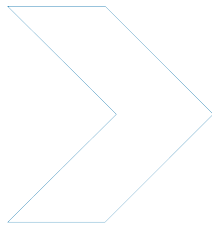


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Vehicle improvements to reduce the number and severity of rear end crashes

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ABSTRACT

This report reviews vehicle technology developed to reduce the incidence of rear end crashes and the whiplash injuries that may result. Chapters cover: crash avoidance measures, passive safety measures built into improved seat and head restraint designs, assessment procedures that have been developed to assess the efficacy of various seat and head restraint designs in rear impacts, testing and assessment programs that are used to inform consumers of the relative performance of the seats in different models of vehicle and includes up-to-date information on the recently released EuroNCAP proposal to assess whiplash protection measures, the uptake of both seat-based whiplash countermeasures and also brake assistive technologies in Australia, and research on the costs and benefits of vehicle based measures to reduce rear end crashes and whiplash injury. Commentary is given on the opportunities for increasing the awareness of consumers in relation to vehicle based rear-end crash and whiplash countermeasures.

KEYWORDS

Rear end crash, Active safety, Passive safety, Whiplash protection, Consumer testing, Head restraints

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The views expressed in this report are those of the authors and do not necessarily represent those of the University of Adelaide or the funding organisations.

Executive summary

Rear end crashes represent a significant burden on compulsory third party schemes in Australia. For example, around 40% of compulsory third party claims and 25% of CTP costs in South Australia arise from rear-end crashes (McColl, 2008), and it is understood that similar percentages apply across Australia. Rear end crashes account for around one third of all crashes reported to police: for example, in the five years to the end of 2006, rear end crashes accounted for 32% of crashes of any severity and were double the number of 'hit fixed object' crashes in South Australia (source, Traffic Accident Reporting System, South Australia).

Rear end crashes often result in minor injuries (or no injuries at all). Less than 5% of rear end casualty crashes result in a hospital admission or a fatality. Ninety five percent of casualties will be either treated by a private doctor, or in a casualty department of a hospital. A large number of these minor casualties are treated for whiplash. Typically 95% of whiplash casualties will recover completely following the crash. However symptoms do not fully resolve in around 5% of people who report whiplash injuries; these casualties are left with some level of disability. A smaller number again (<2%) will not return to work after the injury (Whiplash Commission, 2005).

Whiplash injuries are costly: in NSW, whiplash injuries are involved in around 45% of all compulsory third party (CTP) insurance claims and account for over a quarter of CTP costs (MAA, 2008), thus explaining the high associated costs of rear-end crashes.

This report reviews vehicle technology developed to reduce the incidence of rear end crashes and the whiplash injuries that may result. Chapters cover:

- crash avoidance measures,
- passive safety measures built into improved seat and head restraint designs,
- assessment procedures that have been developed to assess the efficacy of various seat and head restraint designs in rear impacts,
- testing and assessment programs that are used to inform consumers of the relative performance of the seats in different models of vehicle and includes up-to-date information on the recently released EuroNCAP proposal to assess whiplash protection measures,
- the uptake of both seat-based whiplash countermeasures and also brake assistive technologies in Australia,
- research on the costs and benefits of vehicle based measures to reduce rear end crashes and whiplash injury.

Crash avoidance measures include those which aim to stop the host vehicle striking the rear of the lead vehicle, and those measures which aim to stop the host vehicle being struck from behind. The chief means that have been developed to reduce the risk of striking a lead vehicle in the rear have been adaptive cruise control and forward collision warning systems. These are usually combined in the one system, so that the vehicle brakes to avoid short headways and alerts the driver in emergency situations that exceed the braking capacity of the cruise control.

A number of crash avoidance technologies incorporate enhanced braking programs. Chief among the enhanced braking programs has been the Mercedes Benz-developed Brake Assist (BAS), which recognises a driver's attempt at emergency braking and ensures that the vehicle's maximum braking capability is used, without wheel lock-up. Advances on this system in recent years have included BAS PLUS, which detects situations posing a crash

risk and warns the driver, and PRE-SAFE, which, in addition to the BAS PLUS system, automatically brakes when the driver has not reacted to a crash risk warning. Evaluations of these systems on simulators have produced positive results, while crash data have suggested that the base BAS system has reduced crashes.

There have been studies into the potential of activating brake lights earlier in emergency braking situations. The results of a modelling study for a system in which the brake lights are activated when a collision warning is given were positive while the results of a field test of a system in which the brake lights were activated by the rapid release of the accelerator failed to show a benefit. Other researchers have considered using brake lights that flash in an emergency braking situation. The lights can flash when the host vehicle is braking heavily or when detecting a vehicle that is at risk of striking from behind. These systems are still in the early phases of development.

Enhancing rear vehicle conspicuity is another potential means of decreasing the risk of being struck from behind. This is likely to be applicable to night-time crashes and has mainly been discussed with regard to heavy vehicles.

A series of cost benefit analyses were conducted on behalf of the European Commission to determine the most cost-effective vehicle-based countermeasures to recommend for installation into new model cars in the European Union. Of the countermeasures above, conspicuity marking of heavy goods vehicles was one of the most cost-effective, although this was based on a high estimated level of crash reduction. The lack of available information for unit costs made it impossible to calculate cost benefit ratios for forward collision warning systems and Brake Assist, while adaptive cruise control was found not to be cost-effective. The latter was due to its only being applicable to rear end collisions, for which it was expected to be highly effective, but for no other crash types, unlike the more broadly effective collision warning and enhanced braking systems.

Seat design measures have focussed on managing the impact energy in a way that minimises forces placed on the neck, and particular motions thought to be injurious, such as retraction, hyper-extension and hyper-flexion. Despite uncertainty over the mechanism of whiplash injury, basic principles of restraint design have been applied to design seats that reduce the forces placed on the neck in a rear end crash. Such seats were pioneered by Saab, Volvo and Toyota. The Saab and Volvo seats appear to have a measurable effect on long-term injury rates.

There are several current and proposed testing protocols and programs evaluating passive safety measures to reduce rear impact neck injury. Most activity in the establishment of assessment programs that are designed for consumer information has occurred within the International Insurance Whiplash Prevention Group (IIWPG), The Swedish Insurer Folksam and the Swedish Road Administration, and most recently the European New Car Assessment Program (EuroNCAP). Importantly, EuroNCAP will include a vehicle's performance in whiplash tests in the overall EuroNCAP assessment score.

All consumer programs have settled on the use of the BioRID II dummy for dynamic testing and the Head Restraint Measurement Device (HRMD) for static geometry assessments. To assess a seat in a rear impact test requires both a suitable dummy, and also an appropriate metric of injury potential. Broadly speaking, assessment criteria can be split into those that measure impact kinematics closely related to hypothesised mechanisms of injury, and those that measure forces placed on the neck. The latter type may be related to some hypothesised injury mechanism, or may be a simple measure of force or kinematics, on the basis that reducing the force placed on the neck should also reduce the probability of injury. Such criteria favour a short head-to-head-restraint contact time, low forces on the neck and low rebound velocity.

There has only been one cost effectiveness study of passive safety measures to reduce neck injury in rear impacts; a study of head restraint geometry. This study showed that benefit cost ratios are greatest for a minimum gap of 40 mm between the head and the head restraint.

Brake assistive technologies and seats/headrests designed to reduce whiplash injury are being taken up by consumers in Australia. Around 40% of all new cars sold in Australia currently have some anti-whiplash seat installed, and around 63% have some form of Brake Assist.

There are opportunities for greater promotion of anti-whiplash technologies in Australia and New Zealand. The Australasian New Car Assessment Program has generally harmonised with EuroNCAP in the past, and so it is likely they will adopt some or all of the EuroNCAP seat assessment protocol. The Insurance Australia Group is already rating seats according to the results of static and dynamic tests that are a subset of the EuroNCAP assessment. It is feasible to coordinate these two activities and produce a consistent set of ratings data that could include the assessment of both passive and active safety features.

ANCAP has not yet implemented rear-end crash safety assessments and some HCTP advocacy might ensure that it is introduced promptly. Seat testing and scoring could be an important part of ensuring an acceptable minimum standard of protection. Furthermore, active (primary crash prevention) features may be even more important in reducing the incidence of injuries from rear impacts than passive safety features - it would be world-leading to have assessments of primary rear-end crash prevention technology included in an Australian rating scheme.

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1 Introduction

Rear end crashes represent a significant burden on compulsory third party schemes in Australia. For example, around 40% of compulsory third party (CTP) claims and 25% of CTP costs in South Australia arise from rear-end crashes (McColl, 2008), and it is understood that similar percentages apply across Australia. They account for around a third of all crashes reported to police: for example, in the five years to the end of 2006, rear end crashes accounted for 32% of crashes of any severity and were double the number of 'hit fixed object' crashes in South Australia (source, Traffic Accident Reporting System, South Australia).

Rear end crashes often result in minor injuries (or no injuries at all). Less than 5% of rear end casualty crashes result in a hospital admission or a fatality. Ninety five percent of casualties will be either treated by a private doctor, or in a casualty department of a hospital (ibid.). A large number of these minor casualties are treated for whiplash. Typically 95% of whiplash casualties will recover completely in a short period. However, in around 5% of people who report whiplash injuries, symptoms do not fully resolve and they are left with some level of disability. A smaller number again (<2%) will not return to work after the injury (Whiplash Commission, 2005).

Whiplash injuries are costly: in NSW whiplash injuries are involved in around 45% of all compulsory third party (CTP) insurance claims and account for over a quarter of CTP costs (MAA, 2008), thus explaining the high associated costs of rear-end crashes.

There are many theories about the aetiology of whiplash injury and they range from the purely mechanistic, considering only the biomechanics of the crash event, to theories that place the whiplash injury phenomenon solely in the realm of the psychology of secondary gain, where the patient has some interest in remaining "ill". More moderate conclusions can be drawn regarding the importance of non-crash factors that indicate a risk of disabling symptoms. These include initial signs and symptoms (Brison et al., 2000; Berglund et al. 2000), socio-demographic factors (Harder et al., 1998; Cassidy et al., 2000), psychosocial factors (Hendriks et al., 2005), and medico-legal factors (Cassidy et al., 2000).

However, such non-crash factors have not prevented a significant amount of research and development in the area of vehicle based whiplash prevention. Much of it is identifiable as better seat and head restraint designs (passive safety measures), but it also includes important advances in crash avoidance technologies (active safety measures). Both active and passive safety technologies are considered in this report.

This report reviews the vehicle technology developed to reduce the incidence of rear-end crashes and the whiplash injuries that result from rear-end crashes: Chapter 2 deals with crash avoidance measures, while Chapter 3 examines the passive safety measures built into improved seat and head restraint designs. Chapter 4 examines the assessment procedures that have been developed to assess the efficacy of various seat and head restraint designs in rear impacts. Chapter 5 summarises the various testing and assessment programs that are used to inform consumers of the relative performance of different models of vehicle and includes up-to-date information on the recently released EuroNCAP proposal to assess seat-based whiplash protection measures. Chapter 6 presents data on the uptake of both seat-based whiplash countermeasures and also brake assistive technologies. Finally, Chapter 7 examines the limited research on the costs and benefits of vehicle based measures to reduce the incidence of rear-end crashes and whiplash injury.

2 Crash avoidance countermeasures

This section is concerned with technology or changes in vehicle design that can decrease the likelihood of rear-end collisions or at least reduce their severity. Such vehicle-based countermeasures can either operate to decrease the likelihood of the “host vehicle” (the vehicle to which the countermeasure has been applied) striking a vehicle ahead (Section 2.1), or to decrease the likelihood of the host vehicle being struck from behind (Section 2.2). Countermeasures of the first variety have been the subject of the majority of recent research, and include technological innovations such as adaptive cruise control, collision warning systems and various enhanced braking programs. This research has been led by vehicle manufacturers, including Toyota, Volvo, Mercedes Benz of Daimler AG and General Motors, the latter engaged in a long running collaboration with the National Highway Traffic Safety Administration of the US Department of Transportation. Countermeasures designed to decrease the likelihood of the host vehicle being struck from behind include enhanced rear conspicuity and various forms of enhanced brake lights. The literature reviewed in this section is restricted to research published in scientific journals or forums.

2.1 Measures to stop the host vehicle striking the rear of a lead vehicle

2.1.1 Collision warning systems

As noted by Mortimer (1993), drivers do not immediately brake upon seeing the activation of brake lights on a vehicle in front of them. They use the brake signal on vehicles ahead only as a signal of the *possibility* of needing to brake. Whether or not they do brake is decided on the basis of their perceptions of the necessity of braking to avoid colliding with the vehicle in front. These decisions require consideration of the distance to the vehicle in front and the rate of closure between the two vehicles. Studies of drivers’ perceptual processes have found that judgements about the rate of closure between a driver’s own vehicle and the one in front are based largely on the visual angle of the leading vehicle. As a result of this, drivers do not perceive relative velocity cues until there is only a short time and distance to the vehicle in front, which, in turn, is likely to contribute to the occurrence of rear-end collisions (McGehee, Dingus, & Horowitz, 1992; Mortimer, 1990).

Given this limited capacity of drivers to make accurate judgements on relative velocities based on visual cues, a number of intelligent transport systems have been designed to aid the drivers in avoiding rear-end collisions. There are two main types of such systems. One is ‘adaptive cruise control’, which detects slower moving vehicles ahead and automatically, through deceleration and braking, adjusts the speed of the ‘host’ vehicle to a comparable level. The other type is a ‘collision warning system’, which detects slower vehicles ahead and warns the driver of the host vehicle so that he or she can then take appropriate action (National Transportation Safety Board, 2001). Most recent research has been focussed on the effectiveness of the combination of the two systems. That is, investigations have been conducted into the crash avoidance properties of systems in which the vehicle reduces its speed in response to slowing vehicles ahead by releasing the accelerator and lightly braking, but, in situations requiring heavier braking to avoid a collision, warns the driver that further action is necessary. Evaluations of prototypes of these devices have been conducted using complex mathematical and computer modelling, driving simulator experiments, and field trials in fleet vehicles being driven on public roads.

There are a number of issues in need of resolution with regard to the successful implementation of adaptive cruise control and collision warning systems. The two most researched aspects of collision warning systems have been the sensory modality of the warnings given to drivers and the algorithms used for activation of those warnings.

Sensory modality of warnings

Considerable research has been conducted that provides guidance for the choice of the sensory modality most likely to attract the attention of drivers. The options investigated have included visual, auditory, tactile and multimodal (i.e. a combination of sensory modalities). There are also choices to be made within modalities, such as the choice of a verbal auditory warning or a simply a tonal one.

Scott and Gray (2007) conducted a driving simulator-based study assessing 16 drivers' reaction times to various forms of rear-end collision warning. The participants were required to maintain a two second headway behind a lead vehicle that would unpredictably accelerate, decelerate and brake to a stop. Reaction times to heavy braking of the lead vehicle were longest for the no warning condition, followed, in order, by the visual, auditory and tactile conditions. Although this would seem to suggest that tactile warnings are preferable, the difference between reaction times for the tactile and auditory warning conditions was not statistically significant, and participants also rated the tactile warnings to be the most irritating, while few were irritated by the auditory warnings (Scott & Gray, 2007). The ecological validity of the study is questionable given that the brake lights on the lead vehicle were not enabled during the experiment. That is, a standard visual cue to lead vehicle braking was not provided to the participants. However, as the lack of brake lights was consistent across all conditions, the comparisons between the warning signal types should remain valid.

Ho, Reed and Spence (2007) also examined the utility of a number of different warning types, investigating reaction time on a simulator in response to a leading vehicle braking and warnings of either an auditory, vibrotactile or audiotactile (a combination of auditory and vibrotactile) modality. Visual warnings were not included because the authors claim there is a need to reduce visual overload, and because, as claimed by Sivak (1996), auditory and tactile sensory modalities are under-utilised in driving. In this study, warning signals were presented simultaneously with the rapid deceleration of the lead vehicle, the brakelights of which were disabled on half of the trials. The 15 participants were required to maintain a headway of between 1.8 and 2.2s, with the in-car navigation providing feedback for this. A radio program was playing throughout the trials, which the authors claimed enhanced the ecological validity of the study, given the high prevalence of listening to the radio while driving. The radio was not loud enough to disrupt hearing the auditory signals. The results of the study were that reaction times were shortest for the audiotactile warnings, with the longest reaction times occurring for the vibrotactile warnings. An unusual facet of the study was the presentation of the warnings simultaneously with the deceleration of the lead vehicle. In real driving situations, as noted by the authors, there would be an algorithm to determine the need for a warning that would necessarily involve a delay between the lead vehicle braking and warning onset (Ho et al., 2007).

Another study that investigated multimodal warnings but which did use a realistic algorithm was that by Lee et al (2006). Lee et al used a sophisticated driving simulator to investigate brake reaction time and time to collision for drivers responding to warnings that combined a visual alert with either a tonal auditory alert, a seat vibration alert, a brake pulsation alert, or all three combined. Thus, all alerts were multimodal but one involved more modalities than the others. Sixty drivers were divided into four groups for the study with each group responding to one of the alert types. All participants completed trials that lasted for 35 minutes, including eight situations requiring mild braking, four requiring moderate braking and two requiring severe braking, half in each case associated with a lead vehicle braking and half associated with a vehicle moving into the lane in front of the participant. The events requiring braking responses were timed to occur simultaneously with the participant responding to a secondary distraction task. The most notable finding with regard to the

different warning types was that brake reaction times were longer for the alerts combining all sensory modalities, with the fastest responses occurring with the warnings combining visual and auditory alerts. The latter warnings produced reaction times 400ms faster than the warnings combining visual, auditory, seat vibration and brake pulsation alerts. The authors had expected that the greater redundancy inherent in the more multimodal warnings would result in faster responses but did note that there have been previous studies, including one into lane-departure collision warnings, similarly finding slower responses to multimodal alerts. They speculated that multimodal warnings may be perceived as multiple cues rather than as a single one and that further research would be needed to identify the properties of different modalities that are necessary to produce a 'gestalt' (i.e. combine to create a single cue) (Lee et al., 2006).

