp. 821-830.

Ishikawa H., Kajzer J. and Achroeder G. *Computer Simulation of Impact of the Human Body in Car-Pedestrian Accidents.* Proceedings of the 37th STAPP Car Crash Conference (SAE paper 933129), 1993.

Janssen E.G. and Wismans J. *Experimental and mathematical Simulation of Pedestrian and Cyclist Vehicle Accidents.* Tenth International Technical Conference on Experimental Safety Vehicles, Oxford, England, US dept. Of Transportation, NHTSA, USA, 1985, pp. 977-988.

Mohan D., Kajzer J., Bawa-Bhalla K.S. and Chawla A. *Impact Modeling Studies for a Three Wheeled Scooter Taxi.* Accident Analysis and prevention, 29:2, 1997, pp. 161-170.

Mohan D., Patel R. and Kumar A. *Development of Ergonomic Evaluation Facility for Indian Tractors.* Transportation Research and Injury Prevention Program, Indian Institute of Technology, Delhi, 1997.

Van Wijk, Wismans J., Maltha J. and Wittebrood L. *MADYMO Pedestrians Simulations*. Proceedings of Pedestrian Impact & Assessment, P-121, International Congress and Exposition Detroit, SAE Warrendale, USA, 1983, pp. 109-117.

Yang J. and Kazjer J. *Computer Simulation of Impact Response of the Human Knee Joint in Car-Pedestrian Accidents*, 1992.

Yang J. and Kajzer J. *Mathematical Model of Pedestrian Lower Extremity.* Proceedings of the 14th International Conference on Enhanced Safety Vehicles, Munich, Germany, 1994.

Yang J.K., Lovsund P., Cavallero C. and Bonnoit J. *A Human-Body 3D Mathematical Model for simulation of Car-Pedestrian Impacts*. International IRCOBI Conference on the Biomechanics of Impacts, 1997.