INTELLIGENT RESTRAINT SYSTEMS – WHAT CHARACTERISTICS SHOULD THEY HAVE?

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ABSTRACT

Current restraint systems represent one of the most effective engineering developments which have prevented and mitigated car occupant injuries worldwide. However, they are fixed systems, optimized in design terms around a single crash condition with a single occupant in one sitting position. Population issues are addressed only partially through use of the 5th percentile female and 95th percentile male dummies again in a single crash condition. Real world crash injury studies of current seat belts indicate five limitations to occupant protection: head contacts with steering wheels for drivers, intrusion, rear loading by unrestrained objects, mispositioning of the seat belt and injuries from the belt itself. A restraint system of fixed characteristics cannot address the variations in weight, sitting position, biomechanical tolerance and crash severity which occur in the crash populations. Intelligent restraint systems have the potential to address these varying demands so that protection could be optimized for a specific person, in a specific sitting position in a specific crash. The techniques for achieving these aims are variable pretensioners, discretionary web locks and load limiters, position sensing, and airbags with variable inflation rates and volumes.

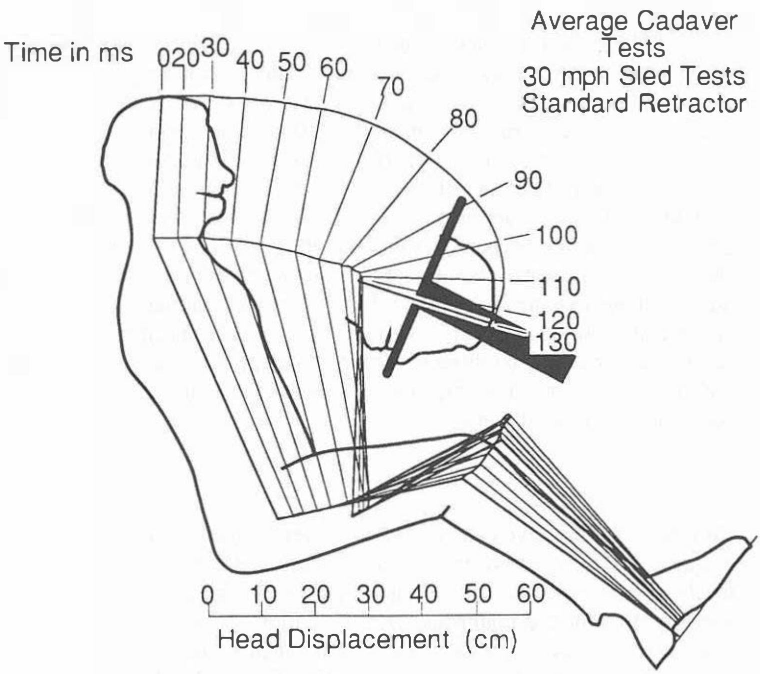
Current seat belts have been shown to be very effective in diminishing the frequency and severity of injuries to car occupants. So much so that high levels of seat belt use are a prime aim of all national transport safety policies in motorized countries. The limitations of the protective abilities of current seat belts have been well documented in many analyses of both field accident data and experimental studies [Bacon, 1989].

Real world accident studies have identified five categories of limitations to the performance of current seat belts. These are:

(1) Head and face contacts with the steering wheel by restrained drivers [Rogers et al, 1992]. It is inherent in the kinematics of a restrained occupant that, in a severe collision at a velocity change of around 50 km/hr, the head will arc forwards and downwards, having a horizontal translation of some 60 to 70 cms. (Figure 1). If a normal steering wheel position is superimposed on such a trajectory, the head and face necessarily will strike

Figure 1

SEAT BELT EXCURSION



the steering wheel. Such contacts usually produce AIS 1 to 3 injuries and are best addressed with the supplementary airbag systems becoming common throughout the new vehicle fleet.

(2) Intrusion of Forward Structures. A seat belt requires a zone ahead of the occupant so that the occupant can be decelerated by the compliance of the restraint system. If intrusion compromises that space, then specific localized contacts can occur. The injury risk from such contacts may well be small if they are occurring with structures which have been engineered appropriately. Indeed, in the ultimate condition, it is better for the occupant to be decelerated not just by the seat belt alone but through a combination of belt loads and contact loads. Those contact loads are through the feet at the firewall, through the knees into the lower dash and through the airbag and belt at chest level. In severe collisions, however, major intrusions are destroying the passenger compartment so that exterior objects are actually striking the occupants. This is a feature of restrained fatalities in frontal impacts [Mackay et al, 1990].

