Occupant and exterior safety of low mass cars (LMC)

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Abstract

The increasing public demand for vehicles characterized by a low energy consumption combined with a favourable emission profile is currently leading to the development of low mass cars (LMC). Typical masses are anticipated to be around 500 kg for a vehicle capable of accommodating two occupants and an acceptable baggage load. The fuel consumption should not exeed two litres per 100 km (or electric equivalent). These cars will however circulate in general traffic together with many much heavier vehicles. Due to cost and weight restraints as well as due to the involvement of manufacturers lacking in-depth experience in mass production of cars and in safety engineering, conventional low mass vehicles must be expected to be associated with a severe occupant safety problem.

Conventional car crashworthiness features include an exterior deformation zone of maximal possible size in combination with a rigid passenger compartment allowing for a favourable occupant ride-down in the case of a frontal collision. Side collisions are given increasingly more attention while offset and oblique impacts remain problematic. Already a crude analysis shows that a comprehensive safety concept has to be worked out for LMC's which can only partially be adopted from conventional design. A stiff exterior which is largely identical with the passenger compartment, an increased size of this compartment as a partial compensation, a possible removal of the steering column, the steering wheel and the foot pedals allowing the integration of safety seats into the vehicle structure, combined with a customized airbag, an advanced belt system and an injury reducing interior contact zone highlight the topics of the future development of LMC's. Since low mass vehicles are expected to be used predominantly in urbanized areas with a high percentage of unprotected road users, furthermore, special attention will have to be given also to the exterior collision safety.

A comprehensive safety improvement for LMC's includes also a number of measures in the area of accident prevention and collision avoidance.

General aspect of traffic safety of low mass vehicles

From a physical point of view the passive safety potential of low mass vehicles is limited a priori due to unfavorable mass ratio effects and geometrical incompatibilities (Fig.1). Satisfactory collision compatibility at a mass ratio of, e.g., one to five can not be achieved by practical passive safety measures at cruising speed levels of 100 km/h.

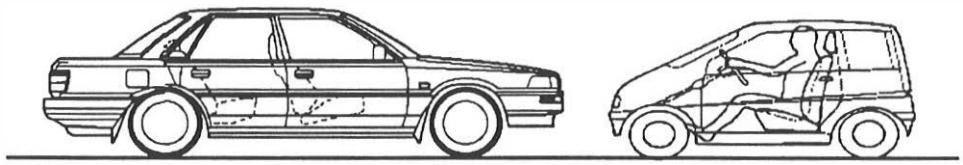

Fig. 1. The injury risk of the occupants of small lightweight cars is high due to the infavourable mass ratio and the geometrical incompatibility. Unconventional safety designs have to be evaluated.

Yet, an accident does not occur per se but rather some driver is responsible for the collision, althemore as technical defects have become very rare. Therefore, the goal of safety improvement for LMC's should not be restricted to passive safety elements but include a number of measures in the area of accident prevention and collision avoidance, in particular,

- human factors (safety education, psychology, ergonomy, health related ability to drive)
- road and road environment (traffic engineering)
- law and enforcement
- vehicle (ergonomy, active safety).

The driving behaviour is influenced by many conscious and unconscious elements, in particular aggressive car advertisements and social stress situations may play an unfavourable role. The damage files of insurance companies contain furthermore an unproportionally large share of high powered sporty cars. In contrast, a psychologically well designed car can contribute to a safe driving style, e.g., by a non-aggressive car shape, an agreeable interior lay out, a presentation of information based on ergonomic considerations, a relaxed seating position, and a comfortable environment in the compartment (noise, vibration, temperature). Advanced suspension concepts should not primarily lead to higher possible velocities but to an error-tolerant vehicle behaviour.

