MONASH University
Accident Research Centre

DEVELOPMENT OF THE VISIONARY RESEARCH MODEL

APPLICATION TO THE CAR/PEDESTRIAN CONFLICT

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Abstract:

This report describes a study undertaken to improve road safety through a fundamentally different approach. The study draws on the Swedish Vision Zero road safety philosophy, in which it is ethically unacceptable to trade the lives and health of people in traffic for other benefits in society. The research's main purpose was to develop a model, known here as the Visionary Research Model, to identify research needs and priorities needed to create safe traffic environments. Unlike conventional approaches to traffic safety research and countermeasure programs, which generally result in incremental improvements at best, the Visionary Research Model adopts an ambitious goal of no deaths or serious injuries within the road-transport system. The car/pedestrian conflict situation was chosen to explore and demonstrate the model's potential. From this highly challenging starting point, the model generates new research needs and priorities that will enable a "quantum step" to be taken towards safe traffic environments for pedestrians. The structure of the conceptual model has a pedestrian at the centre of five concentric layers of protection. Collectively, these layers aim to manage crash and injury risk so as to avoid death or serious injury to the pedestrian in traffic. The five layers target various forms of threat to the pedestrian. The protective layers seek to: avoid collisions in which the biomechanical limits of humans to violent forces are exceeded; manage the transfer of kinetic energy from car to pedestrian at impact; minimise the amount of kinetic energy at impact; minimise the risk of a crash for a given level of exposure; and minimise the risk of a crash as a function of exposure. The model's conceptual structure challenges researchers and practitioners, encourages innovation and evidence-based assessment of risk, as well as consideration of the full sequence of events in a situation of conflict between a car and a pedestrian. Though well developed in its conceptual form, the Visionary Research Model requires further research and development of its mathematical capability to enable changes in risk as a result of countermeasure application to be quantified. The model is believed to be of generic form and, therefore, suited to other categories of serious trauma, such as vehicle-to-vehicle crashes at intersections and single-vehicle crashes with roadside hazards.

Key Words:
Vision Zero; Visionary Research Model, Pedestrians; Car/pedestrian conflict; Crash risk; Injury risk; Kinetic energy; Countermeasures.

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Preface

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Acknowledgments

The inspiration for and the original conceptualisation of the Visionary Research Model came in the late 1990s from the then Director of MUARC, Professor Claes Tingvall. Around that time, there was a realisation that progress over recent decades in road safety was characteristically incremental in nature and rarely, if ever, exhibited a “quantum step” towards a fundamentally safe road-transport system. A better way of generating critical new research ideas and priorities, that would enable such a step to be taken, seemed possible.

The need for such an approach received the enthusiastic support of the Centre’s baseline sponsors, namely, VicRoads, TAC, Department of Justice, Victoria Police and RACV. The on-going conduct of the study has continued to be supported fully by current MUARC Director, Professor Ian Johnston.

Leading a group of the Centre’s senior and mid-level researchers from a wide range of professional backgrounds, Professor Tingvall conceived of a research-based model whose over-riding vision was to prevent death and serious injury within the road-transport system. The model would define how the system should “look and operate”, and be capable of identifying the research required to be undertaken to realise the vision. A small project team, comprising Adjunct Professor Max Cameron, Dr Teresa Senserrick, Dr George Rechnitzer and Bruce Corben, assumed responsibility for developing the model’s structure and defining its essential attributes. This more detailed work benefited greatly from discussion and ideas of another group of senior MUARC researchers whose input was invaluable in the development of the model at its broadest level. Professor Tom Triggs, Dr Narelle Haworth, Dr Michael Regan, Professor Joan Ozanne-Smith and Ms Kathy Diamantopoulou made particularly important contributions to the early formation of the model. Professor Tingvall has continued to contribute to the development of the model during his professional visits to the Centre, as part of his appointment as an adjunct professor to Monash University following his return to Sweden.

The continuing support, patience, review and constructive comments on the model by representatives of the baseline sponsors are greatly appreciated.

Although this report was written by Bruce Corben, with the benefit of editorial input from other team members, the report’s authorship attempts reflect the very important intellectual and technical contributions of the entire project team.

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EXECUTIVE SUMMARY

This study was borne from a realisation that, historically, the most successful road safety programs and initiatives tend to make incremental progress only. It is rare in Victoria to observe a quantum fall in serious road trauma following the implementation of a particular initiative. Usually sizable gains build over a number of decades rather than over a number of years. This project set out to identify the road safety research needs and priorities that would enable a quantum step to be taken towards a safe road system.

By adopting the highly ambitious, long-term goal of no deaths or serious injuries occurring within the road-transport system, and drawing upon scientific evidence, and on essential knowledge and insights, a conceptual model was developed. The model, known as the Visionary Research Model, represents how the road-transport system must look and operate if death and serious injury are to be prevented. That is, it starts with the desired end-result and works backwards to define the boundaries of design and operation, for the system to achieve its goal. In defining these boundaries, research opportunities and priorities required for the achievement of the goal are also generated by the application of the model.

With this background, a conceptual model was created as a means of understanding more fully the factors that affect crash and injury risk and, where possible, quantifying the effects on risk of changes in these factors. Constructing a conceptual model that faithfully represents the wide array of crash scenarios that occur in the road-transport system is a complex task. For this reason, the initial development of the model was restricted to the comparatively simple situation of a pedestrian under threat of being struck by an approaching car.

The basic structure of the conceptual model has the pedestrian placed at the centre of five concentric "layers of protection", each layer attempting to protect the pedestrian from a defined form of either injury risk, in the event of a crash, or crash risk.

1. The first layer immediately surrounding the human attempts to minimise injury risk by maximising the biomechanical tolerance of the pedestrian to the kinetic energy of an impacting car during the crash phase. Aside from the intrinsic tolerance of humans, which varies with age, health status, stature and other factors, there are few practical methods known for raising or preserving the level of biomechanical tolerance of the human. New, unexpected possibilities may emerge in the future.

2. The second layer of protection also addresses injury risk. It attempts to manage the transfer to the pedestrian of kinetic energy of an impacting car during the crash phase. The most promising research options for increasing the protection to a pedestrian struck by a car lie with car-front design features, such as optimising styling, geometry and stiffness, and developing energy-absorbing features and devices. Other possibilities include protective clothing and helmets for pedestrians, and, depending on the relative extent to which injuries occur on impact with the car or on impact with the road surface, the development of energy-absorbing road surfaces in pedestrian activity areas.

3. Surrounding the pedestrian at the centre, and the first and second layers, the third layer of protection aims to reduce injury risk by minimising the kinetic energy of the car at impact. Kinetic energy is a function of the square of the speed. Lower

travel speeds, therefore, offer the greatest potential for cutting kinetic energy of cars at impact. A range of possibilities can be identified, many of which will require research for their further development. In-vehicle technology, such as crash warning or avoidance systems to slow more effectively the vehicle before impact, intelligent speed adaptation (ISA), improved sight distances, skid resistant road pavements, traffic-calming measures (e.g., roundabouts, medians, road narrowing, speed platforms), narrower roads/wider footpaths and lower urban speed limits are among the more promising options.

4. Unlike the first three layers of protection, which target *injury* risk, layer 4 seeks to reduce *crash* risk, for a given level of exposure. Many of the same countermeasure opportunities apply to layers 4 and 3, with similar research needs and priorities. Improvements in infrastructure to assist pedestrians with the often-complex gap selection task, in combination with traffic-calming and lower speed limits in pedestrian areas, show considerable promise. Not only can such measures lower crash risk but they can also contribute substantially to lower injury risk, through reductions in the kinetic energy of the car during the crash phase. Education, publicity and other behaviour change initiatives, while helping pedestrians and drivers to cope better with the demands of the traffic environment, do nothing to change the basic levels of risk within the physical/traffic environment.

5. The fifth and outer-most layer of protection also addresses crash risk. It acts to reduce the exposure of pedestrians to crashes, by reducing vehicle volumes, pedestrian volumes, or both. The research areas identified include: the application of disincentives for private-car use; incentives for public transport use; revisions to road functional classifications; the use of traffic design and management, or ITS (in the form of vehicle- or infrastructure-based route guidance systems), to discourage drivers from using pedestrian-sensitive routes; and innovative use of traffic signals and signal co-ordination philosophies. Again, further research effort will be required to assess the potential of these and other options to create safe pedestrian environments.

To ensure that the VRM is comprehensive in its approach to pedestrian safety, it is important to consider systematically the characteristics of each of these layers of protection. Within each of the defined layers, it has proven helpful to define components that represent the principal risk factors, namely, the human, the car, the road and roadside and, finally, the system operation. These components not only encourage a more comprehensive and systematic approach but also help focus attention on countermeasures that directly address the most important sources of risk. However, the most effective countermeasures do not necessarily come from the same category as the main source of the risk. For example, the best countermeasure for poor gap selection by pedestrians is unlikely to involve improving the functional performance of pedestrians in traffic, through education and skills training but, rather, to provide a median or central refuge to simplify the gap selection task, or traffic-calming measures to create a traffic environment that is forgiving of human errors.

One of the potentially valuable features of a fully developed model is the ability to not only predict the direction of changes in crash and injury risk as a result of introducing a particular measure but also to quantify the likely magnitude of any effects. At this early stage of model development, these possibilities have been recognised but considerable further research and development work is needed to operationalise the VRM. Providing a reliable mathematical capability appears feasible with further work. It may even permit synergistic effects to be estimated.

The VRM has been successful in identifying a large number of new areas of research with the potential to improve dramatically the level of safety afforded to pedestrians in the road-transport system. Among the more promising research opportunities on which to concentrate during the immediate future are:

- Better understanding the relationship between car design and pedestrian injury risk, with the longer-term view to stimulating design and purchase of vehicles with high ratings with respect to pedestrian protection in crashes;

- How to cause drivers to afford speed a higher level of respect, and understand more accurately the true relationship between speed and crash and injury risk, especially for pedestrians, leading ultimately to lower travel speeds in pedestrian areas;

- The use of in-vehicle ITS applications such as intelligent speed adaptation (ISA). Other ITS applications that result in reduced driver perception-reaction-time, reduced vehicle “perception-reaction-time” (i.e., leading to more rapid and effective automated application of vehicle braking systems in the event of a pedestrian conflict), or both, should also be investigated;

- Demonstration projects in hazardous pedestrian areas to evaluate the combined effects of lower urban speed limits and infrastructure design that supports lower speed environments, and provides more effective and comprehensive separation of vehicles and pedestrians, while meeting aesthetic and environmental goals for urban settings;

- Investigation and countermeasure development aimed at ensuring pedestrians benefit fully from the intrinsically safer operation of roundabouts. Enhancements to roundabout design and operation for all vulnerable road users are envisaged;

- A meta-analysis of the national and international literature on the effectiveness of lower vehicle speeds in reducing serious pedestrian trauma. This research activity would also aim to identify the most effective means for realising any trauma savings found elsewhere or within Victoria;

- Investigation of ways of improving driver and rider compliance with speed limits through advances in effectiveness of enforcement strategies and technologies;

- Identification and assessment of all options for road-based ITS applications to achieve lower vehicle speeds in pedestrian areas;

- Strengthening Victoria’s overall approach to speed management, drawing upon the meta-analysis referred to above and to the basic laws of physics concerning vehicle braking distances and impact speeds with pedestrians;

- Reviewing and strengthening urban speed-zoning practices;

- Evaluating the effectiveness of full-time 50 km/h speed limits in Victoria's provincial cities and towns, and part-time 40 km/h speed limits in shopping strips of Metropolitan Melbourne;

- Investigation of the potential for the innovative use of traffic signal control and linking strategies along selected routes to both promote traffic use on low risk routes and discourage traffic use on pedestrian-sensitive routes;

- A literature review of congestion pricing schemes and their effects on traffic volumes on roads in congested cities of the world. The potential for applying such a strategy in Melbourne and its potential to reduce pedestrian crash risk would also be assessed;

- Assessment of the potential for innovative, alternative modes of transport in major city centres, to reduce private vehicle use in these high pedestrian activity centres.

It is clear from the systematic assessment of crash and injury risk promoted by the VRM that the travel speeds adopted by drivers and riders, the urban speed limits set by road authorities and the type of infrastructure and traffic engineering philosophies practiced by road authorities (both state and local) exert a major influence on the intrinsic level of safety available to pedestrians using the system. For this reason, research activities that focus on these areas should receive high priority.

In addition, to directing future research effort, the model has also identified countermeasures that could be implemented now. Implementation could proceed on the basis of a "first principles" assessment of countermeasures, with preference being given to countermeasures which:

- Fully separate pedestrians where the required infrastructure is feasible and appropriate for the urban environment in which it would be located;

- Ensure drivers do not travel at speeds exceeding 30 km/h in areas where pedestrians and vehicles continue to mix;

- Provide comprehensive spatial coverage of road lengths where pedestrian crash risk is significant;

- Deliver potential synergies through a compatible combination of speed moderation and improved road infrastructure, the latter aiming to "calm" vehicular traffic and increase the degree of separation between pedestrians and vehicles;

- Enhance the aesthetics of pedestrian environments to promote walking and legitimise its place in the overall transport context.

Finally, it is concluded that the VRM is highly relevant to pedestrian safety in Victoria, Australia and, indeed, other countries, especially developing countries where pedestrian trauma is a major concern. It is expected the emphasis of research and countermeasures would vary according to the conditions in any particular country or jurisdiction.

For these reasons, it is recommended that further development of the VRM take place, particularly with respect to its mathematical capability, and that the VRM also be applied to other categories of serious road trauma. The highest priority categories of serious trauma would include vehicle-to-vehicle collisions at intersections, single-vehicle crashes with roadside hazards and motorcyclist crashes with cars.

1 INTRODUCTION

1.1 BACKGROUND

Road safety in Australia and overseas has made tremendous progress in recent decades, due largely to the use of a systematic, targeted approach, based upon scientifically rigorous methods. In Victoria, reductions in road trauma had stalled until very recently, with little change occurring since the mid-1990s. It is apparent that when innovative or radical programs and initiatives are introduced, marked gains in safety are usually achieved. When more conventional approaches are applied, trends in road deaths and serious injuries level out or, in some instances, rise gradually as traffic growth takes over.

In 2003, the Victorian road toll of 330 deaths had fallen by 18% compared to the previous five-year average of 404 deaths (Australian Transport Safety Bureau, 2004). The major reduction occurred in the Melbourne Metropolitan area, which reported its lowest road toll on record. Specifically, pedestrians, whose death toll fell by 42% on the previous five-year average, motorcyclists by 20% and bicyclists by 40%, enjoyed the greatest benefits (Australian Transport Safety Bureau, 2004). Insufficient time has elapsed for a full and rigorous study of the reasons for these major reductions but at this early stage road safety agencies regard the success to be due to metropolitan wide drops in average vehicle speeds of around 4 km/h. The most vulnerable road users, pedestrians, motorcyclists and cyclists appear to have benefited more than vehicle occupants from these lower speeds.

1.2 PROJECT AIMS AND SCOPE

This project sets out to identify new research opportunities and priorities that will lead to quantum advances in the effectiveness of crash and injury countermeasures. Ultimately, the resulting research activities will lead to countermeasures and to new ways of designing and operating the road-transport system that, in turn, will accelerate dramatically progress in reducing death and injury on Victorian roads. The project involves the development of a conceptual model of the road-transport system. Ideally, such a model will be capable of being applied to all types of road trauma.

1.3 A GENERIC MODEL APPLIED TO PEDESTRIAN SAFETY

The Visionary Research Model (VRM) has been developed in conceptual form for one important type of crash, namely, the scenario of a pedestrian struck, or at risk of being struck, by a car. Under this scenario, the model examines ways of preventing the pedestrian from being killed or seriously injured. However, the VRM is believed to be general in nature and, therefore, able to be adapted to other crash and injury circumstances of interest to road safety researchers and practitioners. Other possibilities were considered when formulating recommendations for possible future development of the VRM.

Experience with use of the VRM on pedestrian safety will be valuable in assessing both its generic applicability and its ability to generate crash and injury countermeasures, as well as identify research opportunities and priorities.

1.3.1 Pedestrian Trauma – the Victorian Perspective

Over the past 20 years in Victoria, there have been two periods in which very substantial reductions have occurred in road trauma involving pedestrians. There is compelling evidence to support the view that these reductions have resulted from the introduction of major initiatives in the generalised enforcement of driver and rider compliance with speed limits across Victoria.

Following the introduction in late 1989 of speed cameras to Victoria (and a concurrent boost in random breath testing for the presence of alcohol in drivers and riders), pedestrian traffic deaths fell from an annual average frequency of 150 during the decade from 1980 to 1989, to an average of 80 fatalities per year for the decade spanning the years 1990 to 1999, inclusive. This represents a 47% reduction in pedestrian fatalities between the decades of the 1980s to the 1990s. Both decades showed fairly stable trends in fatalities, with a marked drop occurring after 1989.

In early 2002, following the introduction of a strengthened approach to enforcing driver and rider compliance with speed limits, through the reduction in the size of the enforcement tolerance value exercised by Police, pedestrian fatalities again fell dramatically. In 2003, there were just 41 pedestrian fatalities, a fall of 46% compared with the ten-year average of 76 for the period immediately preceding the introduction from 1997 to 2001, which immediately preceded the introduction of the reduced speed enforcement tolerance levels in March-April 2002. The number of deaths in 2003 represented an almost halving of the average annual number of deaths during the decade of the 1990s.

By 2003, these 41 pedestrian deaths were more than 70% below the ten-year average from 1980 to 1989. Speed cameras and tighter enforcement tolerances were the only initiatives to have been implemented in Victoria that could reasonably explain both the timing and magnitude of these reductions. These trends in pedestrian trauma were also discussed in Corben and Diamantopoulou (1996).

The observed reductions in average speeds followed announcements by the Victoria Police in March 2002 that the threshold level for enforcement would be reduced for the operation of automated speed enforcement cameras. Soon after this announcement, a marked downward trend in road deaths commenced both in general and in the frequency of vulnerable road user deaths in particular. While much of the evidence for attributing the reduction in some deaths in metropolitan Melbourne (to a new record low level) to this change in speed enforcement practice is circumstantial and not yet the result of rigorous evaluation, it is nevertheless consistent with experience in Victoria around 1990, soon after speed cameras were introduced to Victorian roads.

These trends in Victoria’s pedestrian traffic deaths are shown in Figure 1.1 below.

