PRE-CRASH SENSING OF OCCUPANT CHARACTERISTICS AND POSITION : ENHANCING SECONDARY SAFETY SYSTEM PERFORMANCE

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ABSTRACT

Current vehicle secondary safety systems are designed to maximise protection for a specific section of the population. Hence certain car occupants, particularly those who sit in an unusual position or are not of 'average' size, may be more likely to be injured in a car accident.

This paper reports the ongoing work of the project team working on Smart Seat design at Loughborough University and how their system gathers live data about the physical characteristics and position of the vehicle occupant(s). Data is used by the secondary safety system to tailor its response to an individual, reducing levels of injury by making the best possible use of available technology.

THE TECHNOLOGY AVAILABLE to the designers of vehicle occupant restraint systems has advanced rapidly as the need for improvements in secondary safety has been realised by the public and legislative bodies. Products such as airbag inflators have been produced which can be mechanically or electrically adjusted to provide a range of responses, allowing designers to incorporate a degree of adaptability into a previously fixed system. An airbag inflator of that type could have variable deployment times, maximum inflation pressures and gas mass flow rates (Galer, 1993). The increase in performance and reduction in cost of microprocessor based control systems available for automotive applications has provided the intelligence necessary to make decisions about how an adaptable system should be deployed (Galer and Jones, 1993).

It has been stated that if an intelligent safety system is developed, which combines the now available technology with a "smart" decision making system, improvements in the response should easily justify the capital outlay to make them possible (Digges and Morris, 1991).

Design and optimisation of a typical current safety restraint system will usually have been based around what is seen to be the "normal" crash condition for a given vehicle. These include:

- Crashes at 0 degrees into a rigid barrier at about 50kph (unbelted) and 56kph (using all the safety features).
- 30 degree barrier testing to give an indication of off-axis accelerations.
- Fiftieth percentile occupant.

• Seat and other adjustable features in the middle position.
• Standard temperature and pressure.

The restraint system is then usually subjected to supplementary testing to ensure that it will provide a level of protection for crashes involving different directions and speeds, and other sizes of occupants sitting in various positions. Adjustments will be made to provide an adequate response for each tested situation but the system is optimised around the "normal" condition.

It is extremely rare for a crash to occur under the conditions defined above. The adaptability of newer restraint systems should make it possible to optimise their response in a crash where one or more of the variable factors is not as anticipated.

The challenge lies in defining which of these variables are most important, and how one should go about measuring them if they are deemed to be significant.

The following factors are perceived to be most important in defining how the secondary safety systems should be deployed in the event of a crash:

• Presence of the occupant.
• Physical characteristics of the occupant (age, sex, size, weight etc.)
• Position of the occupant relative to the vehicle interior.
• Direction and speed of impact.
• Accelerations expected before and/or experienced during impact.
• Ambient conditions.

The Smart Seats project team at Loughborough have concentrated their initial efforts on identifying the occupant's characteristics and position within the vehicle. The last three factors mentioned in the above list have not been addressed directly in this project but are the subject of other research.

PHYSICAL CHARACTERISTICS OF CAR OCCUPANTS

The response of a human being in a given crash depends to some extent on their physical characteristics. These include their physical size and shape and other factors such as age, sex and habitus. If you know these characteristics, it is possible to build up a picture of an individual's biomechanical tolerance to injury in a crash, and to decide which loads they can best withstand. It is also possible to calculate the effect of an occupant's build on their crash-response. Aibe et al, (1982) show that there is a clear relationship between body size and injury levels for a given seated position, irrespective of other factors.

The anthropometric characteristics of car occupants are well documented (Haslegrave, 1980), and car designers normally create their cars and safety systems to fit a range of physical sizes from 5th percentile female to 95th percentile male, as recommended by E.C. and FMVSS regulations and the S.A.E.'s codes of practice (SAE HS-13, 1991).

