

Developments in designing safer vehicles for urban transport: an issue of sustainable development

Sudipto Mukherjee and Dinesh Mohan

Transportation Research and Injury Prevention Program
Indian Institute of Technology, Delhi

Introduction

The performance requirements of the sustainable urban vehicle for private transit are examined with focus on projected demands in India. We suggest that light weight small vehicle designed for use in mixed traffic in India would have to be maximise both for occupant and pedestrian safety and probably also limit operating speeds and area of operation. Two significant emerging technology, micro structuring at millimetre scale and the finite element human body models for impact analysis would play a significant role evolving the urban vehicle.

Demand

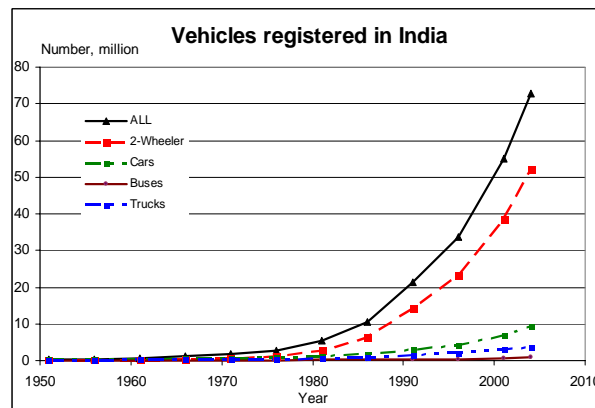


Figure 1 Growth of registered motor vehicles in India (Source: Ministry of Road Transport and Highways).

Figure 1 shows the growth of motor vehicles registered in India according to official data available (Department of Road Transport & Highways, 2008). The rise in two wheeler (MTW) growth rate has been higher than that of cars, buses and trucks but the relative growth rate as compared to cars has been reducing since 1990. These statistics probably over represent the number of private motor vehicles in India as those vehicles which go off the road due to age do not get removed from the records. This is because annual registration of private vehicles is not necessary and owners only pay a one time tax at the time of purchase. There is some official statistics that indicate so.

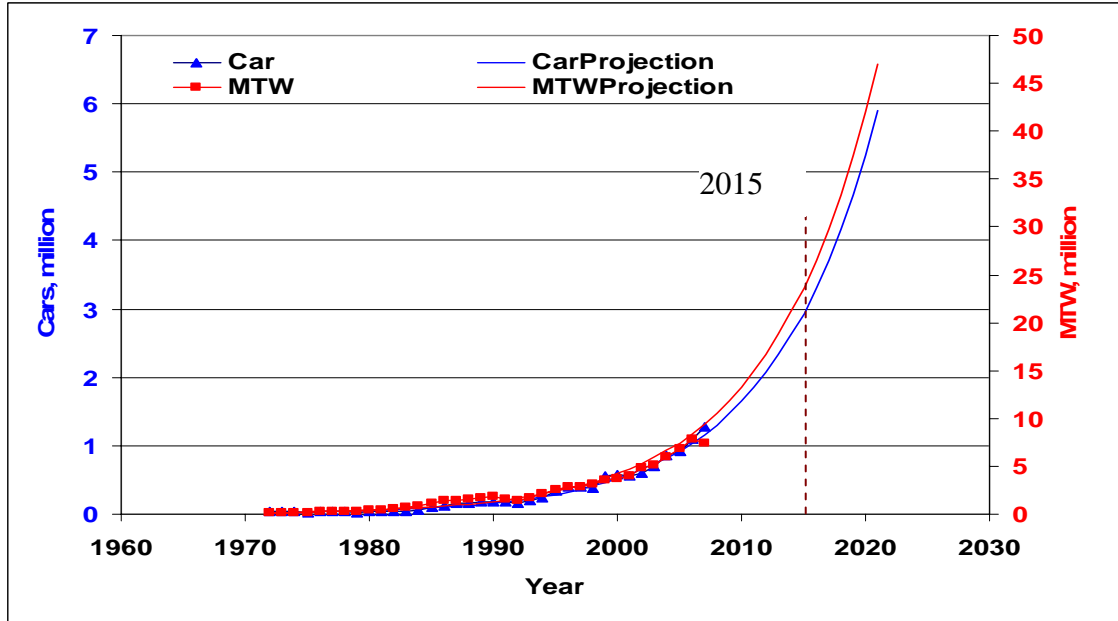


Figure 2. Car and mortised two-wheeler sales in India (Source: SIAM) and sales projections.