(3) Rear Loading. Correctly restrained front seat occupants can receive injuries from unrestrained occupants, luggage or animals from the rear seats. Such events contribute to some 5% of restrained front seat fatalities [Griffiths et al, 1976].

(4) Misuse of the Seat Belt. Seat belts must be positioned correctly on the human frame to work effectively. Dejeammes (1993) in a survey of belt use in France found that some 1.6% of front seat occupants had the shoulder belt under the arm or behind the back whilst some 3.3% had introduced slack because of the use of some clip or peg to relieve the retraction spring tension. A more important type of misuse relates to the positioning of the lap section. Many occupants, especially the overweight, place the lap section across the stomach instead of low across the pelvis. Indeed for the obese, it is often impossible to position the lap section so that it will engage on the iliac spines of the pelvis in a collision. These problems are reflected in abdominal injuries from the lap section of the seat belt [Gallup, St-Laurent, Newman, 1982].

(5) Injuries from the Seat Belt Itself. As with any injury mitigating device there are limits to effectiveness. Those limits are when biomechanical tolerances are exceeded and thus the most vulnerable segment of the population begin to receive injuries. The usual thresholds are sternal and rib fractures occurring, especially in the elderly [Hill et al, 1992].

Current restraint design aims to achieve a compromise in the sense of optimizing protection for the largest number of people exposed in the largest number of injury-producing crashes. The end point, however, is a fixed design with single characteristics optimized around a single crash condition. That crash condition for most manufacturers is usually the 35 mph (56 km/hr) rigid barrier crash test.

The next evolutionary stage in restraint design is to move away from a restraint system with fixed characteristics towards one which has variable characteristics. This paper addresses some of the population characteristics which need to be considered if the concept of variability is introduced into restraint design.

POPULATION CONSIDERATIONS

The ideal restraint system would be tailored to the following variables:

- the specific weight of the occupant,
- the specific sitting position of the occupant,
- the biomechanical tolerances of that occupant,
- the severity of the specific crash which is occurring,
- the chances of specific passenger compartment intrusion occurring which might compromise restraint performance,
- the specifics of the compartment geometry and crush properties of the car.

Anthropometric Considerations - Current dummies and modeling cover the 5th percentile female to 95th percentile male range. Assuming for simplicity that males and females are exposed equally and that there are few males smaller than the 5th percentile female or females larger than the 95th percentile male, these conventional limits put 2.5% (1 in 40) of the small population and 2.5% of the larger population beyond those limits; 5% or 1 in 20 overall.

Table 1 gives the 1% and 99% ranges for height, sitting height and weight. These data show what would be required if the design parameters were extended to cover this wider range, so that only 1 in 50 of car occupants would be outside the design parameters [Society of Actuaries, 1979].

Table 1 - Population Ranges for Height, Sitting Height and Weight

Adult	Height		Sitting Height		Weight	
	ins	cm	ins	cm	lbs	kg
1%ile female	57	145	28	72	82	37
5%ile female	59	150	29	75	90	41
95%ile male	73	185	37	93	225	102
99%ile male	75	190	38	96	236	107

More importantly, it is implicitly assumed in current designs that height (or sitting height) and hence sitting position are colinear with the weight of the occupant. In fact, there are data available to suggest that the relationship between height and weight are rather complex. For example, the body mass index (i.e., the ratio of weight in kilograms to height in meters squared) varies to a greater degree in women than in men, and particularly at the 75th percentile and above, women have higher BMIs than men. In addition, the prevalence of overweight increases with age, more with females than males [Williamson, 1993].

Therefore to optimize a restraint system it would appear appropriate that sitting position and body weight should be assessed independently if variability is to be introduced into restraint design.

Population Characteristics by Position in the Car - European data show that some 80% of drivers in injury-producing collisions are male, whilst some 65% of front seat passengers are female [Bull and Mackay, 1978]. Approximately one-third of rear seat passengers are children of 10 years of age or under [Huelke, 1987]. These simple frequencies suggest that restraint characteristics should not necessarily be the same for all sitting positions in the car.

Sitting Positions - Current design is predicated on the positions established for the three conventional dummies. Observational studies by Parkin et al (1993) have demonstrated that there are substantial differences between those three positions and an actual population of drivers. Passive observations of drivers in the traffic stream have been made using video recording techniques, and drivers classified by sex and general age groups of young (≤35 years), middle (36-55 years) and elderly (56 years and older). Make and model of car were recorded and measurements made of the following distances:

- nasion to steering wheel upper rim and hub,
- top of head to side roof rail,
- back of head to head restraint, horizontally and vertically,
- shoulder in relation to 'B' pillar.