Multimodal warnings, in this case the combination of visual and auditory cues, were compared to the component unimodal cues in a study by Maltz and Shinar (2004). Using a simulator, the study employed 135 participants and an in-vehicle collision avoidance warning system of varied reliability (i.e. the study included false alarms and alert failures). With regard to the alert modality, the shortest response times were recorded for alerts using an auditory tone, rather than speech-based, visual or multimodal alerts. In addition to performance benefits, participants also rated the auditory tone alerts as the most helpful (Maltz & Shinar, 2004).

Fung et al. (2007) concentrated their work on determining the optimum form of auditory warnings. Using a driving simulator, they assessed 30 participants' reaction times in response to a lead vehicle cutting in front of the participant and braking. The different conditions included no warning, a verbal warning, and a beeping tone warning. It was found that the beeping tone warning was associated with the shortest reaction time, and that it was significantly shorter than the reaction times for the no warning condition (Fung et al, 2007).

It has also been suggested (Ljung et al., 2007) that another consideration apart from reaction time to warnings in research studies is the ability of drivers to understand the meaning of a rarely given warning. If a collision warning is rare, a driver may not understand what a tonal signal means. Instead, a verbal warning may be necessary for the driver to realise what the vehicle warning system is indicating. The authors note that such a verbal warning assumes that the driver speaks the same language as that used for the warning system. An alternative solution, in order to retain the tonal signals associated in the literature with shorter reaction times, is to have regular 'training' provided by the vehicle at start-up (Ljung et al., 2007).

Lind (2007) of Volvo Corporation focussed his research on the effects of the location of visual warnings on drivers' reaction times. Using a driving simulator, Lind examined the utility of "head up" displays, steering wheel displays, "high head down" displays and "cluster" displays. Warnings were randomly presented to drivers who were distracted by a secondary traffic sign discrimination task. The head up display was associated with the shortest brake reaction times and the fewest missed warnings. The participants also expressed a preference for the head up displays used in the study (Lind, 2007).

Campbell, Richard, Brown and McCallum (2007) provide a summary of conclusions drawn from years of research conducted collaboratively between General Motors Corporation and the National Highway Traffic Safety Administration of the US Department of Transportation. The system envisaged by Campbell et al included both Cautionary Collision Warnings (CCWs) and Imminent Collision Warnings (ICWs), the former warning of a dangerously close headway and the latter warning of a high likelihood of collision without hard braking or steering input from the driver. The authors claimed that CCWs would be more common and so should be less intrusive than the more important but less common ICWs. Their

suggestion was a visual display that was easily perceived but not too intrusive (head up or high head down). The suggested colour was red, for its association with danger, but orange or amber were acceptable alternatives in the case of too many other red icons in the visual display. Drivers should also be able to adjust the intensity of the warnings. For ICWs, the authors argued for a multimodal alert, comprising an auditory tone and flashing visual signal. The auditory alarm has to be loud enough to be heard over the background ambient noise but the authors caution that there are diminishing returns for performance gains above 75 db and a system with alerts that are too loud will annoy the driver. One of the main arguments for an auditory alert was that it is 'omnidirectional' and so can be detected by drivers even if they are not looking at the road. The visual alert is a backup if there is high ambient noise or a hearing impaired driver (Campbell et al., 2007).

Algorithms for activation of collision warnings

The second main issue for the design of in-vehicle collision warning systems is the determination of the appropriate algorithms for collision warnings. Algorithms are needed to determine when a warning is necessary. If an algorithm is inappropriate, it can either give warnings that are too early or too late, or it can warn the driver about non-hazardous situations (e.g. about obstacles that are not in the path of the host vehicle). If warnings are given too early or in response to non-hazardous objects, there will be too many false alarms and drivers will begin to disregard the system (Kodaka et al., 2003; Lee, McGehee, Brown, & Reyes, 2002). This loss of trust in the system may subsequently transfer to other vehicle warning systems (Ljung et al., 2007). Horowitz and Dingus (1992) noted that the typical driver probably has a rear-end collision once every 25 years and so warnings should ideally be rare. However, if the system is set so that warnings are given too late, then the system will be ineffective because it will not give drivers sufficient time to avoid a collision (Kodaka et al., 2003; Lee et al., 2002).

One study that directly addressed the issue of the timing of warnings given to drivers was that conducted by Lee et al. (2002). This study compared rear-end collision avoidance on a simulator according to drivers receiving an early or late warning, or no warning at all, and according to whether the drivers were distracted or not by a secondary task. Different speeds, headways, and lead vehicle deceleration rates were employed in order to investigate the warning timing over a range of conditions. The system being tested used a combination of auditory warning tones and the appearance of crash icons on the instrument panel, and worked on the basis of an algorithm combining information on distance to the vehicle in front, the assumed driver reaction time to a warning and deceleration capability of the vehicle. The early warning condition involved the system acting as though the vehicle was capable of 0.4 g deceleration, while the late warning condition was based on a 0.75 g deceleration capability. The other two parameters were kept constant. It was found that early warnings were associated with the least number of crashes on the simulator, followed by late warnings and no warnings. This reduction in crashes was found to be due to faster reaction to the lead vehicle braking (assessed by measuring release of the accelerator). Drivers receiving no warning of the deceleration of the vehicle ahead were forced to brake more heavily than drivers receiving the early warning. Therefore, an early warning protects the driver from colliding with the vehicle in front but also means less need for heavy braking, and so may reduce the likelihood of being struck from behind. The fact that the early warning was associated with milder braking than occurred for conditions in which the driver reacted later demonstrates that drivers modulate their braking response according to the evolving situation. The warning is therefore mainly a cue to release the accelerator and attend to the vehicle in front, rather than immediately triggering a strong braking response. This pattern of results was the same in the distraction and no distraction conditions. Furthermore, the warnings conditions (early, late, none) had a greater effect on crash involvement rates than did levels of distraction. The authors acknowledged that the results

of simulator studies must be treated with caution because the threat of collisions is not a real one, and also that the study did not evaluate the effects of false alarms on the success of the warning system. However, they argued that since the system was found to influence driver's attention rather than to lead to immediate braking, the system would be unlikely to lead to unnecessary braking and so the safety benefits would outweigh any negatives (Lee et al., 2002).

Kiefer, LeBlanc and Flannagan (2005) reported on a complex on-road study used to develop warning signal timing algorithms as part of the collision warning system research program of General Motors. In particular, the researchers were interested in the braking and steering profiles of drivers in realistic rear-end crash conditions. An age- and sex-balanced sample of 72 drivers had to follow a surrogate lead vehicle (the shell of the rear of a car with working brake lights towed by another vehicle using a collapsible tow beam), and were required to brake or steer around the vehicle as they normally would on some trials and as late as possible on others. The surrogate vehicle was either stationary, travelling more slowly than the participant's car, or decelerating. Required deceleration and time to collision were measured at the onset of braking or steering for each trial. A total of approximately 3,500 last second braking judgement trials and 790 last second steering judgement trials were undertaken. It was found that last second steering manoeuvres were undertaken later than last second braking, particularly at high speeds, suggesting that alert timing based on last second braking could result in alerts occurring prior to intentional lane manoeuvres. It was also found that drivers' deceleration varied greatly across different kinematic conditions, suggesting that timing alerts assuming consistent deceleration will result in alerts perceived by drivers as inappropriate across a wide range of conditions. Using logistic regression to predict whether a trial involved hard or normal braking, the researchers found that inverse time to collision was the best predictor. The authors argued that this makes sense as inverse TTC "is directly tied to the visual looming properties of the looming vehicle... As the driver approaches a distant lead vehicle travelling at a constant speed, the visual angle subtended by this vehicle ahead will steadily increase prior to undergoing a rapid expansion prior to a collision" (p300). Reflecting this, as TTC reduces to low values, the value of inverse TTC increases rapidly. On the basis of the results of this study, the authors developed an algorithm for warning alerts that when activated would require a deceleration at brake onset of no more than 0.45 g (Kiefer et al., 2005).

There is reason to suggest that collision avoidance warning systems would be more effective if warnings could be given earlier when drivers are distracted. Working on this principle, Kimura, Nakagoshi and Kanamori (2007) of Toyota conducted studies to determine if it were possible to use facial direction as an indication of driver inattention. The choice of facial distraction was governed by the belief that most distraction involves horizontal face rotation, and that it would be easier to design a system to detect facial rotation rather than eye gaze. Using both laboratory and on-road studies of drivers aged from their 20s to their 50s, Kimura et al. found that the head moves when the required point of fixation is beyond 20 degrees from directly ahead, and that such head movements were associated with longer brake reaction times in response to visual warning signals. The authors concluded that collision warning systems would be improved if warnings were given earlier when the system detects drivers' faces are directed more than 15 degrees away from directly ahead (Kimura et al., 2007).

Another issue for developing algorithms for collision warning systems is whether to allow for the possibility of driver override of the system. As Coelingh, Jakobsson, Lind and Lindman (2007) of Volvo argue, drivers have more information available to them than the most advanced warning systems and so may be in control of the situation even when the system detects the possibility of danger. Based on testing in real life traffic situations with volunteer drivers, the system developers at Volvo determined that it is reasonable to

assume a driver is taking control if they brake, steer or release the accelerator. The warning system in this case uses an algorithm based on the product of driver reaction time and vehicle speed, the product of the system reaction time and vehicle speed, and the braking distance required to avoid an impact with the lead vehicle, the speed of which is also taken into consideration. If the system detects driver input, the assumed driver reaction time component is reduced for the calculations and there is a consequent lower likelihood of the driver being given a warning (Coelingh et al, 2007).

A great deal of work has been done in the NHTSA research program to develop collision warning systems (Campbell et al., 2007; Najm, Stearns, Howarth, Koopmann & Hitz, 2006; NHTSA, 2005). Initial findings suggested that designing a system that is free of nuisance alerts (to roadside objects, to turning vehicles, during lane changes) was a “formidable technical challenge” (NHTSA, 2005, p95). One suggested solution was that warnings to objects never seen to be moving could be eliminated (Najm et al., 2006; NHTSA, 2005). This would eliminate nuisance alarms in response to fixed roadside objects but would mean that stationary vehicles never detected to be moving by the system would not be the subject of warnings. Other suggestions by Najm et al. (2006) included adding digital image processing of the forward scene to discern objects being tracked, and vehicle to vehicle communication. The latter would be dependent on wider deployment of the warning systems within the vehicle fleet (Najm et al., 2006). Campbell et al. (2007), meanwhile, provided a summary of lessons learned from all the research done in NHTSA’s program of collision avoidance systems research. The authors argue that the aim of the system should determine whether there are only ‘imminent crash warnings’ (one stage warning model) or additional ‘cautionary crash warnings’ (multi-stage warnings model). If the aim of the system is to maintain appropriately large headways, then cautionary crash warnings should be included (visual alerts only). If the system is chiefly designed to alert distracted drivers of an imminent collision, with few nuisance alarms, then only imminent crash warnings should be used. A multi-stage model, in addition to promoting safe headways, would also be useful for heavy vehicles, for which it is unwise to rely on heavy braking, and, by virtue of occurring more often than the very rare imminent crash warnings, would keep drivers aware of the system. A one-stage model, on the other hand, in addition to cutting down on nuisance alarms, would offer a simpler mental model for drivers to comprehend, and would potentially avoid the ineffectiveness and confusion of cautionary crash warnings (Campbell et al., 2007).

A final study that is of interest with regard to development of algorithms for collision avoidance alerts, is that by Maltz and Shinar (2007), which investigated the effects of system reliability. A sample of 43 students with an average age of 26 completed a simulator drive in which they had to maintain a set headway and perform a concurrent, distracting visual task. The simulator was fitted with a collision warning system using auditory tone alerts that was meant to activate when headways to a vehicle ahead dropped below one second. Of interest in this study was that the system was not 100 percent reliable. Participants experienced both false alarms and system failures in which an alert should have been given but was not. The usefulness of the system, even an unreliable one, was demonstrated by the finding that participants whose simulated drive was performed with the aid of the warning system spent less time with dangerous headways of less than one second than control group participants without the warning system operating. The surprising result was that the warning system was more helpful when it was less reliable. When the system was more reliable, participants began relying on it when faced with the additional workload of the visual task. This meant that when the system failed to give a warning in a hazardous situation, the driver was less likely to brake to avoid conflict with the lead vehicle. Drivers with the less reliable system learned to recognise a one second headway and used their own judgement more (Maltz & Shinar, 2007). It is debatable whether it is prudent to generalise from participant behaviour when in a simulator to actual driving behaviour on the

road but the paradox of the results does at least illustrate the potential danger of system failures if drivers are reliant on a warning system.

Field tests of collision warning systems

Many factors can influence the effectiveness of collision avoidance warning systems, in addition to the nature of the warnings and the algorithms used to trigger them. These include adverse weather, the possibility of drivers turning the system off, and other changes to driver behaviour induced by the presence of the system, such as greater willingness to engage in secondary activities or travel at a higher speed. For this reason, the most convincing evidence of system effectiveness prior to implementation in the vehicle fleet is a field operational test. Only field tests can reveal the real world interactions between drivers and the technology, and the likely benefits or otherwise of fitting the technology to the vehicle fleet.

There are few published reports of field tests of collision warning systems. Two of those that have been published recently have come from the NHTSA program of research (Najm et al., 2006; NHTSA, 2005). Initial algorithms for the forward collision warning system were field tested using 30 drivers, before a final field test on the third algorithm was conducted using 66 drivers. The different algorithms were developed in response to unacceptably high levels of false alarms in the initial tests. The field test of the final system was analysed by Najm et al. (2006), while the University of Michigan Transportation Research Institute (UMTRI) evaluated the entire set of field tests (NHTSA, 2005). The final system involved the combination of the collision warning system with adaptive cruise control. The adaptive cruise control could be set to a desired headway at any of six steps between one and two seconds, and operated with a maximum braking deceleration of 0.3 *g*. Cautionary alerts were delivered using visual icons in a head-up display, and the timing of the alerts could be set by the driver. Crash imminent alerts, however, did not allow for adjustable timing and were presented using the combination of a flashing visual display and an auditory alert (Najm et al., 2006).

The field test of the final algorithm involved 66 drivers, divided evenly by sex and three age groups, and ten vehicles. Each driver had the vehicle for four weeks, with the first week used for collection of baseline data. It was found that false alerts continued to be a problem. There were 0.62 crash imminent alerts given per 100 km travelled, 44 percent of which were for obstacles that were not in the path of the vehicle. An examination of all available data revealed that only three percent of the crash imminent alerts were true alerts to an impending rear-end collision, and so the true rate of alerts required was 1.8 per 100,000 km. The combined effects of the adaptive cruise control and forward collision warnings resulted in decreased exposure to conflicts associated with lead vehicles decelerating or having stopped. Combining the field test data with data from the General Estimates System, the authors concluded that the system could reduce rear-end crashes by 10 percent, with the 95 percent confidence interval ranging from three to 17 percent. Most of the reductions were due to reduced exposure to conflicts for vehicles travelling at more than 35 mph (56 km/h). There were no crashes during the field test but, defining near crashes as situations with a time to collision of less than three seconds and deceleration of greater than 0.3 *g*, the system resulted in a reduction of near rear-end crashes of 10 to 20 percent. No unintended negative safety consequences were detected, based on analysis of travel speed, headway, driver distraction and eyes off the road (Najm et al., 2006). It must be borne in mind, however, that this would not rule out negative consequences emerging after a longer period of time exposed to the system.

The evaluation conducted by UMTRI also found a high rate of false alarms for crash imminent alerts but did also find that there was a marked reduction in drivers adopting short headways, chiefly associated with the adaptive cruise control component of the system. It

was also noted that the rate of adaptive cruise control operating at its maximum braking capacity reduced throughout the trial, which was due to drivers intervening themselves at the onset of adaptive cruise control braking, suggesting that drivers did not merely rely on the cruise control to brake for them (NHTSA, 2005).

Both sets of researchers analysed the study participants' acceptance of the systems. Both found that participants rated the adaptive cruise control component more highly than the forward collision warning component. Less than a quarter reported a likelihood of purchasing the collision warning system, compared to over 40 percent for the cruise control. Over 40 percent said they would have switched the collision warnings off because of the false alarms (Najm et al., 2006). The reported likelihood of purchasing the systems was higher for the UMTRI study. However, results were of a similar magnitude when UMTRI also asked about cost. If the two systems cost US\$1,000 each, 30 percent would buy both; if the combination cost US\$1,600, 35 percent reported a high likelihood of purchase. The UMTRI study also found a higher degree of approval of the adaptive cruise control component. The authors argued that the higher appeal of the cruise control is due to the nuisance alarms of the forward collision warning system and to the reduction of workload and stress associated with the cruise control. It was found that brake application rates during freeway driving were markedly (25 times) lower than rates during baseline driving because of adaptive cruise control (NHTSA, 2005).

