A SCIENTIFIC METHOD FOR ANALYSING VEHICLE SAFETY

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Paper Number 98-S11-O-05

ABSTRACT

This paper describes an analytical technique that compares the actual performance of the vehicle structure in absorbing crash energy with an idealised (perfect) performance. The same methodology is applied to the restraint system performance. This can be used as basis of an objective assessment of the vehicle's crashworthiness within the constraints of its particular design. Such an analysis can direct designers to focus on areas of the vehicle that can be improved, such as crush structure and/or particular parts of the restraint system.

INTRODUCTION

Since the New Car Assessment Program began in the US nearly 20 years ago, people have wrestled with how to present the crash results in a form that is easily understood by the consumer.

There have been a number of rating systems used over the years but all have involved subjective assessments to one degree or another. With consumer crash testing occurring worldwide, it has become increasingly important to develop an objective, scientific method of rating vehicle crashworthiness. The aim of such a rating system should be to not only help the consumer make an informed choice but also to assist manufacturers in improving their vehicle designs.

To maximise the protection to an occupant during a crash, the vehicle structure and the restraint system must be optimised to achieve the minimum acceleration for the occupant over the longest possible time within the design constraints of the vehicle.

METHOD

The best restraint condition for an occupant during a crash is to have the minimum possible acceleration applied for the maximum possible duration in order to bring the occupant to rest. Minimum possible acceleration is achieved if the acceleration is held constant at a level sufficient to reduce the velocity from impact velocity to zero over maximum time. To achieve maximum time for this velocity change requires all available distance to be utilised. For restraint of an occupant's head, this ideal distance is from the head to the furthermost impacted extremity of the vehicle. Therefore, the vehicle's crush structure and the performance of the restraint system both have an effect on how well the occupant is protected.

Vehicle Analysis

From an occupant safety point of view, an ideal vehicle would crush progressively, with a constant force required to produce deformation and with the impacted surface of the vehicle displacing as far as possible without intruding into the occupant cell. Moreover, the occupant cell itself must not collapse or deform and all kinetic energy should be absorbed through deformation. In practical terms, if the deceleration of an "ideal" vehicle were measured, it would be constant over time and for the maximum possible duration as determined by the available crush before occupant cell deformation. This concept is illustrated schematically in Figure 1. For a frontal 90° impact against a rigid 0° barrier, an ideal vehicle would crush until the front bumper reached the firewall. The optimum (ideal) crush distance of the vehicle is denoted as S_{opt}. The vehicle has an initial (impact) velocity V_{imp}.

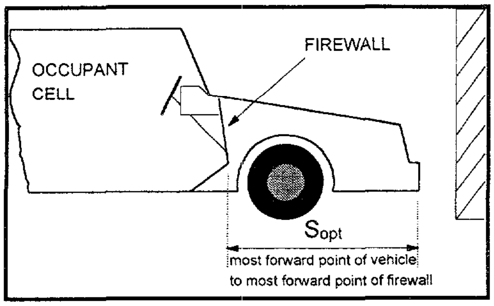

Figure 1. Optimum vehicle crush distance.

Given that minimum constant acceleration should be maintained, simple principles of the physics of motion under constant acceleration may be applied to calculate *ideal crash conditions* as follows:

Velocity change $=$ Final Velocity - Initial Velocity
$= 0 - V_{imp}$ (rebound should be avoided)

Optimum acceleration (aopt) $= V_{imp}^2/(2*S_{opt})$.

Optimum crush time $(t_{max}) = V_{imp}/a_{opt}$.

The ideal instantaneous velocity at any time t is given by $V_i(t) = V_{imp} + a_{opt}*t$.

Hence the ideal specific (massless) energy at any time t is $E_i(t) = V_i(t)^2/2$.

The *actual* specific energy of a vehicle crash $E_a(t)$ can be calculated as $V_a(t)^2/2$, where $V_a(t)$ (the actual instantaneous velocity) is found by integration of the measured vehicle acceleration.