Figure 2 shows the sales trend of MTWs and cars from 1972 to 2007 in India and these data are used to project future sales by using an array formula and fitting the curves to the data available. The fitted curves show that the sales ratio between MTWs and cars (~ 7.5) is not expected to change much in the next decade. These projections are based on the past trends, do not take into account future changes in relative car or fuel prices and there is an implicit assumption that the income growth rates experienced in the past 5-8 years continue over the next decade. With these assumptions (“business as usual”) we get projected car sales of 2.9 million and MTW sales of 23.6 million in 2015.

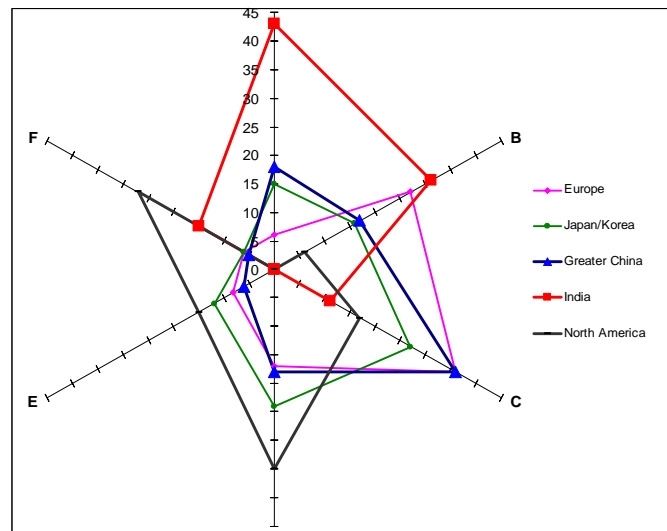


Figure 3. Regional car segment share in 2013 (Adapted from Cather, 2007).

CSM projects that the “A” segment will constitute about 43% of the car market in 2013. Based on this we get “A” segment sales of 1.3 million cars assuming business as usual and no major hiccups in development trends. The entry of even smaller cars may comprise a portion of the segment A sales (around 1 million or less in 2015) and greater proportion of the segment occupied by TWs today (> 1 million in 2015). International data show that countries that have a history of high motorcycle ownership, also have relatively lower car ownership rates. This is not likely to change dramatically in the next few years.

Pollution

Starting the late twentieth century we were alarmed by the effects of vehicular pollution but improvements fuel efficiency and reduction in vehicle emissions through technological interventions lulled us into business as usual future planning. The recently released WHO World Report on Road Traffic Injury (Peden et al., 2004) has heightened concerns regarding road safety but not really alarmed us into rethinking the current transportation paradigm to take care of the millions of deaths and disabilities caused annually by road traffic.

The release of the IPCC report on climate change has changed the ground rules and transportation planning will have to keep these issues centre stage (IPCC, 2007). The implications of the IPCC report are at one level very simple – if the human race has to survive it has to limit CO₂ emissions in a very short time. This means that the developed countries have to reduce their CO₂ emissions by more than 60% in the next 40 years and India cannot increase its average emissions more than two or three fold. Both goals are very difficult. For us in India, it means that while the poorer sections of the population may increase their consumption to reach “comfortable” living norms, the richest in India (read car owners) will have to reduce their CO₂ emissions like in European. This will have to form the base of our sustainable transport policies for the near and long term future.

Studies concerning car use and CO₂ emissions tend to favour the opinion that the maximum reductions will come from reductions in use rather than improvements in engine efficiencies (Lumbreras et al., 2008).

	Internal combustion engine vehicles	Hybrid electric vehicles	Fuel-cell vehicles methanol	Fuel-cell vehicles hydrogen	Battery-powered electric vehicles
Energy use (kW h/10 km)	4	3	3.2	2.6	1.7
NO _x (g/km)	0.06	0.04	0.04	0.03	0.04
VOC (g/km)	0.043	0.010	0.010	0.008	0.001
PM (g/km)	1.20	0.90	0.96	0.78	2.50
CO ₂ (g/km)	12.0	9.0	0.6	0.78	1.5

Table 1. Energy used and life-cycle emissions (tail-pipe plus pre-vehicle emissions (Georgakellos, 2008).