Further research co-ordinated by NHTSA is planned for the near future as part of this ongoing program. Ferenc (2006) reported on plans for another field operational test to be conducted by UMTRI, this time looking at a variety of in-vehicle safety systems in both light vehicles and heavy commercial trucks. The forward collision warning system will involve a long range, forward-looking radar; a long range, forward-looking camera, GPS and map database; a short range, forward-looking camera; and two short range, forward-looking radars. The light vehicle tests will involve 108 participants driving with the systems fitted for six weeks, with two weeks of baseline data collection and four weeks of data for system evaluation. Safety benefits will be estimated based on conflicts and near misses. Crash data are ideal but field tests do not yield sufficient crash numbers. The rear-end crash scenarios of interest are the host vehicle changing lanes and approaching a stationary lead vehicle, the host vehicle travelling at constant speed and approaching a lead vehicle travelling at a lower speed, the host vehicle closely following a lead vehicle that decelerates, and the host vehicle travelling at constant speed and approaching a stationary lead vehicle. It is expected that the trial will begin in July, 2008 and be completed in 2010 (Ferenc, 2006).

2.1.2 Collision avoidance warning systems combined with enhanced braking capability

An advance on collision warning systems is the development of systems that additionally feature enhanced braking in situations detected by the system to be hazardous. The main enhanced braking system developed in recent years that is being used in combination with collision warning systems is the Brake Assist™ (BAS) system developed by Mercedes Benz of Daimler AG (Breuer, Faulhaber, Frank & Gleissner, 2007). Testing by Mercedes Benz found that drivers, although capable of reacting quickly in an emergency braking situation, often do not brake heavily enough, thus not using the technical braking capability of the vehicle to its fullest when trying to avoid a collision. BAS uses pedal application speed as an indicator of emergency situations and automatically produces maximum brake boost in order to mitigate against insufficient brake force applied by the driver. Some systems also pre-tension the brakes in response to rapid release of the accelerator. The effect of BAS is heavier braking, but with ABS preventing wheel lockup, and thus shorter stopping distances. Stopping distances on a dry test track with volunteer drivers were found to be 45 percent shorter with BAS. Daimler Chrysler looked at German crash data and compared rear-end

collision rates in the financial year 1998-99 for vehicles registered in 1996-97 with rates in 1999-2000 for vehicles registered in 1997-98. It was found that the rear-end crash rate decreased for Mercedes Benz cars, fitted with BAS as a standard for the second time period, but remained consistent for other makes of cars (Breuer et al, 2007). The success of BAS has translated into its use by other car manufacturers, such as BMW and Volvo, and a request from the European Commission that it become standard on all cars sold in the European Union by 2009.

More recently, Mercedes Benz has developed BAS Plus (available in S and CL class Mercedes Benz vehicles), which uses radar technology to detect distance to vehicles ahead, warns the driver if the gap is too small, and calculates the brake force necessary to avoid a collision if emergency braking is required. Testing was conducted on a driving simulator with 110 drivers exposed to critical situations that were only avoidable with heavy braking. BAS Plus fitted to the simulated car resulted in a reduction in crashes from 44 to 11 percent. A further advance is the PRE-SAFE Brake system. If a driver of a vehicle fitted with this system does not react to BAS Plus warnings and the system detects a situation involving a major crash risk, automatic partial braking is triggered, with deceleration up to a maximum of 0.4 g. The partial braking is designed to act as an additional cue to the driver to the emergency situation. If the driver subsequently reacts with braking, then the BAS Plus system initiates maximum braking force. In the worst case scenario, if the driver does not react to the PRE-SAFE warning, then at least the partial braking up to 0.4 g will reduce the severity of the impact. The effect of this system was also tested in a simulator. Study participants were distracted by a crash in the adjacent lane while a traffic queue formed suddenly in front of them. It was found that in 53 percent of trials, participants reacted to the warning and there was no crash; in 17 percent the driver reacted to the partial braking of the system and there was no crash; and in the remaining 30 percent of trials the partial braking of the system reduced the severity of the impact (Breuer et al., 2007).

Volvo also has a safety system involving the combination of collision warnings and automatic application of the vehicle brake, called Collision Warning with Auto Brake (CWAB) (Coelingh et al., 2007). The CWAB system uses a long range radar fitted to the front of the vehicle and a forward-sensing wide-angle camera fitted in front of the interior rear-view mirror to detect traffic conflicts that could pose a crash risk. An earlier system (Collision Warning with Brake Support) used Brake Assist to pre-charge the brakes and fully apply them if the driver's braking surpassed a threshold level. The CWAB supersedes this by actively braking when it detects the threat of a crash. The earlier system did not include warnings for stationary objects but the addition of the camera allows for detection of stationary objects in the vehicle path that pose the risk of a crash. The level of threat is determined by comparing the maximum achievable lateral and longitudinal acceleration with the acceleration needed to avoid a collision. These comparisons produce threat ratios for braking and for steering. The steering threat ratio is usually the smaller number. Warnings given to the driver consist of a horizontal red line projected onto the lower portion of the windshield and auditory tones presented with a simultaneous muting of the vehicle's sound system. As noted previously, the system allows for driver override (Coelingh et al., 2007).

Lindman and Tivesten (2006) attempted to evaluate the effectiveness of Volvo's CWAB using calculations based on multiple sources of crash data. The crash data included those recorded in the Volvo crash database, which is all Volvo crashes in Sweden with a repair cost of SEK 45,000 or more (approximately A\$8,000), and those recorded in the database of the German In-Depth Accident Study (GIDAS), which involves large samples of crashes investigated by university researchers in Hannover and Dresden, Germany. In their analysis, the authors applied the effects of the system to the pre-crash conditions of the real world crashes (using GIDAS data), and used relationships between crash severity and injury risk to calculate injury savings (using the Volvo crash database). Restricting the analysis to crashes

involving frontal impacts for the host vehicle (48% of crashes), the authors calculated that applying an acceleration of -3 m/s^2 would result in the elimination of 45 percent of frontal impacts and the mitigation of a further 48 percent. If the acceleration was -6 m/s^2 , the percentage of impacts eliminated rose to 57, and for -8 m/s^2 , it was 68 percent. For the case of acceleration of -3 m/s^2 and considering the impacts that were only mitigated rather than totally eliminated, AIS1 spinal injuries would reduce by 11 percent for the occupants of the host vehicle and 22 percent for the struck vehicle. The authors acknowledge that these are best-case scenario results, relying on 100 percent reliability and market penetration, and discounting any effects of low friction (Lindman & Tivetsen, 2006).

2.1.3 Effects of collision warning systems on following vehicles

In assessments of collision warning systems, it is important to consider not just the likelihood of a collision with a vehicle in front but also any effects of the system on following vehicles. Touran, Brackstone and McDonald (1999) conducted a modelling study of an adaptive cruise control and rear-end collision warning system, in which they considered its effects on the likelihood of the equipped vehicle striking the one in front and the likelihood of it being struck from behind, or of other rear-end collisions occurring further back in the traffic stream. The device assessed in this study maintained a target headway of 1.4s and, when braking capabilities of the device were insufficient to avoid a collision, the driver was warned that intervention was necessary. Models were developed of the braking profiles of four vehicles travelling on a highway, with the second vehicle being equipped with the device and responding to heavy braking of the front vehicle. The outputs of this model, in terms of crash involvement probabilities, were compared to the outputs of the same models, except with no device fitted to the second vehicle. Various parameters (e.g. level of braking by the front vehicle, driver perception reaction time) were varied and 5,000 iterations were run. It was concluded that the probability of the second vehicle striking the first was decreased by the addition of the device but that there was an increased likelihood of the third vehicle striking the second, in cases of heavy braking of the front vehicle, and an increased likelihood of the fourth vehicle striking the third at all levels of braking. It was concluded that equipping a car with the device could “significantly reduce the probability of the collision with the car ahead” but that it “may adversely affect the situation for the following cars” (Touran et al., 1999, p567). The authors noted that the actual outcomes of use of the device could be affected by the ability of drivers to see several cars in front of the one they are following, by the reliability of the system, and by the many factors associated with driver interaction with the system that are unable to be determined without a field operational test (Touran et al., 1999). Effects of such devices would presumably also change with greater degrees of implementation within the vehicle fleet. Presumably, the more vehicles there are fitted with the devices, the less likely the problems described by Touran et al. would occur.

A more recent study into the effects of collision warning systems on the crash risk of vehicles behind the host vehicle was conducted by Zheng, McDonald and Wu (2006). The authors used a database of braking events in real traffic, collected with instrumented vehicles, as input into computer simulations of following vehicles responding to the braking of the host vehicle. Braking behaviour in response to collision warning system alerts was modelled and thousands of simulations of braking events were run. These involved different combinations of:

- Host vehicle braking severity – harsh (0.42 *g*), medium (0.31 *g*), or smooth (0.17 *g*)
- Alert type – none (i.e. normal braking behaviour), cautionary (smooth braking), intermediate (medium braking), or imminent (harsh braking combined with automatic brake application), with alert algorithms based on those used in the NHTSA system

- Vehicle headways (normal distribution ranging from 0.5 to 3.3s, mean = 1.5)
- Deceleration capabilities of the system (normal distribution ranging from 0.3 to 0.8 g)
- Driver reaction time (normal distribution ranging from 0.4 to 3.3s, mean = 1.3s)

A total of 12,000 simulations were run and it was found that rear-end collisions between the following and host vehicle were most common when the host vehicle was responding to a crash imminent warning (40%), followed by an intermediate warning (21%), harsh braking without the collision warning system (21%), a cautionary warning (11%), medium braking without the warning system (6%), and smooth braking without the system (none). Therefore, a following vehicle is more likely to strike the rear of a vehicle responding to a cautionary alert than the rear of a vehicle braking with a deceleration of 0.31 g. The authors acknowledged that the models assumed that no drivers of host vehicles respond to the traffic conflict ahead prior to a warning being given and that realistically lower levels of driver distraction would reduce the additional risk of the collision warning system. They also acknowledged the limitations of modelling and noted that warnings may be rare (Zheng et al., 2006).

These modelling studies provide a basis for concerns that the introduction of collision warning systems and associated technologies may increase the risk of host vehicles being struck from behind by following vehicles. This has provided impetus for research looking at vehicle-based means by which the threat of a rear impact can be reduced. This research is described in the following section.

2.2 Measures to stop the host vehicle from being struck from behind

2.2.1 Earlier brake lights

Zheng et al. (2006), on the basis of the modelling study described above, argue that the additional risk of being struck from behind associated with drivers responding to collision warning system alerts might be offset by giving the drivers of following vehicles a warning that the driver of the host vehicle may be about to respond to a collision risk alert. Zheng et al. propose that, when a warning is issued to the driver of the host vehicle, the host vehicle's brake lights should be activated, thus giving the driver of the following vehicle effectively more time to respond to the braking of the host vehicle. The authors, assuming the same reaction time for the drivers of both vehicles, modelled the result of such a system and found that the adjusted risk of being struck from behind in the case of imminent crash warnings was no greater than the mean risk associated with the baseline braking scenarios. For intermediate warnings, the risk was lower, and for cautionary warnings, it was zero. Overall, the researchers found, for all the simulations, that the base risk (i.e. without a collision warning system in the car) of being struck from behind was nine percent. The addition of a collision warning system increased the risk to 24 percent, but the further addition of the advance brake warning reduced the risk down to 4.5 percent (i.e. less than the baseline risk) (Zheng et al., 2006). Again, it needs to be stressed that these results are based on computer modelling only and may fail to take into account all sorts of factors that would only be detected in the event of field operational testing.

One such field operational test into advanced brake lights was that conducted by Shinar (2000). This study looked at the crash involvement of a fleet of 764 government vehicles, half of which were fitted with an advanced brake warning system, which activated the brake lights whenever the accelerator was released rapidly (a minimum of 0.3 metres per second). The theory behind the system is that such rapid disengagement of the accelerator is typically followed by braking, and so earlier activation of the brake lights would give drivers in following vehicles an average of 0.25 seconds of extra warning of the need to brake. In

the study, the odds of “relevant” rear-end collisions were calculated for the two sets of cars (those with and those without the advanced brake warning system). Relevant rear-end collisions were those in which the vehicle was struck from behind by an attentive driver after abrupt braking. Crashes in which the vehicle was stationary prior to the impact were excluded. No significant difference was found between the two sets of vehicles over a period of three years in the odds that they would be involved in a relevant rear-end collision. It was concluded by the authors that, if the warning system has an effect, it is a small one, and so the system is not likely to be a cost-effective device for reducing rear-end crash occurrence (Shinar, 2000).

2.2.2 Flashing brake lights

Another means by which brake lights can be altered to alert drivers of following vehicles of the possible need for hard braking is by making the lights flash or flicker when heavy braking is occurring in the host vehicle. A study by Berg, Berglund, Strang and Baum (2007), for example, demonstrates the attention capturing properties of a light that flickers at a high frequency. This was a simulator-based study in which 24 participants were required to brake as soon as possible after detecting the illumination of a red light in their field of view. The light was either steady or flickered at a rate of 20 Hz, which is the approximate optimal frequency for peripheral vision, and was presented at three different eccentricities from the centre of the visual display. It was found that reaction time to the flickering light was shorter than for the steady light by an average of 14 ms, or four percent. A follow-up study was conducted in which participants were additionally required to keep a safe headway behind a vehicle that varied its speed between 48 and 121 km/h. With the more complex driving task, the mean difference in reaction time between the flickering and steady lights increased to 29 ms or seven percent. The effects of the eccentricity manipulation approached significance in the second study, with a trend toward a greater advantage for the flickering light the further it was located away from central vision. The authors concluded that a flickering brake light would be more effective at capturing the attention of drivers in following vehicles, particularly those drivers who are distracted. As the authors noted, the stimuli to be responded to with braking were not embedded in the primary task (i.e. were not brake lights on the vehicle being followed), thus raising questions of ecological validity (Berg et al., 2007). The authors also did not comment on whether the lights to be detected were synchronised with slowing in the vehicle being followed in the second experiment. If not, ecological validity is further brought into question. The authors did equate the reaction time reductions with small reductions in stopping distance. However, reaction times in real world driving situations are likely to be longer than those measured in a laboratory-based simulator study. If the reductions in reaction time are relative rather than absolute (i.e. a reduction of 7 percent rather than 29 ms) then it is possible that real world reductions in stopping distance would be greater. Further research would be needed.

Another study into flashing brake lights, in this case the Centre High Mounted Stop Light (CHMSL), was conducted by Regan, Triggs, Mitsopoulos-Rubens, Symmons and Tomasevic (2007). This study assessed a light that flashed at a rate of 4 Hz when deceleration of the vehicle exceeded 0.5 *g*. Forty two participants aged from 24 to 42 completed a simulator study involving a distracting word detection task while maintaining a set headway to a vehicle in front. Each participant completed drives encompassing the four combinations of a normal or flashing CHMSL, and the presence or absence of the distraction task. Reaction time (time to apply the brake) and maximum brake pressure were measured. It was found that at an intermediate headway (1.4s), brake reaction time was shorter by 280ms when the flashing CHMSL was operating on the vehicle ahead. There was no effect at a shorter headway of 1.0s, presumably due to drivers concentrating more on the vehicle ahead and being primed to brake to avoid a collision. Maximum brake pressure was slightly higher with the brake light but this effect was not as large as the effect on this variable of the shorter

headway (Regan et al., 2007). It is noteworthy that the reduction in reaction time in this study was greater than in the Berg et al. (2007) study, presumably because of the greater ecological validity of the experimental set-up. Although not noted by Regan et al., being a CHMSL, the flashing light examined in their study may be seen not only by the following vehicle but also vehicles further back in the traffic stream.

An earlier form of the flashing brake light was developed by Cohn (2002). This system, suitable for large vehicles like trucks and buses, incorporates radar equipment to detect close following or rapidly approaching vehicles and a series of amber lights that warn the following driver of the high risk of collision. In a laboratory study, Cohn found that if an array of lights lit up sequentially, the reaction time of following drivers would be shorter than if the lights lit up all at once (Cohn, 2002). Field tests of Cohn's light were conducted (Burns, 2005), with assessments made of the degree to which the warning lights changed the braking behaviour of drivers of cars behind buses. This was done by measuring the braking profiles of samples of following vehicles, with and without activation of the light. Even without any education of the public regarding the lights, the field test revealed that drivers exposed to the warning lights had lower levels of braking intensity behind the bus. This was due to their attention being drawn to the bus by the warning lights, and occurred regardless of which of three different algorithms were used to determine the circumstances in which the lights were triggered. Further development, particularly of the sensors used to monitor approaching vehicles and trigger the warning lights, is needed before the system is able to be commercialised (Burns, 2005).

A final study of technology of this general type was conducted by Matsubayashi, Yamada, Iyoda, Koike, Kawasaki and Tokuda (2007) of Toyota Corporation. They assessed a system that was designed to alert drivers of vehicles approaching from behind of the risk of a rear-end collision, combined with headrest technology designed to reduce whiplash injury in the event of an impact. With regard to rear alert system, the vehicle is fitted with a millimetre-wave radar in the rear bumper to detect the approach of vehicles from behind. If there is a high risk of collision, the hazard lights flash to warn the driver in the following vehicle. The sensor used in the system is similar to those used for forward collision warning systems but the task is easier because there is no need to devise means of ignoring irrelevant stationary objects. The sensor detects the distance, relative velocity and directional angle of following vehicles, updating every 20 ms, and transmits the data to a computer that calculates time to collision taking into account road curvature. The hazard lights, when activated, flash for approximately two seconds at a rate of 2 Hz. The authors claim that the system was effective, with the time to apply brakes of the drivers of following vehicles in response to deceleration of the lead vehicle reduced by 20 percent (Matsubayashi et al., 2007) but there were very few methodological details provided to explain how this effect was determined.