The actual specific energy (as a function of time) from a vehicle crash test can then be compared to the ideal specific energy, calculated based on the principles outlined above.

The typical natures of the ideal and actual energies for vehicle crush are shown in Figure 2.

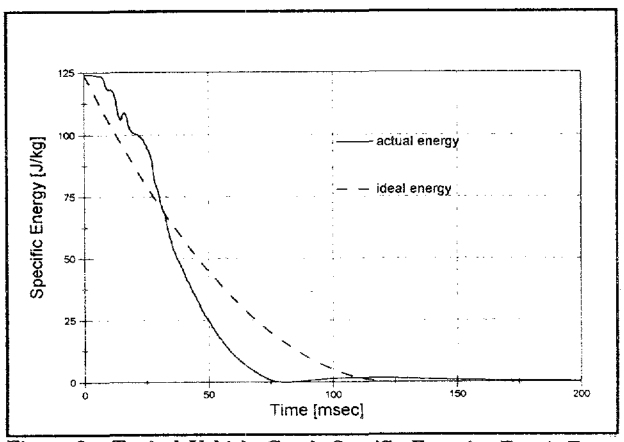

Figure 2. Typical Vehicle Crush Specific Energies For A Frontal 90° Impact Against A Rigid 0° Barrier.

The actual energy depicted in Figure 2 can be considered over three successive time periods as shown in Figure 3.

During the first phase, the actual energy decreases more slowly than ideal. During the second phase, the actual energy decreases more rapidly than ideal, with the vehicle coming to rest at the end of this period. The final phase represents rebound of the vehicle.

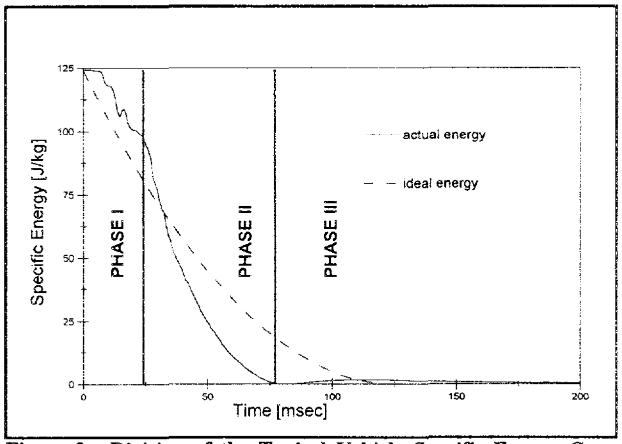

Figure 3. Division of the Typical Vehicle Specific Energy Curves into 3 distinct phases.

The performance of the actual vehicle against the ideal is assessed in each of the three phases. In the first phase, the maximum difference between the ideal and actual curves is divided by the ideal energy at the time that this maximum difference occurs. This resultant term is then subtracted from one. For the second phase the largest negative gradient of the actual energy curve and the ideal gradient at the same moment in time are determined. The ratio of ideal gradient to actual gradient is then used to characterise this phase. The final (rebound) phase is characterised by subtracting from one the ratio of the peak rebound energy divided by the initial energy (energy at time zero).

Occupant Head Analysis

The head analysis technique is based on the same philosophy as the vehicle analysis. A perfect restraint would operate to provide a minimum constant acceleration for the maximum possible time, which in turn is dictated by the available displacement. The occupant should be permitted to move, so long as contact to interior objects is avoided. Figure 4 illustrates the maximum available displacement relative to the ground for an occupant head during a frontal 90° impact against a rigid 0° barrier. The optimum head displacement is the sum of the vehicle crush distance, S_{opt} (bumper to firewall) and the distance from nose to occupant cell boundary, Snsw (usually the steering wheel).