Table 1 shows estimates of energy used and life-cycle emissions from average size cars (Georgakellos, 2008). This shows that CO₂ emissions from internal combustion engines are the highest compared to other technologies. However, none of the other technologies are likely to be economically feasible by 2015, especially for smaller cars. Therefore, there is no choice but to minimise the size of the engine to enable benefits from lower CO₂ and other pollutant emissions as compared to other cars.

Table 2. Estimate for CO₂ emissions for a fleet of 100 cars with expected segment distribution in 2015 in India.

Car segment	Proportion in 2015, %	Average, engine capacity	Estimated CO ₂ /km	Emission/km for car share
A	43	1000	125	5,375
B	31	1500	170	5,270
C	11	2000	200	2,200
F	15	3500	260	3,900
Total CO ₂ per km for fleet of 100 cars				16,745

It is hence imperative to ensure fewer and shorter trips to propose a vehicle with smaller size and hence peak speeds to minimise CO₂ emissions. It is not unreasonable to target a small car with a ~600 cc engine giving 30 km/l fuel consumption and 80 g/km CO₂ emissions. It is expected that technology options for the vehicle in terms of engine efficiency, fuel choice and materials for minimising mass of the vehicle have to be developed. Further, tax based on CO₂ emissions, parking charges and road use charge proportionate to vehicle size and development of software and hardware for optimising use of vehicle as a taxi and in car share programmes will be needed.

Crash Safety

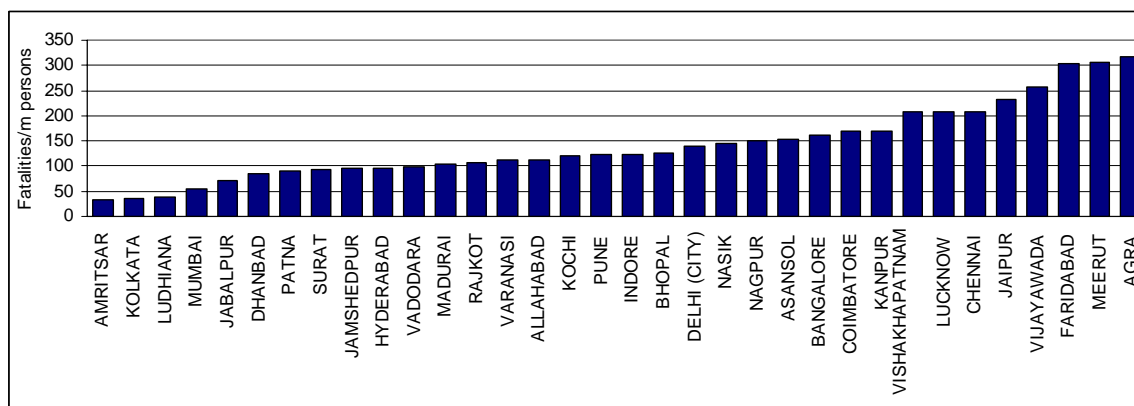


Figure 4 Fatality rates in Indian cities , 2006

Figure 4 shows the fatality rates in cities with million plus population in 2001. A majority of them have rates that are higher than the average for the country and there is no pattern of high or low rates based on region of the country. Figure 5 shows that the majority of those killed are in the working age group. At these rates, road traffic injuries become the major cause of morbidity and mortality for young adults and working age population in India. Any new vehicle design must ensure that these trends are not exacerbated in the future. The vehicles have also to be made pedestrian friendly so that users of public transport feel comfortable with crossing the road.