2.2.3 Vehicle conspicuity

Altering the conspicuity of the rear of vehicles is thought to be a useful countermeasure because low conspicuity has been hypothesised to play a role in rear-end collisions. Sullivan and Flannagan (2003) looked at changes in rear-end collision occurrence in the weeks prior to, and following, a change in ambient illumination caused by daylight saving changeovers in the United States. Such analyses are used to compare the effects of changes in ambient illumination while keeping clock time, and hence driving habits, constant. Using 15 years of fatal crash data, they found that the risk of rear-end collisions in hours of darkness was over double that in hours of daylight. In particular, trucks were eight times more likely to be rear-ended in hours of darkness. The authors concluded that their findings were indicative of an increased rear-end crash risk resulting from reduced conspicuity of vehicles at night (Sullivan & Flannagan, 2003).

One means of increasing vehicle conspicuity is the application of retro-reflective material to the rear of vehicles. Morgan (2001) conducted a study to determine the effectiveness of red and white retroreflective tape for reducing side and rear impacts with heavy trailers (those weighing over 10,000 pounds, or approximately 4,500 kilograms). The application of such tape became compulsory in the United States for all new trailers manufactured after 1993. It was thought that trailers are often not visible at night to other drivers until they are dangerously close, and so adding retroreflective tape would indicate to following drivers that a trailer was ahead. It was also hypothesised to aid drivers in judgement of distance and rate of approach. Morgan collected data on over 10,000 crashes involving heavy trailers and analysed crash involvement according to the presence of retroreflective tape, the level of ambient illumination, and crash type. It was found that retroreflective tape reduced the occurrence of side and rear impacts with trailers by over 40 percent at night on roads without artificial lighting. The tape was especially effective on flatbed trailers, which presumably would be more difficult to see than other trailers without the enhanced conspicuity provided by the tape. Also, larger reductions were found for injury crashes and those in which the trailer was struck by drivers under the age of 50 (Morgan, 2001). The requirements in Australia are not as stringent as those in the USA. Although Australian Design Rule 13 requires heavy trailers (gross mass over 10 tonnes) to have retroreflective marker plates on the rear, they are not required to extend the full width of the trailer. Also, retroreflective marker plates are not required for smaller trailers.

2.3 Summary of crash avoidance technologies

Technology designed to reduce the risk of rear-end collisions has been developed by a number of independent researchers and particularly vehicle manufacturers, with many significant developments in the past decade. Most of the research and development has been concentrated on the prevention of the 'host' vehicle striking the vehicle in front but some work has also been done to protect the host vehicle from being struck from behind.

The chief means that have been developed to reduce the risk of striking a lead vehicle in the rear have been adaptive cruise control and forward collision warning systems. These are usually combined in the one system, so that the vehicle brakes to avoid short headways and alerts the driver in emergency situations that exceed the braking capacity of the cruise control.

Much research has focussed on the best sensory modalities to use to alert the driver of the risk of collision, with the conclusion generally being the combination of a visual alert on a head up display, combined with an auditory tone (Campbell et al., 2007). As Ljung et al. (2007) note, however, the rarity of alerts will mean that drivers may need regular reminders of the auditory tone so that they are aware of its meaning when it does activate.

The development of algorithms and technology for detecting the situations of risk requiring the giving of a warning to the driver have also been the focus of much research. The key is to strike a balance between the need to give the driver warning early enough that he or she is able to react in time with the need to avoid false alarms or warnings considered unnecessary by the driver. Consideration has also been given to providing earlier warnings to drivers who are distracted, and Kimura et al. (2007) of Toyota have developed a promising means of detecting distraction by monitoring the position of the face. It is generally agreed that any system should allow for driver override, and an example of a system which alters its parameters when it detects driver input has been developed by Volvo (Coelingh et al., 2007). A related finding is that crash risk may increase if drivers become overly reliant on a system that is not 100 percent reliable (Maltz & Shinar, 2007).

There have been few published results of forward collision warning system field tests, although there have been detailed accounts published of the collaborations of General

Motors and NHTSA (NHTSA, 2005; Najm et al., 2006). A positive aspect of these reports has been that evaluations have been made independently of vehicle manufacturers, unlike much of the other research published in this area. These independent evaluations of the system developed in this collaboration have found that there is an ongoing problem with reducing nuisance alerts to situations that do not pose a major crash risk, and adaptive cruise control is viewed far more favourably than the collision warning component of the combined system. Further field tests have been planned for coming years (Ferenc, 2006).

Research and development has also created a number of systems incorporating enhanced braking programs. Chief among the enhanced braking programs has been the Mercedes Benz-developed Brake Assist (BAS), which recognises a driver's attempt at emergency braking and ensures that the vehicle's maximum braking capability is used, without wheel lock-up. Advances on this system in recent years have included BAS PLUS, which detects situations posing a crash risk and warns the driver, and PRE-SAFE, which, in addition to the BAS PLUS system, automatically brakes when the driver has not reacted to a crash risk warning. Evaluations of these systems on simulators have produced positive results, while crash data have suggested that the base BAS system has reduced crashes (Breuer et al., 2007). Volvo have also developed an automatic braking system for emergency situations combined with collision warnings (Collision Warning with Brake Support) (Coelingh et al., 2007) and its ability to reduce crashes and injuries is argued on the basis of modelling of in-depth crash data (Lindman & Tivetsen, 2006).

One potential disadvantage of systems that shorten the braking of the host vehicle, whether by collision warnings or by braking enhancement, is that they may increase the risk that the vehicle is struck from behind (Touran et al., 1999; Zheng et al., 2006). This means that there is also a need for means by which vehicles can be protected from this risk.

There have been studies into the potential of activating brake lights earlier in emergency braking situations. The results of a modelling study for a system in which the brake lights are activated when a collision warning is given were positive (Zheng et al., 2006) while the results of a field test of a system in which the brake lights were activated by the rapid release of the accelerator failed to show a benefit (Shinar, 2000). It is notable that the modelling study involved vehicles with forward collision warning systems that theoretically have a higher risk of being struck from behind, while the field study was for otherwise normal vehicles.

Other researchers have considered using brake lights that flash in an emergency braking situation. The lights can flash when the host vehicle is braking heavily (Regan et al., 2007) or when detecting a vehicle that is at risk of striking from behind (Burns, 2005; Matsubayashi et al., 2007). These systems are still in the early phases of development.

Enhancing rear vehicle conspicuity is another potential means of decreasing the risk of being struck from behind. This is likely to chiefly be applicable to night-time crashes (Sullivan & Flannagan, 2003) and has mainly been discussed with regard to heavy vehicles (e.g. Morgan, 2001).

3 Passive safety measures to reduce the risk of whiplash injury in a rear-end collision

3.1 The effectiveness of vehicle measures to reduce the likelihood of whiplash injury in rear-end crashes

Recently, the 'Bone and Joint Decade 2000–2010 Task Force on Neck Pain and Its Associated Disorders' reported on its best evidence synthesis on whiplash-associated disorders and generalised neck pain in the community. The Task Force was a collaboration between Swedish, US and Canadian researchers and it evolved out of the Quebec Task Force on Whiplash Associated Disorders.

One component of their report was a review of the burden and determinants of whiplash associated disorders (WAD) after traffic collisions (Holm et al. 2008). That review found only a few studies on the efficacy of crash severity and seat design in preventing whiplash injury.

They describe the evidence for the effectiveness of head restraint and seat design countermeasures as "preliminary" but conclude that studies using insurance data showed that active head restraint design appeared to lower claims for whiplash injury, especially by females. (These were studies of Farmer et al., 1999 and Farmer et al., 2002). However, more recent studies have continued to show real-world benefits of better seat designs (Kullgren et al, 2007; Farmer et al., 2008 – see later).

Whiplash injury is predominantly a problem of injury to front seat occupants, largely because of low rear seat occupancy rates. Ninety three percent of all police-reported minor casualties in rear-end crashes in South Australia (2003-2007) were either a driver or a front left seat passenger (Source: Traffic Accident Reporting System). While there is some indication that the seat effects on rear seat occupants in a crash may be worse than the front seat in general (Krafft et al. 2003) the need for seat improvements is most acute for front seat occupants.

Details on specific seat designs to reduce injury are described later. But, in summary, a great deal of emphasis is placed on the seat and head restraint, and the interaction between the occupant and the seat in a 'typical' low severity rear-end crash. Various test procedures and rating schemes have been developed (and are being developed) to assess the relative merits of seats from different vehicles. A few studies have been made to see how the ratings correlate with real-world whiplash injury.

Building on previous analyses, Farmer et al. (2003) examined insurance claims from US insurers, whose coverage of the personal automobile insurance premiums was 29% of all drivers insured in the US. The study examined neck injury rates in vehicle models that had changed little between model releases, but for the inclusion of some seat-based measure designed to reduce whiplash injury risk: either an active head restraint, improved geometry, a Volvo WHIPS seat or a Toyota WIL seat. (These types of seats are described in more detail in Section 3.4 on page 20.) The study examined neck injury rates of the drivers of the vehicles in rear-end crashes. All crashes were from a single period (1999-2001), and crashes were divided according to the class of vehicle (according to the type of seat-based measure) and according to whether the vehicle had the newer seat-based measure, or an older standard seat and head restraint.

The rate of neck injury claims from rear-end crashes were generally lower in vehicles that included some seat-based measure. Overall, those vehicles with active head restraints had a neck injury rate 44% lower than the same models without the active head restraints,

although there was a lot of variability from model to model. Restraints with improved geometry and the Volvo WHIPS seat also exhibited benefits, while no real effect was measurable for the Toyota WIL seat. None of the results for the latter three classes of seat were statistically significant.

Further analysis using a logistic regression model that accounted for the angle of impact, repair costs, damage severity, driver sex (struck vehicle), the insurance company and the specific vehicle model revealed that the positive effect of *active restraints* was higher for females, and higher in lower severity crashes. While the analysis estimated a benefit for males too, the results were not statistically significant.

As for the other types of seat-based measure, improved geometry appeared beneficial for females only, and the benefits or otherwise of other, non-active, measures (WIL, WHIPS) were inconclusive. In the case of the WHIPS seat, the estimate of the benefits were encouraging, but the certainty of the result was hampered by low numbers of crashes in the analysis.

In a more recent analysis, Farmer et al. (2008) found that seat rating was (if inconsistently) related to lower acute injury rates and lower long-term injury rates: seats given a 'good' rating by the Insurance Institute for Highway Safety (IIHS) had long-term injury rates 35% lower than seats rated as 'poor'. Seats rated as 'marginal' also exhibited long-term injury rates 35% lower than seats rated as poor. Curiously, the better rating 'acceptable' seats had long-term injury rates indistinguishable from seats rated as 'poor'. The risk of acute symptoms was 15% lower in 'good' versus 'poor' seats, but the risk was indistinguishable amongst seats rated as 'acceptable, 'marginal' and 'poor'.

Kullgren et al. (2007) examined the injury rates of occupants involved in rear-end crashes in Sweden between 1998 and 2006. Their objective was to estimate the relative incidence of whiplash injury in vehicles fitted with seats designed specifically to reduce the risk of whiplash injury (Volvo WHIPS, Saab SAHR, Toyota WIL). They used insurance records from the Swedish insurer Folksam and police reported crashes to determine the risk of receiving an injury and the risk that the injury would exhibit chronic symptoms. They categorised seat by design and by the rating given by the IIHS.

They did not find any correlation between seat performance and the incidence of acute injury, a finding similar to that of Farmer et al. (2008). There was, however, a positive trend between the seat rating and lower relative risks of chronic symptoms. Seats rated as good, either according to the IIHS procedure, or a procedure developed by the Insurer Folksam and the Swedish Roads Administration, were associated with better long term outcomes, with disability rates 30-40% less than for seats rated as 'poor'.

In summary, the analysis of real-world crashes suggest a lower risk of long-term injury and disability from whiplash for seats generally rated as 'good' compared to those seats rated as 'poor'. Estimates of the reduction in the risk range from 30% to 44%. However, a dose-response relationship between seat rating and long term injury risk is not yet firmly established.

3.2 Biomechanics of injury

The exact mechanism of injury in whiplash injury is unclear. Various hypotheses have been proposed, including pressure dynamics in the spinal canal (Svensson, 1993), muscle strains (Tencer, 1999), shear stresses in the intervertebral joints during retraction (Yang and Begemen, 1996) and facet joint impingement (Ono, 1997). These hypotheses are summarised in a previous report published by CASR (Gibson, 2006).

Figure 3.1 shows the kinematic sequence of the motion of the cervical spine during whiplash motion, in the absence of an effective head restraint, in a rear impact. The extension of the neck brought about by the forces transmitted to the seat (upper panel of Figure 3.1) produces two distinct phases of neck motion: in Phase 1, the top and bottom of the cervical spine are approximately parallel, and the mass of the head causes it to lag the forward motion of the thorax. This 'retraction' phase causes the cervical spine to assume an 's' shape. In phase 2, the continued forward motion of the thorax leads to the neck to assume a full extension (or hyper-extension). During this phase, the thorax may be rebounding from the seat back.

The lower panel of Figure 3.1 shows the continuation of the rebound of the occupant. The two phases show that the neck may assume a reverse-'s' shape, followed by neck flexion. High energy in the rebound phase, coupled with restraint by the seat belt can increase the magnitude of these motions in the rebound phase.

Further detail on the kinematics of the head and neck can be found in Gibson (2006).

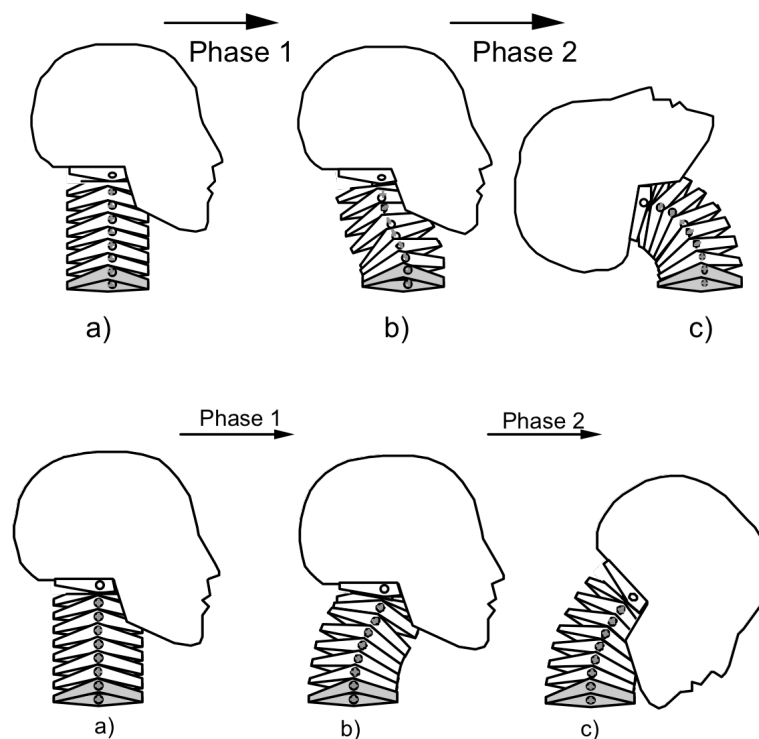


Figure 3.1
Cervical spine motion during whiplash motion (reproduced from Svensson et al., 2005)

3.3 General principles of restraint design and designing for whiplash prevention

While biomechanics of whiplash injury is still the subject of research, basic principles of restraint design can be applied to reduce forces on the neck in a rear impact. For any type of restraint to be effective, several principles have to be observed. These include:

- eliminating 'slack' in the restraint system,
- maximising the proportion of the occupant's kinetic energy that is absorbed by the vehicle structure, and minimising the proportion absorbed by the restraint (this keeps the forces placed on the occupant low),

- maximising the distance over which this energy absorption takes place,
- limiting the loads on the occupant by other means such as load limiters, and
- minimising articulations and relative motions between the segments of the body as these can lead to injurious strains on the joints. (Eppinger, 2001).

Slack, in the context of ahead restraint, is the gap that exists between the head and head restraint in a crash. If the gap is small and the head makes contact with the head restraint early in the crash, there is more opportunity to manage the energy of the occupant's head and torso in a controlled manner. Loads to the head and neck can be reduced by dissipating energy over a longer period. The presence of a gap between the head and the head restraint is liable to cause relative motion between the thorax and the head of an occupant in a rear collision, and may also lead to a higher acceleration of the head once the head is restrained. However, some gap is necessary – indeed, the reason that automotive seats generally reach the shoulder only, with a separate head restraint offset from the head, is to maintain a field of view for the occupant and for comfort (Wiklund and Larson, 1998).