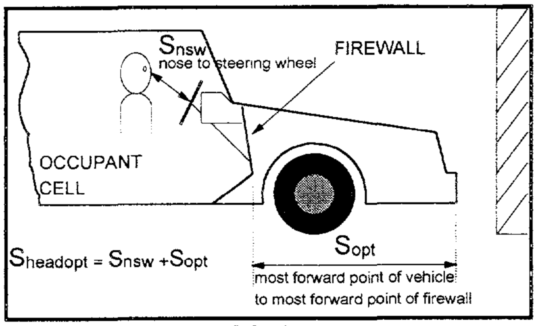

Figure 4. Optimum head displacement.

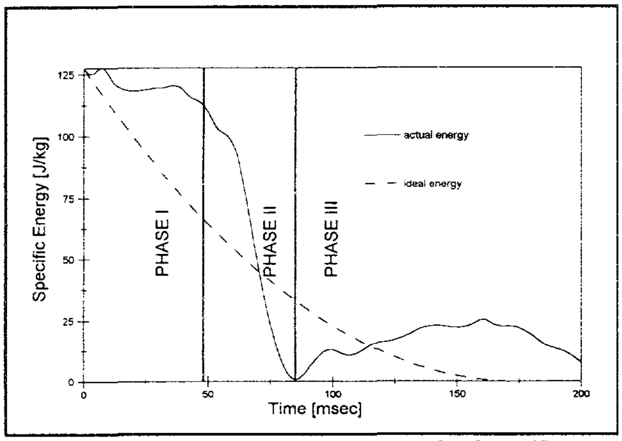

Figure 5. Typical curves showing occupant head specific energy with respect to ground.

The specific energy of the occupant head is considered in the same three phases as the vehicle specific energy as shown in Figure 5. This figure shows that during phase I the head is relatively uncoupled to the vehicle and continues with almost constant energy (constant velocity). In the second phase, the restraint system begins to slow the head and ultimately brings the head to rest. The third stage is the rebound of the head and is clearly more significant than for the vehicle. Performance indices are calculated in the same way as for the vehicle.

RESULTS

A series of 12 tests based on Australian Design Rule (ADR) 69/00 were conducted at a speed of 56 km/h at Autoliv Australia. These tests were 56 km/h frontal 90° impacts against a rigid 0° barrier, with belted occupants. This test condition was chosen to allow correlation with New Car Assessment Program (NCAP) test data. The vehicles tested are listed in Table 1. Unless otherwise stated, all vehicles were equipped with driver airbag.

The test results from the tests listed in Table 1 were analysed using the method described in this paper. The vehicle analysis results are listed in Table 2 and the driver head analysis results are listed in Table 3.

Table 1.
Vehicles Tested at 56 km/h Using ADR 69/00 Test Method

Test Number	Vehicle
TG6C0001	1996 Daihatsu Charade (no airbag)
TG6C0002	1995 Daihatsu Charade
TG6C0003	1996 Holden Commodore (no airbag)
TG6C0004	1996 Mitsubishi Magna
TG6C0006	1995 Hyundai Lantra
TG6C0007	1996 Hyundai Excel Sprint
TG6C0008	1996 Nissan Micra (no airbag)
TG6C0009	1996 Hyundai Excel
TG6C0010	1996 Toyota Corolla
TG6C0011	1997 Toyota Starlet
TG6C0012	1996 Mitsubishi Mirage
TG7C0001	1997 Ford Laser

Table 2.
Vehicle Energy Management Indices for 56 km/h ADR 69/00 Tests

Vehicle	Phase I	Phase II	Phase III
TG6C0001	0.7993	0.2302	0.9862
TG6C0002	0.8182	0.2433	0.9733
TG6C0003	0.8653	0.1549	0.9767
TG6C0004	0.9174	0.2695	0.9914
TG6C0006	0.8991	0.3180	0.9855
TG6C0007	0.8001	0.2690	0.9876
TG6C0008	0.8267	0.2285	0.9831
TG6C0009	0.7744	0.1606	0.9950
TG6C0010	0.8599	0.2637	0.9867
TG6C0011	0.9227	0.2800	0.9836
TG6C0012	0.9119	0.2017	0.9833
TG7C0001	0.8545	0.2728	0.9856