These design criteria are somewhat inadequate. To illustrate with an example, let it be said that males and females are equally likely to be involved in a crash. Let us also believe that all but a few males are larger than a 5th percentile female and that all but a few females are smaller than a 95th percentile male. If the preceding statements were true then 5% of the total population are outside the vehicle's design range, which (as stated in the introductory paragraphs) does not take the best account of the population extremes in the first place. The above example only concerns the physical build of an occupant. There seems to be little or no consideration of their age or sex when designing a safety system, both of which are major factors when deciding how resistant they are to injury (Evans, 1988). These factors should be included when designing a safety / restraint system to fit a whole population, particularly as more accurate data about the changes in injury tolerance with age becomes available.

Any restraint system which can adapt to suit different occupant characteristics would enable those occupants outside or towards the extremes of the design criteria to be better protected. From U.S. Census Bureau 1990 estimates (Hyde, 1992) this would, at worst, improve the protection for 12 million car using adults who are outside the 5-95th percentile size group, let alone those who are younger or older than designed for. In addition to the above mentioned variables, an ideal safety system should take account of an occupant's habitus. Habitus is the way they appear, and the meaning of that appearance. For example, someone may have a neuromuscular disease or a prior medical history which means that they are more susceptible to impact injury (Hyde, 1992).

The physical characteristics of a person can be broadly classified into two groups when attempting to 'size' them for a safety system. The first group contains dimensions currently used in the design of vehicles such as height, weight, leg length and the second contains other factors such as age, sex and habitus. The difference between these two groups is that one is easier to measure mechanically or electrically (and emulate with dummies or models) than the other. This needs to be borne in mind when attempting to create a smart system, as there is a clear division between what the system can measure and what it has to be told. An individual's physical characteristics will dictate to some extent the position they adopt in the vehicle, requiring the two factors to be considered together.

WHERE PEOPLE SIT IN CARS

The seated position of an occupant will affect what happens to them in a crash. An occupant's position is dictated by their build, the vehicle's layout and personal preference. In addition the occupant may temporarily move away from their usual position.

Parkin et al. (1993) has shown that drivers do not necessarily sit in the places dummies are put for crash testing, and that the discrepancies can be large; up to 9.2cm further foward than expected for a 5th percentile female. This is a cause for concern as a person sitting close to a deploying airbag runs a high risk of face, brain, neck and chest injuries (Augenstein et al, 1994). Perchard (1994) has shown detailed relationships between people's size and where they choose to sit in their vehicle.

If the posture of the occupant is slumped or slouched or if an active restraint system such as the seatbelt is incorrectly fitted, the response of the safety system may be far from ideal. We cannot predict where a car occupant will choose to sit because two very similar individuals may prefer a completely different position, or two differently sized people may choose the same. If the solution to that problem requires some kind of active position measurement and / or an adaptive restraint system, then there is a possibility that out of position occupants (i.e. persons not in any expected driving position) can be catered for using the same techniques. That would give the system two purposes, helping to justify its cost.

THE CRASH

The nature of the impact is the single most important variable in determining the extent and types of injury inflicted on an occupant. The key factors are the direction and energy of the main impact. The direction of impact determines how the occupants contact the safety restraints. The energy affects the force and timing of those contacts, and whether or not intrusion occurs.

If an impact is of high energy or occurs at a weak spot on the impacted vehicle, it may result in massive destruction of the passenger compartment. In a study of restrained car occupant fatalities (Mackay et al 1990), the performance of the restraint systems was deemed to be irrelevant in about 80% of cases due to destruction. In such cases it is unlikely that an adaptable restraint system will reduce the level of injury any better than existing systems. When the energy of impact is lower, there is the potential that an adaptable system will be able to make a difference to the severity of the injury outcome.

The majority of safety restraint systems are designed to deal with frontal impacts. When involved in a crash from this direction, the occupants have more space to move and accelerate before contacting the interior of the vehicle than in other crash circumstances. When coupled with the high probability of any given accident being a frontal (58% according to Harms and Tunbridge, 1991), there is a persuasive argument for optimising seatbelt and airbag restraints for that situation.

INJURY OUTCOME IN RELATION TO PHYSICAL CHARACTERISTICS AND SEATED POSITION

Let us consider the behaviour of a belted front-seat occupant in a moderate severity frontal impact. As the vehicle decelerates, the occupant's knees will probably strike the lower fascia but the likelihood of a steering wheel contact is low (approximately 22% from Mackay and Hill, 1993). A passenger is unlikely to hit the fascia if belted, and only when the restraint system fails will either the driver's or passenger's head strike the windshield.