Such techniques allow thousands of observations to be made quickly and therefore population contours can be drawn. Figure 2 illustrates how particularly for the 5th percentile female population the actual sitting position is significantly closer than that of the 5th percentile dummy, by some 9.2cm. The 5th percentile, small female population sits some 38cm (15 inches) or closer to the hub of the steering wheel.

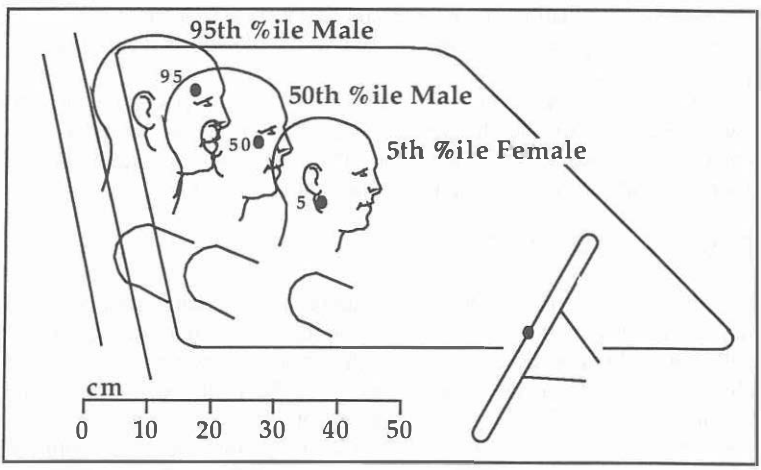


FIGURE 2. Drivers' Sitting Positions

Black dots are the nasion positions for the three Hybrid III dummies.

Biomechanical Variation - An extensive literature exists concerning human response to impact forces, mostly conducted in an experimental context. A general conclusion from that body of knowledge is that for almost any parameter, there is a variation of at least a factor of 3 for the healthy population exposed to impact trauma in traffic collisions [McElhaney, Roberts, Hilyard, 1976]. That variation applies to variables which are relatively well researched such as the mechanical properties of bone strength, cartilage, ligamentous tissues and skin. It is likely to be even greater when applied to gross anatomical regions such as the thigh in compression, the thoracic cage, the neck or the brain.

How such variability is demonstrated in populations of collisions is less well understood. Data from a ten year in-depth study of European crashes for restrained front seat occupants are given in Figures 3 and 4. The methodology of that work has been described elsewhere [Mackay et al, 1985].

Figure 3 illustrates the effect of age on injury outcome in terms of the frequency of AIS 2 and greater injuries for three age groups. The 60+ age group especially shows greater vulnerability than the younger groups. As a broad generalization one may conclude that for the same injury severity, the younger age groups must have a velocity change of some 10 km/hr more than the elderly. The effect is more marked if a more severe injury level is chosen. Figure 4 illustrates the cumulative frequencies for the three age groups for injuries of AIS 4 and greater.

Figure 5 shows similar frequency curves for crash severity by sex of occupant. Thus at a velocity change of 48 km/hr (30 mph), some 2/3 of male and some 80% of female AIS 2+ injuries have occurred. As a starting point, therefore, as well as specific body weight and sitting position, a combination of age, sex and biomechanical variation could be developed as a predictor of the tolerance of a specific person within the population range.

An intelligent restraint system therefore would perhaps require a smart card, specifying the height, weight, age and sex of the occupant. On entering the card for the first time, the card would be read and the characteristics of the seat belt and airbag adjusted according.

SENSING CRASH SEVERITY

Besides assessing the specifics of the occupant's characteristics before impact, protection could be enhanced if the nature and severity of the collision could be assessed early enough during the crash pulse so that the characteristics of the restraint system could be modified. That would require, for example, sensors to discriminate between distributed versus concentrated impacts, and between, for example, three levels of collision severity such as less than 30 km/hr, 30 to 50 km/hr, and greater than 50 km/hr. In addition, conceptually one might have an array of sensors which would detect the early development of compartment intrusion. Such electronic data could then instruct the restraint system to change its characteristics early enough during the crash phase to alter the characteris-

Figure 3

Crash speed distributions for frontal impacts (PDF of) 1 o'clock) to drivers (by age groups) who experienced injuries w MAIS >= 2