Table 3.
Driver Head Energy Management Indices for 56 km/h ADR 69/00 Tests

Vehicle	Phase I	Phase II	Phase III
TG6C0001	0.3870	0.1492	0.8001
TG6C0002	0.5062	0.1628	0.8606
TG6C0003	0.3857	0.1035	0.7395
TG6C0004	0.7591	0.2021	0.7275
TG6C0006	0.4377	0.1286	0.8195
TG6C0007	0.3948	0.0994	0.8266
TG6C0008	0.2720	0.1020	0.7881
TG6C0009	0.4665	0.1491	0.8256
TG6C0010	0.6258	0.1797	0.7958
TG6C0011	0.5050	0.1533	0.7366
TG6C0012	0.7545	0.2364	0.6803
TG7C0001	0.7370	0.2250	0.7096

DISCUSSION

General Comments

The analysis method detailed in this paper was developed after completion of the tests to which it was to be applied. Whilst the analysis philosophy and technique are clear, the pre-existence of the test data imposed certain difficulties on the calculation procedures adopted.

The performance indices calculated by this method indicate the actual energy management of a given vehicle, compared to the ideal that could be achieved for that vehicle. This must be kept in mind when comparing results from different vehicles as the numbers do not necessarily indicate the injury risk for an occupant, but rather the 'room for improvement' for a given design geometry.

Vehicle Analysis

The analysis method assesses actual energy management compared to ideal energy management. In order to calculate energy, the velocity of the vehicle must be determined. This has been achieved by integrating the longitudinal acceleration of the vehicle. However, the vehicle instrumentation for the 56 km/h ADR 69/00 tests measured longitudinal vehicle accelerations at the engine and rear seat crossmember. The measurements from these transducers reflect vehicle body crush occurring on all parts of the structure forward of the transducer mounting point. The engine acceleration is not useful for this analysis method, and unfortunately, any crush of the occupant cell, which is undesirable from an occupant safety point of view, would be incorporated in the measurements at the rear seat crossmember. In order to accurately characterise the actual vehicle crush behaviour compared to the ideal, it would be necessary to measure accelerations at the most forward point of the occupant cell. In an attempt to compensate for the fact the acceleration data cannot discriminate undesirable occupant cell deformation from desirable vehicle crush, a separate index is calculated to assess the amount of deformation of the occupant cell. This index is the relative crush of the occupant cell, calculated as:

$$\frac{\text{Occupant Cell Initial Size - Occupant Cell Final Size}}{\text{Occupant Cell Initial Size}}$$

Table 4 shows the results of the vehicle performance indices and the relative crush of the occupant cell. These relative crush values must be considered in conjunction with the performance indices. In some cases they may contradict good vehicle energy performance indices, but this is a reflection of the fact that the occupant cell suffered significant deformation, which may have been incorrectly assessed as a beneficial effect in the analysis due to the measurement difficulties.

Table 4.
Relative Crush and Vehicle Energy Management Indices for 56 km/h ADR 69/00 Tests

Vehicle	Relative Crush	Phase I	Phase II	Phase III
TG6C0001	0.8890	0.7993	0.2302	0.9862
TG6C0002	0.8780	0.8182	0.2433	0.9733
TG6C0003	0.9809	0.8653	0.1549	0.9767
TG6C0004	0.9482	0.9174	0.2695	0.9914
TG6C0006	0.9155	0.8991	0.3180	0.9855
TG6C0007	0.9386	0.8001	0.2690	0.9876
TG6C0008	0.9225	0.8267	0.2285	0.9831
TG6C0009	0.9883	0.7744	0.1606	0.9950
TG6C0010	0.9331	0.8599	0.2637	0.9867
TG6C0011	0.9102	0.9227	0.2800	0.9836
TG6C0012	0.9655	0.9119	0.2017	0.9833
TG7C0001	0.9015	0.8545	0.2728	0.9856

The vehicle analysis results indicate that the values from phase III (rebound) are all very similar and near ideal (that is, the actual vehicle rebound energies recorded for the sample vehicles are all very small). Hence, they are of little interest in this discussion, however, some interesting features are evident from the values calculated for phases I and II.