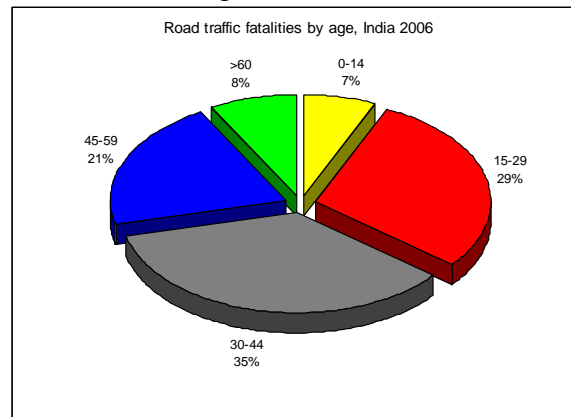


Figure 5 Age distribution of road traffic fatalities in India, 2006

In urban areas in India, pedestrians, bicyclists and MTW rider victims can amount to a total of 70-80% and in rural areas > 50% (Mohan, 2004). Crash patterns also suggest that cars have a significant number of impacts with buses and trucks. Even the smallest mainstream European car has a top speed of around 130 km/h. It also has to pass the same crashworthiness requirements as all other cars. This results in all current cars being grossly over-powered for normal urban and suburban use. It also means that their fuel efficiency and emissions, because of unnecessary mass and engine performance, are far from ideal for the cities of Asia. Their size is a major limitation in conditions of congestion. These factors are especially relevant in the heterogeneous traffic of the megacities of India and our understanding is that no mini car does well in pedestrian impact protection at present.

The case of pedestrian safety has not been ignored by automotive safety professionals. Much is known about the circumstances of pedestrian/car collisions in western environments, and that knowledge has been translated into the EU directive governing exterior design and the pedestrian requirements of EuroNCAP. We feel that under the current model of a single car and standard for every usage, it might be difficult to protect the urban pedestrian effectively. Accident data suggests that the major injuries in reality are to the head and the lower limbs. At speeds below 40 km/h the incidence of serious chest and hip injuries is much less (Ashton and Mackay, 1979; Otte, 2001). We would suggest that the urban car should be evaluated only against head and lower limb measures at 40 km/h.

Technological advances in terms of airbag designs for both the interior, for all crash types, and the exterior for vulnerable road user protection are occurring rapidly. In

addition short range radar is now feasible for the detection of both vehicles and pedestrians at about one second prior to impact. These technologies open up new systems of protection for all road users. Although currently expensive and still under development, high volume production will reduce costs rapidly and some of these advances will become candidates for the proposed vehicle very soon.

Great importance must be attached to the exterior geometry and the compliance of the external structures. Conventional car design today tunes the forward components of the car to provide optimal protection of the occupants in a 50 km/h barrier crash by providing a ride-down distance of around 50 cm. Urban car design of the future should use some of that crushing structural space to minimise the injuries to VRUs. Just 5 cm of appropriate deceleration distance for the pedestrian at the 20 – 40 km/h level at which most pedestrians are struck and injured by today's cars will greatly reduce the risk of those injuries occurring.

The standardisation of the height of bumpers at around 56 cm above the ground coincides with the average knee height of an adult. This has had the unfortunate result that the majority of serious leg injuries involve the knee joint, the disruption of which can produce significant long term disability. The bumper height chosen leads to *maximising* the injury severity at the minimum possible speed. Clinical studies have shown that if the leg is struck either below the knee or above it, but preferably below, the outcomes are more favourable (Cesari, 2007).

Hence a low bumper height is to be preferred, presenting as large an area as possible for the actual contact zone on the leg. This also has benefits for children in that it reduces the incidence of being run over by the vehicle, a particularly hostile and often fatal type of accident. This means that the upper edge of the bumper should be not be higher than about 350 mm.

The incidence of rollover incidents which are associated with high speed crashes will be relatively low as most probable events would be intersection collisions. The main focus therefore should be on frontal, lateral and rear end collisions. Relaxing the rollover requirements would reduce the structural integrity requirements of the upper sections of the vehicle structure, including the windscreen and pillars to be downgraded. This would allow use of softer, impact friendly materials, including plastic.

Structured material

Aluminium honeycomb is a structure made up of hexagonal aluminium foil cells (Figure 6). It derives its name from its close resemblance to a bee honeycomb, though there is no variation in the depth direction. The honeycombs of hexagonal cell structure are characterised by considerable rigidity in shear, high crushing stress, almost constant crushing force, long stroke, low weight and relative insensitivity to local loss of stability.