The relationship between occupant size, position and injury levels is complex. From work performed using Hybrid II and III dummies restrained by conventional belt systems with no pretensioners or webbing grabbers, a general pattern is observed; injury levels increase with increasing occupant size and increase as the occupant's seated position is moved rearwards. This is offset by a higher probability of a smaller occupant striking the fascia or wheel (Aibe et al, 1982).

Fitting an airbag, seatbelt pretensioners and webbing grabbers changes and further complicates any estimation of the injury outcome. The chance of a head contact with the steering wheel or fascia is now virtually eliminated if the system (airbag, seatbelts, pretensioners and webbing grabbers) works as designed, but the possibility of other injuries being introduced has to be considered.

The implementation of any new or different safety restraint produces a shift in the pattern of injuries. A study by Sabey et al (1977) shows an apparent increase in lower limb and neck injuries when vehicle occupants are wearing seatbelts. Fortunately these increases were more than balanced by the reduction in serious upper-body injuries and fatalities. The positive effects of the latest restraint systems may also outweigh harm they may cause as a result of their operation. This is not, however, a reason to become complacent. There is increasing evidence to suggest that occupants with certain physical characteristics or who are seated in particular positions may actually be harmed by the operation of the safety system.

It is estimated by Augenstein et al. (1994) that more than half a million airbag deployments will occur each year by the year 2000. Even if an advanced safety system only causes injury in a tiny percentage of cases, there will still be a significant number of potentially avoidable injuries when so many deployments occur each year.

To date there is limited medical literature showing patterns of injury for airbag protected occupants in crashes. American data is sparse (Augenstein et al, 1994 ; Zador and Ciccone, 1993) and European data is almost non-existent. Despite this, a number of sources are concerned that advanced safety systems can cause injury to occupants who are out of position or close to the airbag at the time of its deployment (Schulte and Weyersberg, 1994 ; Augensteinet al., 1994 ; Smith et al., 1994). Of particular concern are drivers who sit close to the wheel, whether because of personal preference or having a small stature.

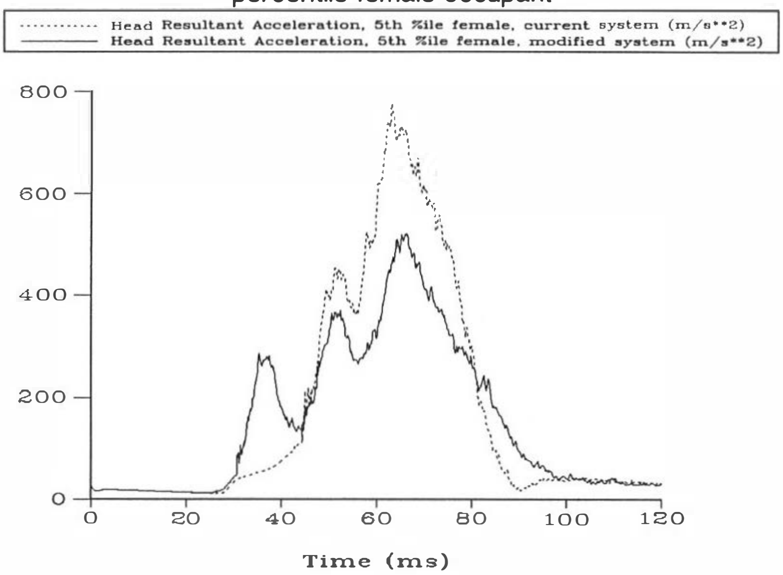
The above is largely concerned with the physical size and position of the occupant, and is presented to illustrate how they can affect the injury outcome in a crash. Those factors are easily emulated mechanically and theoretically in crash simulation. Of equal concern are the other physical factors, namely age, sex and habitus. These variables are closely linked to how an individual can be injured in a crash, but are less affected by the nature of the restraint system. For example, older people are more likely to be killed or injured than younger ones for a given impact and restraint system, no matter which system is used. Reference to Hyde(1992) shows what differences age and sex can make to the outcome of a crash from the occupant's perspective.