Some measures of active car safety - shown to be effective on the proving ground - can lead to an increase of the subjective safety feeling in a general traffic environment and may thus induce a high risk driving style (WILDE 1978, TRIMPOP 1990, BIEL 1987). Moreover, a car rated "very safe" in crash tests or in accidend analysis (GUSTAFSSON 1989) can eventually create additional hazards to other road users, e.g., due to excessive stiffness and weight or due to high front structu-

res, such as is seen with four-wheel-drive off road vehicles or pick up trucks (TERHUNE 1984). Of particular significance in the discussion about safety of low mass cars are the concepts of partner protection and collision compatibility. While conventional low mass vehicles are associated with a higher a priori hazard to their occupants they may contribute to a higher general safety level in traffic since they represent a lower hazard to other road users.

Some of the low mass cars are expected to be made of fibre-reinforced plastic materials of which crash behaviour and toxic properties are not sufficiently known to date. Other components used such as batteries, flywheels etc. have to be chosen according to longterm toxicological and crash related performance.

1. Occupants

a) Frontal, offset, oblique and side impacts

A reasonable requirement for LMC safety performance is that it should at least be comparable to the one of relatively small current production vehicles. The latter can be summarized as follows:

- Frontal impacts: FMVSS 208 standards are fulfilled.
- Offset and oblique impacts: Tests performed by NHTSA, car manufacturers and various consumer organizations (e.g., PLETSCHEN et al. 1990) indicate that the passenger compartment of many current production vehicles are prone to collapse under these conditions thereby generating a high risk to driver and front seat passenger.
- A general limit for severe injuries to restrained occupants of conventional cars is situated at a Δ-v of about 50 km/h (Fig.2)

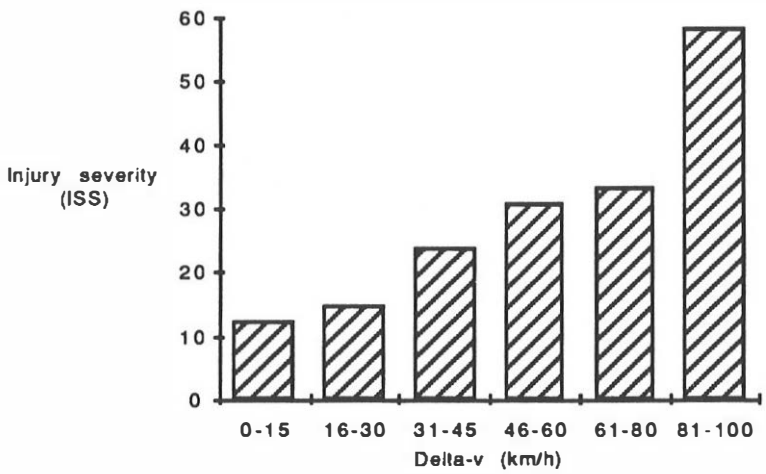

Fig. 2. Δ-v and injury severity (ISS) for injured restrained front seat occupants (MAIS 2+, all directions). IAU (1977).

- In a hypothetical frontal collision between two vehicles of masses $m_1 > m_2$,

with equal but opposite speed v, and under fully plastic conditions, the lighter vehicle (m_2) undergoes a Δ-v which is proportional to $2m_1/(m_1 + m_2)$, i.e., in the limit $m_1 >> m_2$, the LMC experiences a Δ-v which reaches twice the value obtained for equal mass. The highly adverse influence of the mass ratio is also observed in the field (APPEL 1972, MACKAY 1973, EVANS 1984 and 1987, GRIME 1976).