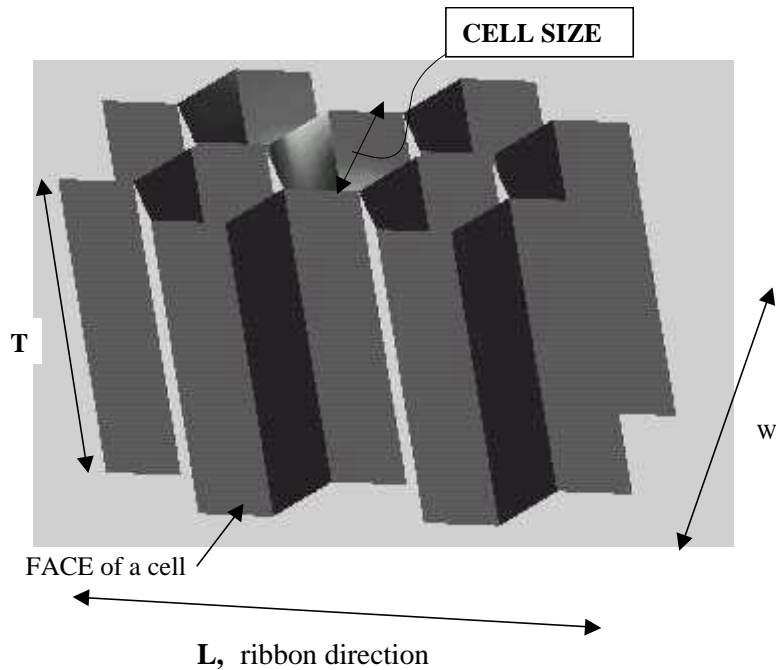


Figure 6, The honeycomb.

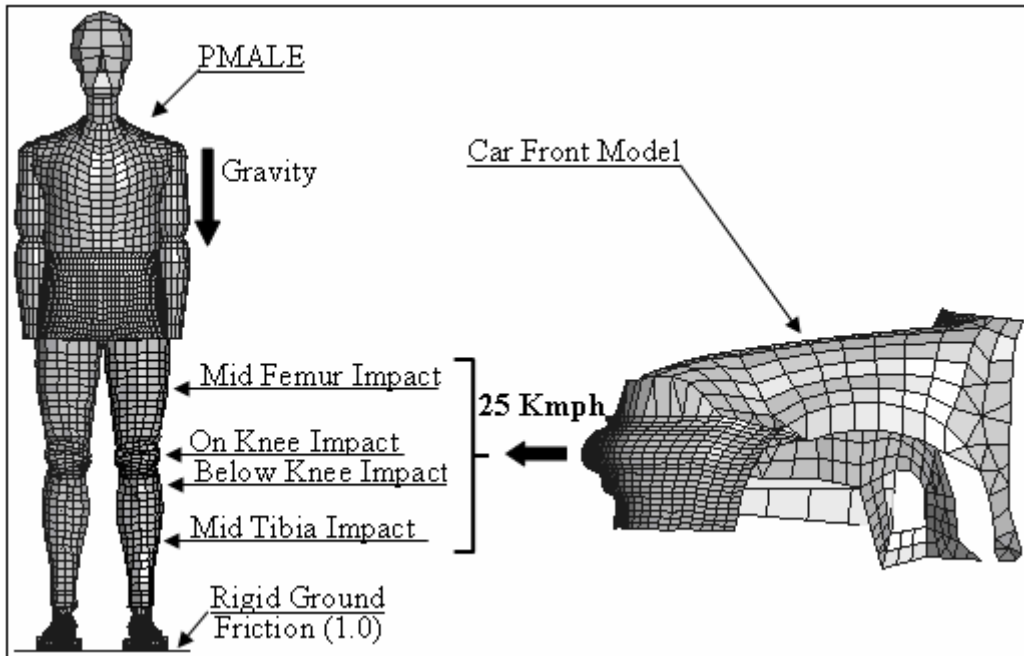
Aluminium has a Young's modulus of 70GPa, initial Yield stress of 265 MPa, density of 2680 kg/m³ and a tangent modulus of 0.6GPa at 300MPa stress. Energy dissipated to failure can be estimated to be of the order of 3 mJ/m³ or equivalently about 1 kJ/kg of material. SHOWA ¾ - AL-5052-0.003N honeycomb has on the other hand has a Young's modulus of 0.7 GPa, Yield stress of 1.6 MPa, effective density of about 20 kg/m³, and crush stress of 0.5 MPa (Dileep Kumar, 2003). At a nearly constant stress value of 0.5 MPa, honeycomb deforms to a strain of 0.6 and then behaves like normal aluminium. So the honeycomb configuration gives an additional energy dissipation capacity of 100 kJ / m³ or 5 kJ / kg of material. Note that the effective stiffness of native aluminium per unit mass 70 GPa divided by 2680 kg/m³ and that of the honeycomb structure made from aluminium, 0.7 GPa divided by 20 kg/m³ are very close to each other.