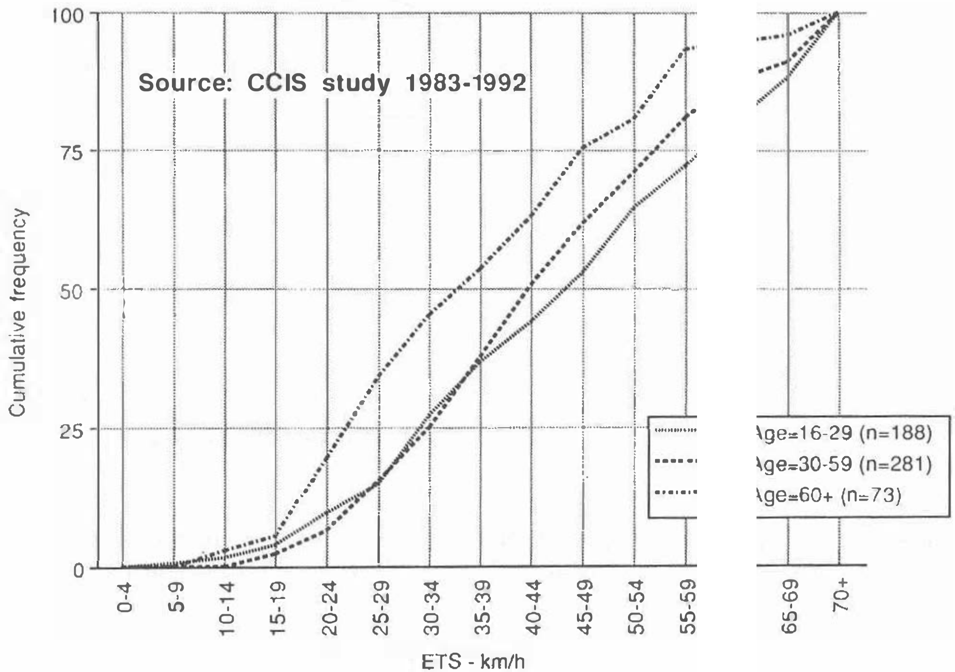


Figure 4

Crash speed distributions for frontal impacts (PDF of 11 t o'clock) to front seat occupants (by age groups) who experienced injurie th a MAIS >= 4

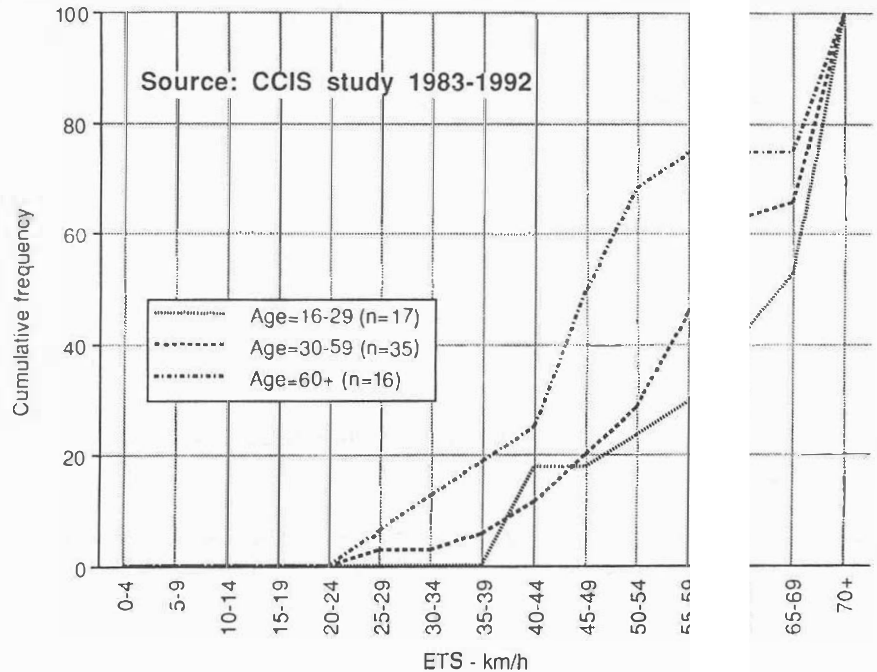
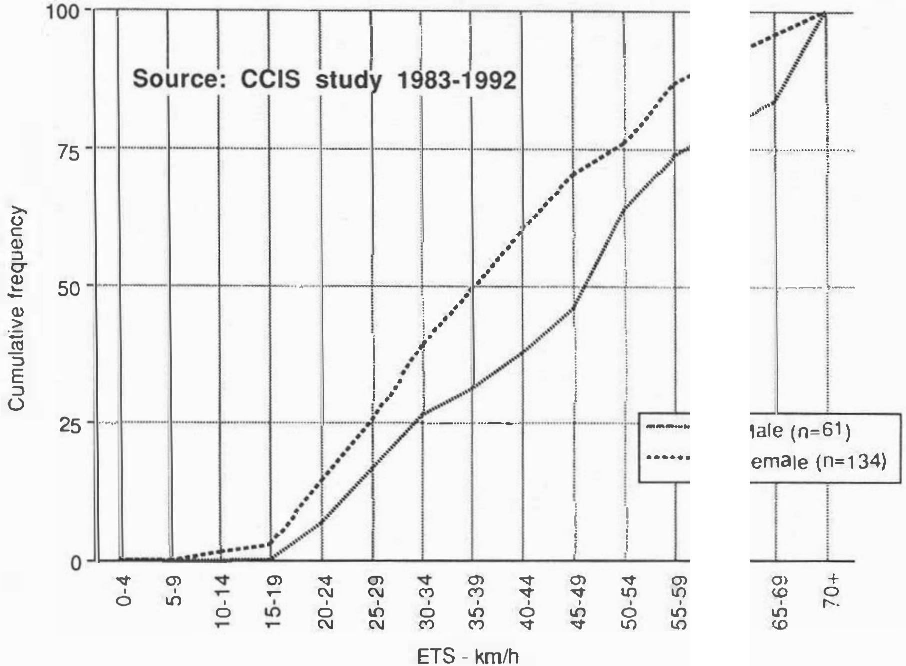