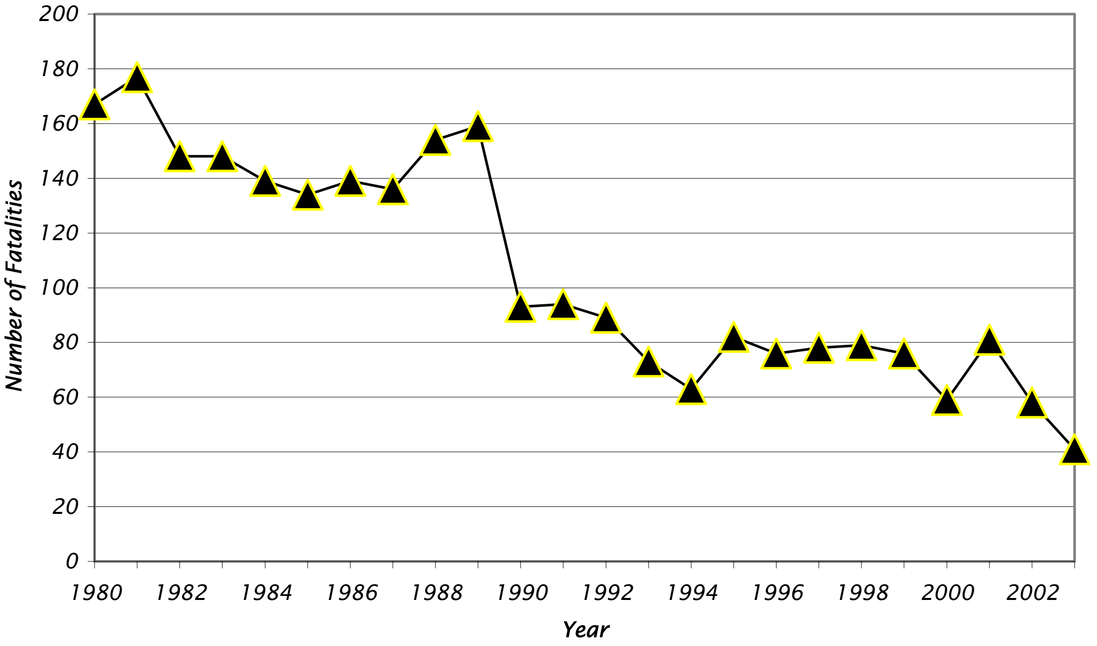


Figure 1.1 Trends in pedestrian fatalities in Victoria from 1980 to 2003, inclusive

1.3.2 Pedestrian Trauma – an International Perspective

On World Health Day 2004, the United Nations Secretary-General Kofi Annan (Annan, 2004) said “despite enormous improvements in road safety in some countries over the past few decades, nearly 1.2 million people are killed every year in road traffic crashes around the world.” In presenting information on the particular plight of some regions of the world and some groups within the traffic system, Annan also said “about 90 percent happen in developing countries, most of them among pedestrians, bicyclists, motorcyclists and passengers of public transport. Between 20 and 50 million more people are seriously injured in such incidents every year, often resulting in disability.”

The high proportions in traffic of these largely unprotected road users (i.e., pedestrians, bicyclists and motorcyclists) explain, in part, their high representation in traffic crashes in developing countries. Campbell (1998) notes that trucks and buses are also more prevalent than in highly motorised countries and that in India and China the major groups of road trauma victims are pedestrians and bicyclists struck by motor vehicles.

Mohan and Tiwari (1998) report data for a number of developing countries, which show that pedestrian deaths make up around one-third to a half of all road deaths in places such as Thailand, India (Delhi), Indonesia (Bandung) and Sri Lanka (Colombo). Vulnerable road users make up some 80 to 90% of all traffic fatalities in these regions.

An important global perspective on the safety of vulnerable road users, past, present and future, was recently published (World Health Organisation, 2004). Among the more telling observations noted in the report are:

- Between 2000 and 2020, the global road toll is predicted to increase by some 65%, with increases of up to 80% expected in the low- to middle-income countries. In these latter countries, most deaths are predicted to occur among vulnerable road users, including pedestrians. By way of contrast, in high-income countries most traffic deaths involve vehicle occupants;

- Comparison of fatality rates reveals that the risk of death in a road crash is far higher for pedestrians, cyclists and motorcyclists, than for car occupants;

- The "shift of paradigms" that has occurred over recent decades with respect to road injury prevention and control has led to "a new understanding". This new understanding is expected to take time to become well established, even in countries known for their commitment to road safety. The new understanding states "common driving errors and common pedestrian behaviour should not lead to death and serious injury – the traffic system should help users to cope with increasingly demanding conditions";

- The global focus on road investment for mobility has meant that the most vulnerable groups – pedestrians and bicyclists – have been overlooked, with a resultant heavy cost to the public health sector. The lack of effective advocacy groups for vulnerable road users has exacerbated this situation;

- Road trauma needs to be viewed as a major public health concern, not as an unavoidable consequence of modern-day demands for high mobility;

- Road trauma problems should be addressed on the basis of scientific evidence to form policies and practices to protect pedestrians, cyclists and vehicle occupants;

- Too rarely countries appear not to recognise the heightened injury risks to pedestrians at collisions speeds of 30 km/h or greater.

It is clear, then, that the development of a model that concentrates research effort on vulnerable road users, pedestrians in particular, has great significance not just for Victoria and Australia, but even more so in the many developing countries of the world, where pedestrian trauma is at acute levels.

1.4 FEATURES OF THE VISIONARY RESEARCH MODEL

A unique aspect of the Visionary Research Model (VRM) is the absolute requirement that the human be protected from kinetic energy or forces that exceed the human tolerance levels. In other words, the project seeks to develop a road safety model that describes how the road-transport system would look and operate if humans were prevented from experiencing mechanical forces that lead to death or serious injury. Thus, the VRM has the potential to enable a *fundamental* reduction to be made in the risk of serious or fatal injuries to pedestrians, rather than continuing to accept the modest, incremental gains that have resulted from traditional approaches to pedestrian safety.

To make such major strides towards a truly safe road-traffic system for pedestrians, it will be necessary, by definition, to stimulate innovation. One of the foremost, anticipated strengths of the VRM is its ability to generate innovative countermeasure options, as well as ideas and priorities for further research into the pedestrian safety problem.

A major challenge in developing the VRM is to identify *practical* ways in which the model can be used to create safe pedestrian environments. The model has a number of general applications to pedestrian safety, as well as some site-specific and category-specific uses, such as to:

- Improve our understanding of the factors that affect pedestrian crash and injury risk, the relative importance of these factors and how they might be moderated, or changed in a fundamental way, to enhance pedestrian safety;
- Assess the effects, both qualitatively and quantitatively, of particular countermeasures and other interventions;
- Understand better the overall effects of applying two or more countermeasures simultaneously, in terms of combined and interactive effects;
- Enable the effects of site-specific improvements to be assessed before they are implemented, thereby raising the cost-effectiveness of treatment programs;
- Enable system-wide interventions to be assessed in terms of their general effects or the specific effects on high-risk categories of pedestrians, such the young, the elderly or the intoxicated;
- Generate research ideas and priorities and to identify countermeasure development possibilities.

These benefits and others can be realised by ensuring that the VRM has an appropriate structure, including valid relationships between elements of the model. The model should also include a mathematical capability, as well as a descriptive capability, to assist with the estimation of changes in crash risk and injury risk, as a consequence of pedestrian safety or other measures that may unintentionally affect safety.

This study is essentially about finding ways to make dramatic safety improvements in the short- to medium-term future. Its main purpose is to identify research opportunities and to define research priorities that will produce the desired quantum shifts in the inherent safety of the road-transport system.

As the main focus of the report is on the safety of pedestrians, some potential countermeasures identified for research, development or implementation tend to be perceived as detrimental to the mobility of drivers and riders. However, in many such cases there is a lack of objective evidence about the real effects of the countermeasures on mobility (and in some instances safety), including the magnitude of the effects. While some effects may be detrimental, they may be of negligible consequence in practice. Further research may be required to address satisfactorily such concerns.

Regardless, this study has sought to identify how to change fundamentally the crash and injury risk for pedestrians in traffic. Decisions about whether to adopt these measures and to what extent the mobility of drivers might be diminished as a result are more properly addressed by the decision-making processes of society and its agencies of government. Accordingly, while noted from time-to-time throughout the report, these issues have not been comprehensively addressed here.

2 THE VISIONARY RESEARCH MODEL IN CONCEPT

Symbolically, the very centre of the VRM is the human, who shall be protected from death or serious injury, either by preventing a crash or by managing the transfer of the kinetic energy of impact with the human. A key feature of the model is the notion of protective layers surrounding the human. These layers describe individual events, phenomena or circumstances in which the potential collision can or does occur.

2.1 INJURY RISK

Consistent with the analogy of protective layers is the notion that thicker layers provide greater protection to the human than do thinner layers. Some layers, generally located in the inner zone of the model, represent attenuators of kinetic energy or ways of minimising the levels of kinetic energy at impact, such that the thicker the layer, the greater the energy attenuation properties, or the lower the kinetic energy at impact and, hence, the lower risk of injury from the particular threats symbolised within the model.

2.2 CRASH RISK

Other layers can be represented as estimates of the probability of specific events occurring. As with the energy attenuation or reduction (i.e., injury risk) concept, thicker layers are associated with greater protection (i.e., a higher probability of preventing an event that would otherwise lead ultimately to death or serious injury).

In summary, the inner group of layers comprise physical attenuators or reducers of kinetic energy, affecting injury risk, and the outer group of layers comprise probability functions defining events preceding or precipitating a crash, that is, reducing crash risk. Thicker layers provide greater protection through greater energy attenuation (or reduction) or through a higher probability of preventing the occurrence of an injury-producing event. How these quantitative indicators might be combined mathematically to predict the risk of death or serious injury will be discussed later (refer Section 4).

2.3 SPECIFIC THREATS TO THE HUMAN

To be able to define the various layers of protection required to ensure that a human avoids death or serious injury in a traffic crash, it is important to first define the specific physical elements posing a threat. Given the decision in this study to develop, at least initially, the VRM in the context of the pedestrian/car conflict, general discussion follows on threats to the human, specifically for the pedestrian in a potential conflict with an approaching car.

It is helpful to consider these threats in the broad framework developed by Haddon (1972) namely:

- Pre-crash phase;
- Crash phase;
- Post-crash phase.

It is most appropriate to start by examining the crash phase, that is, thinking first about the human at the centre of the model and how, during the crash phase when energy exchange occurs between vehicle and pedestrian, the pedestrian's life and long-term health will be preserved. Thus, the model starts by defining the acceptable outcome of a pedestrian/car conflict, and then operates in reverse to specify crash and pre-crash conditions that will produce an acceptable outcome.

This section defines and discusses the vehicle and road characteristics that contribute to the risk of death or serious injury to a struck pedestrian, *during* the crash phase.

The main factors contributing to injury risk during the crash phase are:

Human

- Intrinsic tolerance to mechanical forces
- Orientation of pedestrian to vehicle at impact

Car

- Speed at impact
- Mass
- Stiffness
- Shape and geometry

Road and Roadside

- Pavement surface – stiffness and texture
- Roadside objects – size, shape and stiffness
- Orientation of pedestrian to road or roadside object at impact.

Car speed and mass determine the amount of kinetic energy to be absorbed by the pedestrian, car and, to some extent, the road infrastructure. Car stiffness determines, in part, the share of kinetic energy to be absorbed between the pedestrian, vehicle and environment, particularly with respect to the concentration of forces on the human. The impact heights and contact points on the pedestrian are a direct function of shape and geometry of vehicle body design, and of the age and stature of the pedestrian. The use of smooth flat surfaces by car designers spread impact forces more favourably than distinct, rigid edges or other body features. Pedestrian orientation to the car also determines impact points on the pedestrian and, hence, injury risk as a function of the differential vulnerability of various body parts of the human and their different physical abilities to share in the energy exchange.

It is common in pedestrian crashes for the pedestrian to be catapulted into the air before striking the ground (or other objects within the roadway or roadsides) (European Transport Safety Council, 1993; McLean, 1996). In other instances, the pedestrian is run-over by the car as a consequence of the impact.

Risk factors are now discussed in greater detail.

2.3.1 The Human

Assuming little of practical use can be done, at least in the short-term, to increase the intrinsic vulnerability of humans to mechanical forces, one can consider the possibilities offered by protective clothing or equipment for the pedestrian. Items such as helmets or padded suits/garments theoretically have the potential to reduce injury risk through more effective energy exchange. However, other than in some special cases, such countermeasures are unlikely to be readily accepted by our society in the foreseeable future.

2.3.2 Vehicle Stiffness

Next, we can consider issues of vehicle body stiffness as a means of more successfully sharing the kinetic energy exchange during the crash phase. Vehicles with stiff design features impart higher accelerations to the pedestrian at impact and therefore cause more severe injuries to the pedestrian (Crandall, Bhalla & Madeley, 2002). Reduced body stiffness (i.e., softer structures) enables the levels of acceleration on a human to be reduced by allowing forces to act over a longer time period. Extending the duration of the crash pulse can have a marked beneficial effect on injury risk (Rechnitzer, 2000).

2.3.3 Car Geometry

The geometric design of cars is known to influence injury risk in an impact with a pedestrian (McLean, 1996). Car design features such as bumper height, the presence or absence of bull bars, the height and shape of bonnets, grilles and headlights, the area and slope of bonnets and other car body components can each play a significant part in determining injury outcomes for a struck pedestrian (Crandall et al., 2002; McLean, 1996; Terrel, 1997; Yang, 2002).

Important interactive effects exist between car geometry and car body stiffness. For example, some car styling, especially older models, tend to have stiff, defined leading edges on bonnets (Yang, 2002), while newer styling on passenger cars tends to favour smoother, sloping bonnets which reduce the risk of impact forces being highly concentrated at or along certain styling features. The Honda Civic has made considerable advances in pedestrian protection through car design improvements, at minimal additional cost to the purchaser (Breen, 2002). Also, it is known from in-depth studies of pedestrian crashes that injuries are made more severe when only limited deformation of car body panels is possible before contact is made with rigid car components, such as the engine, located immediately beneath the bonnet (Crandall et al., 2002).

2.3.4 Pedestrian Orientation

When a car collides with a pedestrian the relative orientation of the pedestrian's body to the car has the potential to affect injury outcomes. It is common in pedestrian crashes for pedestrians to suffer severe leg, thorax and head injuries resulting from actual contact with car body parts, such as bumpers, bonnet edges, windscreens, roof pillars (A-pillars), scuttle and even windscreen wiper spindles sitting above the surrounding surfaces of the car (European Transport Safety Council, 1993; Jarret & Saul, 1998). Clearly, the relative orientation of the pedestrian and car at impact will affect the direction of impact forces on the pedestrian and, hence, the ability of knee and hip joints to absorb energy without serious injury. Orientation at impact may also affect injury outcomes, such as face and head injuries, depending on whether impacts, usually with the bonnet or windscreen, occur to the front, side or back of the pedestrian's head.

The vehicle design factors broadly described above may exert their effects differently for pedestrians of varying age, stature, health condition, etc. Also, it is common in pedestrian collisions for the pedestrian to be thrown into the air after impact (European Transport Safety Council, 1993; McLean, 1996). Thus, road infrastructure may also affect injury outcomes when a pedestrian lands on the road or within the roadside environment. This aspect of injury risk is also discussed in more detail later.

2.3.5 Car Mass and Speed

When two objects collide, the physical law of conservation of momentum applies. The momentum of an object is defined as the product of mass and velocity, i.e., momentum of car = $m_c v_c$ and the momentum of a pedestrian is $m_p v_p$. In a collision between a car and a pedestrian:

$$m_{ci} v_{ci} + m_{pi} v_{pi} = m_{cf} v_{cf} + m_{pf} v_{pf},$$

where:

- m_{ci} is the mass of the car before impact
- v_{ci} is the velocity of the car before impact,
- m_{pi} is the mass of the pedestrian before impact,
- v_{pi} is the velocity of the pedestrian before impact, and
- $m_{cf,}$ $v_{cf,}$ m_{pf} and v_{pf}, are the corresponding masses and velocities of the car and pedestrian after impact.

Thus, by re-arranging the above equation:

$$m_{pi} v_{pi} - m_{pf} v_{pf} = m_{cf} v_{cf} - m_{ci} v_{ci}$$

$$\rightarrow m_p \Delta v_p = m_c \Delta v_c$$

The mass of a pedestrian is typically more than an order of magnitude less than the mass of a vehicle. For example, the mass of an adult might commonly fall between, say, 60-90 kg while the mass of a passenger car might range from, say, 800 kg for a small car and up to around 1,500 kg for a large car. For the purpose of illustrating the significance of the conservation of momentum law, consider the case of a human of 80 kg being struck by a vehicle of 1200 kg. Thus,

$$80 \text{ x } \Delta v_p = 1200 \Delta v_c$$

$$\rightarrow \frac{\Delta v_p}{\Delta v_c} = 15$$

In this simple example, it is evident that the change in velocity experienced by the pedestrian is some 15 times greater than the change in velocity of the car striking the pedestrian. The change in velocity experienced by the occupants of the striking car is further reduced according to the crashworthiness of the vehicle, however, in the absence of protective clothing, and a vehicle body with the ability to deform at impact, the pedestrian experiences virtually the full value of the fifteen-fold change in velocity.

Acceleration (or variables derived from acceleration) is the physical variable commonly used in road safety to indicate the risk of injury to humans involved in collisions. That is, if the acceleration imparted to a pedestrian in a collision approaches or, indeed, exceeds a human's tolerance level, then death or serious injury to the pedestrian are highly probable. In the context of the VRM, such an outcome is unacceptable.

Acceleration is defined as the rate of change in velocity with time and is, therefore, directly related to the value Δv_p, described above. The average acceleration imparted to the pedestrian during a given time interval, Δt, is

$$\bar{a} = \frac{\Delta v_p}{\Delta t}$$

Given that the value of ΔV in a crash between a human and a car is typically many times higher for the pedestrian than for the car (e.g., 15 times in the case of an 80 kg human and a 1,200 kg passenger car), it is vital to explore ways in which the acceleration can be maintained below human tolerance levels.