Using $\frac{1}{2} mv^2$ as the measure of energy to be dissipated in each car, it catches up with that of honeycomb only at about 100 m/s. However if crashes below 10 m/s are targeted, we need only a hundredth of the mass of the car, if it is made 'wholly' of honeycomb like material, Typically a 40 mm crush zone would suffice. It is suggested that use of efficiently structured materials could have a significant role to play in the urban car.

Human Body Models

Current understanding of human lower limb response, especially the knee joint, in car-pedestrian crashes is based on the results of cadaver tests in a few configurations. However, real world car-pedestrian accidents involve live human body, and not the cadaver. One of the significant functional differences between a live human and a

cadaver is the ability of live human to generate active forces in its muscles to perform routine tasks. Thus, the effects that muscle contraction could have on the lower limb response have not been studied so far. It is understood that, active muscles when contracted for the locomotion or for the postural control, share the load with ligaments, and eventually unload them.



(a)

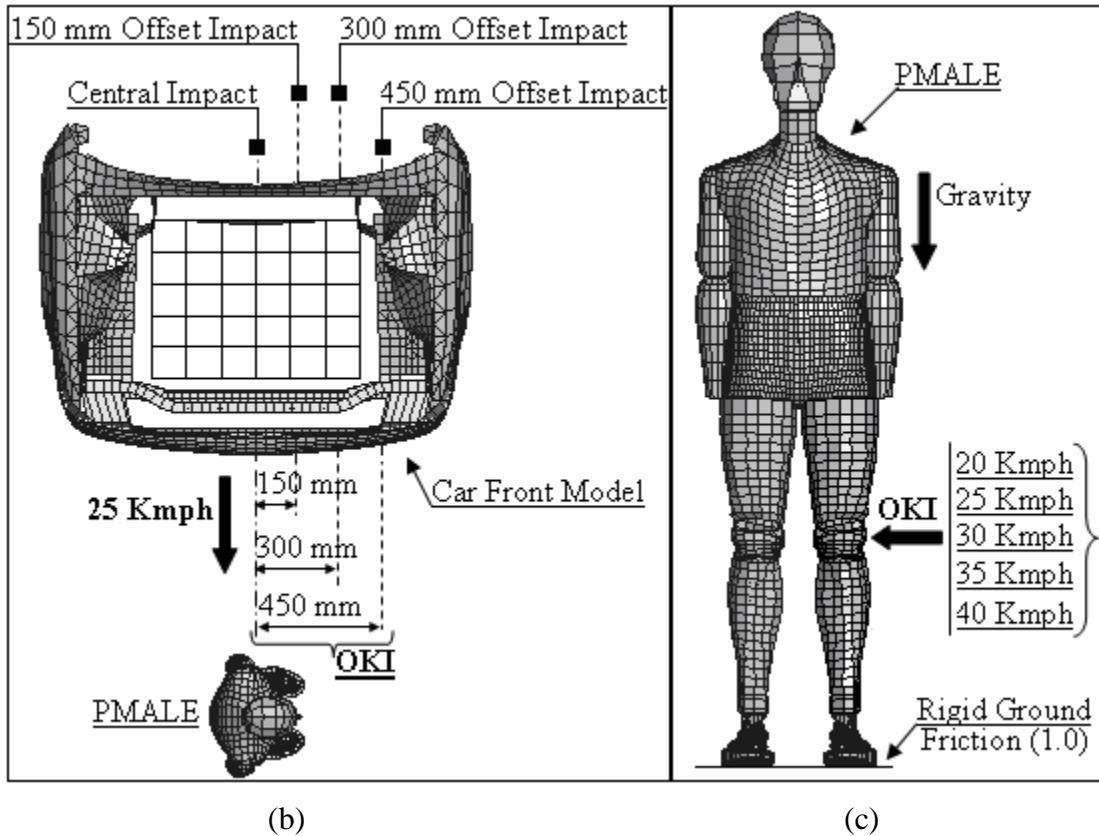


Figure 7 Simulation setup to study the effects of muscle forces in a symmetrically standing pedestrian for (a) impact at four heights (b) four standing positions in front of car and (c) five impact speeds