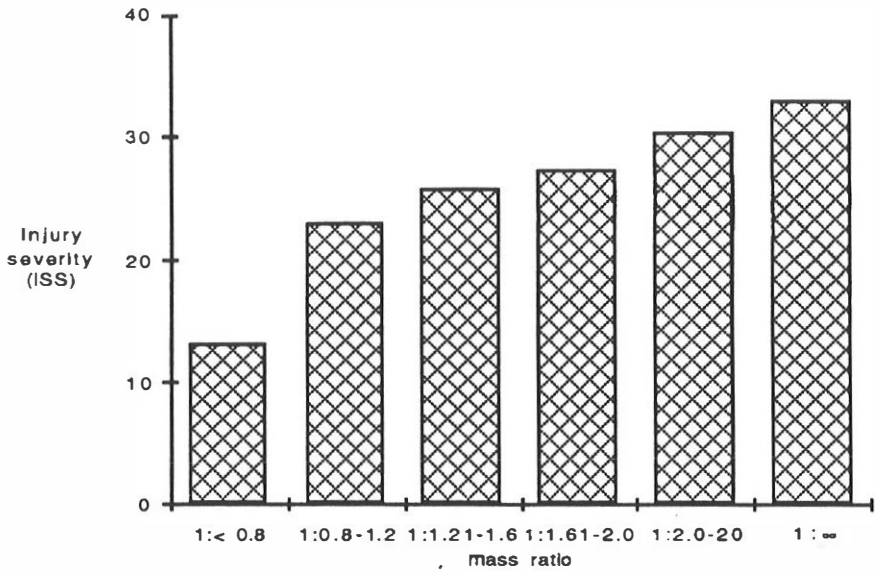

Fig. 3. The mass ratio of the collision partners has a significant influence on the injury severity (restrained occupants with MAIS 2+, all directions). IAU (1977)

- From general accident statistics it is estimated that injury severity in cases of accidents causing severe injuries is increasing monotonically with cruising speed (Fig. 4). Yet, Δ-v values are typically 20% - 50% lower than associated cruising speeds.

From these considerations it is concluded that the maximal speed of LMC's should not exceed 80 km/h, which is compatible with the speed limit on rural roads in many countries.

In order to achieve an acceptable protection capacity, a LMC should fulfill the FMVSS 208 in the first place. In addition, tests should be conducted at 30 degree (left side) as well as in the left side 50%-offset crash configuration. The latter impact configurations are frequent and critical (BAUMANN 1990, PLETSCHEN 1990, ZEIDLER 1990). Since LMC's will be used predominantly in or near the urban areas with lower speed limits the test speed could be reduced in a first phase of development to 30 or 40 km/h (APPEL 1990).

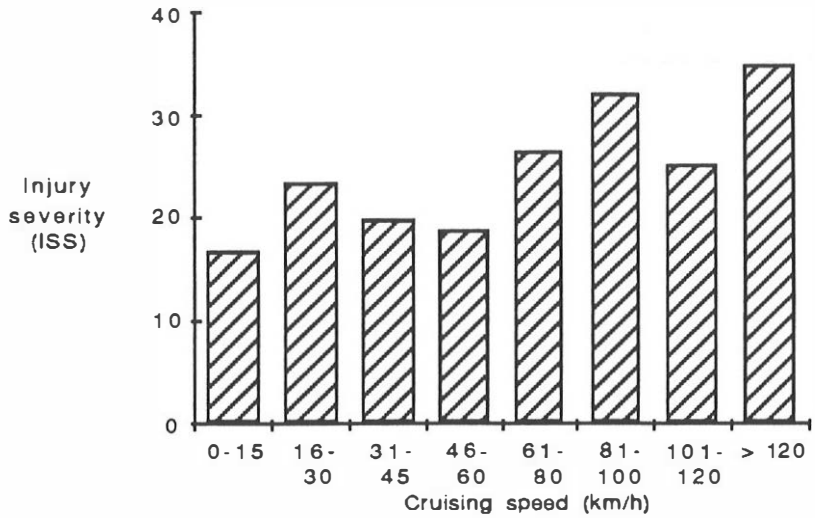

Fig. 4. Cruising speed and injury severity for restrained occupants with MAIS 2+ (all directions, IAU 1977).