Theoretically, two main options exist. The first is to achieve a more equal "contest" between cars and pedestrians in terms of mass. However, it is impractical to achieve this, other than through smaller vehicles. Furthermore, smaller vehicles tend to reduce protection to their occupants, unless vehicle masses for the entire population of vehicles fall in a similar way.

Thus, it becomes apparent that to prevent acceleration values exceeding life-threatening levels, only the duration over which the velocity changes occur, can be systematically manipulated. That is, if the values of Δt can be increased, then the average acceleration imparted to the pedestrian can be decreased, resulting in potentially tolerable acceleration levels.

2.3.6 Road and Roadside Features

As noted above, it is common for a pedestrian who has been struck by a car to also experience a significant secondary impact when landing on the road surface or, depending on the trajectory of the struck pedestrian, when striking one or more of a potentially large number of objects positioned within or beside the roadway (e.g., trees or poles, parked vehicles, traffic signs, etc). If such objects are narrow, rigid or in some other way hazardous to the pedestrian, it is probable that more severe injuries would be sustained than would have resulted from the initial impact with the car. The orientation of the pedestrian in such impacts clearly has the potential to affect injury risk.

On the basis of these injury risk factors of cars, roads and roadsides, individual layers of protection, which moderate these injury risk factors, are needed.

3 LAYERS OF PROTECTION

Having defined, at least in descriptive terms, the threats posed to pedestrians in a potential collision with a passenger car, it is appropriate to define and describe the conceptual layers of protection that must form part of the VRM, if death or serious injury to the pedestrian is to be prevented.

The following sections identify the protective layers needed to address the threats defined above. These layers are described initially in conceptual terms, starting at the centre of the model, working outwards from the main layers of protection aimed at energy reduction or attenuation at impact, towards the main layers of protection aimed at eliminating or, at least reducing, crash risk. Through this sequence of examination, the model establishes how the road-transport system should look and operate to keep the pedestrian safe, and then progressively considers what is required to achieve this.

In later sections, the conceptual description of the layers of protection will be extended and, where possible, important parameters defining each layer will be quantified.

3.1 CONCEPTUAL OVERVIEW

The VRM consists of five main layers of protection for the human. The aim of these layers is to provide:

1. Increased biomechanical tolerance of the human to violent forces (or kinetic energy);
2. Attenuation of the transfer of kinetic energy to the human;
3. Reduced level of kinetic energy to be managed in a crash;
4. Reduced risk of a crash for a given level of exposure;
5. Reduced exposure to crash risk.

Within each main layer are more specific types of protection that could potentially be used to ensure that the human is neither killed nor seriously injured as a pedestrian. These more specific types of protection can generally be categorised according to one of the following factors that contribute to crash risk, injury risk or both;

- Human risk factors;
- Vehicle design risk factors;
- Road infrastructure (including roadsides) risk factors;
- System operation risk factors.

It is somewhat conventional to focus on human, vehicle and road infrastructure factors in assessing crash and injury risk. However, it is less common to focus explicitly on system operation risk factors, which tend to be addressed as part of the human, vehicle or infrastructure factors, or otherwise under-rated. In the context of the VRM, system operation risk factors are defined here as those factors that characterise the policies, practices and decisions that serve as determinants of how the system operates with respect to safety. System operation factors include formal policies, practices and decisions on, for example, the setting and enforcement of speed limits, the design, location, timing and operational strategies of traffic signals, policies which determine the use of traffic-calming measures on high volume roads, and the relative priority afforded to various road user categories such as pedestrians, public transport users and cyclists.

3.1.1 Groupings of Layers

The five main layers fall into one of two broad groupings. The first grouping focuses on injury risk reduction and consists of layers 1, 2 and 3, namely increased human biomechanical tolerance, attenuation of kinetic energy transfer and reduction in kinetic energy at impact.

The second grouping focuses on crash risk and comprises layers 4 and 5, namely reduced crash risk for a given exposure and reduced exposure.

3.1.2 Quantifying Crash and Injury Risk

The model has been developed to enable changes in crash or injury risk to be quantified so that it becomes possible to determine objectively whether safety is improved by a particular measure and, if so, to what extent. The model also provides insights into the mechanism by which risk is reduced. To facilitate the use of the model in this way, the most appropriate measure must be chosen for estimating changes in crash or injury risk. For injury risk, the amount of kinetic energy at the moment of impact was adopted as the single most useful indicator, while for crash risk, the probability of a crash at the system-wide level and the individual-pedestrian level was adopted.

Ideally, the VRM would be developed so that a variety of countermeasure scenarios could be evaluated in advance of their possible implementation. This would require the model to have a mathematical capability that can apply the findings of past research to estimate the potential effects of countermeasures (or other interventions) on the probability of a pedestrian being fatally or otherwise seriously injured in a potential collision with a car. Past research may be empirically-based taking the form, for example, of quasi-experimental, before-after evaluations of implemented measures (singly or in combination), or theoretically-based studies drawing on physical laws of motion, including energy exchange. Put another way, the VRM seeks to apply, in a practical and insightful way, the best knowledge and scientific evidence available from empirical and theoretical research to quantify crash and injury risk for pedestrians in conflict with a car. Thus, the model would have an interactive, mathematically-sound basis for assessment of potential countermeasures and interventions to prevent death or serious injury to pedestrians.

It is recognised that much of the research knowledge on injury risk to pedestrians is expressed using a variety of physical measures, such as linear acceleration, Head Injury Criterion (HIC), rotational acceleration or force, bending moment or bending angle, or shear displacement of, for example, the knee joint. The success of the VRM depends to a large extent on its simplicity, including its ability to utilise the least number of physical or probability measures. Hence, it was decided that for the injury risk component of the model, *kinetic energy* would be the best single measure to be used uniformly within the three main layers protecting the pedestrian during the crash phase. An important challenge in the future development of the model is the conversion of research findings from/to measures of changes in kinetic energy. The practicability and accuracy of such transformations is an important issue in any further work that may follow from this study.

Over time, and with practical experience in using and developing the model, it may be possible for refinements to be introduced through the use of more specific variables describing injury risk, such as rotational acceleration, bending moment and bending force.

Similarly, for the layers describing crash risk, the probability of threatening events was chosen as the most appropriate single measure for estimating the effectiveness of a particular initiative. This is somewhat convenient as much of the research in this area deals with probability functions.

The model should also enable both probability and kinetic energy measures to be combined, either additively or multiplicatively, depending on their physical relationships.

3.1.3 Diagrammatic Representation of the Model

A diagrammatic representation of the model is shown in Figure 3.1. Layers 1, 2 and 3 address, in the main, injury risk and so aim to provide protection during the *crash phase*, while layers 4 and 5 target reductions in crash risk and therefore aim to afford protection during the *pre-crash phase*.

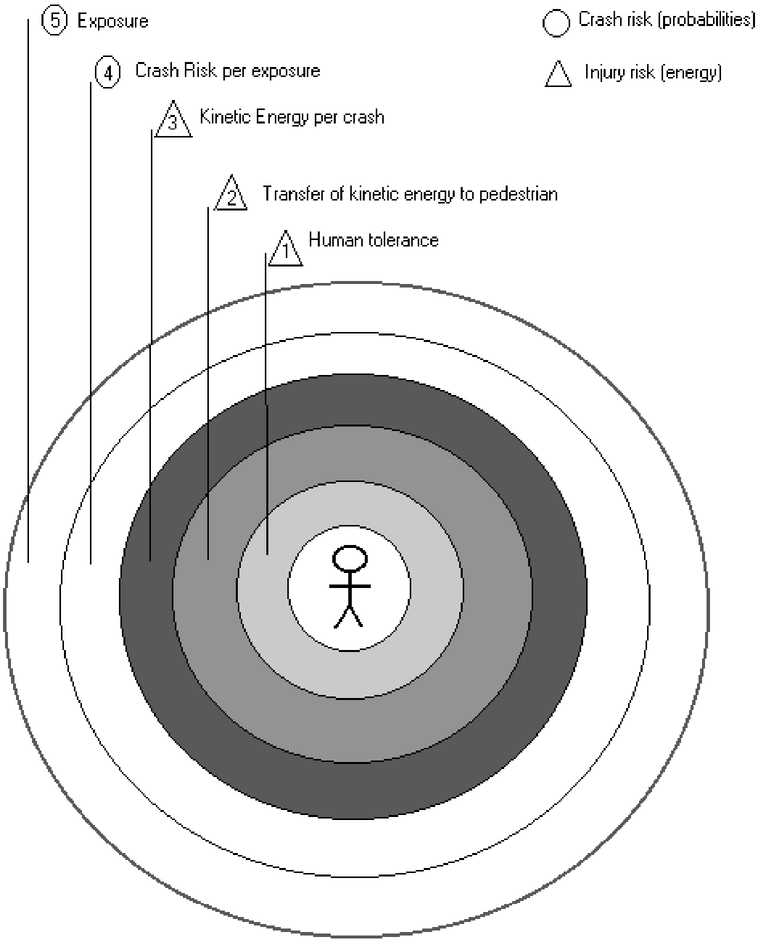


Figure 3.1 The five layers of protection

3.1.4 Kinetic Energy and the Protective Layers

To extend the concept of the VRM, particularly its protective layers, consider the circumstances of the human, as a pedestrian, exposed to kinetic energy. As noted earlier, the kinetic energy takes the form of a car of mass m kg travelling towards the pedestrian at speed v m/sec. The kinetic energy is defined as ½ mv^2 kJ.

Under this generic scenario, the car's kinetic energy presents a threat to the life or long-term health of the pedestrian. Conceptually, the structure of the model is such that a proportion of the kinetic energy is deflected from its trajectory towards the pedestrian, by the protective nature of the two outer-most layers of the model, namely layers 5 and 4.

Figure 3.2 depicts the circumstance of the pedestrian threatened by the kinetic energy of an approaching vehicle and the layers of protection that must ensure that the kinetic energy reaching the pedestrian is below the level that leads to death or serious injury to the pedestrian. Both of these layers can reduce the risk of a crash, by reducing exposure to crash occurrence (layer 5), by reducing the intrinsic risk of a crash for any given level of exposure (layer 4), or both.

The proportion of kinetic energy deflected away from a path that could otherwise harm the pedestrian depends on the overall effectiveness of the countermeasures within layers 4 and 5. More effective countermeasures result in thicker layers and, therefore, greater protection through the harmless redirection of a greater proportion of the kinetic energy away from the pedestrian.

A residual amount of kinetic energy continues to pose a threat to the pedestrian. This residual kinetic energy represents the energy that must be successfully managed in pedestrian crashes that actually occur. Layers 3, 2 and 1 become the only means by which injury severity can be kept below death or serious injury. These three inner-most layers offer protection to the struck pedestrian by minimising kinetic energy at impact, attenuating the transfer of kinetic energy from the car to the pedestrian and by raising or restoring the biomechanical tolerance of the humans to kinetic energy or mechanical forces.

Thus, the notion of using kinetic energy of vehicles in traffic as representing a threat to the lives and long-term health is both meaningful in a physical sense and helpful in conceptualising the protective layers surrounding the pedestrian within the model.

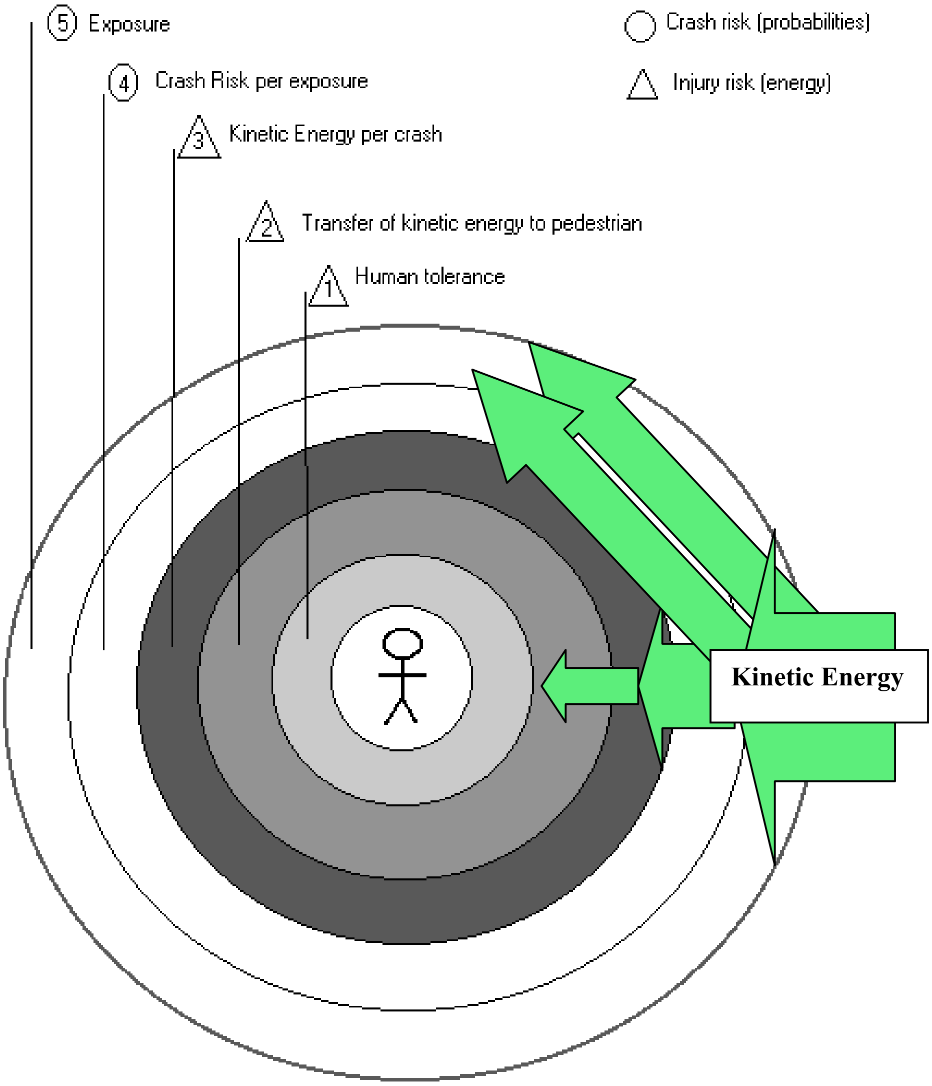


Figure 3.2 Kinetic energy and the five layers of protection

3.2 LAYERS OF PROTECTION IN DETAIL

The previous section presented a conceptual overview of the five main layers of protection comprising the model. These layers are now described in greater detail, where of practical value, highlighting crash or injury risk factors that relate to the human, the vehicle, the road or to system operation.

The following table shows, in overview form, which crash and/or injury risk factors have practical relevance for each of the five main layers of protection defined in the model. A version of this table appears in each section describing one of the five main layers of protection, with the relevant layer distinguished from others for clarity of discussion.

Table 3.1 Relevance of the Five Main Layers of Protection

Protective Layer	Crash and/or Injury Risk Factors			
	Human	Car	Road Infrastructure	System Operation
1. Increased biomechanical tolerance	✓	N/a	N/a	N/a
2. Attenuation of kinetic energy transfer	✓	✓	✓	N/a
3. Reduced level of kinetic energy	✓	✓	✓	✓
4. Reduced crash risk for given exposure	✓	✓	✓	✓
5. Reduced exposure to crash risk	✓	✓	✓	✓

N/a signifies not applicable

3.2.1 Layer 1 - Increased Biomechanical Tolerance of the Human to Violent Forces

Only the human crash/injury risk factor has a meaningful place in the first of the main layers of protection (refer Figure 3.1 and Table 3.2). Its potential role in increasing the biomechanical tolerance of humans to violent forces is discussed below.

Table 3.2 Risk Factors Applicable to Layer 1

Protective Layer	Crash and/or Injury Risk Factors			
	Human	Car	Road Infrastructure	System Operation
1. Increased biomechanical tolerance	✓	N/a	N/a	N/a
2. Attenuation of kinetic energy transfer	✓	✓	✓	N/a
3. Reduced level of kinetic energy	✓	✓	✓	✓
4. Reduced crash risk for given exposure	✓	✓	✓	✓
5. Reduced exposure to crash risk	✓	✓	✓	✓

The first and most fundamental layer of protection is defined as the human's intrinsic ability to withstand mechanical forces and, hence, acceleration, rotation, bending, shearing, etc, of the body or its individual parts. To describe this human characteristic adequately, we need to consider separately individual parts of the human body, such as the head, thorax, pelvis, legs and arms. Each has a different type of vulnerability to energy transfer/force and directions, as well as different levels of tolerance (Yang, 2002). This protective layer endeavours to raise by natural means, or possibly even artificially, the intrinsic ability of the human to withstand mechanical forces.

The biomechanical tolerance levels of humans to mechanical forces are summarised in Table 3.3. Limiting values for various body parts and physical measures of injury risk are shown, together with a number of references from recently published literature.