Furthermore, unlike car occupants, pedestrian crashes occur in a variety of postures (like stationary, walking, running or jogging etc). These postures are directly controlled by muscles; therefore, they are expected to modify the crash outcomes. The need to investigate the effects of active muscle forces on the response of lower limb in car-pedestrian crashes stems from the high muscle activation levels at the onset of such activity.

A typical pedestrian study would involve variations with height if impact and offset position as shown in Figure 7 with outcome differences as shown in Figure 8 (Soni, 2006).

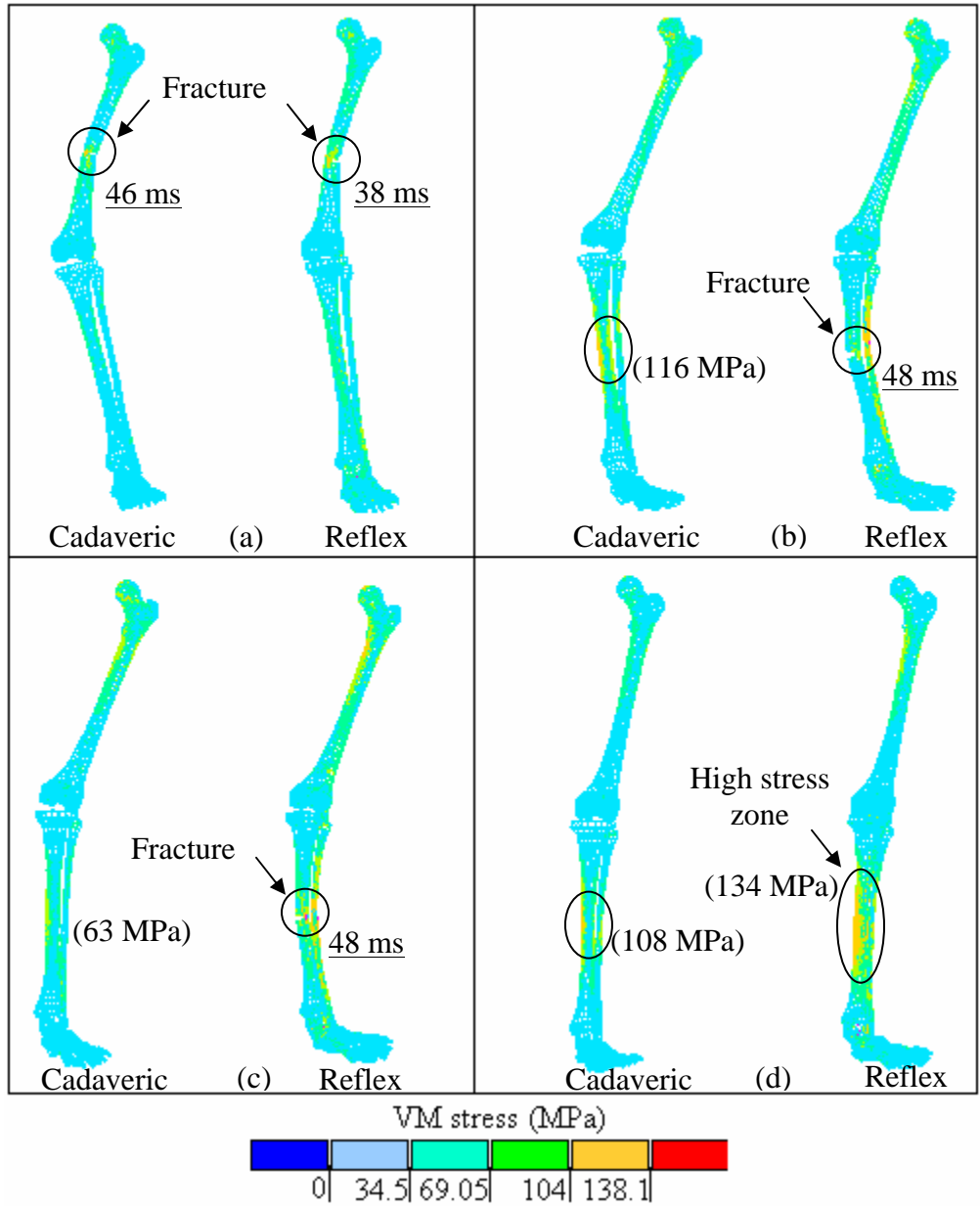


Figure 8 VonMises stress distribution in bones (peak stress values are also given) for (a) Mid Femur Impact (b) On Knee Impact (c) Below Knee Impact and (d) Mid Tibia Impact configurations in both cadaveric and reflex conditions

Chrysler LLC, Ford Motor Co., General Motors Corp., Honda R&D Co., Hyundai Motor Co., Nissan Motor Corp. Ltd., PSA Peugeot-Citroën, Renault s.a.s., Takata Corp., Toyota Motor Corp. and TRW Automotive are all members of the Global Human Body Models Consortium, which created a Limited Liability Company (LLC) in April 2006 following three years of organizing and planning. GHBM plans to build over several years a family of virtual humans, from children to elderly. Please see <http://www.ghbmc.com/> for further details. As shown above, this technology allows us to evaluate all statistically relevant scenarios, which are many for the VRU, to evolve a design for the urban car.

Conclusions

We hence propose an urban car with an engine displacement of 600cc, with peak speed around 50 km/h. With a city reorganised for mass public transit, this urban car would have mean trip durations of 12 mins, enabling a low mass design satisfying occupant and pedestrian safety measures. New materials for the car structure including plastics and microstructured compositions are suggested. Several emerging technology including short range radar and FE human body models would enhance active and passive safety for vulnerable road users.

References