Conventional crashworthiness concepts are generally based on the combination of a frontal crush zone and a rigid passenger compartment. In such a fashion, occupant ride-down characteristics are obtained which allow for a deceleration within biomechanically tolerable limits even under realistic, i.e., non-optimal conditions (out-of-position occupant, belt slack, etc.). In the case of a LMC, the car body exhibits little frontal area in excess of the passenger compartment. Accordingly, occupant protection has to be achieved in essence with a very short frontal deformation zone. Because a collapse of the compartment has to be prevented to the highest possible degree, the load bearing capacity of the structure of the LMC has to be higher compared to the one of a conventional car. This derives from the fact that mutual contact forces between two cars in a collision are equal, but the crush zone of a conventional car is allowed to be deformed while the LMC should resist.

For structural reasons, it will be advantagous to integrate the occupant safety seats into the vehicle body. Since these seats will be fixed, steering column, steering wheel and foot pedals may have to be replaced by an advanced vehicle control system. It should be noted that the removal of the steering column in itself represents a safety feature because this component still constitutes a hazard in many situations. A further advantage of such a concept consists of the possibility to increase the passenger compartment space over current dimensions.

A number of preliminary theoretical simulations was performed in order to evaluate occupant ride-down characteristics in a virtually stiff vehicle. For this purpose, a two-dimensional occupant simulation model (NIEDERER, 1980) (Fig. 5) was used. The simulation included the following typical, in part idealized features:

- smooth, trapezoidal deceleration pulse
- upright occupant position

- belt with energy-absorbing webbing
- optimal belt geometry without slack
- more free space in front of the occupant in comparison to the space available in a usual car (in particular no steering column).