Table 3.3 Biomechanical Tolerance Levels of Humans in Pedestrian Crashes

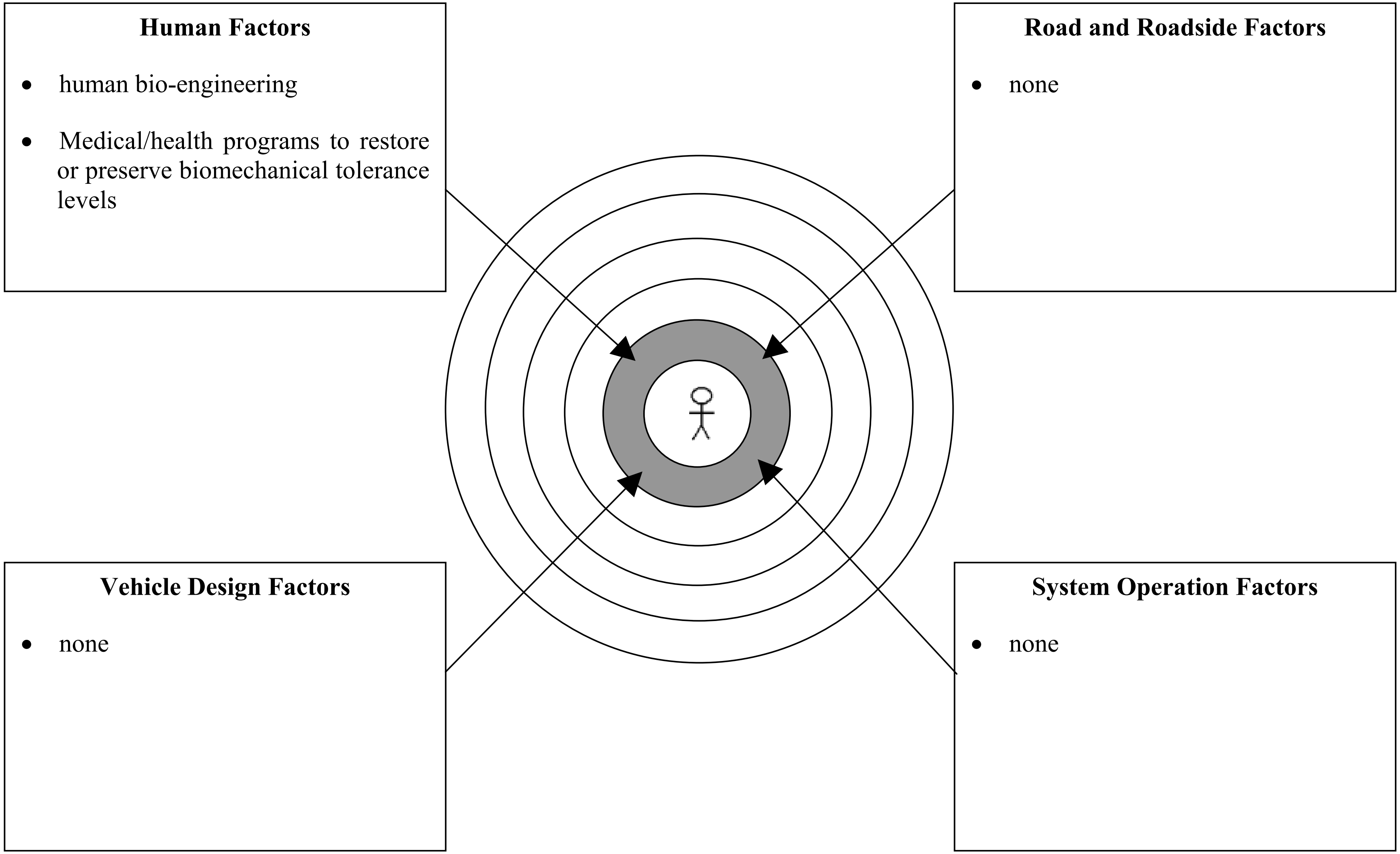
Part of Body	Measure	Tolerance	Reference
Head	Head Injury Criterion (HIC) - Integral of the acceleration (in g's) of the head over 36ms	1000 HIC (or 123 g)	Voigt, Hodgson & Thomas, 1973; Stalnaker, Melvin, Nusholtz, Alem & Benson, 1977; Allsop, Perl & Warner, 1991; Viano, 1997; Yang, 1997.
Thorax/chest	Thoracic Trauma Index (TTI) - based on accelerations of the lower thoracic spine, taking into account weight	85 g (adult) 60 g (child)	Bierman & Larson, 1946; Nahum, Gadd, Schneider & Kroell, 1971; Cavannaugh, 1993; National Highway Transportation Safety Administration, 1993; Yang, 1997.
Pelvis	Acceleration	50g-90g	Tarriere, Walfisch, Fayon, Rosey, Got, Patel & Delmus, 1979; EEVC, 1984; Yang, 1997.
Upper legform	Force	3-10kN	Kress, Snider, Porta, Fuller, Wasserman & Tucker, 1993; McLean, 1996, Yang, 1997, Yang, 2002.
	Bending Moment	320Nm	
Knee	Force	3 kN	Kajzer, Cavellero, Ghanouchi, Bonnoit & Ghorbel, 1990; Kajzer, Cavellero, Bonnoit, Morjane & Ghanouchi, 1993; Ramet, Bouquet, Bermond, Caire & Bouallegue, 1995; Yang, 1997.
	Bending Moment	350Nm	
	Angular deflection	15 deg	
Legform	Force	4 kN	McLean, 1996.
	Acceleration	150g (tibia)	

Given our present understanding and capability in human engineering, and recognising the major uncertainty about its social acceptability, this layer appears to offer little value in terms of immediate, practical opportunities, but is noted within the model both for theoretical completeness and for the potential that may be realised in the long-term future, however unlikely this may appear now. In fact, by its very inclusion in the model structure, it is possible to highlight one of the strengths of the model – namely, its potential to generate new and innovative ways of seeing pedestrian crash and injury problems, and their solutions.

In recent times, increasing recognition has been given to the heightened vulnerability to injury of some categories of pedestrians. Perhaps the most obvious example concerns older pedestrians (e.g., around 65 years of age or older) who, because of their greater physical frailty, have a higher risk of serious injury than do younger adults involved in an otherwise identical crash (Mitchell, 2000). As humans age, their bones become naturally less dense and thus more fragile, resulting in higher risk of fracture. Osteoporosis is a common example of a condition characterised by low bone density in older people. Bone loss increases with age, with more serious outcomes expected from falls or other events that would normally cause only minor injury to younger people (Oxley, Corben, Fildes, O'Hare & Rothengatter, 2004). This physical characteristic results in higher morbidity and mortality from injury, as well as increased recovery time and lower functional status following recovery (Oxley et al., 2004). Other similar concerns arise for people with poor health, even though age, of itself, may not contribute to heightened injury risk (Binder, Schechtman, Ehsani, Steger-May, Brown, Sinacore, Yarasheki & Holloszy, 2002).

Physical stature of the pedestrian also has the potential to affect injury outcomes (Breen, 2002). For example, the height of a struck pedestrian determines, as least in part, the point of impact on the body of the more rigid and, hence, threatening design features of the front of a vehicle. Thus, young children and people in wheelchairs are at greater risk of contact to the head or chest and consequently experience more serious injury outcomes in the event of a collision.

Though pedestrian age is often used as an indicator of the severity of injuries that might result from a pedestrian crash, it serves more as a surrogate for age-related health status. Thus, injury amelioration initiatives that focus on improving or restoring the general health of road users, but in particular those aspects of health that directly affect frailty, have the potential to increase the biomechanical tolerance of humans to kinetic energy at impact in a pedestrian crash. The extent to which this might reduce injury risk is presently unclear.



Human Factors

- human bio-engineering
- Medical/health programs to restore or preserve biomechanical tolerance levels

Road and Roadside Factors

- none

Vehicle Design Factors

- none

System Operation Factors

- none

Figure 3.3 Layer 1: Increased biomechanical tolerance of the human to violent forces

3.2.2 Layer 2 Attenuation of the Transfer of Kinetic Energy to the Human

The second layer of protection addresses several means by which the amount of kinetic energy reaching the human is reduced to such an extent as to prevent or at least reduce the severity of serious injury to the struck pedestrian (see Figure 3.1 and Table 3.4).

Table 3.4 Risk Factors Applicable to Layer 2 – Attenuation of Kinetic Energy Transfer

Protective Layer	**Crash and/or Injury Risk Factors**			
	Human	**Car**	**Road Infrastructure**	**System Operation**
1. Increased biomechanical tolerance	✓	**N/a**	**N/a**	**N/a**
2. Attenuation of kinetic energy transfer	✓	✓	✓	**N/a**
3. Reduced level of kinetic energy	✓	✓	✓	✓
4. Reduced crash risk for given exposure	✓	✓	✓	✓
5. Reduced exposure to crash risk	✓	✓	✓	✓

For this layer, it is relevant to look at human factors, car factors, and road and roadside factors. However, examining system operation factors is unlikely to be relevant.

3.2.2.1 Human Injury Risk Factors

Considering firstly the opportunities to protect the pedestrian through countermeasures based on the biomechanical tolerance of the human, items worn by or fitted to the pedestrian, such as helmets or padded suits/garments, and leg protectors, at least theoretically, have the potential to reduce injury risk through more effective energy exchange.

3.2.2.2 Car Design Risk Factors

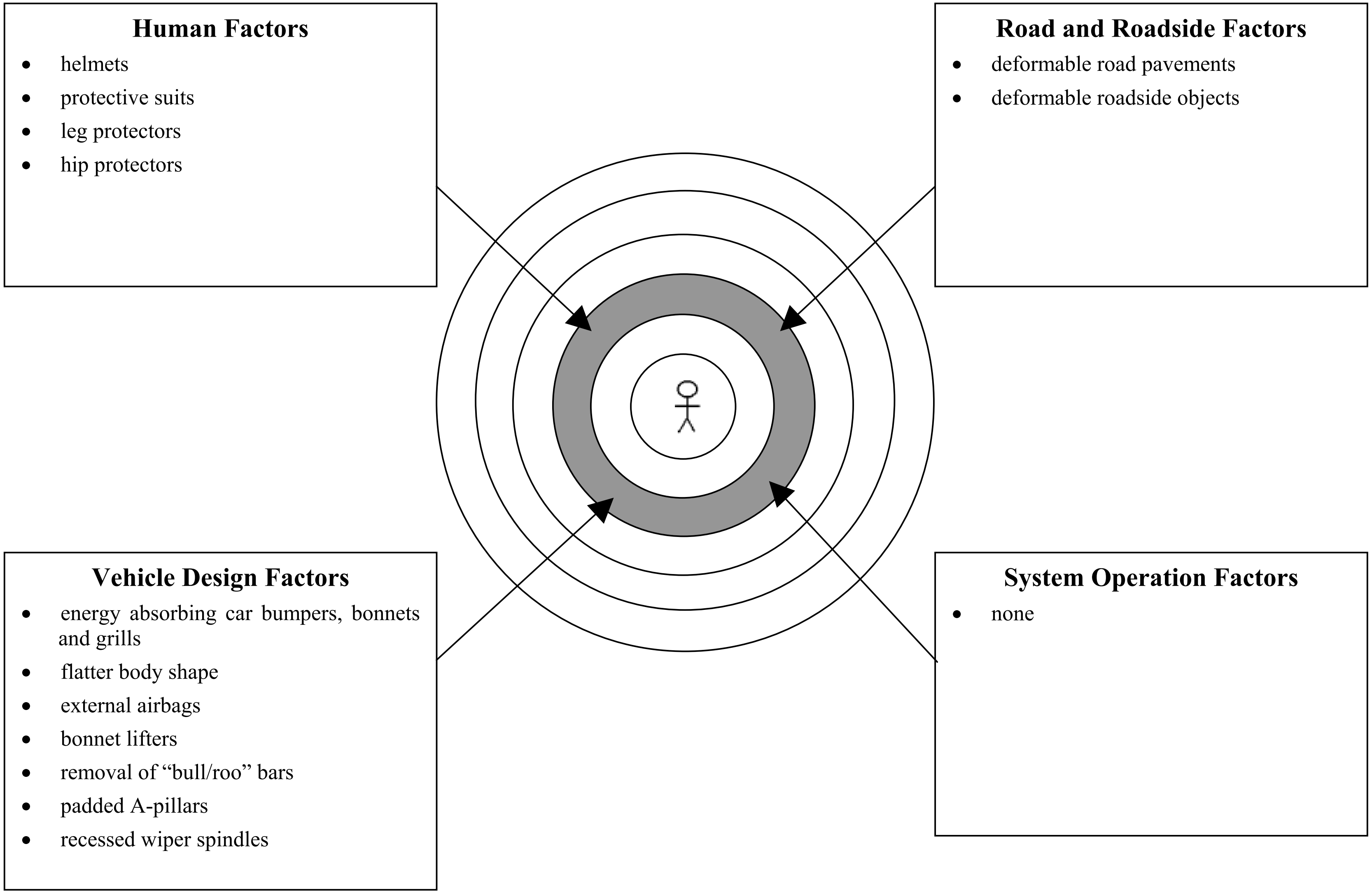
Secondly, the protection offered by attenuating the kinetic energy of the impacting car, focuses primarily on the car's design features (European Enhanced Vehicle-Safety Committee, 1998; McLean, 1996). In an impact between a pedestrian and a car, the risk of serious injury will be affected by physical parameters defining the car, namely its bumper and bonnet. Specifically, car body stiffness, especially of the bumper, the bonnet and its leading edge, the geometry of the car design, particularly the height of the bumper relative to pedestrian stature, and the shape of the car body, are important determinants of pedestrian injury risk (Yang, 2002). The ability of the car to deform and thereby absorb much of the energy of impact reduces pedestrian injury risk.

3.2.2.3 Road and Roadside Design Risk Factors

As noted earlier, pedestrians hit by a car may experience additional injuries during secondary impacts when falling to the road surface. Also, if the pedestrian is thrown clear of the striking vehicle, colliding with a roadside object such as a tree or a pole, the severity of injuries may be increased. The second layer of protection aims to identify countermeasure opportunities, such as the provision of an unconventional type of road surface (or roadside structures) that deforms when the pedestrian lands, thereby reducing injury risk. Rubberised surfaces, such as those used in children’s playgrounds, are examples of material that could attenuate kinetic energy reaching the pedestrian, as well as being designed to improve other aspects of pedestrian safety. Surface colour and texture are two of the options that could be used to enhance pedestrian conspicuity for drivers and, perhaps, to improve car braking performance. These possibilities will be discussed later, under the relevant layer of protection, which deals specifically with reducing crash risk.

3.2.2.4 System Operation Risk Factors

Few, if any, opportunities have been identified within Layer 2 from an examination of system operation factors.



Human Factors

- helmets
- protective suits
- leg protectors
- hip protectors

Road and Roadside Factors

- deformable road pavements
- deformable roadside objects

Vehicle Design Factors

- energy absorbing car bumpers, bonnets and grills
- flatter body shape
- external airbags
- bonnet lifters
- removal of "bull/roo" bars
- padded A-pillars
- recessed wiper spindles

System Operation Factors

- none

Figure 3.4 Layer 2: Attenuation of the transfer of kinetic energy to the human

3.2.3 Layer 3 Reduced Level of Kinetic Energy to be Managed in a Crash

The third layer of protection incorporates ways by which the amount of kinetic energy of the car at impact can be restricted sufficiently to prevent serious injury to the struck pedestrian. If the pedestrian can gain some of the safety benefits available from Protective Layer 2, a higher level of kinetic energy at impact may be permissible.

Kinetic energy (KE) is defined as $\frac{1}{2} m_c v_c^2$, where m_c= mass of car and v_c = velocity of car. Given this mathematical (and physical) relationship, specifically the 2nd power relationship between kinetic energy and speed, the more effective means of reducing kinetic energy to an acceptable level is to reduce impact speed. However, car mass is also a potentially important determinant of kinetic energy and, therefore, should also be managed to reduce the car's kinetic energy at impact.

In the context of the VRM, higher impact speed (and mass) results in thinner layers of protection, while thicker layers are associated with lower impact speed (and mass), i.e., less kinetic energy impinges upon the human, leading to a lower probability of exceeding human tolerance to forces.

As noted above, there exists a second-power relationship between speed and kinetic energy, whereby, for example, halving the car's speed reduces its kinetic energy to one-quarter of its original level. Given this powerful relationship, it is important to examine further the role of speed in pedestrian injury risk.

In a collision between a pedestrian and a car it is well known that the vehicle speed at impact plays a crucial role in the severity of injuries sustained by the pedestrian. Figure 3.5 shows a well-established relationship between the impact speed in a car/pedestrian crash and the probability of the pedestrian dying as a result of that impact. It is clear from this relationship that pedestrian risk of death is very sensitive to impact speed in the range of about 30 to 50 km/h (Anderson, McLean, Farmer, Lee & Brooks, 1997; Ashton & Mackay, 1979). At impact speeds of about 30 km/h, the risk of death to a pedestrian is around 10%. This risk climbs rapidly to around 25% at 40 km/h, 85% at 50 km/h and, by 55 km/h, the risk of death has reached 100%. Comparing these risk-of-death/speed data for pedestrians, with Victoria's general urban speed limits along roads where the vast majority of pedestrian trauma occurs reveals that a substantial shedding of vehicle speed is required before impact, if serious trauma is to be prevented.

A similar relationship has been developed for serious casualties sustained by pedestrians. This relationship is shown in Figure 3.6 together with three separate relationships between impact speed and the risk of death to a pedestrian identified in the literature. Figure 3.6 shows that pedestrians have a substantial probability of sustaining serious injuries at speeds of around 25 to 30 km/h (Anderson et al., 1997; Ashton & Mackay, 1979; Pasanen & Salmivaara, 1993). Such speeds are substantially above Victoria's normal urban travel speeds that range from 40 km/h part-time speed limits in strip shopping centres and around schools, 50 km/h on local roads and in some town centres in regional Victoria, 60 km/h on most undivided arterials, to 70 or 80 km/h on most multi-lane, divided arterials. Once again, to avoid serious injury in a pedestrian crash, drivers must be able to shed a substantial amount of their travel speed prior to impact. Alternatively, an even greater loss of speed is required to avoid a collision altogether. In many common pedestrian crash scenarios, drivers do not receive enough warning to brake prior to impact.