Habitus is possibly the most difficult of an individual's physical characteristics to quantify. It is dependent on all their other characteristics as well as influences such as medical history and individual traits. The best way of considering it is as an overall 'risk factor' attached to a person, perhaps because of a reduction in bone strength due to osteoporosis or an increase in vulnerability (of mother or unborn child) due to pregnancy.

HOW INJURY OUTCOME CAN BE CHANGED BY ALTERATIONS TO THE SAFETY SYSTEM

Having stated that seated position and physical characteristics make a difference to the injury outcome, it is necessary to investigate whether or not an adaptable safety system can influence the injury outcome for a given crash. Work recently performed at Loughborough University using MADYMO simulation has shown that this can be achieved. The graph below (Figure 1) illustrates the response of an airbag and seatbelt restrained 5th percentile female in a simulated 0 degree 30mph barrier test. In both cases, webbing grabbers and pretensioners were also employed by the safety system.

Figure 1. MADYMO Output showing normal and optimised head accelerations for a 5th percentile female occupant



The curve with a high peak is the resultant head g level using the existing safety system, which is optimised around a 50th percentile male and modified to provide adequate protection for 5th and 95th percentile occupants in their 'expected' positions, as per SAE HS-13 (1991). The high g levels are caused by the small occupant striking the still-inflating airbag and being accelerated backwards.

The lower curve is the response exhibited when the airbag was fired sooner after the beginning of the impact (12ms instead of 25ms). All other factors were kept constant. A simple modification such as this can reduce the expected head deceleration by 20g, and it has been shown that further improvements are possible, for example by altering the pressure or tether lengths of the airbag or the amount of seatbelt pretensioning applied.

Schulte and Weyersberg (1994) illustrate that the resultant head acceleration can be reduced to approximately 68% of its existing likely value by optimising the airbag's vent sizes, tether lengths, inflation time and pressure. This ignores improvements possible from varying the belt pretension and so on. Smith et al (1994) also shows that comprehensive optimisation of a safety system can produce impressive results. The sled testing and simulation work undertaken with airbag restrained belted and unbelted occupants shows significant improvements in HIC, 3ms chest acceleration clip and chest resultant accelerations. This is good news for occupants at the extremes of size, position or biomechanical tolerance.

Having defined that there is room for improvement and identified a few ways in which an adaptable system can make a difference, all that is required to close the loop and allow further development is information about the occupant and their position. The next section details how the Smart Seats project team at Loughborough University is gathering that information.

THE SMART SEATS PROJECT

BACKGROUND - The Smart Seats Project began with a comprehensive study to discover how a person's anthropometric characteristics affect the position they adopt within their own vehicle. In order to contain the scope of the investigation, and focus any further work, we decided to limit our work to look solely at frontal impacts not involving intrusion into the passenger compartment. That decision has affected all aspects of the project, as has the assumption that any future occupant will have at their disposal a European-style seatbelt and airbag system, which can have included into its design all the adaptable elements required to make an adjustable system.

The basic problem of providing the safety system with information about the occupant and their position within the vehicle can be solved in two ways. The first method is to predetermine an occupant's anthropometric characteristics and preferred seating position, and issue the vehicle with that information (for example using a smart key system). The main features of that system from our perspective are that it :

- Requires active input from the occupant. This can be ensured for the driver by providing an incentive such as an ignition interlock, but is harder to implement for passengers.
- Can provide all the data required by the safety system to adjust for a nominal situation, but...
- Does not measure any real-time (actual) parameters about the occupant or their position, for example whether or not they are momentarily out of position.
- Can be "fooled" by human error or deliberate action / inaction - for example by swapping coded ignition keys or smart cards. The system has no opportunity to check for such a situation.
- Has some problems with long-term implementation as cars change owners - how do you keep the system updated?

The second method involves using a sensing system to discover as much as it can about the occupant in real time. It has the following main features;

- The ability to measure actual values for most physical measurements of occupant position and proportion / size, and the capacity to update them whenever required.

- It is transparent to the occupant, requiring no active participation to make it function correctly.
- It is harder to fool by error or deliberate tampering.
- It has better long term implications, requiring no support following its initial installation and calibration.
- It will probably will not be able to define an occupant's age, sex or habitus.