Figure 5

Crash speed distributions for frontal impacts to f[...] seat passengers (by sex) who experienced injuries with [...]IS >= 2



tics of the restraint and thus the loads on and forward excursion of the occupant.

VARIABLE RESTRAINT CHARACTERISTICS

The advantages of a variable restraint system are illustrated by considering some examples. A front seat passenger, 70 years of age and female, weighing 45 kg sitting well back, in a 30 km/hr frontal collision with no intrusion, would be best protected by a relatively soft restraint system which would maximize the ride-down distance and minimize the seat belt loads. That would require a low pretensioning force, a long elongation belt characteristic provided by load limiters and a soft airbag.

Such a system is very different from what would be required by a 25 year old, 100 kg male, sitting close to the steering wheel in a 70 km/hr offset frontal collision. He would need a very stiff seat belt, an early deploying stiff airbag and a large amount of pretensioning load.

Consider thirdly a 9 year old girl, weighing 30 kg sitting in a rear seat in a 56 km/hr frontal impact. Maximizing her ridedown distance and minimizing the seat belt loads would require low pretensioning loads and a very soft belt system, but one which would still have a biomechanically satisfactory geometry at the forward limit of excursion. Possible techniques for introducing variability into restraint design are now discussed.

Variable Pretensioning Force - A retractor pretensioner might be devised which would have a variable stroking distance or perhaps two stages of pretensioning to address the population and crash severity requirements outlined above.

Combined Retractor Pretensioner and Buckle Pretensioner - Such a system of pretensioners might maintain good seat belt geometry especially for the small end of the population, such as the 9 year old girl in the rear seat, when soft restraint characteristics and hence large amounts of forward excursion are required.

Discretionary Web Locks - If the seat belt system needs to be stiffened for the heavy occupant with high biomechanical tolerance in a high speed crash, then the switching in of a web lock would be appropriate. Such a device would shorten the active amounts of webbing being loaded and diminish forward excursion at the expense of somewhat higher seat belt loads.

Discretionary Load Limiting Devices - One way of providing for biomechanical variability would be to have a load limiting mechanism which would be calibrated for the specifics of the occupant's age, sex and weight. Such a device could also be adjusted according to transient sitting position. Belt loads would be limited at the expense of increased forward excursion.

Variable Sitting Positions - Ultrasonic, infrared or other techniques of sensing might be used to monitor continuously the head position of each occupant. Such information could be used at a minimum to provide a warning that an occupant was sitting too far forward and in particular too close to the steering wheel. At a more advanced level it could be used to tune the seat belt and airbag characteristics to be optimized for that occupant in that specific position by adjusting the other restraint variables.