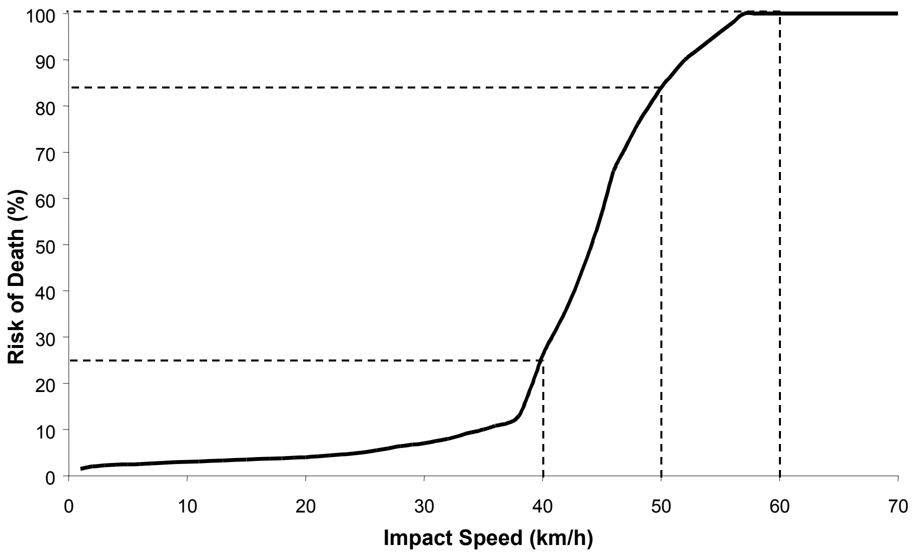


Figure 3.5 Risk of death vs impact speed for pedestrians

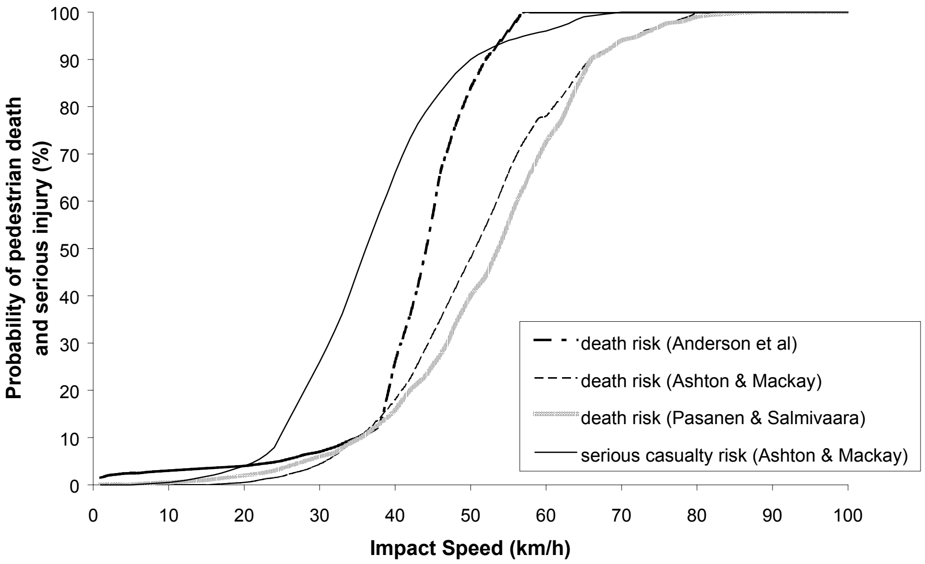


Figure 3.6 Risk of death or serious injury vs impact speed for pedestrians

It is noteworthy that typical stopping distance profiles for vehicles under heavy braking reveal that the major loss of speed does not occur until the latter stages of the braking period. This physical phenomenon is evident in the chart of typical stopping distances of modern-day passenger cars (Figure 3.7). In the example shown, a driver perception-reaction time of 1.2 seconds and a tyre-road coefficient of friction of 0.7 (dry road) have been assumed for the purposes of illustrating the differences in potential impact speeds resulting from small differences (increments of 5 km/h) in initial travel speed, just prior to there being a need to stop rapidly. For example, comparing the stopping distances of two cars, one travelling at 40 km/h and the other travelling at 30 km/h, shows some seven metres difference (approximately 15 metres compared with 22 metres) in the distance required to stop under the assumptions noted above. If the lower speed vehicle (30 km/h) were able to stop *just* before striking a pedestrian on the road ahead, the higher speed vehicle (40 km/h) would collide with the pedestrian at around 37 km/h. These impact speeds pose a serious risk to the lives and long-term health of the struck pedestrians.

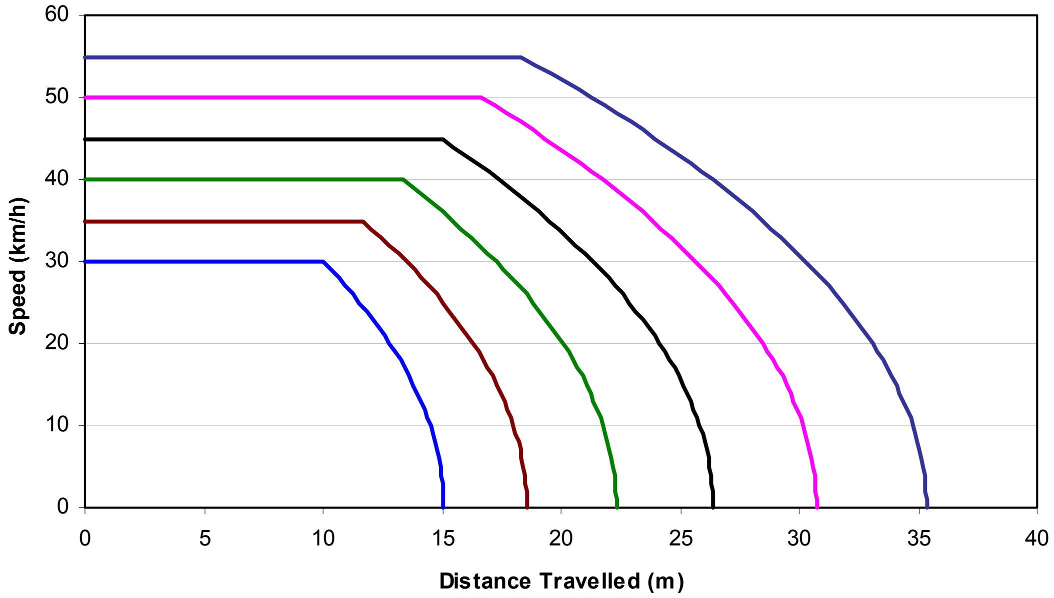


Figure 3.7 Typical stopping distances of cars braking from a range of initial travel speeds

These findings suggest that, in order to minimise the risk of severe injuries to the pedestrian, car speeds should not exceed some 25-30 km/h at impact. However, some humans may be more vulnerable to death or serious injury than others (e.g. older persons, persons with a disability, small children, etc). For these groups, even lower impact speeds are necessary to avoid serious injuries to the pedestrian. For speeds above these levels, the likelihood of serious outcomes would be high and incompatible with the objectives of the VRM. Therefore, preventing impact speeds from exceeding 25-30 km/h becomes a vital objective in pedestrian/car interactions, unless the protection of the human can be assured by reducing the probability of serious events or by successfully managing the transfer of kinetic energy to the human.

For this, the third layer, it is relevant to look at human, car, road and roadside, and system operation.

Table 3.5 Summary of Risk Factors for Layer 3

Protective Layer	Crash and/or Injury Risk Factors			
	Human	Car	Road Infrastructure	System Operation
1. Increased biomechanical tolerance	✓	N/a	N/a	N/a
2. Attenuation of kinetic energy transfer	✓	✓	✓	N/a
3. Reduced level of kinetic energy	✓	✓	✓	✓
4. Reduced crash risk for given exposure	✓	✓	✓	✓
5. Reduced exposure to crash risk	✓	✓	✓	✓

3.2.3.1 Human Injury Risk Factors

This section examines human injury risk factors, specifically those associated with the driver, in terms of how to reduce the level of kinetic energy of the car at impact with the pedestrian.

One such opportunity involves addressing the human tendency or desire to purchase/drive larger vehicles, such as Four-Wheel-Drive vehicles (4WDs) or Sports Utility Vehicles (SUVs) (Ballesteros, Dischinger & Langenberg, 2004). Thus, interventions which diminish market demand for larger (higher mass) vehicles, as well as reducing the average mass of the car fleet would help to reduce, for a given speed profile, the overall kinetic energy of the road-traffic system and of individual vehicles. Reductions in kinetic energy would be linearly related to mass. Synergies between such an initiative and other interventions identified within other parts of the model could be expected as a result of interactive effects with other layers of protection. For example, reducing the number of SUVs purchased and driven, on the basis of reducing the mass of vehicles, would also produce additional benefits in the form of there being fewer vehicles with frontal design features that increase the risk of severe injury to the pedestrian (Ballesteros et al; Crandall et al., 2002).

In relation to speed, the potential effect is much stronger and therefore presents a more attractive option. If drivers could be actively encouraged to adopt more moderate speeds in urban areas, especially where high levels of pedestrian activity occur, substantial reductions in serious pedestrian trauma would follow. Countermeasures targeting human factors of the driver might include improved compliance with speed limits, using both general and targeted enforcement, public education, high-intensity campaigns, changes to the physical appearance of the road environment (e.g., appearance of abutting development, street-scaping of urban areas, etc). The VRM highlights the possibility to influence substantially and, sometimes subtly, driver choice of speed by varying these factors, and others, to bring about a more moderate car speed in advance of any potential conflict.

The probability of a crash occurring between a car and a pedestrian depends, in part, on the ability of the driver to perceive the pedestrian, assess the pedestrian to be at risk of being struck, decide on the appropriate action and then take action to avoid the crash or at least lessen its severity. That is, the time taken by the drivers to perceive, assess, decide and react (generally by braking) can determine whether a collision will occur and, if it does, how severe the injuries to the pedestrian will be.

In this section, opportunities are considered to address human factors in such a way as to reduce the speed of a car at impact, through shortened perception-reaction times (PRTs) of drivers. Typical perception-reaction times vary between 1.2 sec for a younger person in good health and with above-average reflexes to 2.5-3.0 secs for an older driver, for example, or one whose attention is being shared with other driving or non-driving tasks (Green, 2000). Perception-reaction time can be used to calculate the distance travelled by a car, from the moment when the driver perceives the presence of the pedestrian, to the moment when the driver initiates braking (or, perhaps, crash avoidance through steering). The distance travelled during this period is linearly related to the car's travel speed. For a 60 km/h zone (16.7 m/sec) as typically applies on many of Australia's urban arterial roads, the car will travel around 20 m (for 1.2 sec perception-reaction time) and a 0.7 coefficient of friction between tyre and road, before the driver commences braking (or other crash avoidance action) (Green, 2000).

As noted earlier, the distance travelled by a car during the driver's PRT is additional to the distance travelled by the car during braking. Adding the perception-reaction distance to the braking distance gives the overall stopping distance, as well as allowing the relationship of the stopping distance to travel speed to be better understood.

Of particular importance is the task of relating minimum stopping distance for a given travel speed, to sight distances available, in environments known to be especially hazardous to pedestrians (e.g., high pedestrian activity areas along busy arterial roads, where driver and pedestrian sight distances are frequently obstructed by other vehicles, especially large vehicles, such as trams, buses, delivery vehicles and SUVs). Countermeasures that can shorten driver PRT can markedly reduce stopping distance and have an even greater effect in reducing impact speed. Examples of possible countermeasures include hazard perception training (Fisher, Laurie, Glaser, Connerney, Pollatsek, Duffy & Brock, 2002; Regan, Triggs & Godley, 2000) and the use of ITS within vehicles to enhance driver vision (Breen, 2002), especially for older drivers with declining visual performance, all drivers at night or in conditions of poor visibility. The latter countermeasure possibility (i.e., in-vehicle ITS) is directed primarily at improving the functional performance of drivers, even though it can also be regarded as a countermeasure introduced to the vehicle. Shortened PRTs, in turn, reduce the kinetic energy at impact because of the earlier braking that can occur.

Protective Layer 3 of the VRM, which incorporates driver PRTs, enables the identification and/or development of countermeasures aimed at reducing stopping distances, or for research needs and priorities to be determined. A thicker layer corresponds with shorter PRTs and, hence, reduced crash and injury risk, while a thinner layer is associated with longer PRTs and hence reduced protection for pedestrians.

It will be shown in the description of Layer 4 that PRT plays an important part in crash risk, as well as in determining the level of kinetic energy at impact.

3.2.3.2 Car Design Risk Factors

A number of possibilities for offering protection by using car design factors to restrict the kinetic energy at impact of the colliding car can be identified through the VRM. In accordance with the above discussion on the determinants of kinetic energy, this aspect of the model focuses primarily on the mass and impact speed of the car.

3.2.3.2.1 Car Mass

As noted above, cars of smaller mass will have an overall effect of reducing the total kinetic energy in the road-traffic system. Thus, all else being equal, injury risk to the pedestrian will fall accordingly though, of course, such an approach has implications for other aspects of road safety. In particular, it is also well known that smaller vehicles generally offer less protection to their occupants in crashes with other vehicles or with roadside hazards (Buzeman, 1997). Any consideration of reducing vehicle mass to reduce pedestrian injury risk should, therefore, also consider the consequences for other categories of road trauma.

3.2.3.2.2 Car Speed

Since it would be by no means a straightforward matter to build smaller mass vehicles in the future, in order to achieve greater safety for pedestrians, consideration of car design opportunities, that target the other more powerful determinant of kinetic energy, take on even greater importance. That is, the VRM highlights the particular importance of speed to pedestrian injury risk, not only because of its contribution to kinetic energy, but also because it appears to present a more viable, immediate, affordable and socially acceptable option to enhance pedestrian safety.

Car design features that aim to reduce the speed of the car at impact would include intelligent transport systems (ITS) such as collision warning systems, which might incorporate automatic brake activation in the event of a collision with a pedestrian, intelligent speed adaptation (ISA) and more effective braking systems. ISA is a form of in-vehicle speed limiter that can address the problems of drivers exceeding the speed limit and, in addition, have the potential to address crash and injury risks associated with driving within the speed limit, but at speeds excessive for the conditions (Regan, Oxley, Godley & Tingvall, 2001). ISA relies on information from the road environment to define locations where lower speeds may be required for safety (e.g., on the approaches to intersections, areas of high pedestrian activity, hazardous curves, etc) (Hyden, 1993). Swedish trials of speed limiters fitted to a fleet of vehicles in the City of Lund demonstrated that such a system has the potential to offer road safety benefits and to be accepted by the driving public (Booz-Allen & Hamilton, 1998; Carsten & Tate, 2000). Booz-Allen and Hamilton cite a number of ITS applications with the potential to improve safety, including ISA, which has been found in Swedish trials to reduce by 20% pedestrian fatalities and injuries (Carsten & Tate, 2000).

The critical threshold for impact speed to avoid death or serious injury, namely, 25-30 km/h, might be used as a design guide for improved car stopping performance.

The concept of vehicle reaction time as an element of the pre-crash phase has not received great attention until recent years. The opportunity now exists, through ITS, to reduce substantially the time required for a vehicle to commence braking and thereby to either avoid a collision, or else reduce impact speed to below the critical level that can be tolerated by the human. For example, pedestrian collision warning systems are now in use in vehicles (some as experimental prototypes) to detect the presence of a pedestrian on a potentially conflicting path. Once detected, the vehicle braking (and/or steering) system could be automatically activated to avoid a collision or lessen the impact speed (Carsten, 1993).

Such technology has the capability to detect pedestrians sooner than can a driver of normal ability, especially in conditions of poor visibility, though not all detection systems work well under such conditions (Carsten, 1993). Using in-vehicle technology in the future may offer the possibility to cut crucial milli-seconds from the time required for crash-saving or injury-reducing action to commence.

Additional benefits might be generated as a result of combining such in-vehicle collision warning systems with countermeasures identified within the VRM's other layers of protection. For example, a pedestrian collision warning system could also be used to activate, just prior to impact, an external airbag or other energy-sharing device on a vehicle to attenuate the energy transferred to the pedestrian at impact.

Conventional braking methods involve the application of a hydraulic braking system by the driver. The effectiveness of braking systems may be enhanced by the use of anti-lock braking systems (ABS), for example, or by improved tyre design. Other opportunities to be discussed later in this report (e.g., road and roadside design factors) include the use of skid resistant road surfaces and the role of adverse weather conditions. New mechanisms may be developed in the future to bring vehicles to a more rapid and effective stop, and so reduce impact speeds with pedestrians.

Once again, by combining two or more such systems to achieve more rapid and effective application of car braking systems, considerable benefits may result, not only from the combined effects of the countermeasures, but also from potential synergies.

3.2.3.3 Road and Roadside Design Risk Factors

The role of the road infrastructure in determining pedestrian injury risk in a collision with a car has already been discussed in the context of the protection offered by Layer 2, which aims to attenuate the transfer of kinetic energy to the human. In this context, it was noted that providing a more forgiving road surface and roadside could reduce injury risk for a pedestrian struck and thrown onto the roadway or into the roadside.

For Layer 3, the kinetic energy at impact could be reduced by the application of a wide range of countermeasures addressing speed through the design of road and roadside infrastructure. Countermeasures include:

- Skid-resistant road surfaces to improve vehicle braking performance and thereby reduce the impact speed or even better, avoid a collision entirely;

- Traffic-calming devices such as roundabouts, medians, speed humps, road narrowings, kerb outstands, textured pavements, etc. By changing the horizontal and/or vertical displacement of vehicle paths, or the surface on which vehicles travel, drivers can be encouraged or, indeed, required to adopt more moderate car speeds while travelling along treated roads and through treated intersections.

Impact speeds that will not lead to death or serious injury to struck pedestrians become more likely and, in many cases, crashes will be avoided altogether;

- Reduced road widths, or the use of one or more of a range of speed perceptual countermeasures (PCM) to promote lower vehicle speeds. PCMs have been evaluated in both real-world and driving simulator settings, and show some potential to induce lower speeds in drivers who are exposed to them (Godley, 1999). To date, applications have typically targeted non-pedestrian situations but may be suitable for pedestrian safety applications;

- Roadside appearance that accurately reflects the type of land use and level of human activity through which drivers pass. It is especially important that pedestrians, particularly where they mix in high numbers with vehicular traffic, are recognised by drivers as legitimate, frequent and vulnerable users of the road-transport system.

While there seem to be few opportunities to use the road infrastructure to influence the mass of vehicles (as a step towards reduced kinetic energy in a crash with a pedestrian), some forms of traffic-calming and aspects of road design have the potential to prevent or at least limit the use of selected roads by vehicles of higher mass. Speed humps, roundabouts, road narrowing, limited pavement strength and kerb outstands are a few examples of traffic-calming measures that can prevent, or at least discourage, non-essential use by vehicles of high mass in high pedestrian crash or injury risk locations. Ultimately, such an approach can reduce the overall level of kinetic energy existing in the road-traffic system.

3.2.3.4 System Operation Risk Factors

Within the context of system operation factors, a number of countermeasure opportunities can be identified to restrict the effects of mass or vehicle speed on the final level of kinetic energy in a collision with a pedestrian.

Considering first the possibilities of reducing vehicle mass through system operation countermeasures, it may be effective to regulate to prevent (or limit) the use by high mass vehicles of particular roads or areas that are pedestrian-sensitive. As noted above, this type of effect may also be achieved, or an existing approach strengthened, through design improvements to the road and roadside infrastructure. Similarly, road transport regulations could be devised to restrict the maximum permissible mass of future vehicles, and/or to limit their use to specified circumstances and their growth within the transport system. It would seem that a range of other possibilities could also be developed drawing upon the above examples.