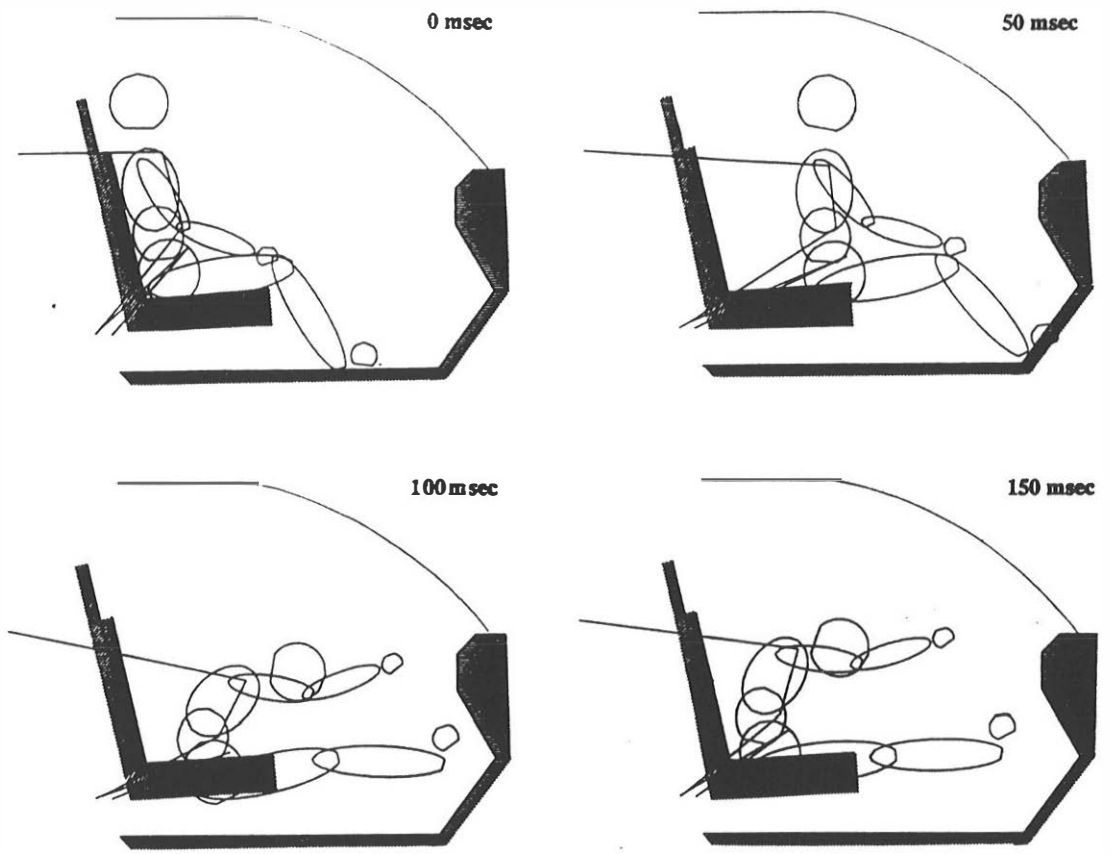

Fig. 5. Typical motion phases in a 40 km/h barrier impact as calculated with the aid of a 2-D motion simulator. The hypothetical deceleration pulse was assumed to be of 20msec duration. Note that the occupant undergoes no contact with the vehicle interior except for seat and foot panel.

Under these idealized conditions it is found that the duration of the deceleration pulse is of minor importance in comparison to other parameters, e.g. impact speed, belt slack, etc..

As an example, Fig. 6 exhibits the dependence of the Head Injury Criterion on the pulse length for 30 km/h, 40 km/h, and 50 km/h impact speed, respectively. The influence of the deceleration pulse is seen to be relatively small. It should however be noted that (i) these are hypothetical results not substantiated by experiments so far, (ii) one single parameter (HIC) cannot be regarded as a comprehensive classification of impact severity, (iii) these results serve as a general feasibility investigation rather than an actual design study. Yet, the present findings indicate that there seems to be a substantial potential for safety improvements, in particular, if more advanced restraint systems combined with appropriately designed air-bags are implemented (see also SAKAI et al.,1986).

Tests of side impacts according to FMVSS 214 should be performed as well. Again, in a first step reduced impact velocities could be used.

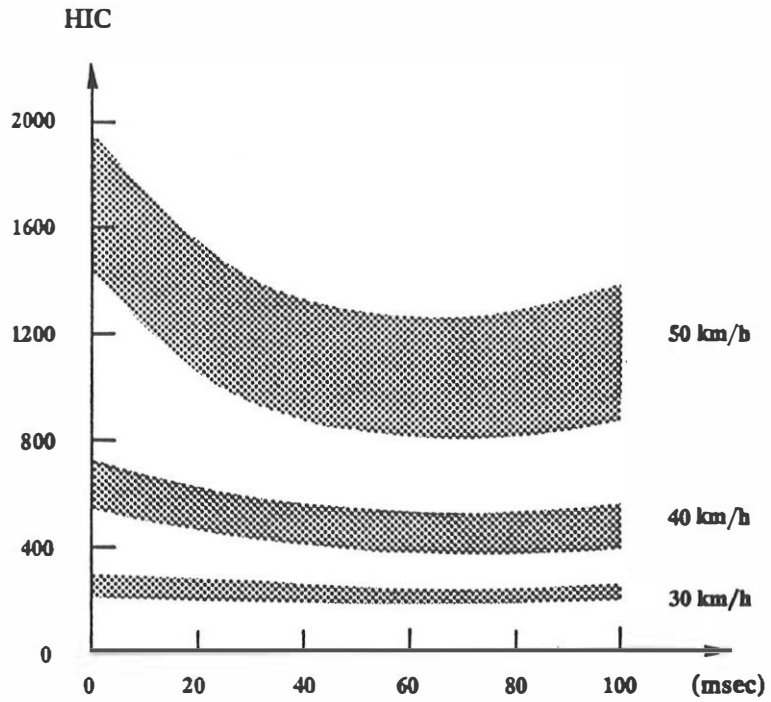

Fig. 6. Ranges of HIC-values estimated on the basis of a 2-D-occupant model as a function of impact duration for various impact speeds. A hypothetical trapezoidal deceleration pulse of the vehicle resulting from a barrier impact and an optimized three-point-harness were thereby assumed.