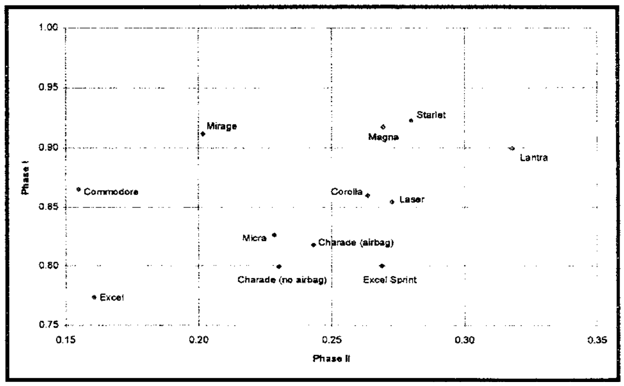

Figure 6. Vehicle Energy Management Indices for phases I and II.

Figure 6 shows the relationship between phases I and II for the vehicle analysis. The upper right corner of the graph represents best performance in both phases. This graph can be used to gain an impression of the overall structural performance of a vehicle and can be used as a means of ranking the structural performances, however, ranking is only valid for vehicles with a similar S_{opt}

(optimum crush distance). For example, it could be concluded that the structural performance of the Starlet was superior to that of the Excel, Excel Sprint and Charade, as these vehicles all have an optimum crush distance in the range 0.90 - 0.99m. The Micra could perhaps be considered in this group, with a crush distance of 0.86m.

It is interesting to note that the results in Figure 6 for the two Charade vehicles are in close agreement, whereas the Excel results are quite dissimilar. This statement is supported by the evidence from the accelerometers measuring the vehicle crash pulses. One possible explanation for this behaviour is that the Excel vehicles had very different crush modes. In other words, the collapse of the vehicle structure was fundamentally different in each of the Excel vehicles.

It would be possible to generate an overall Vehicle Energy Management Index, expressed as a number in the range 0 - 100 if the performance indices for each phase are averaged and multiplied by 100. Using this system, a value of zero would indicate the largest deviation from ideal and a score of 100 would correspond to ideal performance. However, the forming of a single number to characterise vehicle energy management loses the detailed information about individual aspects of the behaviour available for each phase, and could also dilute the significance of a particular phase. Equally, it could be argued that the relative importance of each of the phases are not the same and that weighting factors should be applied to add greater significance to particular phases, instead of simply averaging the individual phase performance indices. Therefore, a single number has not been used to characterise the overall performance.

Occupant Head Analysis

From a purely philosophical point of view, the maximum available displacement for an occupant head relative to the vehicle should be the distance from the initial position of the head to the boundary of the occupant cell. This definition suggests that the steering wheel reduces this idealised distance and that survival space for the occupant would be enlarged if the steering wheel and instrument panel were absent. This would clearly offer improvements in ideal restraint performance, however, to focus this work for realistic application using the sample data available, the distance from nose to steering wheel hub was chosen as the appropriate displacement for the occupant head relative to the vehicle.

The velocity of the driver head relative to ground needs to be determined in order to be able to calculate kinetic energy of the head. The accelerations at the centre of gravity of the head are not suitable for calculating velocity by integration, because the head undergoes angular motion. This angular motion of the head produces a centripetal acceleration that results in a change in angular velocity. However, the instantaneous centre of rotation is not usually known and the angular component of this motion cannot be removed from the total acceleration. Hence integration of the acceleration does not yield the true translational velocity. To overcome this difficulty, motion analysis from high speed films was used to determine the velocity time history of the driver head relative to the ground and this was used to calculate the actual energy of the head.