Principles of design that allow the energy of an occupant to be dissipated in the vehicle structure, rather than in the restraint, are complex. However, the implication of these principles is that the crash pulse characteristics and the restraint stiffness can be coordinated to minimise forces on the occupant (Huang, 2002). In rear-end crashes, the restraint stiffness relates to the structural characteristics of the seat, including the seat foam stiffness and any yielding properties of the seat back. Simple considerations of seat stiffness and neck stiffness indicate that stiffer seats and less stiff necks are more liable to combine in a rear impact to produce more injurious neck loads (Viano, 2003a; Viano, 2003b). However Szabo et al. (2003) found little influence of seat foam properties compared with geometrical differences between seats.

Related to seat stiffness considerations are the principles of maximising the distance and time over which energy is dissipated. For example, allowing a seat back to yield in a rear-end crash follows this principle.

A common objective in seat design for whiplash prevention, is to hold the head and torso in a stable relative position to prevent severe retraction which may produce injurious loads in the neck. However, some hypotheses for whiplash injury contend that very little relative motion is required to injure the neck (Ono, 1997).

The crash pulse characteristics are determined by the speed and mass of the striking and struck vehicles, as well as the structural characteristics of both vehicles. In the test protocols described below, standard pulses are used. Note though, that the range of pulses in real crashes may be wide and varied, and so a reliance is placed on the principle that adequate performance under a limited set of test conditions implies adequate performance in the majority of crash scenarios that may be experienced in the field, and some efforts have been made to try and understand real work crash pulses through the examination of data gathered by crash pulse recorders in real rear-end impacts (Krafft et al., 2000; Krafft et al., 2002; Kullgren et al., 2003; Krafft et al., 2005; Hynd and Willis 2007). A correlation between seat performance in the laboratory and real world injury supports this contention.

3.4 Seat-based passive safety measures

In the late 1990s, a series of seats claiming to reduce the risk of whiplash injury in a rear crash were introduced to the market. These were the SAHR by Saab (Wiklund and Larson, 1998), the WHIPS by Volvo (Jakobssen et al, 2000) and the WIL by Toyota (Sekizuka, 1998). Seats using the SAHR principle are deployed in a range of General Motors Vehicles and brands that have had some GM connection (such as Subaru), as well as others such as Ford,

Nissan and Peugeot (Krafft et al., 2004). Since then, other seats and technologies have emerged in the market.

Seats designed for whiplash protection fall into one of several categories. Thatcham (2008) describes seat categories as follows:

- Reactive Head Restraints: head restraints that automatically move up and forward during the crash, actuated by the weight of the occupant in the seat.
- Reactive Seats: entire seats that absorb the energy of a rear-end crash.
- Passive Seats: seats that use passive foam technology to absorb the energy of the crash and allow the occupant to engage the head restraint without neck distortion.
- Pro-Active Head Restraints: head restraints that automatically move up and forward at the start of the crash, actuated by crash sensors on the bumper, or within the car.

Each of these seats are described below by means of examples.

3.4.1 Reactive head restraints: the Saab Active Head Restraint (SAHR)

The biomechanical and technical aspects of the SAHR are described in a paper by Wiklund and Larson (1998). The SAHR is described as an “active” restraint, but in this context, it is active not in a crash prevention sense, but in the sense that it uses a mechanism that is activated under load from an occupant in a rear-end crash.

The objective of the SAHR is to remove any gap between the head of the occupant and the head restraint by means of a linkage between the head restraint and a pressure plate. In a rear impact, the inertia of the occupant compresses the seat back. In the SAHR, this load acts on the pressure plate which, through the linkage, moves the head restraint upward and forward, supporting the head before any large differential motions can occur between the head and the thorax of the occupant. The mechanism also provides additional ride-down, minimising loads on the thorax and spine, which may have some benefit in reducing neck loads, which might otherwise occur if the natural curvature of the thoracic spine is suddenly straightened by high loads placed on the back. The seat is undamaged by the activation of the mechanism and returns to its original configuration after the crash.

Wiklund and Larsson conducted laboratory tests with a Hybrid III dummy with a RID neck installed. The SAHR reduced neck retraction (the s-bending of the cervical spine caused by the rearward motion of the head) and neck extension (the bending of the cervical spine caused by the rearward rotation of the head) compared with tests using a standard seat. The seat has been shown to be effective in reducing reported whiplash cases in real crashes too, as described earlier in this Chapter.

3.4.2 Reactive seats: the Volvo Whiplash Protection Study (WHIPS) seat

The Volvo WHIPS seat was developed after a decade of research on whiplash that included crash investigation, computer modelling and dummy development (Jakobssen et al., 2000). The objective of the seat design is to reduce the acceleration of the occupant, minimise the relative motion between the vertebrae of the spine, and to minimise rebound (dissipate energy).

The WHIPS seat has a different *modus operandi* to the SAHR. The WHIPS seat is designed to, first, fully engage with the body and head of the occupant and second, provide extended ride-down to minimise occupant accelerations in response to a rear impact. The seat achieves this with two phases of operation. During the first phase, the seat back translates backward under the inertial load of the occupant. This phase allows some ride down, while maintaining the initial seat back angle. In this phase, the occupant sinks into the seat back

while the head comes into contact with the head rest. During the second phase, the seat back reclines under load extending the distance over which the occupant is brought to rest. The intention is to reduce the accelerations applied to the occupant during the collision (Jakobssen, 2000). The two phases are shown in Figure 3.2.

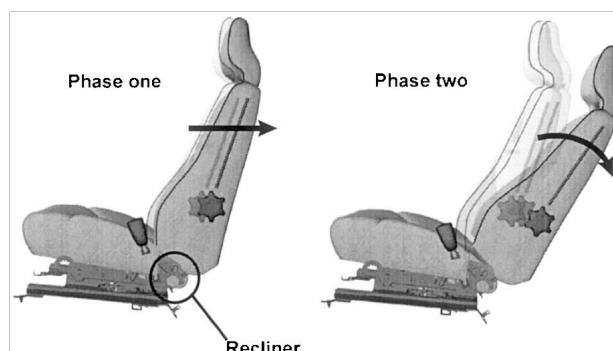


Figure 3.2
The mechanism of the Volvo WhiPS seat (reproduced from Jakobsson et al., 2000)

The WHIPS seat has been shown to reduce many of the head-neck kinematics thought to be associated with whiplash injury (Welcher and Szabo, 2001).

3.4.3 Passive seats: the Toyota Whiplash Lessening (WIL) seat

Toyota's objectives in the development of the WIL seat were to decrease neck motion throughout the rear-impact event, and to control the energy dissipation of the occupant. At the initial stages of a rear impact, the headrest moves toward the head and upward, the upper portion of the seat moves away from the upper body, while the remaining seat back maintains its support to the thorax. The overall effect is to allow the upper body to sink further into the seat, lessening differential motion between the thorax and head. The seat also yields somewhat, increasing the distance over which the occupant's energy is dissipated, lowering acceleration.

To date, in-field benefits of the WIL system have not been observed; evaluations have not found any measureable reductions in the incidence of WAD with the system (Kullgren et al., 2007). Results of testing have been equivocal also (e.g. ADAC, 2007).

3.4.4 Pro-active head restraints: Mercedes-Benz Neck-Pro, BMW pyrotechnic head restraint

Pro-active head restraints are those that automatically move up and forward at the start of the crash, actuated by crash sensors on the bumper, or within the car. The Mercedes-Benz Neck-Pro seat has a deployable spring loaded head restraint that moves forward and upward in the initial stages of a rear impact to remove the gap between the head of the occupant and the head restraint. No real-world evaluations of this seat were identified for this review, but the IIHS has consistently rated this seat as 'good' in its dynamic evaluations.

The BMW pyrotechnic head restraint is similar in principle, but uses a gas filled cartridge to propel the head restraint upward during a rear-end crash. It is available on a limited number of models only and these are all rated as good test programs.

4 Injury assessment tools and criteria

In this Chapter, the most oft-cited tools and criteria that have been developed for whiplash injury risk assessment are summarised. All consumer programs have settled on the use of the BioRID II dummy for dynamic testing and the Head Restraint Measurement Device (HRMD) for static geometry assessments. However, there is an ongoing lack of agreement on the best tool to be used in a proposed Global Technical Regulation for Head Restraints where some members of the working group developing test procedures have proposed use of the Hybrid III dummy (WP.29, 2008).

4.1.1 Head rest measurement device (HRMD)

The HRMD was developed by the Insurance Corporation of British Columbia (ICBC) to measure static head restraint geometry (Gane and Pedder, 1996). The HRMD uses a standard “H-point” machine, which is used for the measurement of seat ergonomics. Its use in the measurement of head restraint geometry is described in Section 5.1.1 on Page 29 of this report.

4.1.2 Hybrid III

Prasad et al. (1997) evaluated the use of the Hybrid III dummy for rear impact testing. They compared the results of this dummy with results using earlier versions of the RID2 neck (described below) (RID, TRID) and a dummy with an articulated spine (TAD-50). They found that the Hybrid III response was similar to the response of cadavers measured in previous rear-impact studies. They concluded that the biofidelity of the Hybrid III was at least the equal of the other dummies tested and that it is suitable for rear impact testing.

In the US Federal Motor Vehicle Safety Standard 202a, the dynamic test specifies a Hybrid III dummy. Working Party 29 of the UNECE World Forum for the Harmonization of Vehicle Regulations is developing a Global Technical Regulation on head restraints also. (Australia has recently become a signatory to the 1998 Agreement on Global Technical Regulations.) There is an unresolved disagreement at this forum over the use of the Hybrid III dummy and the merits of the BioRID II dummy for use in the GTR. The IIHS oppose the use of the Hybrid III for regulatory impact testing (Zuby, 2008).

More recent studies have found evidence that the Hybrid III is less suitable than current RID2 and BioRID dummies. Some of these studies are described in Section 4.1.5.

4.1.3 BioRID

BioRID is a rear impact dummy that was developed in the late 1990s (Linder and Svensson, 2000). The dummy went through a series of prototype revisions, and the current final version of the dummy is referred to as BioRID II. The dummy is illustrated in Figure 4.1.

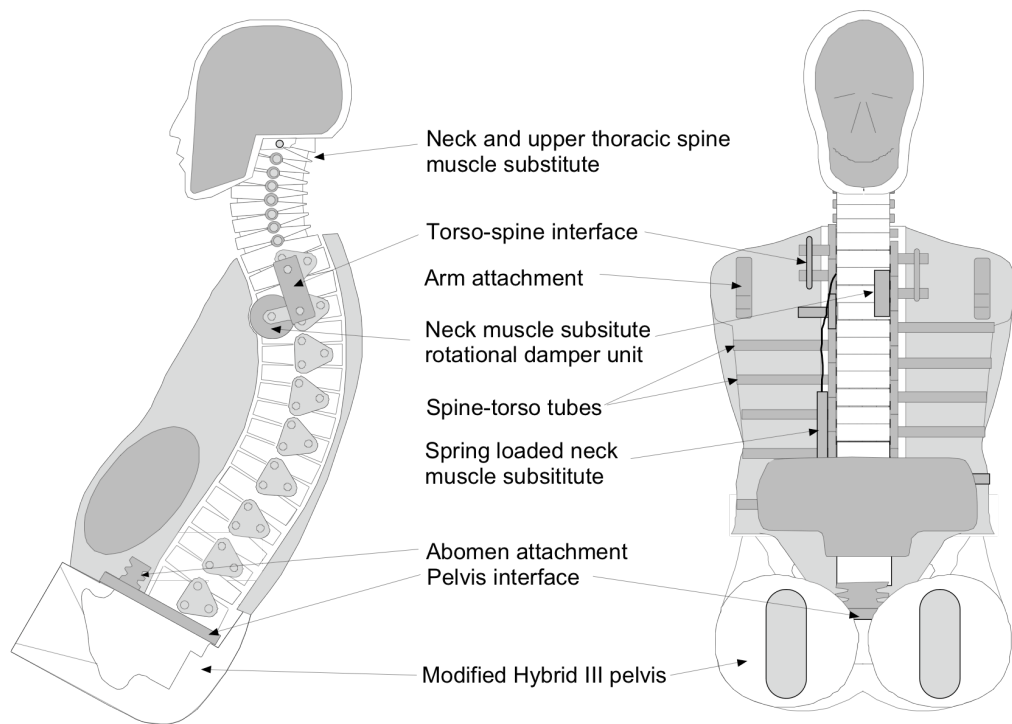


Figure 4.1
BioRID II dummy used for rear impact seat assessments. (reproduced from Davidsson, 1999)

The dummy features an articulated spine that is designed to respond to rear-impact seat loads similarly to the human neck and spine. Specifically, the flexion, extension and retraction typical of the human neck in rear-impacts are replicated by the dummy neck (Linder et al., 2002b). The 24 vertebra of the thoracic and lumbar spine are able to straighten under rear impact, similarly to a human spine (Linder and Svensson 2000). It has been used extensively in dynamics assessments of seat performance by Thatcham, IIHS and the Swedish Road Administration (amongst others).

4.1.4 RID2

Cappon et al. (2001b) presented test results from a rear impact dummy called RID2. Like the BioRID, RID2 was developed to overcome deficiencies in the suitability of the Hybrid III for rear-impact testing (Cappon et al., 2001a). It is designed to reproduce human-like neck kinematics in the initial stages of the impact, rather than the rebound phase.

The RID2 is built on the foundation of the Hybrid III crash test dummy, but replaces the Hybrid III's standard components with a more flexible neck and spine, and also with some components of a THOR dummy (an advanced occupant dummy still under development). The dummy is illustrated in Figure 4.2.

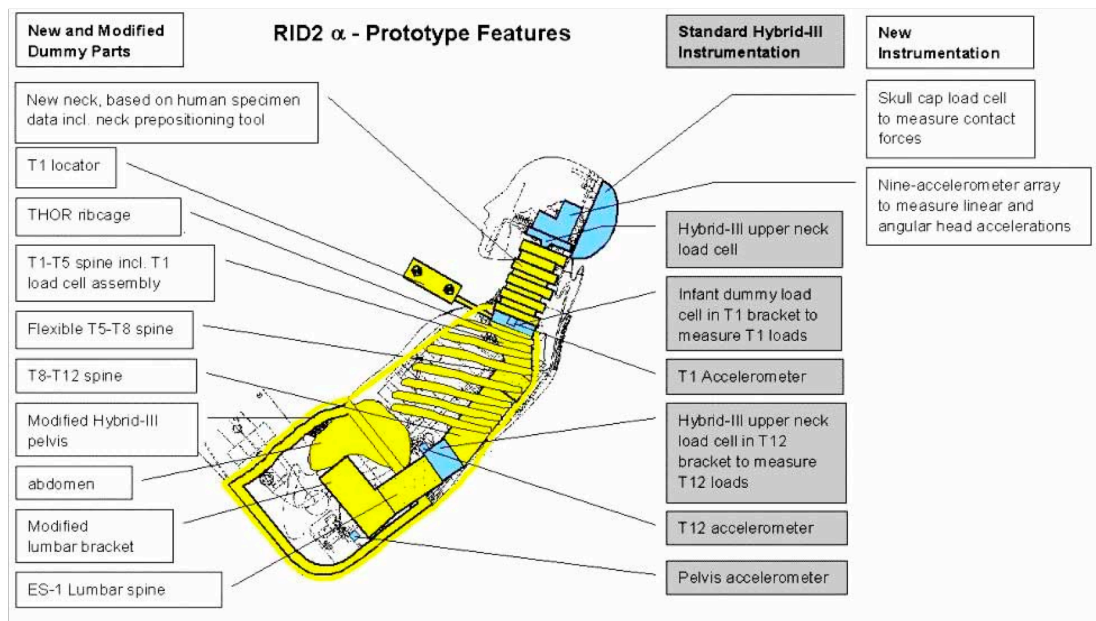


Figure 4.2
RID2 dummy used for rear impact seat assessments. (reproduced from Cappon et al., 2001a)

Croft and Philippens (2007) assessed the biofidelity of RID2 against volunteer tests. This study is of interest, as the evaluation was of RID2 against volunteers in side-by-side (literally, in the same vehicle), in full scale, vehicle-to-vehicle crash tests. Although the number of tests was small (nine), and only one injury parameter was reported (NIC), there were some discrepancies between volunteer results and dummy results. Dummy results were most similar to those of a 50th percentile male volunteer.

4.1.5 Relative performance of Hybrid III, BioRID and RID2 dummies

The nomination of the Hybrid III dynamic test in FMVSS 202a, and the draft GTR, has prompted research on the relative performance of the Hybrid III, BioRID and RID dummies.

The RID2 was compared to the BioRID and Hybrid III by Philippens et al. (2002). The study showed that both the BioRID and RID2 show good biofidelity especially when compared to the results of tests using the Hybrid III. Although the BioRID and RID2 dummies' performances were similar, the BioRID was slightly more life-like overall, although the RID2 appeared more life-like on certain measures.

Linder et al. (2002a) performed low speed rear impact tests using the BioRID I and the Hybrid III and compared the resulting head kinematics with those of human volunteers, and examined particularly the motions of the neck of the dummy. They found that the motion of the BioRID neck (displacement and acceleration) matched the motion of the human volunteers in a manner that the Hybrid III did not. These findings are similar to those of Cappon et al (2001a).

Testing by Linder et al. (2002b) using pendulum impacts to the thoracic spine of Hybrid III and the BioRID dummies showed that the relative motion of the head and neck is more closely reproduced by the BioRID II than the Hybrid III. Viano et al, (2002) found that, generally, both the Hybrid III neck and the BioRID neck matched the displacements of the necks of volunteers in rear-impact tests. One of their conclusions was that the problem with the Hybrid III was not so much in the design of the neck, but in the design of components that represent the thoracic spine.