b) Rear impacts

The short dimensions in longitudinal direction of a LMC do not allow for a significant deformation zone in the rear. As mentioned above, to prevent intrusion the exterior shell therefore must be very stiff. This, in turn, causes a higher acceleration of the occupants also in rear end collisions. Current head restraints often are positioned too far away from the occiput and do not prevent neck injuries sufficiently in rear impacts, partly due to the fact that they can not prevent the translatory rearward movement of the head in the very first phase until contact with the head rest takes place (Fig. 7). Advanced head restraints should be positioned as close to the occiput as possible and they should support the neck also (Fig. 8).

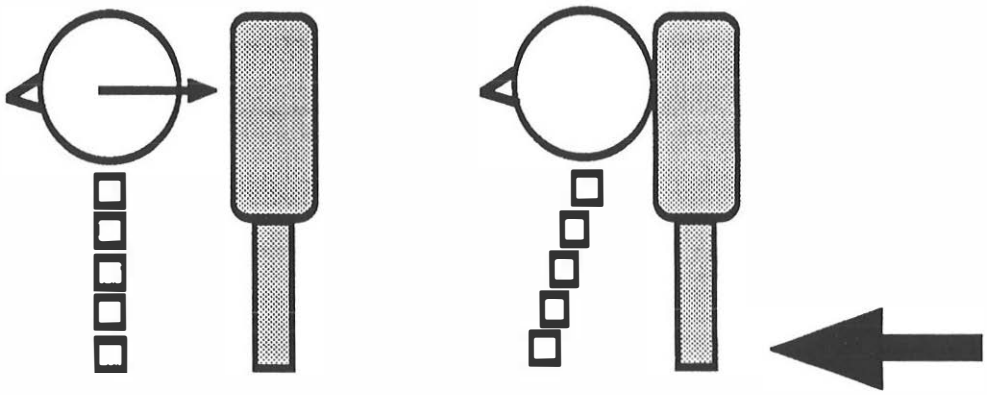

Fig. 7. During the first short phase of a rear end collision the head movement is translatory. This causes shearing forces between the vertebral bodies of the cervical spine.

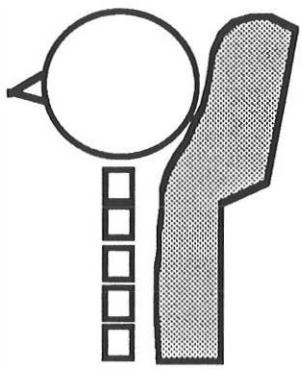

Fig. 8. Advanced head restraints should support the neck also.

2. Exterior safety (pedestrian and bicycle collision)

Though low speed limits and soft traffic engineering in urban areas are prerequisits for pedestrian safety, improvements of the car front structure can reduce the injury potential of the exterior road user. With current cars, the critical collision velocity for pedestrians is around 30 km/h. In a former design study it was shown that the biomechanical loading of a pedestrian dummy can be reduced to half in a 25 km/h collision if an appropriate front design with an active mechanism and adapted stiffness and form of the front structure is used. The principle of the mechanism described earlier (KAESER 1984 and WALZ, NIEDERER, KAESER 1986, Table 1) is:

- the pelvis/thigh contact accelerates the sliding hood backwards (50 ms)
- a guide shoe slides up a ramp and the rear part of the hood is lifted up (100 ms)
- the head impact deforms the lifted hood (150 ms).