Secondly, the harmful contribution of speed to kinetic energy can also be curtailed through system operation choices. Leading examples include the setting of lower default urban speed limits, enhancements to speed zoning practices (primarily in urban areas), operational strategies for traffic signals (for both peak and off-peak periods), including the linking of traffic signals to facilitate the progression of platoons of vehicles and the provision of priority to public transport or other categories of vehicles, and on-street parking policies that affect the ease with which traffic can flow along arterial roads.

It is important to recognise that these and other system operation policies and standards can potentially have subtle, and in many cases unintended, effects on vehicle speeds. So too is it vital to understand that even small increases in the travel speeds of vehicles will markedly increase the level of kinetic energy that a pedestrian must withstand in the event of a collision, in order to avoid a serious injury or, indeed, death.

Oxley, Corben and Diamantopoulou (2001) reported substantial reductions in the annual numbers of pedestrians killed in Victoria after 1989. Figure 3.7 shows that pedestrian fatalities in Victoria averaged 144 per annum during the seven-year period between 1983 and 1989. In 1990 there was a dramatic drop to 93 fatalities in that year. This new level, which steadily decreased during 1991 to 1994 to 64 deaths in that year, represents a 43 percent reduction in pedestrian fatalities, over the period 1983 to 1994. However, the number of fatalities increased again in 1995 to 84 pedestrian deaths, representing a 31 percent increase on the previous year. The increasing trend did not continue, with the number of pedestrian fatalities falling to under 80 deaths per annum from 1996 to 1999.

Figure 3.7 Pedestrian road fatality statistics for Victoria (1983 – 1999).

A similar though less marked reduction (26 to 33 percent) in crashes involving serious pedestrian injuries, was also observed.

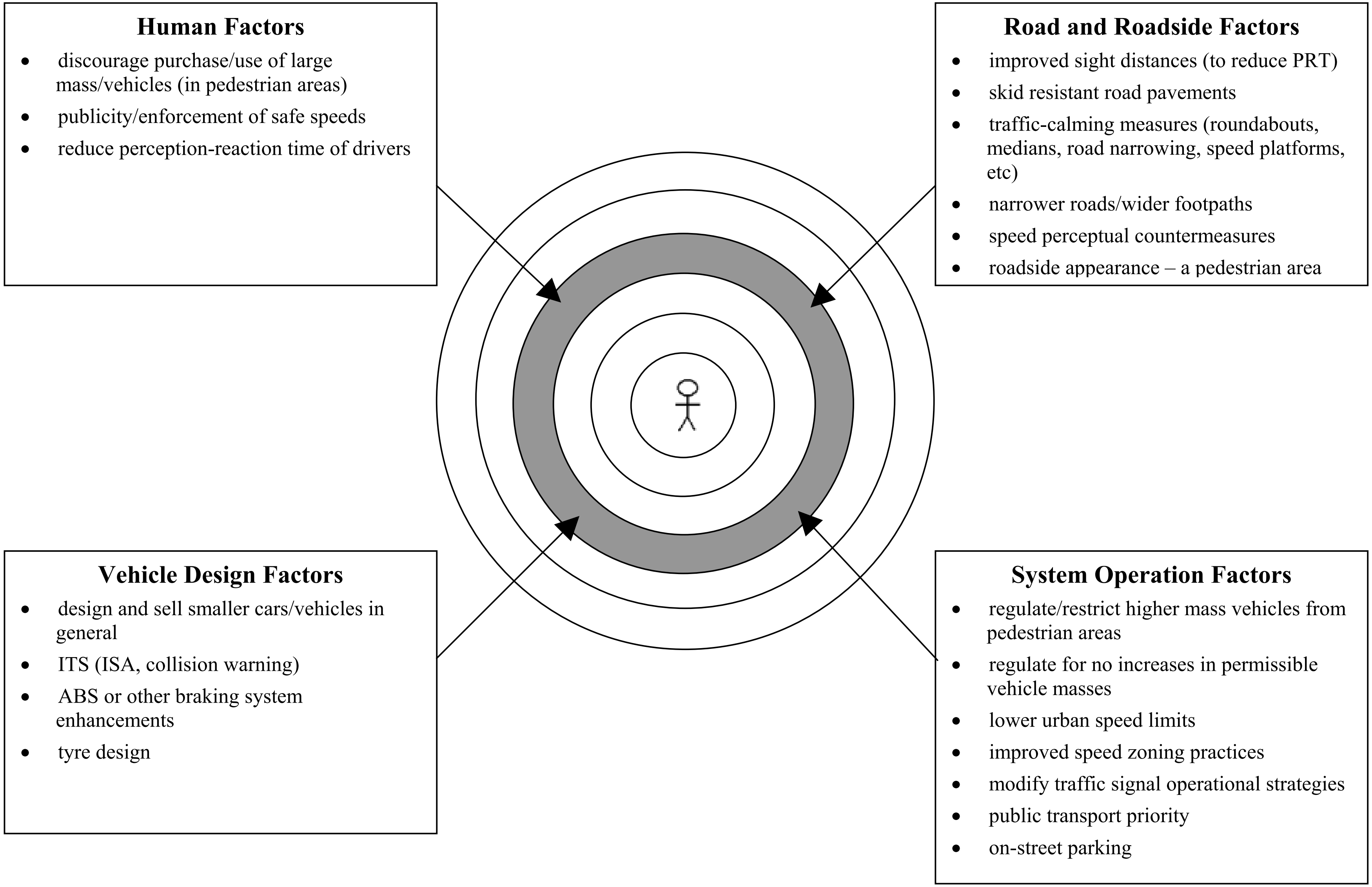
Oxley et al. (2001) suggested that a major contributing factor in these overall downward trends appeared due to a general downward trend that occurred in Victoria's road toll after 1989. It seems that pedestrians benefited significantly from measures targeted at drivers, such as the introduction of speed cameras and a boost in random breath testing, which were introduced in 1989/1990.

Action by the Victoria Police to reduce the enforcement tolerance for speed camera operation in March-April 2002 appears to have contributed substantially to a record low road toll for the Melbourne metropolitan area for 2003. This overall reduction in fatalities includes a major step reduction in fatalities involving unprotected road users, whose death toll fell by 42%, 20% and 40% on the corresponding previous five-year averages for pedestrians, motorcyclists and bicyclists, respectively (Australian Transport Safety Bureau, 2004). During this period, average vehicle speeds in the Melbourne metropolitan area fell by around 4 km/h, suggesting that relatively small reductions in the average travel speeds of vehicles can result in substantial reductions in serious trauma, especially for the more vulnerable road user categories (Australian Transport Safety Bureau, 2004).

The main objective of most present-day traffic signal linking strategies is to improve the traffic carrying capacity of urban arterials, where a large number of individual sets of traffic signals are located in close proximity. Focusing on the maximisation of route capacity tends to promote higher vehicle speeds and higher throughput of vehicles in a given time period. Such strategies can impact detrimentally on the kinetic energy characteristics of individual vehicles and of the traffic stream overall.

While more relevant to Layer 4, which deals with the reduction of crash risk for a given level of exposure, present-day traffic signal linking strategies often lead to longer traffic signal cycle times and, therefore, lengthy delays to both pedestrians and side-street traffic. As a result, pedestrian compliance with traffic signals declines and crossing movements occur not only against the red signal, but also at locations near to, but not on, the pedestrian cross-walks (Corben, Deery, Diamantopoulou, Dyte, Shtifelman, 1997a; Corben, Deery, Diamantopoulou, Shtifelman & Wilson, 1999a; Corben & Diamantopoulou, 1996; Corben, Diamantopoulou, Shtifelman & Wilson, 1999b; Insurance Institute for Highway Safety, 2000). In both instances, pedestrians are exposed to greater risk, relying solely on their ability to select safe gaps in high-speed, high-volume traffic.

Signal linking strategies that better accommodate the needs of pedestrians and explicitly recognize the vulnerability of pedestrians in traffic have the potential to cut pedestrian crash risk along particular routes or within busy commercial and business environments.



Human Factors

- discourage purchase/use of large mass/vehicles (in pedestrian areas)
- publicity/enforcement of safe speeds
- reduce perception-reaction time of drivers

Road and Roadside Factors

- improved sight distances (to reduce PRT)
- skid resistant road pavements
- traffic-calming measures (roundabouts, medians, road narrowing, speed platforms, etc)
- narrower roads/wider footpaths
- speed perceptual countermeasures
- roadside appearance – a pedestrian area

Vehicle Design Factors

- design and sell smaller cars/vehicles in general
- ITS (ISA, collision warning)
- ABS or other braking system enhancements
- tyre design

System Operation Factors

- regulate/restrict higher mass vehicles from pedestrian areas
- regulate for no increases in permissible vehicle masses
- lower urban speed limits
- improved speed zoning practices
- modify traffic signal operational strategies
- public transport priority
- on-street parking

Figure 3.8 Layer 3: Reduced level of kineic energy to be managed in a given crash

3.2.4 Layer 4 Reduced Crash Risk for a Given Level of Exposure

The fourth layer of protection comprises countermeasures that aim to prevent crash occurrence, which contrasts with the aims of the countermeasures of Layers 1, 2 and 3, that are concerned with reducing injury risk in the event of a collision. That is, layers 4 and 5 address opportunities to protect pedestrians during the pre-crash phase, while layers 1, 2 and 3 offer protection during the crash phase.

In seeking to identify and describe countermeasures that prevent crashes, the features of Layer 4 assume that exposure to crash risk is generally stable and that reductions to crash risk through exposure reduction will be generated from within Layer 5.

As with other layers described so far, the risk categories of human, vehicle, road and roadside, and system operation help to assure systematic and comprehensive generation of countermeasure possibilities. Some countermeasures could logically be presented under more than one risk category as they can have multiple effects. For simplicity, discussion of such countermeasures generally occurs under the risk category deemed to have the primary relevance (see Table 3.6).

Table 3.6 Summary of Risk Factors for Layer 4, Reduced Crash Risk for given Exposure

Protective Layer	**Crash and/or Injury Risk Factors**			
	Human	**Car**	**Road Infrastructure**	**System Operation**
1. Increased biomechanical tolerance	✓	**N/a**	**N/a**	**N/a**
2. Attenuation of kinetic energy transfer	✓	✓	✓	**N/a**
3. Reduced level of kinetic energy	✓	✓	✓	✓
4. Reduced crash risk for given exposure	✓	✓	✓	✓
5. Reduced exposure to crash risk	✓	✓	✓	✓

3.2.4.1 Human Injury Risk Factors

In the context of Layer 4 – reduced crash risk for a given level of exposure – it is useful to consider human factors separately in terms of drivers and pedestrians.

3.2.4.1.1 Driver Perception-reaction Time

In the case of drivers, car speed at impact has already been detailed as being of fundamental importance to pedestrian injury risk. It has also been shown that driver choice of speed plays an important part in the determining impact speed and, indeed, whether a crash will occur (Oxley & Corben, 2002). Travel speed immediately prior to a potential conflict is important in terms of the reaction distance (i.e., the distance travelled during the period when the driver first perceives a potential conflict, recognises what lies ahead, decides that there is a need to brake and then commences braking. This time period typically ranges from around 1.2 seconds for alert drivers with good reflexes, to 2.5 to 3.0 seconds for drivers who may be distracted or whose performance is otherwise impaired (Green, 2000). The reaction distance is linearly related to the speed of travel meaning that, for example, a car will travel twice as far during the reaction distance if driven at 60 km/h instead of 30 km/h.

There are many countermeasures that aim to improve driver perception-reaction times, especially in cases where the driver is:

- Fatigued or otherwise temporarily impaired, such as after consuming alcohol, or other drugs or medications;
- Inexperienced;
- Suffering from declining performance due to aged-related deficits.

Common countermeasures that target human risk factors of this type include driver training initiatives, media campaigns, police enforcement, Occupational Health and Safety legislation and policies applicable to vehicle use, in-vehicle collision warning systems, etc. However, in general, efforts to improve the PRT of drivers, through specific skills training, have met with only limited success (Christie & Harrison, 2003).

3.2.4.2 Car Speed

Another potentially valuable approach to reducing pedestrian crash risk is to influence car speeds, especially in terms of driver choice of speed. If drivers can be influenced to choose lower travel speeds, not only will crash risk fall as a result of reduced reaction distance, but braking distances will be reduced even more dramatically. The greater gains achievable in braking distance reductions are a direct result of the second-power relationship between travel speed and braking distance (McLean, Anderson, Farmer & Brooks, 1994).

There are many opportunities to reduce the speeds at which drivers *choose* to travel. Some of the more promising possibilities are:

- Strengthen speed-zoning practices to have an over-riding safety objective. Particular attention would be paid to speed-zoning in areas where there is high pedestrian activity (Oxley & Corben, 2002);
- Strengthen police enforcement through a reduction in, or removal of, speed enforcement tolerances and continue to use new, upgraded speed enforcement technology, together with strategic deployment of resources (Cameron, Fitzharris, Corben & Jacques, 2002);
- Counter public perceptions that automated speed enforcement is essentially aimed at revenue-raising (Oxley & Corben, 2002);
- Increase community knowledge and awareness of the importance of speed to road trauma in general, and pedestrian trauma in particular, combined with active support for police enforcement using carefully targeted media campaigns;

- Sharply focus speed management strategies with explicit attention to situations where pedestrians and vehicles mix in high numbers (Oxley & Corben, 2002).

3.2.4.2.1 Pedestrian Gap Selection

One of the most common causes of pedestrian trauma is the pedestrian's inability to select safe gaps in traffic (Corben & Diamantopoulou, 1996; Corben, Diamantopoulou & Triggs, 1997b; Corben et al., 1999a; Corben et al., 1999b; Oxley, Fildes, Ihsen, Charlton & Day, 1999). While this human failing occurs in all age groups, it is accentuated among the higher-risk categories, namely the young (Simpson, Johnston & Richardson, 2003) or elderly (Oxley, Fildes, Ihsen, Day, 1997; Oxley et al., 1999) and the intoxicated (Corben, Diamantopoulou & Mullan, 1998; Oxley, Lenné, Corben & Potter, 2002). Even when functioning within the normal range of human capability, pedestrians fail to select a safe gap in traffic, especially when high speeds, high traffic complexity, wide roads and high traffic volumes are present, singly or in combination.

Many countermeasures for poor gap selection have been developed through road and traffic engineering means. These physical treatments will be described later, within the section on road and roadside infrastructure factors. Notwithstanding the physical nature of such measures, they aim primarily to address human risk factors by assisting pedestrians in the gap selection process, either by forcing safe gaps in traffic or by easing the demands on a pedestrian who is choosing a gap.

Only limited attention seems to be directed towards improving the gap selection abilities of pedestrians. Some examples include traffic safety education in schools, programs to assist the elderly, and others to encourage responsible consumption of alcohol by (and serving to) pedestrians (Corben et al., 1997a; Corben et al., 1997b). In relation to older pedestrians, it may be feasible and effective to re-train them so as to restore at least some aspects of functional performance essential to safe gap selection. Similarly, countermeasures could be devised to accelerate the development in children of road-crossing skills, while for intoxicated pedestrians the introduction of a legal limit may restrict alcohol consumption and, hence, reduce crash risk.

An aspect closely related to the problem of poor gap selection by pedestrians is the tendency for pedestrians not to use facilities provided for them, unless they are conveniently located and do not impose significant delays (Corben & Diamantopoulou, 1996). To reduce crash risk, countermeasures that promote and encourage the safe use of pedestrian crossing facilities and other safety measures may be needed in specific locations. Police enforcement, supported by media and publicity campaigns, may be used from time to time in more acute problem locations. Other opportunities may be generated as a result of modifying road and traffic engineering design and operation standards and guidelines to afford greater priority to pedestrians. This matter is discussed in greater detail under the road and roadside infrastructure, and system operation risk factors.

3.2.4.2.2 Pedestrian Mobility

Another important human risk factor for pedestrian crashes is the degree of physical mobility of pedestrians. Studies by Oxley (Oxley et al., 1995; Oxley et al., 1997) have shown that the gap selection performance of older pedestrians is adversely affected by ageing. Among the specific factors contributing to higher crash risk among older pedestrians is their impaired mobility in terms of their "start-up" time to commence crossing a road, once a gap has been selected, and the actual crossing time. That is, with the increases in start-up time and crossing time that accompany ageing, or other forms of loss of mobility and agility, comes an increase in pedestrian crash risk. By definition, reduced mobility is also present among people with disabilities, with diminished mobility also characterising pedestrians affected by alcohol and, for example, adults accompanied by young children.

Countermeasures that aim to reduce pedestrian crash risk by improving pedestrian mobility and agility might include:

- Health and physical conditioning programs that delay the onset of mobility impairment among older pedestrians or that assist people to regain at least some of their mobility losses. While little is known about the effectiveness of such countermeasures, significant improvement in the general health and well-being of the older population could be expected;

- Education programs to encourage people with heightened crash risk, as a result of mobility impairment, to compensate by using safe crossing locations, in a safe manner, or to otherwise avoid the usual risks involved in crossing busy roads, especially through fast-moving traffic;

- Encourage GPs and other health-care professionals to inform at-risk patients about the true risks involved and of possible solutions;

- Encourage families and friends, or community care groups, to make essential trips (e.g., shopping, library, etc) with, or on behalf of, people with mobility impairments. However, care should be taken to prevent such an approach further reducing the mobility and health of those at risk by limiting their engagement in otherwise healthy activities;

- Provide specific (re-) training to the mobility-impaired to assist with the selection of safe gaps in traffic. A number of existing programs (e.g., Walk with Care, Safe Routes to Shops, etc) might be amenable to modifications of this type.

3.2.4.3 Car Design Risk Factors

Car design factors contributing to crash risk, for a given level of exposure and for a given speed of travel, are concerned mainly with:

- vehicle braking distance;

- vehicle reaction distance;

- the use of vehicle daytime running lights, as well as the choice of bright vehicle colours to improve vehicle conspicuity, which can help pedestrians to select safe gaps and, hence, cut pedestrian crash risk;

- windscreen design and light transmission properties of windscreen glass to the extent that they affect the ability of the driver to detect the presence of a pedestrian ahead, especially at night or in other times of poor visibility (Rompe & Engel, 1987). Similar design issues apply to pedestrians located in the driver's peripheral field of view or at the rear of a reversing vehicle;

- vehicle body shape (e.g., bonnet, A-pillars, rear of vehicle, etc) and driver position, again to the extent that they affect the driver's ability to see pedestrians. Research by Sweatman, Ogden, Haworth, Corben, Rechnitzer and Diamantopoulou (1995) highlighted the problems experienced by truck drivers already stopped at traffic signals being unable to see slow-moving pedestrians, still on the pedestrian cross-walk when the signals change to green for vehicular traffic;

- in-vehicle technology or other equipment such as radios, sound systems, mobile phones that might act to distract the driver at critical times during the emergence of a pedestrian conflict;

Other possibilities to influence driver choice of speed are offered by in-vehicle technologies, such as speed alerting devices or cruise control, both commonly available in vehicles manufactured during the last five to ten years. These devices have the potential to alert drivers who may otherwise inadvertently adopt higher travel speeds because of inattention, distraction or other factors affecting their ability to monitor and maintain legal and safe speeds (Regan & Young, 2004).