Other evaluations have supported the view that there are better alternatives for rear-impact crash testing than the Hybrid III (e.g. Bortenschlager et al., 2003; Davidsson et al. (2001). A summary of such research is given in Hynd (2007).

4.2 Assessment criteria

To assess a seat in a rear impact test requires both a suitable dummy, but also an appropriate metric of injury potential. Broadly speaking, assessment criteria can be split into those that measure impact kinematics closely related to hypothesised mechanisms of injury, and those that measure forces placed on the neck. The latter type may be related to some hypothesised injury mechanism, or may be a simple measure of force or kinematics, on the basis that a low force placed on the neck should be related to a reduced probability of injury.

The most important criteria of the first kind is the Neck Injury Criterion (NIC). Examples of the second kind are those used in assessment programs developed by the International Insurance Whiplash Prevention Group (IIWPG). IIWPG tests are conducted by Thatcham in the UK and the Insurance Institute for Highway Safety in the US. More detail on these procedures is given in Chapter 5.

Other criteria have also been proposed : Lower Neck Load (Heitplatz et al., 2003), IV-NIC (Panjabi et al., 1999) and NDC (Viano and Davidsson, 2001). As these are not currently used in assessment procedures, they will not be discussed further here.

4.3 Neck Injury Criterion (NIC)

The Neck Injury Criterion (NIC) was proposed in 1996 by Boström et al. It is based on the hypothesised injury mechanism of pressure changes in the spinal canal, affecting the basal ganglia, in response to neck retraction during rear impact. Considering the fluid mechanics of these changes led to a criterion based on the magnitude of the pressure pulse generated in the spinal cord, but calculated in terms of the horizontal acceleration and velocity of top of the neck relative to the base of the neck.

Its formulation is

$$NIC = 0.2a_{rel} + v_{rel}^2$$

with an injury threshold value of $NIC_{max} = 15 \text{ m}^2/\text{s}^2$.

The NIC is widely used in whiplash prevention research and in some consumer test assessments, although some have questioned whether NIC and the threshold of $15 \text{ m}^2/\text{s}^2$ have been properly validated (Croft et al., 2002). However, testing has shown the NIC_{max} predicts performance of seats with different real-world injury rates (Eriksson and Boström, 2002).

4.3.1 N_{km}

Schmitt et al. (2002) proposed an alternative to NIC. As NIC uses the relative horizontal motion of the top and bottom of the neck in its calculation, a problem emerges if there is a large extension of the neck: the top and bottom of the neck are no longer parallel, and so there is a practical problem in measuring the required motions.

Schmitt et al. proposes an alternative criterion, N_{km} . It has as some similarities with the neck injury criterion used for the assessment of serious neck injury potential in frontal impacts,

the N_{ij} . N_{km} measures the instantaneous sum of two ratios. The ratios are the shear force and bending moment normalised by critical limiting values. i.e.:

$$N_{km}(t) = \frac{F_x(t)}{F_{int}} + \frac{M_y(t)}{M_{int}}$$

where F_{int} and M_{int} are critical limiting values. The objective is to reduce the overall loading on the neck. N_{km} combines the effects of force and moment measured at the occipital condyles. F_{int} and M_{int} are based on the tolerance levels for axial compression and bending moment.

Schmitt et al. did not propose a tolerance level for N_{km} , but a value of 0.3 has been used in the past to denote good performance in ratings of seats and head restraints performed by the Swedish Road Administrations (Krafft et al., 2004).

Schmitt et al. note little correlation between NIC and N_{km} , but note also that N_{km} is useful over a longer part of the impact event. They note that in the absence of an accepted biomechanical basis for neck injury, it might be prudent to design seats that produce safe test results as measured by a variety of criteria.

4.3.2 Rebound velocity / T1 acceleration

Muser et al. (2000) highlighted the potential importance of the rebound phase, where the occupant, having made contact with the seat and head restraint in the first phase of the rear impact, is propelled forward into the seat belt. A large neck flexion may result during this phase of the impact. They proposed examining the energy dissipated in the seat as an indicator of the propensity of the seat to generate a large rebound velocity – a lower energy dissipation leading to a higher rebound velocity. However, in ratings programs, the rebound velocity itself is used to check this seat parameter (e.g. Krafft, 2004). In the IIWPG procedure, the acceleration on the thorax is measured and this is related to rebound also as a large acceleration indicates that the occupant is being propelled forward.

4.3.3 IIWPG dynamic test criteria

The IIWPG divide their assessment criteria into two groups: seat design parameters and dummy response parameters (RCAR, 2008b). The T1 acceleration mentioned above is one seat design parameter considered. The other is the 'time to head restraint first contact'. As mentioned previously, minimising the gap between the head and restraint ensures that ride-down is maximised, and measuring the duration between the beginning of the pulse and the head restraint contact is a direct measure of this.

Low T1 accelerations and a short time to head restraint contact should ensure that loads on the neck are minimised (ibid.). The dummy response parameters measure this directly by measuring shear force and tension placed on the neck during the test. These are measured at the junction between the BioRID head and neck.

5 Rear-end crash testing protocols and programs for the evaluation of seats and head restraints

This section describes active and proposed testing protocols and programs evaluating passive safety measures to reduce impact injury. Most activity in the establishment of assessment programs has occurred within the International Insurance Whiplash Prevention Group (IIWPG), (including, individually Thatcham, UK and IIHS, USA) Folksam/Swedish Road Administration, The General German Automobile Club, (ADAC), Working Group 20 of the European Enhanced Vehicle-safety Committee (EEVC WG20), The International Standards Organisation (ISO), EuroNCAP, the UNECE World Forum for the Harmonization of Vehicle Regulations (WP.29), and the US National Highway Traffic Safety Administration (NHTSA). It should be noted that some of these organisations contain a reasonable overlap of membership and expertise, and so there has been a good deal of cross-fertilisation of principles and practices in the evaluation. It is also important to realise that some of this activity concerns the development of regulatory tests, while other activity concerns the development of consumer information tests.

Most programs have in common the measurement of static head restraint geometry and the dynamic evaluation of head restraint performance. The most significant differences in the protocols centre on the choice of impact pulses and the injury measures in the dynamic assessment of seats. Procedures proposed by NHTSA contain further differences. They propose the use of a Hybrid III dummy for testing, whereas all other procedures propose the use of a dummy known as BioRID. The use of the Hybrid III dummy lacks support (Zuby, 2008; Hynd, 2007).

This section will describe and discuss two testing procedures: the IIWPG assessment procedure currently employed by the IIHS, and the just-released EuroNCAP procedure. The reason for doing so is that these procedures are most relevant to any potential consumer testing program in Australia; the IAG already has seats assessed to the IIWPG procedure, but ANCAP have historically harmonised vehicle assessment procedures with EuroNCAP. Of importance also are the procedures developed by Folksam and the Swedish Road Administration (SRA). The Folksam/SRA procedures have been incorporated into the EuroNCAP procedure and so these will be touched on in the discussion of the EuroNCAP procedures.

The differences between the IIWPG and EuroNCAP procedures centre on the approach taken in the assessment. The IIWPG assessment takes a 'best-practice' approach, ranking the performance of seats against other seats' performances in the laboratory and in the field. The EuroNCAP approach (which is also based on work initiated by Folksam/SRA) is to use IIWPG measures but also to measure parameters which reflect favoured hypotheses on the mechanisms of whiplash injury. The EuroNCAP assessment will require seats to be subjected to three different impact pulses, whereas the IIWPG procedure required only one dynamic test. Essentially, the EuroNCAP procedure is an amalgamation of the IIWPG and the Folksam/SRA procedures.

5.1 International Insurance Whiplash Prevention Group (IIWPG)

The IIWPG is a consortium of research groups supported by insurance companies from around the world (Insurance Institute for Highway safety in the USA, Thatcham in the United Kingdom, Allianz Centre for Technology in Germany, the German Insurance Institute for Traffic Engineering, Folksam Insurance in Sweden, Insurance Corporation of British Columbia in Canada, Insurance Australia Group, and CESVIMap in Spain)(RCAR, 2008a). The IIWPG is a project run by the Research Council for Automobile Repairs (RCAR).

Procedures developed by the IIWPG are built on procedures and programs run by the Insurance Corporation of British Columbia and the Insurance Institute for Highway Safety (Zuby and Avery, 2002).

5.1.1 Overview of the IIWPG test procedure

The IIWPG procedure comprises two parts: a static geometric assessment of the head restraint and a dynamic rear impact test. A dynamic assessment is only made for seats that have 'good' or 'acceptable' head restraint geometry.

Measurement and rating of static head restraint geometry

The objective of the static head restraint geometry rating is to identify those head restraints that will provide protection to the largest proportion of the population and do so by minimising the distance from the rear of the head to the back of the restraint.

The test requires that the seat and head restraint be placed in a typical driving position. Seats with adjustable headrests are placed in the mid-position between the highest and the lowest positions and the mid-position between the rearmost and foremost positions, unless the head restraint cannot be locked into that position. In that case, the lowest/rearmost position is assessed. Geometry is measured with a Head Restraint Measurement Device (HRMD) attached to a H-point machine. (The latter machine is used in the evaluation and design of various ergonomic aspects of vehicle seats.)

The rating requirements for the assessment are illustrated in Figure 5.1. Good restraints are identified as those where the top of the head restraint is not more than 6 cm below the top of the top of the HRMD and the backset is no more than 7 cm from the rear of the HRMD. These measurements are shown in Figure 5.2.

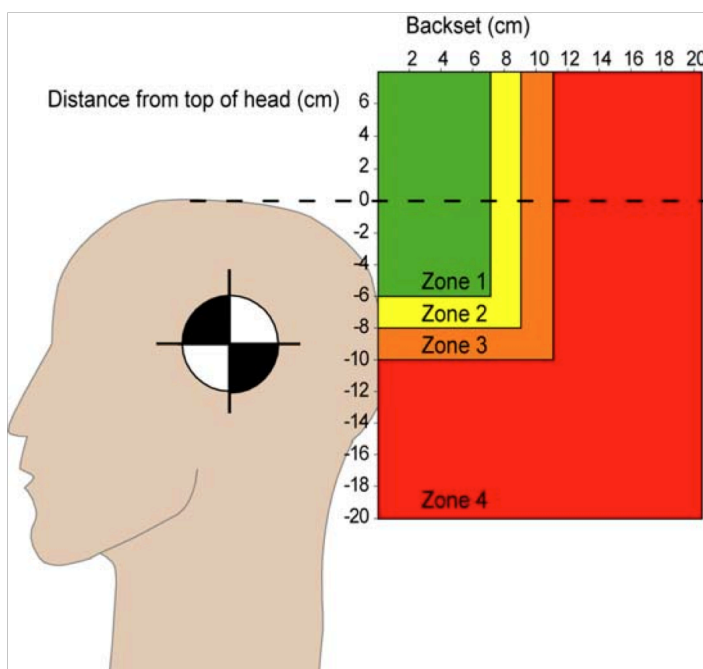


Figure 5.1
Schematic representation of the RCAR static head restraint evaluation. Green = good, yellow = acceptable, orange = marginal, red = poor. (reproduced from RCAR, 2008a)

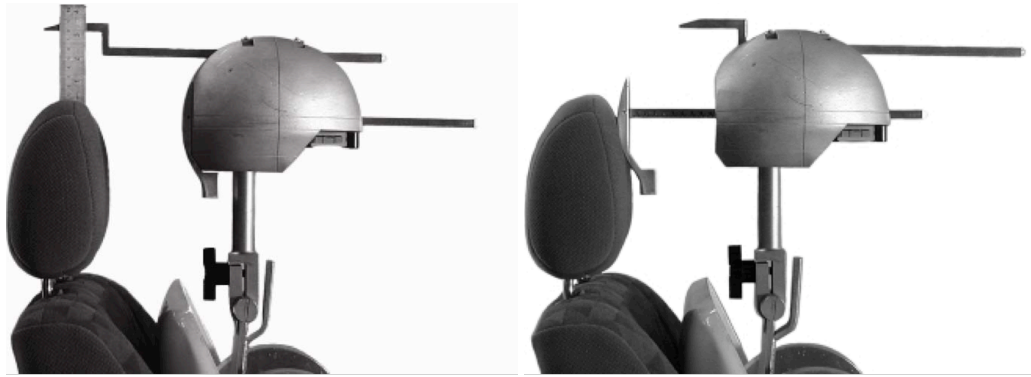


Figure 5.2
Measurements of head restraint height (left) and backset (right) according to the RCAR procedure for the measurement and rating of static head restraint geometry (reproduced from RCAR, 2008a)

Dynamic test requirements

The purpose of the dynamic test evaluation is to examine both seat responses and crash test dummy responses to a typical low-speed rear-end impact pulse. In assessing the seat's response to the impact, reliance is placed on seats that have demonstrated effectiveness in the field; the performance of these seats is used to define what is acceptable. In assessing dummy responses, the objective is to limit loads placed on the neck, and designations of 'low', 'moderate' and 'high' forces are based on a ranking of the force levels compared to a range of seats tested in 2004 (IIWPG, 2004). Therefore, the biomechanical principles behind the assessment are simple, and supported by crash data, and no reliance is placed on hypotheses of detailed injury mechanisms.

The procedure involves testing the seat in isolation from the vehicle. It is acknowledged that the performance of the seat is dependent on the rear-end structure of the vehicle, as well as the front structure, mass and speed of the striking vehicle (IIWPG, 2004), and so it is worth noting that the assessment is only of the seat under conditions that the IIWPG have accepted as being typical. (More discussion about the impact pulse used is contained in Section 5.2).

The seats and headrests are positioned in the dynamic test in a similar way to the static assessment. A BioRID dummy is placed in the seat so that the head restraint backset is the same as that measured with the HRMD in the static test. The seat and dummy are subjected to a rear-end crash pulse with a peak acceleration of 10 g, and a change in velocity of 16 km/h.

The assessment of the seat's design performance has two aspects: one related to the seat's response and the other related to the dummy's response. The seat's response is rated according to the time taken for the head of the dummy to make contact with the head restraint and also the acceleration of the dummy spine measured at 'T1' (the level of the first thoracic vertebra).

The time-to-contact requirement is that the head should make contact with the head restraint within 70 ms of the beginning of the pulse and remain in contact with the head restraint for at least 40 ms. These requirements are based on the performance of active head restraints such as the SAHR, and other seats with good or acceptable head geometry in the static assessment. The T1 acceleration requirement is that the acceleration should be less than 9.5 g. This requirement is based on the performance of the Volvo WHIPS seat in

the test. as noted earlier, both the SAHR and the WHIPS seat have demonstrable ability to reduce chronic whiplash incidence in the field (Jakobssen, 2004; Kullgren, 2007).

The dummy response is assessed by classifying the forces placed on the neck. Two aspects of the neck forces are measured: upper neck tension and upper neck shear; and these are considered in combination. As mentioned previously, the lack of conclusive evidence about the tolerance of the neck to whiplash-causing forces means that the limits of performance are based not on biomechanical principles as much as a ranking of the seat's performance against other seats. And so the loads on the neck are considered low if they fall in the lowest 30% of seats tested, moderate if the loads fall into the 30th – 75th percentile of seats tested, and high if the loads fall into the highest 25% of seats tested. (Baseline results were from all seats from 2004 model cars tested; IIWPG, 2004.) Corridors for neck load assessment are shown in Figure 5.3.

The overall dynamic rating is given by combining the seat design criteria and the neck force classification. The rating requirements are given in Figure 5.4.

The overall rating is formulated according Figure 5.5. The only rating requiring some explanation is those seats that have an 'acceptable' backset but 'good' height characteristics. These seats earn a 'good' overall rating if the dynamic rating is 'good' (RCAR, 2008b).