		Average values of three tests		
Front structure	v_{coll} km/h	a_{max} (g)	dt (ms)	HIC
Renault 18 original	**35**	148	10.3	1347
Renault 18 modified	**35**	97	2.2	377
Renault 18 original	**25**	138	3.0	545
Renault 18 modified	**25**	87	1.1	200

Table 1. The loading of the dummy head could be reduced significantly by an active protection mechanism integrated in the front end combined with appropriate form and stiffness.

The shape of the car front also has a significant influence on the trajectory of the pedestrian; a high upper leading edge has a better protection potential for the head since the head contact occurs farther to the front end (covered with deformable material) instead in the area of the lower windshield or the hard frame.

3. Safety design propositions for LMC's

In this first phase of the study we can propose the following design principles for LMC's (see also Fig. 9):

- The load bearing exterior must be hard and stiff in order to prevent intrusion. A wedge or egg shaped form at the front could induce a favourable glance-off (no snagging). By modifying the weakest points in the design of the load bearing structure a considerably better crash performance could be achieved: longitudinal beams with open sections should be closed. The structural continuation of the car front leading to the longitudinal beams of the passenger compartment is mainly a simple sheet structure lacking structural stiffness. Here again the introduction of closed sections, stiffeners or sandwich type structure would lead to much better crash performance.

- Frontal and side intrusion should be prevented up to 80 cm above ground (upper leading edge of current cars). Therefore, the LMC should be higher than current cars (prevention of geometrical incompatibility). An interesting approach to a collision safe structure is to design a very stiff protection belt around nearly the whole car at a height which avoids intrusion of impacting cars which is around 80 cm above ground level. Concerning side collisions it would significantly ameliorate the situation if longitudinal beams with high closed sections and corresponding doors would be used. The relatively low top speed of 80 km/h allows some compromize in aerodynamic optimization which usually requires a low car shape. The higher driver position may also contribute to the avoidance of accidents (better overview).

• The load bearing structure of the future LMC will on one hand have to resist collisions with current high mass cars. On the other hand it has to withstand collision with a hard fixed obstacle such as a wall. The first condition asks for a "stronger" structure than current cars, this means collapse at higher loads. The second condition implies that the survival space of the passenger compartment needs a stronger structure than the front part of the LMC and that the crushing behaviour of the front part allows to absorb the kinetic energy. Thereby, a general proof of feasibility of acceptable crashworthiness with lightweigt structures has been given by a newer generation of helicopter design where crashes at 45 km/h are managed with a weight increase of less than 4% (KINDERVATER 1989).

• The low mass leads to a relatively high Δ-v in car to car impacts. The hard exterior shell (intrusion protection) increases this negative effect. As one compensation of this mass related incompatibility the seats must be anchored immovably to the car body structure and the pedals must be made adjustable (or removed completely). In order to reduce the body loading in rear impacts the seat back must be designed to give way (but not to collapse!) as a second compensation of the higher Δ-v. A third compensation could be belt pretensioning at centre anchor points, belt elongation control by viscoelastic deformation elements and an airbag for both front seats.

• Materials and structural design must be chosen such as to mitigate the body impact in the passenger compartment since at higher collision velocities even air bag and advanced restraint systems can prevent a head and thorax impact only if the compartment space in increased considerably. There is a principal advantage of deformation zones in the passenger compartment versus conventional deformation zones in front of the car: due to the time gap between the begin of the collision and the full coupling of the occupant with the car structure, the conventional exterior deformation zone can not be used up fully for occupant protection because it gives away precious centimeters in the early collision phase. In contrast to that shortcoming inner deformation zones can be used up fully by the impacting occupant.

• The protection of exterior road users requires soft front surface design with a high upper leading edge. Special active protection front end structures, triggered by the impact of the pedestrian could perform even better.

• Despite new and promising concepts for increased passive safety occupant protection will still be critical; therefore, a comprehensive safety improvement for LMC's includes also a number of measures in the area of accident prevention and collision avoidance.