3.2.4.4 Road and Roadside Design Risk Factors

The physical environment within which cars and pedestrians move and mix, strongly influences pedestrian crash risk. For example, roads with high traffic speeds (e.g., while urban speeds of 40-50 km/h or higher are common and not generally considered high, reference to the research evidence of Figure 3.5 indicates that, *from the perspective of the pedestrian and his/her risk of death in a crash*, it is legitimate to classify such speeds as high), multiple lanes, wide undivided carriageways, complex traffic conditions or visually cluttered roadsides are generally more difficult for pedestrians to negotiate safely than are roads that ensure moderate vehicle speeds, calm-traffic behaviour, have few or preferably a single lane in each direction, medians or refuge islands, and simple, predictable traffic flows. Where vehicle speeds are above, say, 30 km/h, there will often be a need to upgrade the infrastructure to provide safe crossing opportunities for pedestrians.

The main opportunities for reducing crash risk for pedestrians (and in some important instances, also reducing injury risk) can be captured by four objectives (Corben et al., 1999a) namely:

1. moderating vehicle speeds;

2. increasing the separation between pedestrians and vehicles;

3. reducing road widths;

4. reducing traffic volumes.

Most, if not all, pedestrian crash countermeasures fall into these four main categories. In many instances these individual countermeasures involve changes to the physical environment, in the form of traffic engineering devices or general road infrastructure, specifically to assist pedestrians to cross busy, high-speed or otherwise hazardous roads.

Each of these four countermeasure categories comprises individual countermeasures that could be discussed under several of the risk categories; however, the road and roadside infrastructure category is central to crash risk reduction. Although reducing traffic volumes falls mainly into Layer 5, "Reduced Exposure to Crash Risk", it also has important links to both the design and operation of the road infrastructure.

3.2.4.4.1 Moderating Vehicle Speeds

The importance of vehicle speed to pedestrian safety has been discussed at length in each of the model layers described so far. So too has a range of methods by which speed can be reduced to cut injury risk and to reduce the likelihood of a crash from occurring. In this context, vehicle speeds may be reduced in areas where pedestrians and vehicles mix, by using a wide range of changes to the road infrastructure. Infrastructure countermeasures that attempt to reduce vehicle speeds include vertical and lateral diversions in vehicle paths using, for example, speed humps, chicanes or other forms of changing road alignment, coloured or textured road pavements, gateway treatments, roundabouts, lateral or longitudinal line markings to influence driver perception of travel speed or reductions in road width to elicit lower speeds by drivers (Corben & Duarte, 2000).

Less conventional opportunities to moderate vehicle speeds include technology such as a speed indicator display (Corben, Lenné, Regan & Triggs, 2001), intelligent road markers, active warning signs on the approach to intersections, or retractable road humps, all activated by the arrival of a vehicle (or vehicles) at a speed regarded as excessive for safety.

Other measures being used in Victoria (and elsewhere) involve the use of variable speed limit signs in strip shopping centres and 40 km/h part-time speed limits around schools.

3.2.4.4.2 Increasing the Separation between Pedestrians and Vehicles

Conventional types of pedestrian facilities, such as traffic signals, installed either as part of intersection signals or at mid-block locations, attempt to reduce crash risk by artificially creating safe gaps in traffic through the change of signals from red to green. That is, they increase the separation between pedestrians and vehicles, either in time or space. Zebra crossings and school crossings, on the other hand, create gaps in traffic by giving pedestrians priority over vehicles, once a pedestrian has stepped onto the crosswalk. These types of crossings have undergone numerous design modifications over recent years. "Pelican", "Puffin" and "Pussycat" crossings illustrate some of the variations on the basic design of pedestrian facilities that have evolved in an effort to eliminate poor gap selection by pedestrians, especially older pedestrians, and reduce delays to vehicle occupants.

A small number of pedestrian facilities provide full separation between pedestrians and vehicles, namely tunnels and overpasses. Because of the high cost, in terms of both finance and urban space, the use of these types of crossings tends to be confined to locations of particularly high crash risk, together with high vehicle flows and pedestrian demand.

Other enhancements to the basic objective of better separating pedestrians from vehicles include high-conspicuity signal displays for drivers, highlighted (yellow) cross-walks at intersection signals to make pedestrians more conspicuous and the potential conflict more obvious to turning drivers (Corben et al., 1997a; Corben & Diamantopoulou, 2001), audiotactile devices to assist pedestrians who are vision-impaired, raised pavements to moderate vehicle speeds through the device, and a host of other signs and design features to improve general operation. While most of these devices aim to assist the pedestrian with gap selection, their safety benefits are restricted largely to those pedestrians who wish to cross sufficiently close to the devices for their use to be convenient. Thus, one of the major limitations of conventional pedestrian facilities, especially in areas where pedestrian crossing demand is high but spatially dispersed, is that pedestrians will walk only relatively short distances to use the facilities (Corben & Diamantopoulou, 1996; Corben et al., 1997a; Corben, 1999). This leaves long lengths of roadway between crossing facilities, with little or no assistance for pedestrians undertaking the demanding task of gap selection. That is, if pedestrian facilities are located at an inconvenient distance, many pedestrians will revert to crossing unassisted. In situations of complex, fast moving traffic or wide roads this can be a high-risk strategy.

Given the tendency for many pedestrian crashes to occur in strip shopping centres, where pedestrian crossing movements are randomly located along many hundreds of metres of arterial road, over which only a relatively small proportion of roadway is covered by pedestrian facilities, a new, more comprehensive form of assistance with pedestrian gap selection is required. Ideally, the characteristics of any new form of countermeasure should cover the full length of the roadway or area where pedestrians wish to cross, not just at and near the relatively small number of isolated locations that pedestrian facilities can cover. Medians, road narrowing or wider footpaths, and lower speed limits, have these characteristics of both complete coverage and provision of significant assistance with gap selection.

These devices tend to be responsive to pedestrian demand, in that upon arrival of a pedestrian they either force a gap in traffic or give priority to the pedestrian, whereas design features such as medians, kerb outstands and pedestrian refuge islands are inactive by comparison. The latter devices do, however, have the potential to assist with gap selection by allowing crossing movements to be staged or to be performed over a much less challenging road width.

Often used in conjunction with conventional pedestrian devices, pedestrian fencing or other types of barriers (e.g., landscaping and planting) can assist in directing pedestrians to safer crossing locations, and hence improve separation. Effective fencing or other barriers can be important around road-based public transport access points where a significant number of passengers interact, as pedestrians, with passing vehicles. For Melbourne, many existing roadside tram stops and tram safety zones typically have large numbers of passengers who are waiting to board or alight from trams, and frequently do so in a hazardous manner (Corben & Diamantopoulou, 1996; Corben et al., 1999a; Tingvall & Corben, 2001). Lack of effective fencing or barriers, including gaps in existing fencing, allows disorderly or unpredictable passenger movements to occur on the roadway (Corben & Diamantopoulou).

3.2.4.4.3 Reducing Road Widths

The third of the main methods by which pedestrian crash risk may be reduced by improvements to the road infrastructure involves reducing the width of the roadway to be crossed. Crossing a narrower road not only makes the gap selection task simpler and more reliable, but it also means that the pedestrian spends less time on the roadway, and so is exposed to crash risk for substantially less time per crossing movement.

There are various alternatives for narrowing roads, ranging from general footpath widening throughout the full length of a pedestrian area, restricted numbers of lanes of traffic to be accommodated in a pedestrian-sensitive area, kerb outstands either at or away from intersections, to the construction of splitter islands on the approaches to intersections, the provision of medians or pedestrian refuges, or the provision of safety zones at tram stops.

Treatments such as these offer multiple benefits. Not only do they reduce the width of roadway to be crossed and, hence, the time spent on the roadway by a pedestrian, but they also improve sight lines between drivers and pedestrians, can elicit lower speed choices by drivers, assist with the gap selection task by enabling pedestrians to cross the road in two separate stages and, finally, they can create an environment in which drivers expect to encounter pedestrians and therefore will be more likely to share the road space, rather than regarding it as primarily for vehicular traffic.

Some of these treatments may also be used in combination with other measures, such as traffic signals, zebra-crossings and changes in vertical deflection (e.g., speed humps or raised platforms). Countermeasures that reduce vehicle speeds, as well as cutting the time pedestrians spend on the roadway while crossing, are likely to offer even greater road safety benefits to the pedestrian.

It is intended that VRM, in its operationalised form, will have the capability to estimate the effectiveness of selected measures in reducing pedestrian crash risk, either separately or in combination, though further real-world evaluations of measures will be needed to establish baseline estimates, where they are not already available. This is especially important for assessing combined and interactive effects of chosen measures.

3.2.4.4.4 System Operation Risk Factors

Consideration of the VRM in respect of Layer 4, and specifically the opportunities to reduce pedestrian crash risk by addressing system operation factors, leads to the identification of several conventional or new countermeasures:

- reductions in urban speed limits, especially in areas of high pedestrian activity;
- continuation of automated speed enforcement programs by police, using cameras or other technology that may become available in coming years;
- reductions in on-street parking, to improve sight lines between drivers and pedestrians, though the removal of on-street parking could lead to higher travel speeds unless other measures are also put in place to counter this unintended effect;
- revisions to road traffic regulations to provide higher priority for pedestrians in traffic. The fact that pedestrians do not have any right-of-way at roundabouts, for example, highlights why pedestrians are at heightened risk at some intersections, as a result of a lack of legal status and initiatives to protect them. Also of concern is that, without proper and adequate consideration to their inherent vulnerability in traffic, they may not be seen as fully legitimate users of the road-traffic system;

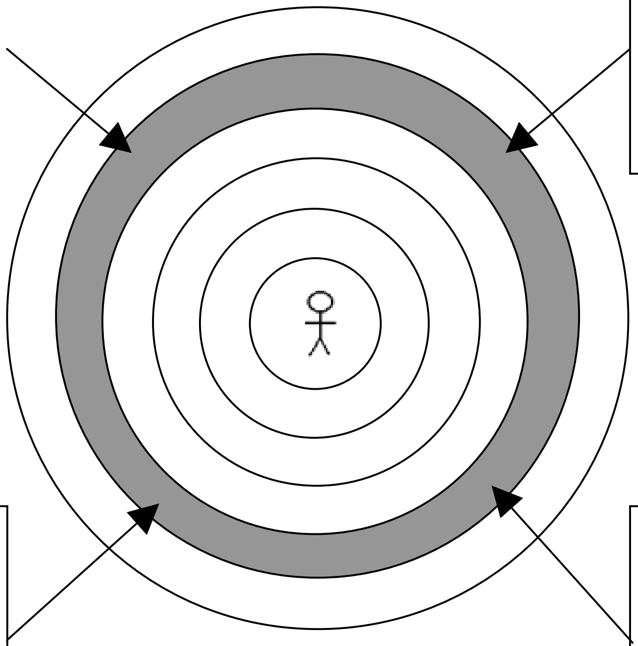
- revisions to current road design and system operation standards that preclude the use of speed humps or raised platforms on all but low volume roads. From the perspective of achieving a safe pedestrian environment, it is the high volume roads, on which high posted speed limits exist (i.e., 60+ km/h), that account for by far the major proportion of pedestrian trauma in Victoria (Transport Accident Commission, 2004) (and in many other jurisdictions of the world).

Human Factors

- reduce driver PRT
- enforce safe and legal speeds
- road user education re speed
- safe gap selection by pedestrians (education, training, alcohol programs, safe crossing locations, proper use of pedestrian facilities)
- programs for mobility impaired:
  - health/physical conditioning
  - training
  - education
  - health-care professionals
  - family/friend support

Road and Roadside Factors

- speed reduction (traffic calming, SIDS, road-based ITS, etc)
- separation of pedestrians and vehicles (crossings, medians, tunnels, overpasses, fences/barriers
- road narrowing



Vehicle Design Factors

- ITS (esp. for braking distance)
- daytime running lights
- windscreen design
- driver vision
- reduced driver distraction

System Operation Factors

- strengthened speed zoning practices
- better speed management strategies
- variable speed limits
- lower speed limits

Figure 3.9 Layer 4: Reduced risk of a crash for a given level of exposure

3.2.5 Layer 5 Reduced Exposure to Crash Risk

The fifth and final layer of protection defining the VRM concerns the reduction in exposure to crash risk, without necessarily reducing the fundamental level of risk to an individual pedestrian. Layer 4 addresses this latter component of risk. Once again, a thicker layer signifies lower exposure for pedestrians to crash risk and therefore offers greater protection for the pedestrian, while a thinner layer corresponds to higher exposure to a given level of risk and, hence, offers reduced protection overall.

In traffic safety terms, exposure is a measure of the extent to which people and vehicles are in a situation of risk (Ogden, 1996). It is common practice for road safety researchers and practitioners to use the concept of exposure to crash or injury risk to identify high priority problems and to estimate whether crash or injury risk has fallen as a result of some countermeasure or intervention.

In the context of pedestrian crashes with cars, it is also usual to attempt to quantify risk by counting the number of events that occur, in a given time period, that can lead to crashes, injuries or both. Broadly, exposure is quantified by counting, in a chosen time, the number of vehicles along a given length of road and the number of pedestrians crossing that section of road. Such counts help to estimate the exposure of pedestrians to crash risk, while the addition of vehicle speed distributional data can introduce to these estimates the influence of speed on both crash and injury risk.

Furthermore, incorporating exposure data categorised according to, say, pedestrian age enables another exposure–based refinement to be made to capture pedestrian age-related factors that affect crash risk, injury risk or both.

At the coarsest level, reducing exposure is a powerful means by which to reduce crash and injury risk to a pedestrian. No longer allowing activities that can lead to crashes, by definition, eliminates the possibility of a crash. Thus, for every pedestrian or vehicle removed from the road-traffic system or from a particular section of road, there will be one fewer opportunity for a pedestrian crash involving the particular vehicle or pedestrian to occur. Though at risk of "stating the obvious", it also apparent that vehicle exposure reduction is rarely used as a means of reducing (pedestrian) crash risk, presumably because it is viewed as inconsistent with modern-day social values that expect private car travel to receive a very high priority.

In simple terms, reducing exposure to a given level of crash risk can be achieved by reducing:

- the number and types of *vehicles* using roads, as well as the distances driven. Specific types of driving known to be associated with elevated crash risk, especially for pedestrians, might also be targeted. Examples of riskier types of driving include drink-driving and driving while fatigued or distracted (e.g., mobile phone use);

- the number and types of *pedestrians* crossing roads, as well as the distances walked. Specific types of walking known to be associated with elevated pedestrian crash risk might be targeted. Examples of riskier types of walking include walking by intoxicated (Corben, Diamantopoulou, Mullan & Mainka, 1996; Oxley et al., 2002), young (Delaney, Newstead & Corben, 2002; Simpson et al., 2003) or older pedestrians (Oxley et al., 1999), and walking in periods of reduced visibility such as in darkness or poor weather;

- the number and types of *pedestrians* walking beside busy roads or across driveways, in situations where they may be struck either by vehicles leaving the roadway (intentionally or unintentionally) or by vehicles leaving or entering private, commercial or other types of driveways. Crash scenarios of this type make up only a minor proportion of serious pedestrian trauma overall (Hunter, Stutts, Pein & Cox, 1995; Transport Accident Commission, 2004), but in the case of driveway crashes, can present a substantial risk for young children, because of their small stature combined with the difficulty drivers have in seeing them while reversing, and for older people who may have difficulty hearing or seeing the approach of a vehicle leaving a driveway, and who may lack the agility to take evasive action.

The structure for discussing countermeasure possibilities within this layer follows the now established approach of considering the human, car design, road and roadside design, and system operation risk factors. Table 3.7 sets out the relevance of each factor to countermeasure identification within Layer 5.

Table 3.7 Summary of Risk Factors for Layer 5, Reduced Exposure to Crash Risk

Protective Layer	**Crash and/or Injury Risk Factors**			
	Human	**Car**	**Road Infrastructure**	**System Operation**
1. Increased biomechanical tolerance	✓	**N/a**	**N/a**	**N/a**
2. Attenuation of kinetic energy transfer	✓	✓	✓	**N/a**
3. Reduced level of kinetic energy	✓	✓	✓	✓
4. Reduced crash risk for given exposure	✓	✓	✓	✓
5. Reduced exposure to crash risk	✓	✓	✓	✓

3.2.5.1 Human Injury Risk Factors

3.2.5.1.1 The Driver

Finding viable ways of reducing the modern-day dependence on private car travel is a major, long-term challenge for most western societies. Governments have directed considerable attention, using a broad and varied range of initiatives, in an effort to moderate growth in, and dependence upon, the private car (e.g., Copley, Dodgson, Bright, Coombe, Davidson & Barrett, 2003; Department of Sustainability and Environment, 2002). However, progress is slow at best. Alternative modes of transport, such as tram and train use, have been promoted to lessen the demand for costly, on-going but unsustainable development and maintenance of the road-transport system, as well as to reduce the adverse impacts of car travel on both the amenity of urban areas and on the environment in general.

However, modern society values highly the personal convenience and mobility provided by the private car, and will need tough incentives to shift towards other forms of transport. Strong economic incentives and, perhaps, changes in traffic regulations have some potential to make at least some progress but the political risks would be unacceptable to many governments. It could be argued that extreme or extraordinary circumstances may need to arise before any government would risk the almost-certain backlash of voters.