It is evident that the best way to get the required data would be to use both types of system together, allowing them to communicate discrepancies and spot errors of judgement. The Smart Seats project team at Loughborough University decided to concentrate their first efforts on creating a dynamic system which would determine the occupant's actual size and position, leaving identification of the non-physical characteristics for further research.

It was also decided to create a system using as much existing technology as possible, in order to reduce costs and lead times. These decisions led to the concept of a Smart Seats System, which uses information from instrumentation fitted in or near the seat to gather the required data about occupant size and position.

WHY TAKE THE SMART SEATS APPROACH? - The position to which an occupant adjusts their seat tells a great deal about what shape they are and where certain parts of their body are normally located relative to the interior of the vehicle (Perchard, 1994). If these data are added to information about whether or not the occupant is sitting conventionally in the seat, one should be able to build up an accurate picture of who is in the seat and where they are located in space.

The Smart Seat offers a number of benefits; Most of the sensor technology required is tried and tested and already fitted to so-called 'memory' seats (those which have several user-defined set positions), which are available on high series vehicles. This reduces development costs and brings a working system closer to market. Sensors used for automatic seat positioning and information feedback would be serving two purposes, lowering manufacturing costs and adding value to existing systems.

Perhaps the most important benefit is that real-life, real-time measurements are taken, and can be updated whenever required with little chance of anyone tampering with the system. The seat unit can be constructed as a self-contained unit and could be offered as a simple retrofit or upgrade to a vehicle if required.

Whilst other systems involving sensors mounted on various parts of the vehicle interior are also being developed, it can be seen that the Smart Seat presents an attractive prospect and an appropriate direction for further research.

WORK PERFORMED SO FAR - In order to create the best possible system, a number of different avenues had to be explored.

Background research was mainly concerned with how occupants' anthropometric characteristics and seated position affect injury outcomes in a crash, and how adaptable safety systems could make a difference if supplied with the required data. Salient points from this work are presented in the earlier sections of this paper. The work included an extensive literature survey, modelling with MADYMO and consultation with car manufacturers.

Identification of the relationships between occupant size, seated position and seat adjustment - A study was undertaken to provide exact information about how the adjustment of the seat relates to occupant size and position (Perchard, 1994). The purpose was twofold: to isolate mathematical relationships between seat adjustment, occupant size and seated position; and to discover the minimum number of measurements required to assure the accuracy and reliability of those relationships.

In this study one hundred drivers selected from the normal driving population had their principal physical characteristics, seated position and the adjustment of their seat in their own vehicle measured with the vehicle at a standstill. The illustrations below (Figures 2 and 3) show the measurements which were taken during the study. The mass of the occupant is not shown.

Figure 2. Anthropometric measurements taken during the study

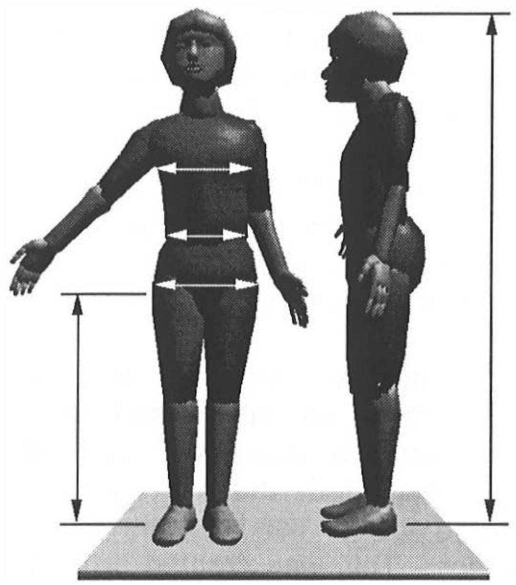
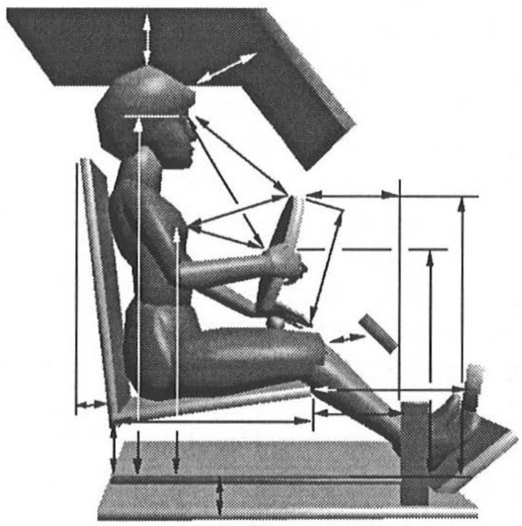