Fig. 9: See end of paper

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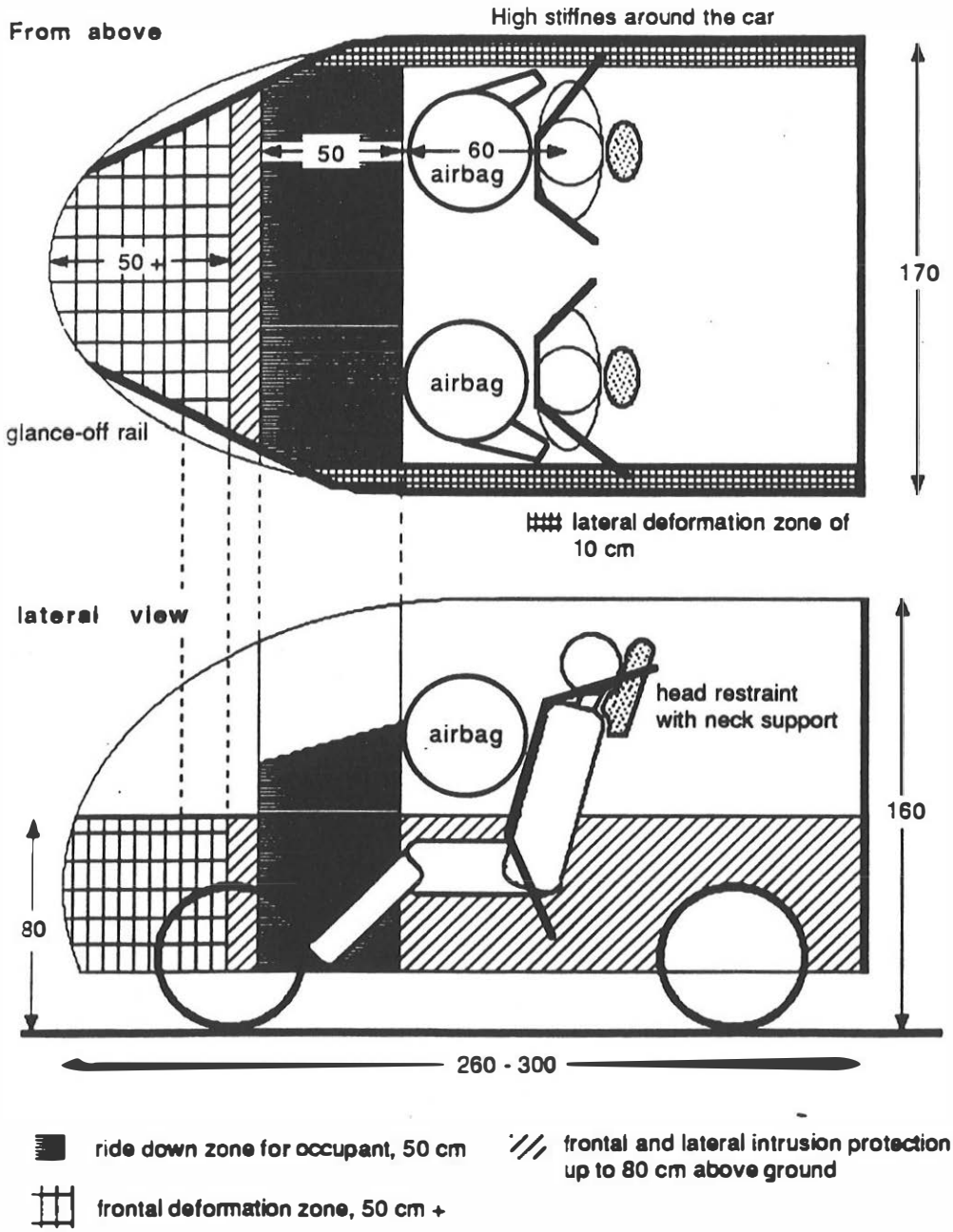

Fig. 9. Safety prerequisites for low mass cars (proposal).