This film analysis method yields the head motion relative to ground, however, it does not indicate whether this motion is due to desirable vehicle crush or undesirable crush. To compensate for this fact, the relative steering wheel intrusion was chosen as a separate index to assess the extra risk imposed by steering wheel intrusion. Unfortunately, the dynamic steering wheel intrusion was unable to be measured in all vehicles, and hence static measurements taken before and after the tests were used. The relative steering wheel intrusion is calculated as:

$$\frac{\text{Snsw} - \text{Steering wheel intrusion}}{\text{Snsw}}$$

where Snsw is the distance from the driver dummy nose to the centre of the steering wheel hub, and steering wheel intrusion is the difference between the pre-test and post-test horizontal distances from the rear bumper to the centre of the steering wheel.

The result from this method is the potential for a relative steering wheel intrusion greater than one if the steering column had a residual displacement away from the occupant head. This is considered desirable as it allows an effective increase in survival space for the occupant, and this is reflected in the relative steering wheel intrusion. Table 5 shows the head restraint performance indices and relative steering wheel intrusion. Again, the relative steering wheel intrusion values should be considered in conjunction with the performance indices. A good head restraint performance index can be largely overshadowed by a poor result from the steering wheel intrusion.

Table 5.
Relative Steering Wheel Intrusion and Head Energy Management Indices for 56 km/h ADR 69/00 Tests

Vehicle	Relative Steering Wheel Intrusion	Phase I	Phase II	Phase III
TG6C0001	0.7175	0.3870	0.1492	0.8001
TG6C0002	0.9553	0.5062	0.1628	0.8606
TG6C0003	0.8677	0.3857	0.1035	0.7395
TG6C0004	1.1418	0.7591	0.2021	0.7275
TG6C0006	0.9816	0.4377	0.1286	0.8195
TG6C0007	0.9175	0.3948	0.0994	0.8266
TG6C0008	0.8048	0.2720	0.1020	0.7881
TG6C0009	0.8977	0.4665	0.1491	0.8256
TG6C0010	0.9380	0.6258	0.1797	0.7958
TG6C0011	0.9052	0.5050	0.1533	0.7366
TG6C0012	0.9321	0.7545	0.2364	0.6803
TG7C0001	1.0544	0.7370	0.2250	0.7096

The values for head restraint performance in phase III clearly indicate that the rebound energies for the head are much more significant than those for the vehicle.
The performance index for phase II is calculated using the peak gradient of the actual energy curve. This value represents the peak power applied to the head and therefore the performance index is the ratio of ideal power to peak actual power. For the vehicles tested the time of occurrence of the peak actual energy gradient (from motion analysis) was compared with the time window found for 36 millisecond Head Injury Criterion (HIC36) for the data obtained from accelerometers mounted at the centre of gravity of the dummy head. The peak energy gradient was always at a time within the HIC36 window, and was typically 5-10 ms after the beginning of the HIC36 window.

It is interesting to look at the relationships between each of the phases for the head restraint.
Figure 7 shows the relationship between phases I and II for head restraint. As a general trend, the better the phase I performance, the better the phase II performance. This indicates that a good performance in phase I acts as a firm basis for a good performance in phase II and a poor performance in phase I makes it difficult to achieve a good performance in phase II.

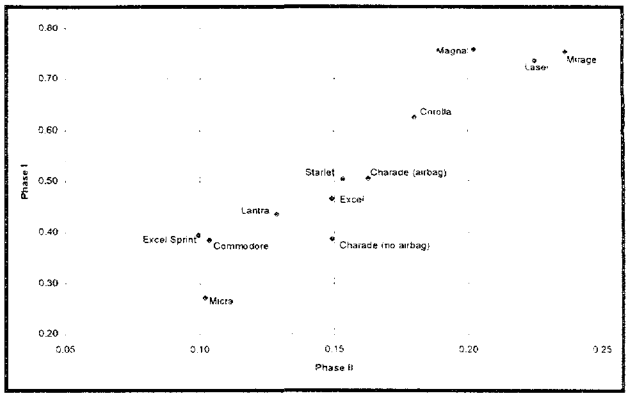

Figure 7. Head Energy Management Indices for phases I and II.