Figure 3. Position measurements taken during the study.



Several points about the study are worth noting here. The drivers were measured in their own vehicles in their usual driving position to ensure that their seat adjustment was what they perceived to be the optimum. A wide range of vehicle types and ages were included in the study, helping to establish car-independent relationships between the factors we are interested in. These include the correlation between the seat adjustment position and the following factors; nasion to steering wheel distance, sternum to steering wheel distance, occupant mass and the occupant's physical characteristics.

Whilst the cars were not being driven at the time of measurement, every attempt was made to ensure that the drivers adopted as relaxed and natural a position as possible before measurements were taken.

Results of the study were tabulated and prepared by Perchard (1994). Statistical analysis using simple regression, stepwise analysis and multiple regression was undertaken. From the work performed, those measurements critical to the identification of occupant size and seated position were isolated and it was confirmed that a strong (if complex) relationship exists between an individual's size, position in the vehicle and their chosen seat adjustments.

Technical Investigations - An accurate estimate of an occupant's position could be made by measuring their chosen seat adjustments. This estimate would be enhanced by measuring the position of the occupant relative to the seat - allowing the system to compensate for different driving postures.

The seat adjustments measured were fore/aft position, squab rake angle, squab height and seatbelt payout. A multiturn potentiometer was installed to measure seatbelt payout. Individual optosensors were combined into arrays and fixed to the seat so they could read the seat's position from stationary encoded strips, working in much the same way as a punched-tape reader.

A comprehensive survey of the available methods for measuring the position of an occupant relative to the seat was undertaken. A number of suitable sensors were identified and their various benefits compared. For reasons of cost, ease of installation and technical suitability, it was ultimately decided to use a capacitive sensor in the back of the seat to detect occupant presence and position. The use of such sensors is suggested by Smith et al (1994) and some development work has been performed by Muser (1994), albeit for a different purpose.

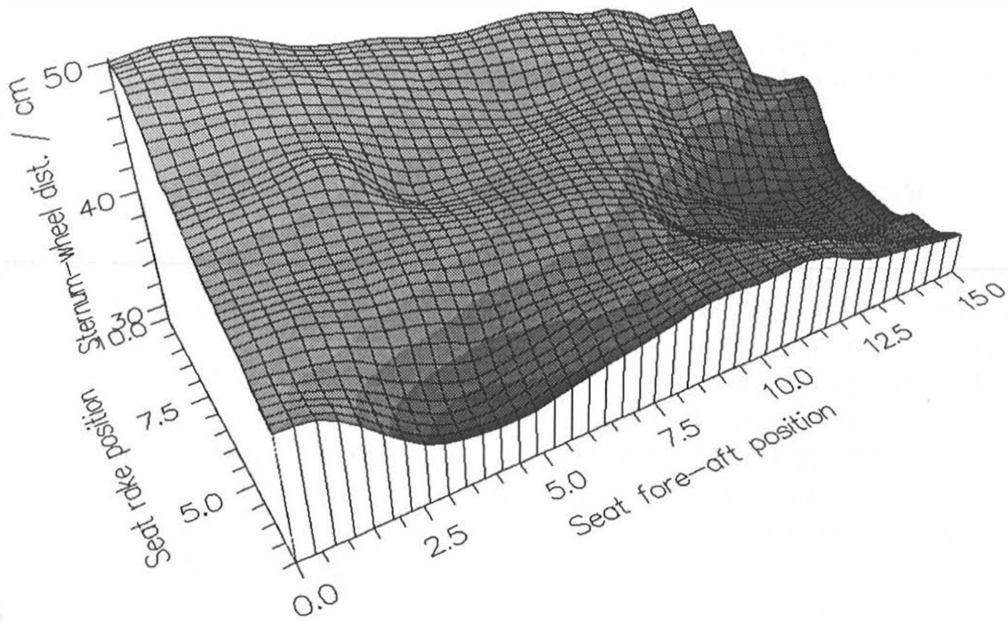
A successful prototype sensor and signal conditioning circuit has been developed, allowing accurate measurement of a human body's position in a space envelope of approximately 500mm from the sensor. The sensor is extremely flexible in application and method of construction and combines these benefits with low cost, weight and size.