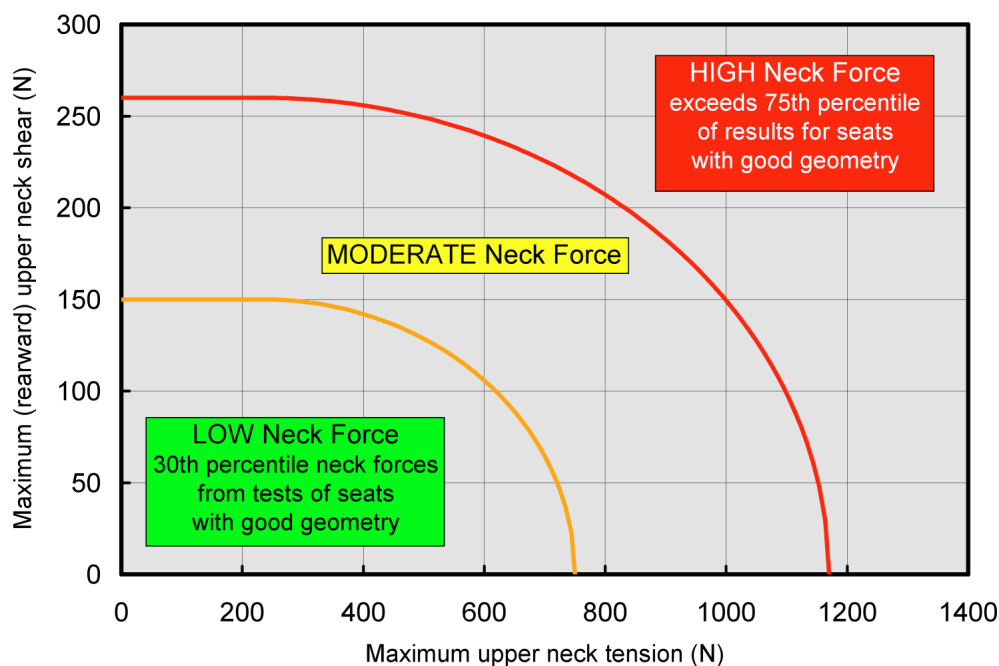


Figure 5.3
Corridors used in the assessment on neck loads in the IIWPG dynamic assessment of seats (reproduced from RCAR, 2008b)

Seat Design Criteria	Neck Force Classification	Dynamic Rating
T1 X-acceleration ≤ 9.5 g OR Time to head restraint contact ≤ 70 ms	Low	Good
	Moderate	Acceptable
	High	Marginal
T1 X-acceleration > 9.5 g AND Time to head restraint contact > 70 ms	Low	Acceptable
	Moderate	Marginal
	High	Poor

Figure 5.4
Dynamic rating requirements for the RCAR-IIWPG seat rating (reproduced from RCAR, 2008). This rating is combined with the static rating to give an overall assessment (see Figure 5.5). (Reproduced from RCAR, 2008b)

Geometric Rating	Dynamic Rating	Overall Rating
Good	Good	Good
	Acceptable	Acceptable
	Marginal	Marginal
	Poor	Poor
Good Height	Good	Good
Acceptable	Good	Acceptable
	Acceptable	Acceptable
	Marginal	Marginal
	Poor	Poor
Marginal	No dynamic test	Poor
Poor	No dynamic test	Poor

Figure 5.5
Formulation of the overall RCAR-IIWPG seat rating (reproduced from RCAR, 2008b)

5.1.2 Evaluation and commentary on the RCAR-IIWPG test procedure

Edwards et al., (2005) summarised testing undertaken to the IIWPG protocol. Of note was the improvement in head restraint geometry. Between 1995, when the static only assessments were initiated by the Insurance Institute for Highway Safety in the US, and 2004, the proportion of assessments rated as 'good' or 'acceptable' rose from 7% to 78% of seats.

Edwards et al. also report on the results of dynamic assessments of 73 seat/head restraint combinations from vehicles from model years 2004 and 2005. These seats earned good or acceptable static geometric ratings. Eight of the 73 received good ratings. These were seats that either used active head restraints or specific strategies to absorb energy, such as the Volvo WHIPS seat.

The overall assessment of seats in the IIHS program appear to correspond well with an alternative rating system, published by the Swedish Road Administration (SRA) (ibid.). More recent analysis of the correlation between seat ratings and real-world whiplash injury

showed that highly rated seats have lower injury rates and that the SRA and IIHS ratings had a similar level of discrimination (Farmer et al., 2008; Kullgren et al., 2007).

5.2 The European New Car Assessment Programme (EuroNCAP)

EuroNCAP have recently publically released a draft protocol for the dynamic assessment of car seats for neck injury protection testing (EuroNCAP, 2008a). Testing will commence in August 2008 and initial results will be published in November 2008. While several laboratories in Europe have been accredited by EuroNCAP to conduct the testing, initially only Thatcham will perform the testing (Avery, 2008a).

The EuroNCAP procedure includes many elements of the EuroNCAP procedure that are similar to the RCAR-IIWPG procedure, including the static head restraint procedure. The EuroNCAP procedure also includes other elements that are based on test methods developed for the Folksam/SNRA assessment program. The following sections concentrate on the differences between the IIWPG procedures and the EuroNCAP procedures.

5.2.1 Static head restraint assessment procedure

The EuroNCAP procedure includes a static head restraint geometry assessment. The main difference between the EuroNCAP procedure and the IIWPG procedure is in the assessment of acceptable head restraint backset and height: the equivalent of a good rating is only earned for a head restraint backset less than 40 mm coupled with a head restraint higher than the top of the HRMD. The geometric assessment of pro-active and locking re-active systems may be made in the deployed position (Avery, 2008b).

Figure 5.7 illustrates the differences in the static assessment of head restraint geometry under each protocol. Compare especially the EuroNCAP 'green' zone with the larger 'Zone 1' defined in the IIWPG procedure.

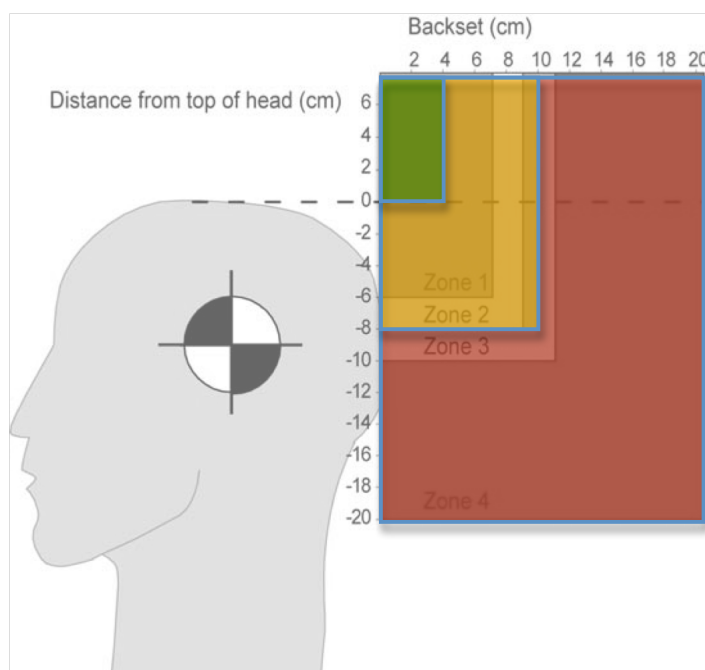


Figure 5.7
Schematic representation of the EuroNCAP static head restraint evaluation overlaid on the IIWPG assessment. Green/yellow boundary = higher performance, yellow/red boundary =lower performance limit

5.2.2 Dynamic assessment procedure: the EuroNCAP impact pulses compared to the IIWPG pulse

The dynamic assessment is somewhat similar to the IIWPG procedure, but there are differences in the number of pulses the seat is subjected to and to the nature of pulses. Injury assessment criteria are also different.

One potentially significant point of difference between the EuroNCAP procedure and the RCAR-IIWPG procedure is the requirement for testing with three pulses (the IIWPG procedure requires a single test). Both procedures use a skewed triangular pulse with a peak acceleration of 10 g, and a change in velocity of 16 km/h (Figure 5.8 and Figure 5.9). A 16 km/h 'delta-v' is produced when a vehicle is struck from the rear by another vehicle of equal mass travelling at 32 km/h.

Additionally, the EuroNCAP procedure calls for two additional tests using 'low' and 'high' severity pulses (Figure 5.10). These three pulses are those used by Krafft et al. (2004) in the 2004 ratings of seats for the Swedish National Roads Administration and Folksam. The rationale for the three pulses is to avoid optimisation of the seat for a single test condition, at the detriment of other crash conditions (Lorenz, 2005). Such an approach is also supported by EEVC WG20 (Svensson et al., 2005). However, based on reported results, the use of three pulses does not appear to lead to seat ratings that vary significantly from ratings that use the single IIWPG pulse (Edwards et al., 2005).

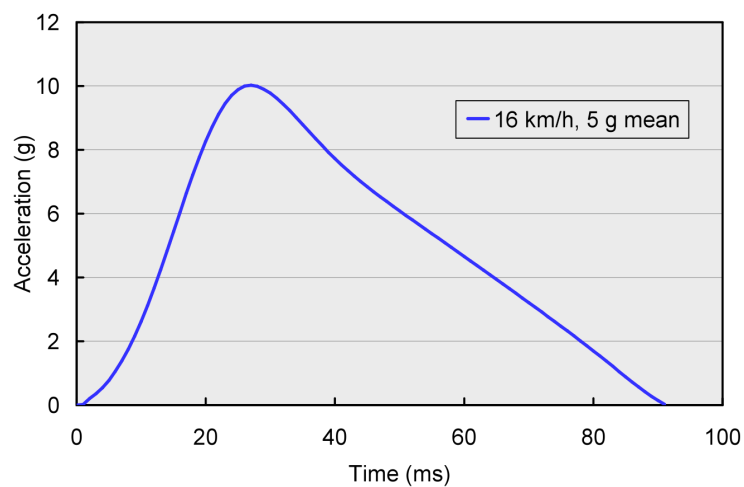


Figure 5.8
IIWPG target acceleration pulse (reproduced from IIWPG, 2004). Vertical scale is acceleration (g) and the horizontal scale is time (ms).

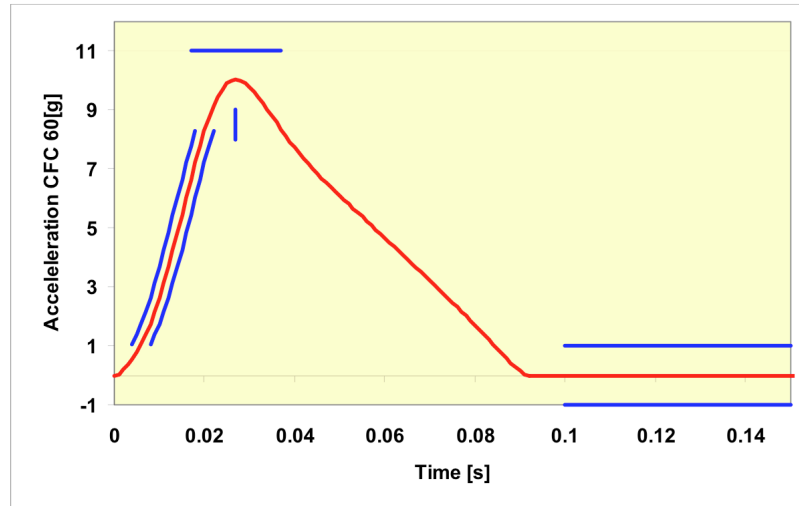


Figure 5.9
EuroNCAP target acceleration pulse (red) and corridor (blue) for the medium severity pulse (reproduced from EuroNCAP, 2008a)

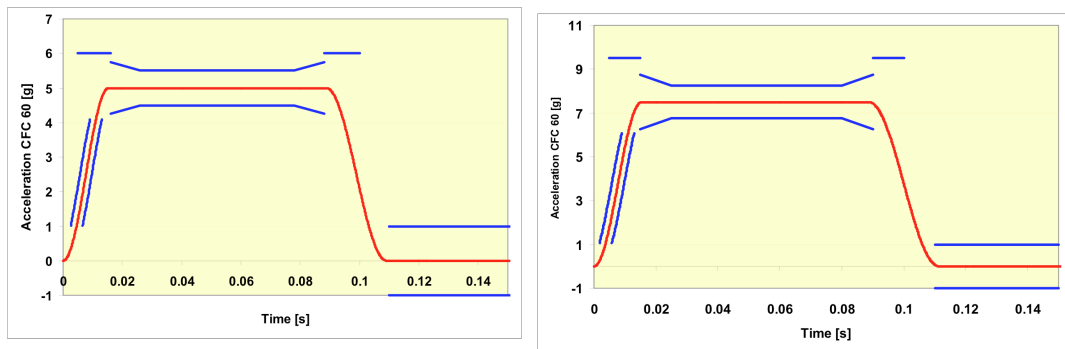


Figure 5.10
EuroNCAP target acceleration pulse (red) and corridor (blue) for the low and high severity pulses (reproduced from EuroNCAP, 2008a)

5.2.3 Seat and injury rating measures

In common with the IIWPG procedure, time-to-contact and T1 acceleration are measured in the EuroNCAP procedure to indicate the seat's response. However, there are differences between the two procedures in the parameters that are used to assess neck injury risk. In addition to the upper neck shear force and the upper neck tension specified in the IIWPG procedure, the EuroNCAP procedure also calls for the measurement of head rebound velocity, NIC, and N_{km} . To ensure that performance is not achieved by excessive seatback deformation, the dynamic seatback deflection is also measured in the high severity test to ensure that there is no risk of occupant ejection through excessive collapse of the seatback in a rear impact.

Both rating systems combine the results of tests into an overall classification or score. The IIWPG rating system was described earlier. The EuroNCAP rating procedure examines each output parameter separately, assigning 0.5 of a point to each parameter that falls under the higher performance limit, and summing over all parameters (up to a maximum score of 3) (EuroNCAP, 2008b). Parameters falling outside the lower performance limit are given a score of zero, and parameters falling between the higher and lower limits are given a linearly interpolated score.

The weighting given to each element of the assessment is shown in Table 5.1. The performance in the dynamic test accounts for 9/11ths of the assessment. A much smaller weighting is given to the static head geometry assessment, which is treated akin to a 'modifier' – a good static geometry contributes 1/11th to a maximum score.

Table 5.1
Scores used in the overall rating of seats under the EuroNCAP assessment protocol (EuroNCAP, 2008b)

	Points available
Static assessments	
HR geometry	-1 to +1 points
Ease of adjustment	1 point
Dynamic assessments	
Low severity pulse	3 points
Medium severity pulse 3 points	3 points
High severity pulse 3 points	3 points
Modifiers	
Seatback deflection	-1 point
Dummy artefact loading	-2 points
Maximum points	11 points

As the two procedures vary somewhat in their rating systems, it is instructive to compare the limiting values of parameters used to score a seat under each procedure. Limiting test parameter values are shown in Table 5.2. It may be noted that the EuroNCAP procedure is a blend of the IIWPG and the Folksam/SRA procedure. It is more demanding than either of them.

Table 5.2
Higher and lower performance criteria for 16 km/h rear impact head restraint assessments under IIWPG and EuroNCAP

Performance level	RCAR -IIWPG		Folksam/SNRA (all three pulses)		EuroNCAP mid severity pulse	
	Higher	Lower	Higher	Lower	Higher	Lower
Time to head restraint contact (ms)	70	n.a.	-	-	57	82
T1 acceleration (g)	9.5	n.a.	-	-	9.3	13.1
NIC (m ² /s ²)	-	-	15	18	11	24
N _{km}	-	-	0.3	0.4	0.15	0.55
Rebound vel. (m/s)	-	-	4.5	6	3.2	4.8
Upper neck shear (N)	150	260	-	-	30	190
Upper neck tension (N)	750	1170	-	-	360	750

In defining performance criteria for each pulse, the approach taken by EuroNCAP was similar to that taken by IIWPG: the assessments of a range of current seats were used as a benchmark against which other seats can be rated. Thirty one seats were tested by Thatcham and the SRA in 2006. For each parameter, the 5th percentile score was used to define the higher performance limit and the 70th percentile score was used to define the lower performance limit. These percentile criteria were determined for each of the three pulses (Avery, 2008b). Additionally:

- The geometric assessment of pro-active and locking re-active systems may be made in the deployed position.
- Pro-active systems must deploy in all three dynamic tests.
- All active systems must fully deploy and lock in lower energy rear-end bumps too, in addition to the three EuroNCAP pulses.

- If any test parameter exceeds the 95th percentile value, no score is given for the pulse.
(Avery, 2008b)

To summarise the important similarities and differences between each procedure:

- Neck load requirements appear to be more strict under the EuroNCAP rating. For example, the higher-performance limit of the IIWPG procedure is close to the lower-performance limit in the equivalent mid-pulse test of the EuroNCAP rating.
- Seat performance parameters in mid-pulse test of the EuroNCAP procedure (time to head restraint contact and T1 acceleration) are roughly equivalent to the RCAR/IIWPG procedure.
- Higher and lower severity impacts are also used by EuroNCAP, to prevent optimization only on the mid-severity impact. This is also the case in the Folksam/SRA ratings.
- Excessive seat yielding (which may cause occupant ejection in severe rear-impacts) is also checked in the EuroNCAP procedure.

Differences in overall rating of the seats are therefore possible (indeed probable) under the three protocols. However, it might also be noted that, given the raw test results from a seat assessment, the IIWPG rating (and the Folksam/SRA rating) may be derived from a EuroNCAP assessment. To a limited extent, EuroNCAP ratings may be estimated from existing IIWPG assessments. So the correspondence between the two rating systems is amenable to some further analysis in advance of the widespread deployment of the EuroNCAP assessment program. Importantly for Australia, a correspondence between the two rating systems may allow ratings of seats from both test programs to be used to publish homogenous rating of seats for consumers. Notably, Thatcham intends to continue rating seats to the IIWPG procedure, deriving the rating from EuroNCAP test results (Avery, 2008a). Note though, that given that a large proportion of seats now tested by IHS perform well (Edwards, 2005), a tightening of the criteria used to assess 'good' seats may produce more differentiation between seats, and higher performance in the future.

Nevertheless, it is unclear what additional benefit will be gained by testing with three pulses, over the rating that is made using a single pulse. It is probable that the EuroNCAP procedure represents something of a compromise. Membership of EuroNCAP includes the SRA and Thatcham, each of which has established assessment programs, Thatcham using the IIWPG procedure and the SRA using the Folksam/SRA procedure. The consistency between seat ratings using each of these procedures has already been demonstrated (Edwards, et al. 2005; Kullgren et al., 2007), and so the benefit of an expanded test procedure is open to question.

5.3 Overall rating

EuroNCAP has recently proposed a revision to its vehicle rating protocols. Until now, ratings were given to occupant and pedestrian safety separately. The offset frontal and side impact tests were combined to give an overall occupant safety rating. The revised rating protocol takes a different approach.