The relationship between phases II and III is shown in Figure 8. The features of most interest in this graph are the results for the Mirage, Magna and Laser. These three vehicles have the best performance indices for phase II and the worst for phase III. This indicates that the power applied to restrain the head was nearer optimum for these three vehicles than the other vehicles, but that the rebound energy was greater (i.e., a more severe rebound). This is in contrast to other airbag vehicles in the sample and may be an indication that the airbags in these vehicles are overpowered, resulting in a favourable HIC result, but a high rebound velocity. If the Magna, Mirage and Laser data are ignored in Figure 8, the general trend relationship between phases II and III is that a good performance in phase II corresponds to a good performance in phase III.

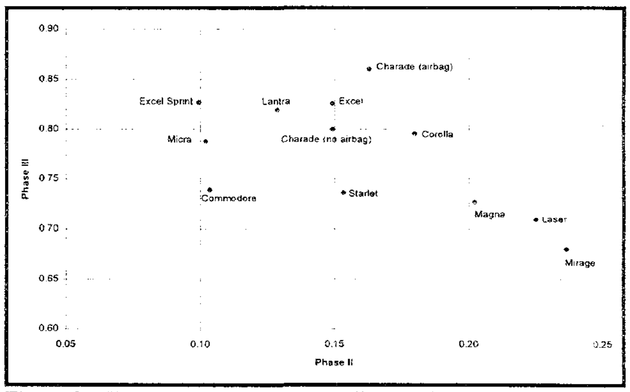

Figure 8. Head Energy Management Indices for phases II and III.

APPLICATION

This vehicle safety analysis method does not give a direct indication of the risk of injury of a given restraint system in a given vehicle. Instead, it quantifies the relationship between the actual restraint performance and an idealised perfect restraint for the physical dimensions of a particular vehicle and a particular test speed. A perfect restraint performance would yield the lowest possible injuries to any occupant. The calculated index gives an assessment of "how close to ideal" a restraint system may be and hence indicates the "room for improvement". This can be used to quantify improvements in restraint for various restraint systems in a given vehicle. It can also be used as a basis for ranking the restraint performances of various vehicles, provided the vehicles are of a similar size.

However, there is a great deal that may be revealed about the relative merits of different aspects of a particular restraint in a particular vehicle. For example, a poor vehicle structure performance and moderate head restraint performance would indicate that the belt and/or airbag system are working reasonably well, and that a more ideal restraint performance would be best achieved by improvements to vehicle crush behaviour.

The performance indices for each of the three phases can also indicate the characteristics that deviate the most from ideal and hence would yield the most benefit from an improvement. For example, a poor result for Phase I for the driver head may indicate excessive belt slack that could benefit from belt pretensioning. A poor result in Phase II is an indication that the restraint is too stiff and this should be targeted for improvement.

Such information is useful to restraint designers and safety performance analysts as it gives an objective reference and/or assessment of improvement with which to work when optimising restraint design.

CONCLUSION

The scientific method for analysing vehicle safety performance outlined in this paper:

1. Can be used to indicate the "room for improvement" of the restraint system and vehicle structure of any given vehicle in a frontal 90° impact against a rigid 0° barrier.
2. Does not directly indicate the injury risk to an occupant.
3. Can facilitate restraint development by indicating the relative merits of various aspects of the restraint system and vehicle structure to indicate the most beneficial area for improvement.

RECOMMENDATIONS

It is intended that this method will undergo further validation by analysing data from a controlled set of experiments.

It would be desirable to extend this method for body parts other than the head, to allow a more complete assessment of the performance of a restraint system.

ACKNOWLEDGEMENTS

Grateful thanks are extended to Brendan Chambers and Robert Judd (Autoliv Australia Pty Ltd) for useful discussions and to John Fabre (Psycorp Pty Ltd) for helpful discussion regarding characterising the actual data with respect to the ideal data. The authors also acknowledge the input from Robyn Attewell (INTSTAT Pty Ltd) for comments on the mathematics of the method, presentation and interpretation of results