A computer fitted with suitable input/output circuitry is used to gather and interpret the data from the various sensors, perform calculations and display the results on-screen. By combining the position data with statistical information from Perchard (1994), it is expected that an accurate representation of the occupant's size and seated position can be achieved.

Construction of a Technology Demonstrator - This was created around a Rover 400 bodyshell in order to validate the data acquired during the Perchard study and the conclusions drawn from it. It is also being used to verify the operation and usefulness of the occupant position sensing. All required instrumentation is fitted as outlined above and is almost invisible to the occupants of the vehicle.

Verification of the system's repeatability, reliability and immunity to error is being undertaken. Initial results from trials with drivers of known anthropometric characteristics are showing good correlations between driver size, seated position and chosen set adjustment. Figure 4 shows an example - the raw (uncompensated) relationship between seat fore-aft position, seat rake position and sternum-steering wheel distance. The data has not yet been fully analysed, but the figure shows a clear trend developing in the results from the experiment.

Figure 4. Contour chart showing relationship between seat fore-aft position, seat rake position and sternum-steering wheel distance



THE WAY FORWARD

Further analysis of Perchard's work can be combined with data from the ongoing driver trials using the Rover 400 vehicle rig to obtain data and further correlations which are vehicle specific. Repeated trials on other vehicle packages will allow us to decide how difficult it will be to adapt the system to different vehicles, and will allow us to improve the accuracy of the data it provides, if necessary.

Reliability trials using the technology demonstrator will verify its operation. It is essential that the limitations of the system are correctly understood prior to further development. Extensive trials will help to identify problem areas and scope for improvements.

More work is required on the sensing method employed. At present the device itself is a prototype, supported by smart electronic circuitry. Further design work will improve its accuracy, directivity and ease of use / installation.

The system should be packaged so that it will fit within the constraints of vehicle mass production and closer ties with vehicle manufacturers are essential to that end.

An examination of how the system can be combined with other intelligent or semi-intelligent systems to reduce costs and increase its usefulness is a next step. An example of this would be combining the Smart Seat with a collision avoidance or obstacle detection mechanism, which would allow the position of the occupant and settings of the safety system to be optimised before the crash actually occurs. It would also provide information on the direction and likely energy of the crash (Galer and Jones, 1993). Also of interest would be research into using a Smart system to observe what is happening to the occupant during a crash, with a view to dynamically altering the safety system. An example of this would be firing a second pretensioner to take up excessive slack in the belt system or dynamically load limiting the seatbelt to smooth out deceleration peaks.

This project paves the way towards a safety system capable of optimising its protection for any individual, taking account of their position or the nature of the crash.

CONCLUSIONS

There is an opportunity to enhance the performance of current secondary safety systems in frontal collisions by tailoring the performance to the characteristics of the driver.

Certain critical characteristics and dimensions can be measured and / or calculated from data obtained from the seat and seatbelt configuration.

Sensors have been implemented in a prototype Smart Seat that predict the physical characteristics of the seat occupant and their location with regard to critical vehicle features such as the steering wheel.

A capacitive sensor positioned in the seat back is capable of providing accurate information about the position of the occupant relative to the seat.

The robustness and reliability of the prototype is currently being evaluated in large-scale trials.

Such a system can in the future be combined with predictive sensors to identify the occurrence of a crash and identify the direction and likely energy.

This is a very exciting and forward looking research activity.

REFERENCES

Aibe, T., Watanabe, K., Okamoto, T. & Nakamori, T., 1982. Influence of Occupant Seating Posture and Size on Head and Chest Injuries in Frontal Collisions. Proc. of 9th Int. Tech. Conf. on Enhanced Safety of Vehicles.