- Ashton, S., Mackay, M., (1979). Car design for pedestrian injury minimisation. National Highway Traffic safety Administration, Department of Transportation, Washington D.C., pp. 630-640.
- Cather, C., (2007). Faster, Better, Cheaper & Cleaner: The Dynamics Driving the Global Automotive Industry. CSM Worldwide, Delhi.
- Cesari, D., (2007). Pedestrian leg injuries. Institut National de Recherche sur les Transports et leur Sécurité (INRETS), Paris.
- Chawla A, Soni A and Mukherjee S, (2006) Effect of active muscles on knee ligament forces during impact, Journal of Biomechanics, Vol 39, Suppl 1, 2006, P-S160.
- Department Of Road Transport & Highways, (2008). Traffic Data. Ministry for Shipping, Road Transport and Highways, New Delhi, <http://morth.nic.in/index2.asp?sublinkid=369&langid=2>. Accessed 8-20-2008.
- Dileep Kumar, A Chawla, S Mukherjee, T Nakatani and M Ueno, (2003), Prediction of Crushing behaviour of honeycomb structures, International Journal of Crashworthiness, Vol 8, No 3, pp 229-235, 2003.
- Georgakellos, D. A., (2008). A polygon-based environmental appraisal of new vehicle technologies combined with renewable energy sources. Transportation Research Part D 13, 283-288.
- IPCC, (2007). Climate Change 2007: Synthesis Report. Intergovernmental Panel on Climate Change, Geneva.
- Lumbreras, J., Valdes, M., Borge, R., Rodriguez, M. E., (2008). Assessment of vehicle emissions projections in Madrid (Spain) from 2004 to 2012 considering several control strategies. Transportation Research Part A: Policy and Practice 42, 646-658.
- Mohan, D., (2004). The road ahead: Traffic injuries and fatalities in India. Transportation Research and Injury Prevention Programme, Indian Institute of Technology Delhi, New Delhi, pp. 1-30
- Otte, D., (2001). Analysis and load assessment of secondary impacts to adult pedestrians after car collisions on roads. Proceedings 2001 International IRCOBI Conference on the Biomechanics of Impact. International Research Council on the Biomechanics of Injury, Zurich, pp. 143-160
- Peden, M., Scurfield, R., Sleet, D., Mohan, D., Hyder, A. A., Jarawan, E., Mathers, C., (2004). World report on road traffic injury prevention. World Health Organization, Geneva.