The overall rating will be a weighted combination of individual 'boxes' that group test results applicable to adult occupant protection, child occupant protection, pedestrian protection and safety-assist technologies. The whiplash assessment is a component of the adult occupant protection score and the current proposal is that it contribute four (or six) out of 36 points to the adult occupant component of the rating.

The safety-assist component of the rating recognises that there are great advances to be made in primary (active) safety technologies such as Electronic Stability Control (EuroNCAP, 2008c). However, currently, only certain technologies are proposed as part of the vehicle assessment. Brake assistive technologies and collision warning systems that might assist in the prevention of low speed rear impacts do not yet appear to be part of the assessment.

Including the whiplash component of the testing in the overall score will have an effect on manufacturers who wish to achieve a maximum rating overall, as they will have to perform adequately in the whiplash tests to receive the highest EuroNCAP rating. However, EuroNCAP propose to communicate whiplash ratings directly only in the third level (of three) of consumer information.

The first level of EuroNCAP consumer information is the overall star rating. The second considers overall protection to adults, children, pedestrians and separately rates safety assist technologies. The third level deals with individual test results, including the whiplash assessment (EuroNCAP, 2008c). This strategy may have the effect of 'tucking away' the whiplash ratings, although undoubtedly there will be specific communication strategies to promote whiplash countermeasures.

5.4 Opportunities and challenges for future consumer rating programs in Australia

Passenger vehicle consumer safety ratings are published in Australia and New Zealand by the Australasian New Car Assessment Program (ANCAP). ANCAP is a consortium of Australian and New Zealand automobile clubs, the state government road and transport authorities of NSW, Victoria, South Australia, Queensland, Tasmania, Western Australia, the New Zealand Government, the Victorian Transport Accident Commission and the Insurance Australia Group. ANCAP has historically harmonised testing and assessment protocols with EuroNCAP; this has had the advantage that ANCAP assessments can be viewed alongside assessments from Europe, leveraging the information generated in Australia.

Dynamic seat and head restraint assessments have not been part of the ANCAP assessments up until now (in the 1990s, some geometry ratings were included). However, the Insurance Australia Group (IAG) Research Centre coordinates and publishes head restraint ratings for vehicle sold in Australia. These ratings are published through IAG member websites. The IAG is a member of the IIWPG. Static head restraint assessments are performed in Australia and seats have been dynamically assessed by Thatcham and IIHS under contract to the IAG.

Regarding ANCAP's plans for whiplash assessments, ANCAP's Technical Manager, Michael Paine (2008), writes:

"[...] ANCAP will be reviewing the re-introduction of a rear impact protection (whiplash) rating later this year. Up to 1999 ANCAP published a geometric rating, based on IIHS procedures. These were later incorporated into the RCAR procedures that now include a dynamic test for vehicles that perform well in the geometric assessment [...]"

"[IAG] uses the RCAR procedure [...]. This covers most cars on sale in Australia."

"Euro NCAP recently indicated that it would be introducing a rear protection rating late in 2008. It appears that they will be conducting three dynamic tests to evaluate a range of occupant sizes and crash severities. I understand that RCAR (particularly IIHS and Thatcham) has been involved in the development of the Euro NCAP procedures but intend to remain with the single dynamic test. The Euro NCAP test is regarded as

"complementary", in that it should minimise cases of manufacturers tuning the head restraint to one particular set of tests.

"[IAG] became an ANCAP stakeholder last year and I expect that they will be keen to see ANCAP reintroduce the whiplash rating. The simplest approach would be for ANCAP to republish the [IAG] rating. However, as I explained, it is proposed to review the need for ANCAP to publish a rating and, if so, to determine the most appropriate methods (either RCAR or Euro NCAP).

"So I am unable to give firm advice about ANCAP's plans for a whiplash rating. However, I consider it would be wise to at least design to do well in the RCAR test.

"Similarly, ANCAP will be considering the major review of the scoring process that is likely to be introduced by Euro NCAP. Under this proposed system adult occupant protection will be rated on a combination of frontal offset, MDB side impact, side pole impact and rear impact crash performance. Seat belt reminders will be part of a separate "Safety Assist" rating (the other components are ESC and "speed limitation devices"). It is therefore possible that the whiplash rating will influence the occupant protection rating in a few years."

ANCAP is also considering recognising the importance of rear-collision avoidance technology in their assessment of whiplash protection (Paine, 2008).

Fundamentally, ANCAP will need to choose whether to harmonise with EuroNCAP, requiring the expanded EuroNCAP test protocol and/or adopt the IIWPG assessment protocol that is already in use by the IAG. It should be noted that these are not 'either/or' choices: it appears that IIWPG ratings will be able to be derived from EuroNCAP test results. As noted earlier, Thatcham intends to continue to publish IIWPG ratings separately from EuroNCAP, deriving the ratings from the EuroNCAP test results (Avery, 2008b).

The advantages of Australasia harmonising with EuroNCAP are twofold: primarily, it will ensure that some seat-based anti-whiplash countermeasure is required to achieve the highest overall ANCAP rating. This might guarantee the more widespread adoption of anti-whiplash countermeasures, as the overall safety level may send a more powerful marketing message to consumers than an isolated whiplash rating. Secondly, harmonisation will allow straightforward republication of test results from EuroNCAP – it may prove confusing to have two systems of ratings in the marketplace, where manufacturers may choose to promote the EuroNCAP rating over an alternative ANCAP rating.

As EuroNCAP ratings may be used to derive IIWPG ratings, an opportunity would still exist to create a separate whiplash assessment and communication strategy. A potential disadvantage of the EuroNCAP assessment protocol, as far as whiplash protection is concerned, is a reduced emphasis on active measures to avoid minor rear-end collisions. The opportunity would exist for ANCAP, or another group in Australasia, to create a communication strategy based on IIWPG assessments and active safety measures, as a complement to the ANCAP/EuroNCAP assessment. (Specific EuroNCAP whiplash information would not then need to be promoted.)

Another disadvantage of the adoption of EuroNCAP protocols lies mainly in the extra expense of carrying out the additional tests. There is no consensus that the additional tests provide additional information over the single IIWPG test. Back-to-back comparison of assessment results suggests that little is gained (Lund, 2008; Avery, 2008b; Edwards et al., 2005). Both rating methods relate equally well with real-world outcomes (Kullgren et al., 2007).

Note that these different assessment options are complementary also in the sense that there is unlikely to be inherent conflicts for manufacturers in meeting the design challenge of good performance. Tentatively, it is not expected that the ranking of seats will be different under EuroNCAP and IIWPG protocols (Lund, 2008; Avery, 2008b).

6 The uptake of measures in vehicles available in Australasia

While vehicle based measures to minimise the incidence of whiplash injury in rear impact exist, they are only effective to the extent that the technology is deployed into the new car fleet.

To examine the uptake of vehicle based countermeasures, a survey of models was undertaken. Models comprising the top 80% of vehicle sales were included. Sales data used to construct the list were for the 12 months to the end of June 2007 (Federal Chamber of Automotive Industries, 2007).

Information on the technology used came from websites and brochures of the current specifications (as at 25th June 2008) of the vehicles in the list. Therefore, the analysis is of current models, but based on sales data to the end of June 2007.

Table 6.1 shows the results of the analysis. The table is constructed as follows:

- Passenger vehicle models are listed in order of sales: the top selling vehicle heads the list.
- All models covering the top 80% of new vehicle sales are included.
- The inclusion of an anti-whiplash seat and some kind of brake assist is noted.
- The charts show the accumulated proportion of all vehicle sales both with and without the safety measure. The boundary of the red line shows the accumulated proportion of all new passenger vehicle sales and the green bars show the accumulated proportion of all new vehicle sales with the technology.

The table and charts show several notable characteristics of the uptake of the technology in Australia:

- Around 40% of all new passenger cars in the top 80% of sales have some anti-whiplash seat. This may be noted by the relative proportions of red and green at the bottom of the chart.
- For the two top sellers, the Holden Commodore and the Ford Falcon, we could identify no anti-whiplash seats available to consumers. These two models account for nearly 13% of all new passenger vehicle sales.
- Brake assistive technologies have a higher uptake. Around 63% of new vehicles sold in the top 80% of sales have some brake assistive technology.
- The Commodore and the Falcon include this technology and, indeed, eight of the top ten sellers include some brake assist technology.

Table 6.1
Uptake of anti-whiplash seats (AWS) and brake assist technology in new passenger cars in Australia

Make and model in sales rank order	AWS	Cumulative new car sales coverage	Brake assist technology	Cumulative new car sales coverage
Holden Commodore	-		✓	
Ford Falcon	-		✓	
Toyota Corolla	P		✓	
Toyota Hilux	-		-	
Mazda 3	PA		✓	
Toyota Yaris	P		✓	
Toyota Camry	P		✓	
Holden Astra	-		✓	
Hyundai Getz	A		-	
Nissan Navara	-		✓ *	
Ford Focus	-		✓ *	
Mitsubishi Lancer	-		✓	
Holden Rodeo	-		-	
Ford Territory	-		-	
Honda Accord	A		-	
Toyota Landcruiser	-		✓	
Honda Civic	R		-	
Toyota Aurion	P		✓	
Toyota RAV4	-		✓	
Toyota Prado	-		-	
Nissan Tiida	-		✓	
Holden Barina	-		-	
Subaru Forester	R		-	
Mazda 6	PA		✓	
Suzuki Swift	-		✓	
Nissan X-Trail	A		✓	
Mitsubishi Triton	-		-	
Honda Jazz	-		-	
Volkswagen Golf	R		✓	
Mitsubishi 380	-		-	
Honda CR-V	R		-	
Toyota Hiace	-		✓(o)	
Hyundai Accent	-		-	
Subaru Impreza	R		-	
Holden Viva	-		-	
BMW 3-Series	-		-	
Subaru Liberty	R		-	
Kia Rio	-		-	
Nissan Patrol	-		-	
Holden Captiva	-		✓	
Mazda Mazda2	PA		✓	
Mitsubishi Outlander	-		-	
Subaru Outback	R		-	
Ford Fiesta	-		✓ *	
Hyundai Elantra	A		-	
Mitsubishi Pajero	-		✓	
Chrysler Jeep	-		✓	
Peugeot 307	-		✓	

P = Passive seat A = Active head restraint PA = Proactive head restraint
 Green = cumulative proportion of all new vehicle sales with feature
 Red = cumulative proportion of all new vehicle sales without feature
 (o) = optional
 * = some variants

7 Cost benefit analyses

In order to determine which in-vehicle technologies are most worthwhile pursuing, it is useful to conduct cost-benefit analyses, comparing the different technologies available. Such analyses are notoriously difficult to conduct for road safety, with uncertainty associated especially with the benefits side of the ratio. There are great uncertainties in calculating the expected reductions in crashes resulting from the technology and also in determining the most appropriate monetary costing to be applied to the crash reductions.

The only published cost benefit analyses of the vehicle-based countermeasures described in this report were one conducted on behalf of the European Commission (COWI, 2006) and another on the benefits of static head restraint geometry improvements for the European Enhanced Vehicle-safety Committee (Hynd et al., 2007). We identified no studies on the cost-benefit analysis of technologies designed to perform well in dynamic assessments.

The aim of this study published by the EC was to determine the most cost-effective vehicle-based technology to recommend for new vehicle models in the European Union. COWI assessed 21 vehicle safety technologies, using existing European data and literature to compare the costs of installation with the likely benefits in terms of crash and injury reduction. For four technologies, the lack of cost data meant that break even costs only could be specified, while for another four technologies, even break even costs could not be specified due to the lack of available data. All evaluations considered only the individual technology in isolation, so that, for example, the analysis was conducted separately for adaptive cruise control, without considering its possible incorporation into a broader collision avoidance system also including forward collision warnings (COWI, 2006). There may be cases in which the installation of combined systems would cost less than the sum of installation of the two technologies separately, possibly reducing the cost side of the ratio. However, separate technologies would be likely in many cases also to target and reduce the same crashes and so the added crash and injury reduction benefits of the combination may not outweigh the increased cost.

Adaptive cruise control was estimated to have a cost benefit ratio of 0.4, making it one of the few technologies that was found not to be cost beneficial. The cost benefit ratio was sensitive to unit cost price and also to the percentage of crash reductions used in the calculations but, even so, the ratios were always below one. Part of the reason for this is that adaptive cruise control was viewed as only being applicable to rear-end crashes, while other technologies were applicable to a number of different crash types. It was expected to be particularly effective, however, within the rear-end crash category. It is also important to note that the cost of new technology and systems tends to reduce over time and so non-cost-effective countermeasures may become cost-effective in the future (COWI, 2006).

Brake Assist programs were assumed to affect many crash types, including collisions with pedestrians, but only in crashes in which the driver brakes. After estimating cost benefit ratios for a number of unit costs, it was found that a break even cost for putting Brake Assist programs in all new cars was 460 Euros (COWI, 2006).

Forward Collision Warning systems were also assumed to affect many crash types but, unlike Brake Assist, were also assumed to affect crashes in which the driver would not otherwise have braked. The system evaluated by COWI also includes some pre-crash systems to reduce injury (e.g. headrest technology). It was concluded that the break even cost for such a system to be fitted to all new European cars was 1,200 Euros. Sensitivity analyses modelling ranges of crash reduction effects produced a range of break even costs from 700 to 1,700 Euros (COWI, 2006).

The other countermeasure described in the current report that was evaluated by COWI (2006) was the use of conspicuous marking on the rear of heavy goods vehicles. This was found to be one of the most cost-effective countermeasures, with a cost benefit ratio of 2.5. This would be related to the relatively low cost of conspicuous marking but would also be due to the high expected likelihood of crash reductions used in the analysis. It was assumed to lead to reductions of 86 percent of relevant crashes, compared to the 40 percent calculated in Morgan's (2001) American study.

The EEVC study (Hynd et al., 2007) examined only the costs and benefits of improved head restraint geometry. The options considered were changes in the minimum standards in head restraint geometry, namely increasing height beyond 800 mm (the distance between the top of the restraint and the hip of an occupant) and reducing the backset of the head restraint.

The minimum change required to produce a BCR of 2 was found to be to introduce a minimum backset requirement of 70 mm. The greatest BCR would come from a minimum backset requirement of 40 mm. Further increases in net benefit (at the expense of a declining BCR) would be realised by increasing the height of the restraint to 840 mm.

8 Summary and discussion

Seat design measures have focussed on managing the impact energy in a way that minimises forces placed on the neck, and particular motions thought to be injurious such as retraction, hyper-extension and hyper flexion. Despite uncertainty over the mechanism of injury in whiplash cases, basic principles of restraint design have been applied to design seats that reduce the forces placed on the neck in a rear-end crash. Such seats were pioneered by Saab, Volvo and Toyota. The Saab and Volvo seats appear to have a measurable effect on long-term injury rates.

Assessment procedures emphasise both good geometry (a high head rest and a small gap between the head and head restraint) and good dynamic performance (low forces on the neck during simulated rear-impacts). A significant amount of research has been conducted to identify the most life-like dummy for such testing, and as a consequence, the BioRID II dummy is now widely used in rear impact assessment programs. There are alternatives however (RID2, Hybrid III) but there is disagreement over the use of the Hybrid III in rear impact testing.

Holm et al. (2008) rate as 'preliminary' the positive evidence for the effectiveness of seat-based strategies to reduce whiplash. While recent studies appear to confirm benefits of better seat designs (Kullgren et al, 2007; Farmer et al., 2008) it is worth keeping Holm et al.'s conclusions in mind when evaluating the merits of passive safety measures to reduce whiplash injury. Such benefits will be able to be confirmed once technology becomes more widely deployed in the entire passenger vehicle fleet.

Emphasis on secondary crash injury prevention, while important, should not be at the expense of primary crash prevention measures, such as crash avoidance technologies. Crashworthiness rating programs will increasingly have to consider primary safety technology when assessing vehicles. Technologies that reduce crashes or reduce the severity of crashes by reducing impact speed may significantly potentiate crashworthiness measures, not only through avoidance, but also through reduced impact severity. The extent to which such technologies can contribute is worthy of further research. A complicating factor in such research is that the technologies need to exist on different vehicles (crash avoidance on the striking car; anti-whiplash seats on the struck car). It may be only after some experience in the field, as the technologies become more common, that the relative contribution of crash avoidance technologies becomes apparent. In the mean time, rating programs should recognise and promote the benefit of rear impact avoidance technologies.

There is potential for some inconsistency between the assessment programs run by EuroNCAP and those run by IIHS (USA) and Thatcham (UK). There are differences in the tests conducted, injury measures used, and the weighting of the results, which may have the potential to create some inconsistency in the communication of ratings. However, there is unlikely to be inconsistencies in the ranking of seats.

The EuroNCAP whiplash assessment will be used in EuroNCAP's overall assessment of a vehicle. This will have the important effect of ensuring good performance in those models that have the highest EuroNCAP rating. As the whiplash assessment itself will be only promoted at a level that many consumers may not see, there is an opportunity for a separate communication strategy on whiplash measures, possibly reworking the EuroNCAP results into a form consistent with IIWPG ratings, and including the rating of active systems designed to avoid crashes or reduce their severity. While many new cars sold in Australia are equipped with such technologies, significant numbers of new vehicles have no countermeasures, and the measurement of the performance of the systems that do exist may be useful to consumers and insurers alike.

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