Augenstein, J.S., Perdeck,E., Stratton, J., Digges, K., Lombardo, L., Malliaris, A., 1994. Injuries Sustained by Air Bag Occupants in Frontal Crashes. Proc. 14th Int. Tech. Conf. on Enhanced Safety of Vehicles.

Digges K.H. & Morris, J.B., 1991, Opportunities for Frontal Crash Protection at Speeds Greater than 35 m.p.h., SAE Tech. Paper 910807, Society of Automotive Engineers, Warrendale, U.S.A.

Evans, L., 1988. Risk of Fatality from Physical Trauma versus Sex and Age. J. Trauma, 28 : 3, pp. 368-378..

Fife, D., Barancik and Chatterjee, 1984. North-eastern Ohio Trauma Study II : Injury Rates by Age, Sex and Cause. Am. J. Public Health 74 : 5 p 473-478.

Galer, M.D. and Jones, S.R., 1993. Intelligent Occupant Protection Systems. Proc. 26th Int. Symposium on Automotive Technology and Automation.

Galer, M.D., 1993. Advanced Technology Applications for Primary and Secondary Safety. C642/2/091. In C462/2 Road Transport Informatics, Institution of Mechanical Engineers, London.

Haslegrave, C.M., 1980. Anthropometric Profile of The British Car Driver, Ergonomics, 1980, Vol 23, no. 5, 437-467

Harms, P. L and Tunbridge, R. J. (1991). Patterns and causes of serious injuries amongst car occupants. Proc. 13th International Enhanced Safety of Vehicles Conference, Paris, 1991.

Hyde, A.S. 1992. Crash Injuries : How and Why They Happen. HAI, Box 490034, Key Biscayne, Florida, USA. ISBN 0-9637057-0-9

Mackay, G.M., Cheng, L., Smith, M. and Parkin, S., 1990. Restrained Front Seat Car Occupant Fatalities-The Nature and Circumstances of their Injuries. Proc. Association for the Advancement of Automotive Medicine 34th Ann. Conf., p139-162.

Mackay, G.M. and Hill, J.R., 1993. The Kinematics of Restrained Front Seat Occupants in Frontal Crashes as Deduced from In-depth Crash Investigations. Proc. 26th Int. Symposium on Automotive Technology and Automation. Dedicated Conf. on Road and Vehicle Safety.

Muser, M.H., 1994. Neck Injury Prevention by Automatically Positioned Head Restraint. Proc. Advances in Occupant Restraint Technologies : Joint AAAM-IRCOBI special session, Lyon, France.

Parkin, S., Mackay G.M., Cooper A., 1993. How Drivers Sit in Cars. 37th Annual Proceedings, Association for the Advancement of Automotive Medicine.

Perchard, M.F., 1994. The Anthropometry of Car Drivers for the Optimisation of Secondary Safety Systems in Frontal Collisions. Unpublished M.Sc. Thesis, Department of Human Sciences, Loughborough University of Technology, UK.

Sabey, B.E., Grant B.E., Hobbs, C.A., 1977. Alleviation of injuries by use of seat belts. TRRL Report No. 289. Transport and Road Research Laboratory, Crowthorne

Schulte, U. and Weyersberg, A., 1984 Theoretical Optimisation of an Airbag System. Proc. 14th Int. Tech. Conf. on Enhanced Safety of Vehicles.

Smith, B.W., Bergfried, D., Faye, I., 1994. SMART™ Airbag System. Proc. 14th Int. Tech. Conf. on Enhanced Safety of Vehicles.

Society of Automotive Engineers Inc. 1991. SAE HS -13 : Vehicle Occupant Restraint Systems and Components - A compilation of SAE, ASTM and FMVSS Standards, Recommended Practices and Test Methods. SAE, Inc. Warrendale, USA. ISBN 1-56091-140-9

Zador, P.L. and Ciccone, M.A., 1993. Automobile Driver Fatalities in Frontal Impacts; Air Bag Compared with Manual Belt. American Journal of Public Health, May; 83(5) : 661-66.

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