Variable Airbag Firing Threshold - The need for an airbag varies according to seated positions in the car and the characteristics and sitting position of the occupant. For most drivers in most sitting positions a supplementary steering wheel airbag becomes desirable in crash severities above 30 km/hr [Rogers et al, 1992]. For a front seat passenger however, particularly one who is towards the top end of the biomechanical tolerance spectrum and sitting well back, an airbag at 30 km/hr is unnecessary. For a child sitting a long way forward in such a crash, it might also be disadvantageous. Hence specific sensing techniques at a minimum could discriminate between the presence or absence of a passenger, and at the next level assess the need for the airbag to inflate or not.

Variable Airbag Characteristics - In response to the sensing data about the occupant's characteristics and transient sitting position, and the accelerometer data about the nature and severity of the collision which is occurring, the airbag properties could be varied. Specifically, gas volume and inflation rate could be changed. Compressed gas systems instead of chemical gas generators have the potential for providing those characteristics by having time-based adjustable inflation ports. This requires very advanced sensing and control systems but these aims could well be addressed through future research and development.

OTHER CRASH CONFIGURATIONS

The discussion so far has focused on frontal collisions which constitute some 50% to 65% of injury producing collisions in most traffic environments. Lateral, rear and rollover crashes also suggest opportunities for optimizing protection through intelligent restraint systems.

Lateral Collisions - The technology is now developing for side impact airbags with two versions becoming available on 1995 model-year passenger cars. The observational data of Parkin et al (1993) have illustrated the range of driver sitting positions which reflect the requirements of side impact airbag geometry to cover both the door and the B pillar. Because a significant part of the population, tall males, choose to sit as far rearward as possible, in a side impact in many four door vehicles the thorax would be loaded by the B pillar rather than the door.

A practical issue is the nature and position of the sensor for a side impact. Because of the extremely short time available for sensing, around 5 milliseconds, a simple switch system is appropriate [Haland, 1991]. An analysis of a representative sample of AIS 3 plus lateral collisions has demonstrated that if a switch sensor is located in the lower rear quadrant of the front door then approximately 90% of all such side impacts would be sensed appropriately. A set of several sensors would be required to address the remaining few collisions, whilst rear seat occupant protection would also be addressed in large part by a sensor in the same position in the front door as is appropriate for front seat occupants [Hassan et al, 1994].

Rear Impacts - Occupant protection in rear end collisions is addressed largely through the appropriate load deflection characteristics of seat backs and the provision of correctly positioned head restraints. The real world data of Parkin et al (1993) demonstrates that head restraints are frequently positioned both too low and too far to the rear of the occupant's actual head position. The head position sensors discussed above could also be used for adjusting automatically both the vertical and horizontal position of the head restraint. Such a technology is relatively simple but the costs and reliability, as well as acceptability by the driving population, present serious practical problems.

Rollover Accidents - Actual mechanisms of injury in rollover accidents have been well researched by Bahling et al (1990) for occupants in current seat belts. Conceptually one can suggest that a buckle pretensioner might have some benefits in rollover circumstances by diminishing the relative vertical motion of an occupant. However, in rollovers current dummies do not have the appropriate soft tissue or thoracic and lumbar spine response characteristics, in comparison to the human frame. The basic clearance of current bodyshell design and packaging limit intrinsically the ability of any restraint system to modify the nature of any roof contacts under the forces of actual rollover circumstances even with no roof deformation taking place. Raising current roof lines leads to many undesirable consequences. Nevertheless it would be of interest to explore occupant kinematics in rollovers using more realistic techniques with volunteer and cadaver subjects in the context of buckle pretensioners and the requirements of a sensor to detect incipient rollover.

CONCLUSIONS

This paper only attempts to outline in conceptual form some of the issues which need to be addressed in advancing from today's seat belts and airbags towards some form of intelligent restraint system. Of fundamental importance is to recognize the population issues of size, sitting position, biomechanical variation and changing crash exposures. Beyond these issues lies a larger amount of challenging research and development to actually produce the sensors and hardware to provide variability in a seat belt and airbag system. Proximity sensing has its advocates, and if radar techniques could actually discriminate an impending collision from a near miss or a passing object, then the provision of say 500 milliseconds warning would alter many of the restraint issues reviewed in this paper. However, the basic premise remains; the next generation of restraints must change from having single fixed characteristics towards variable ones which recognize the real world population variables of weight, sitting position, biomechanical tolerance and crash exposure.

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