While it is contended that reducing exposure to crash risk for pedestrians by reducing vehicle use is somewhat unrealistic or, at best limited, for the foreseeable future, unless a major change in society in general or the transport system in particular were to occur (e.g., world oil shortage affecting fuel prices), it may be feasible to reduce particular types of driving, especially where pedestrians are at heightened risk. Drink-driving, illegal speeds, unsafe speeds within the speed limit, and driving while fatigued and/or using a mobile phone are examples of types of driving that place pedestrians at elevated risk. These categories of driving are exceptionally relevant to urban areas where pedestrians mix frequently with vehicles, along roads where vehicle speeds exceed 40 to 50 km/h. Legislation, promotion, publicity and enforcement that target these forms of behaviour have the potential to cut crash risk by reducing pedestrian exposure to these (and other) risky forms of driving.

In summary, efforts to reduce exposure to pedestrian crash risk, by reducing the amount of driving in general, are unlikely to succeed in present–day societies. However, measures which actively discourage or, indeed, prevent demonstrated, unsafe types of driving can have the joint effect of cutting both crash risk for a given level of exposure, as well as the actual levels of exposure.

3.2.5.1.2 The Pedestrian

Reducing the crash risk of pedestrians by reducing the amount of walking is also unlikely to be a desirable or acceptable strategy. All else being equal, less walking means an unhealthier society, with growing problems of obesity and related disease, a more polluted atmosphere (if walking is substituted with driving), with its accompanying forms of respiratory illness, and communities that suffer under the negative impacts cars and trucks impose. A loss of social connection, especially for the elderly, the mobility-impaired and otherwise disadvantaged members of communities, will adversely affect general health and well-being for people who depend on walking as their main mode of transport.

Thus, precise and insightful targeting of any behaviour-change initiatives to reduce the amount of walking is required to avoid unintended negative impacts. Such a strategy might therefore target, for example, hazardous forms of walking, including one or more of "drink-walking", unaccompanied road-crossing by older pedestrians or young children, crossing wide roads with high speed limits and high traffic volumes, and crossing roads during adverse weather or periods of low visibility.

3.2.5.2 Car Design Risk Factors

There are a number of possibilities for using car design factors to reduce exposure to crash risk and thereby offer greater protection to the pedestrian. To illustrate the possibilities, consider the use of in-vehicle technology to influence route choice by drivers so as to avoid pedestrian-sensitive areas, such as city centres or strip shopping centres through which arterial roads run.

Increasingly, vehicle manufacturers offer in-vehicle route guidance systems, which utilise Global Positioning Systems (GPS) to inform the drivers of modern vehicles how to reach their destinations by the optimum route, for a chosen objective function (Regan et al., 2001). Commonly available functions include the selection of the route that minimises travel time, number of stops, distance travelled, fuel consumption and vehicle emissions. Other objective functions could be developed based on pedestrian safety criteria, such that drivers are guided, where practicable, away from pedestrian-sensitive routes, in favour of other routes where pedestrian crash risk is demonstrably lower. While not reducing total exposure across the entire road system, such a strategy would target exposure reduction in high-risk locations, while also delivering environmental and amenity advantages, and enhanced safety in general.

When describing Layers 3 and 4, the possibility of using intelligent speed adaptation (ISA) was discussed. ISA has the potential to reduce kinetic energy at impact, as well as travel speed and, hence, crash risk (Regan et al., 2001). In addition to these possibilities, ISA might also be effective in reducing the number of vehicles using routes that are sensitive in terms of pedestrian safety. However, to be effective in discouraging the use of sensitive routes, it would be highly desirable for such routes to have lower speed limits than alternative routes (refer also to discussion of system operation risk factors below). The perceived increase in travel time resulting from the use of ISA combined with lower speed limits may well reduce vehicle volumes where pedestrians mix with vehicles and, hence, reduce exposure to crashes. Moreover, there would be an even more fundamental improvement in safety as a result of the effects of a lower speed limit on pedestrian crash and injury risks. Thus, substantial synergies could be expected.

3.2.5.3 Road and Roadside Design Risk Factors

Road and roadside design countermeasures present numerous possibilities to enhance pedestrian safety through exposure reduction, for a given level of risk. They include:

- Improved, more sensitive land-use planning practices, such as the development of regional shopping centres in lieu of strip shopping centres, the latter commonly being characterised by threatening vehicle speeds, and high pedestrian and vehicle volumes. Urban design practices, for example, that locate risky interactions in high-speed traffic situations to low volume, low-speed settings would likely assist. Specific examples include positioning public transport services, such as taxi ranks and bus stops, away from arterial roads, and encouraging/requiring courier and goods deliveries to be made to the rear of commercial buildings rather than via street front access. Each has the potential to reduce exposure to crash risk;

- Construction of by-pass routes around pedestrian activity areas to reduce pedestrian exposure to traffic;

- Traffic management initiatives to encourage traffic to use routes along which little pedestrian activity occurs. This can be achieved through traffic signal timings and phasing, turn bans, geometric design of intersections to facilitate selected movements and to discourage others, and through road capacity improvements or restrictions supportive of traffic management strategies.

3.2.5.4 System Operation Risk Factors

This section examines how the operational strategies and policies of the road-traffic system can be modified and refocussed to reduce pedestrian exposure to crash risk and, hence, to ultimately reduce the incidence of pedestrian crashes.

As with other countermeasures described above, the more realistic options for restricting vehicle volumes are to target particular locations, routes or areas, selected times of day or days of week, or to other circumstances of elevated pedestrian crash or injury risk.

On this basis, the following initiatives warrant assessment to determine their effectiveness as pedestrian crash or injury countermeasures:

- Implement lower speed limits (full-time, part-time or variable) in areas of high risk, such as strip shopping centres, schools, pre-school or child-care centres, parkland and recreational areas, central business districts, busy public transport centres and routes, hospitals, aged care centres and major sporting and entertainment precincts. Lower speed limits of these types have the potential to not only discourage drivers from using pedestrian-sensitive routes, where suitable alternative routes are available, but will deliver powerful reductions in crash and injury risk as a result of even small reductions in travel speeds;

- Review road functional definitions and classifications to reflect better the type of use that is made of roads in terms of both vehicles and roadside activity, and how these road user groups interact in reality. Road classifications that are more sensitive to the safety and mobility needs of pedestrians would formalise and facilitate the use of road infrastructure countermeasures that would otherwise be deemed inappropriate for use on arterial routes that are especially hazardous to pedestrians;

- Make innovative use of the considerable capabilities of traffic signals to encourage, prevent or discourage specific traffic movements in urban areas. Decisions on operational strategy by traffic signals designers and system operators can almost certainly be used to reduce exposure along pedestrian-sensitive routes and to redirect traffic to suitable alternative routes. Specifically, traffic signal phasing, timings, geometric design and signal linking strategies all have the potential to manage traffic on a system-wide basis so that exposure to crash risk can be managed with the special interests of pedestrians in mind.

  Today's sophisticated traffic signal technology can readily deliver this type of performance and flexibility, and is limited largely by operational philosophies applied by signal system designers and operators. In addition to traffic signal operation, other traffic system design elements could be adapted and used to reduce exposure where pedestrian crash and injury risks are high, and to redirect at least some traffic to alternative routes, where they exist or can be developed. Related to signal linking strategies is the choice of "green-wave" progression speed. That is, by offering drivers a reduced chance of stopping if they travel at a lower speed, both safety and efficiency may be enhanced.

- A number of major cities of the world, such as London and Singapore, have successfully introduced congestion pricing to limit the use of private cars in city centres and to also contain future traffic growth to sustainable levels. A direct consequence of these systems is the reduction in exposure to crash risk. As with other countermeasures that reduce vehicle volumes, it is important to ensure that pedestrian and other safety gains from reduced use of vehicles are not eroded by an increase in vehicle speeds as a result of freer flowing traffic. That is, speed management or other traffic-calming measures may also be needed to avoid the loss of safety benefits due to lower exposure to crash risk.

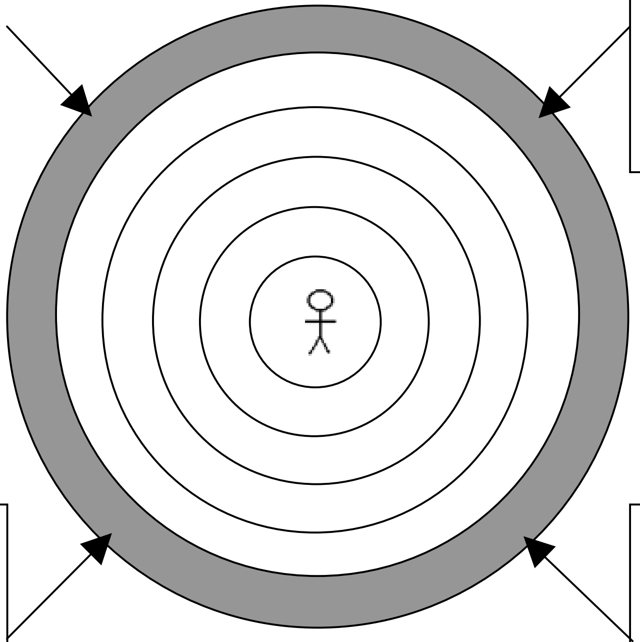
- Some European cities, including Amsterdam, have promoted cycling within city centres by providing bicycles for short-term use at no or low cost to workers and visitors. Such a scheme is under consideration by the Melbourne City Council as a means of reducing vehicle volumes within its central business area (City of Melbourne, 2004). A program of this type would benefit pedestrians by reducing their exposure to risk but would need to be assessed comprehensively to identify any unintended hazards that might result from such an initiative. One such concern might centre on a potential increase in conflict, and hence injury risk, between trams or other heavy vehicles, and bicyclists.

Human Factors

- disincentives for private-car use
- promote alternative forms of transport
- incentives for public transport use
- discourage/prevent risky forms of driving, e.g., drink-driving, speeding, mobile phone use;
- discourage/prevent hazardous forms of walking, e.g., drink-walking young/aged crossing wide, busy roads

Road and Roadside Factors

- pedestrian-sensitive land-use planning
- construction of by-pass routes
- traffic design and management to discourage traffic from using pedestrian sensitive routes



Vehicle Design Factors

- ITS to reduce vehicle exposure on pedestrian sensitive roads:
  - route guidance systems
  - intelligent speed adaptation (ISA)

System Operation Factors

Discourage drivers from using pedestrian-sensitive routes, by:

- lower speed limits
- review/revise road functional classifications
- innovative use of traffic signals and signal system operational philosophies
- congestion pricing

Figure 3.10 Layer 5: Reduced exposure to crash risk

4 THE VRM AS A FUNCTIONING MODEL

Much of the discussion of the VRM to date has centred on its conceptual structure and its potential to be used to identify countermeasure options, as well as research needs and priorities to create a safe pedestrian environment. This section describes how the model might be operationalised, so that countermeasures may be assessed and their effects on crash risk, injury risk or both may be quantified. The model aims to allow countermeasures to be assessed individually or in combination.

A challenge in the further development of the model concerns the diverse range of physical measures used to quantify biomechanical limits and how they can be used in practice to estimate changes in injury risk, as a result of countermeasures or other interventions to minimise or attenuate the level of kinetic energy reaching the pedestrian in a crash. As noted elsewhere in this report, there are clear advantages in using just one or two metrics that are both valid and relatively simple to use.

This study proposes the use of kinetic energy and crash probability, either singly for layers 1, 2 and 3 and for layers 4 and 5, respectively, or both metrics for all layers. If both metrics were adopted for all layers, the crash probability function in layers 1, 2 and 3 would simplify to a value of one. Considerable further work is required to develop the mathematical capabilities of the VRM. However, this work lies beyond the scope of the current study.

While there are advantages in the use of a small number of relatively simple metrics, this desire for simplicity should not compromise the validity and precision of the model. To illustrate this point further, the notions of kinetic energy and a probability (or likelihood) of a crash are relatively easy to understand, however, much of the literature on the biomechanical tolerance levels of humans is expressed in terms of a variety of physical variables. These include acceleration, force, delta-v, moment of force, etc.

To a degree, this variety of measures works against the aim of limiting the model to, say, kinetic energy and probability functions only. To overcome this difficulty it may be necessary, as part of further development and operationalisation of the model, to define mathematical relationships between *all* of the variables of relevance. For example, from a number of basic relationships derived from Newtonian mechanics, it should be possible, at least in some cases, to relate variables quantifying motion, force, mass, distance and time to the basic metric of kinetic energy. That is, by manipulating the following basic equations, the VRM may be able to function adequately with a minimum number of fundamental, meaningful metrics:

- $KE = \frac{1}{2} m.v^2$
- $Force = m.a$
- $Work = f.s = KE$
- $Acceleration = dv/dt$ (i.e., differentiation of velocity as a function of time),

where m = mass, s = distance, t = time, v = velocity, a = acceleration, f = force, w = work and KE = kinetic energy.

Operationalisation of the model, therefore, requires it to take on a numerical capability, whereby a countermeasure may be applied to a given circumstance and a new, measurable level of safety estimated. Within the scope and purpose of the model this requires definition and/or quantification of the following data items:

- input value of kinetic energy or pedestrian crash risk for each layer of the VRM;
- layer being assessed (i.e., Layer 1, 2, … 5);
- risk factor being targeted (i.e., human, vehicle, road infrastructure or system operation);
- description of countermeasures (e.g. pedestrian helmet, car bonnet design, ISA, etc);
- known (or estimated) effect of the countermeasure on the input level of kinetic energy or crash probability;
- referenced sources for the estimated effect of the model;
- estimated level of output from the model as a result of applying the subject countermeasure to the input level of kinetic energy or crash probability. Defining the output level for one layer automatically defines the input layer for the next layer in the sequence, moving from inner to outer layers of the VRM.

Thus, in summary, operationalisation of the model requires entry of the following data or other information:

- input to layer (output from previous layer)
- layer name
- risk factor category
- countermeasure description
- countermeasure target (crash risk, injury risk or both)
- estimate of risk reduction effect
- source of estimate
- output from layer (i.e., input to next layer)

As noted earlier, one of the main challenges for the model is to estimate numerically the reduction in kinetic energy and/or crash probability as a result of using the countermeasure. In the more complex cases, this estimate will be made independently of the operational model and the estimate entered within the model.

Given the characteristics of the model and the need for mathematical capability, a spreadsheet application was developed. In this form, the operationalisation of the model takes place in two stages:

- the first stage enables specific countermeasures to be assessed individually, one at a time;
- the second, more challenging stage, would enable selected combinations of countermeasures to be assessed to estimate the overall effect. If this can be successfully incorporated, the model will prove especially valuable in seeking synergies among compatible countermeasures.

Another important feature of the VRM must be taken into account in operationalising the model. A non-negotiable requirement of the model is that the human will not be exposed to kinetic energy (or corresponding mechanical forces) that exceeds human tolerance. Thus, in its operationalised form, the model will function in the opposite direction to conventional consideration of the effects of countermeasures.

To illustrate this more clearly, consider the circumstances whereby a pedestrian cannot withstand more than x KJ of kinetic energy when struck by a car. The application of a countermeasure (e.g., an energy absorbing structure on the front of the car) that reduces the amount of kinetic energy transmitted to the human by, say, one-third means that the kinetic energy at impact could be as high as 1.5 times greater (i.e., 1.5x KJ), without the biomechanical tolerance of the human being exceeded. That is, an impact value of 1.5x KJ upon the 2nd main layer of protection (namely the layer which reduced the transfer of kinetic energy to the human) is permissible because the “enhanced car bonnet” structure reduces the energy transfer to an acceptable value of just x KJ.

The model will, therefore, be structured so that the maximum permissible input value to the next layer will be calculated based on the successful application of a countermeasure of known effect.

4.1 MATHEMATICAL CAPABILITY OF THE VRM

Crashes and injuries in crashes are intrinsically probabilistic in nature and, therefore, it is important that the VRM captures an appropriate level of uncertainty in predicting crash and injury occurrence. As has been outlined throughout earlier sections of this report, both crash and injury risk are influenced to varying extents by the factors that characterise humans, vehicles, roads and roadsides, and the policies and practices that determine how the road-transport system will operate, especially with respect to travel speeds.

To create a model with a mathematical capability that enables changes in crash or injury risk to be quantified as a consequence of a countermeasure being applied or other intervention being introduced, it would be necessary to develop mathematical relationships between crash or injury risk (the dependent variables), and factors that significantly influence crash or injury risk (the independent variables). The development of such mathematical relationships, other than in the simplest cases, is outside the scope of the current study. However, the development of such relationships presents a potentially valuable but challenging area for further research.

Without such relationships, the VRM is limited to describing, in qualitative terms, what factors affect pedestrian crash and injury risk, the likely direction of any effects (i.e., beneficial or detrimental), and in a limited number of cases, quantifying the likely effects of a countermeasure in terms of the percentage change in crash or injury risk, or both. That is, it may not be feasible to accurately estimate changes in the absolute value of risk, using mathematical models of the form described above. It should, however, be possible to estimate changes in risk for countermeasures that have already been rigorously evaluated or otherwise assessed.

Thus, if the VRM is to offer significant mathematical capability to quantify changes in the risk of serious pedestrian trauma, a substantial research effort would be needed to develop the model(s). In the meantime, the VRM in its current form provides an insightful and generally comprehensive means of thinking about pedestrian safety, especially with respect to serious trauma. Quantifying the magnitude and direction of changes in risk to pedestrians, other than for a relatively small number of countermeasures used one-at-a-time, will be limited until further research has been undertaken.

The development of quantitative capability within the model can occur at a number of levels. First, the nature of the model encourages the quantification of model parameters, such as:

- The biomechanical tolerance of humans to impact forces;
- Attenuation of kinetic energy during a pedestrian crash;
- Minimisation of kinetic energy before impact in a pedestrian crash;
- Minimisation of the risk of a pedestrian crash, and
- Minimisation of exposure to pedestrian crash risk.

Secondly, within each of these model parameters are variables that are direct or indirect measures of the broader model parameters. For example, for biomechanical tolerance parameters, physical variables such as force, acceleration and delta-v (change in speed as a result of a collision) are commonly used to quantify changes in injury risk, while for parameters describing minimisation of kinetic energy at impact, mass of the impacting vehicle and speed at impact are the principal measures. Variables indicating changes in crash risk for a pedestrian, for a given level of exposure, include travel speeds of vehicles (McLean, 1994), road widths and sight distances (Corben & Diamantopoulou, 1996; Corben et al., 1999a; Oxley et al., 2001).

Another important requirement in quantifying changes in crash or injury risk is to define the outcome measures. Changes in the frequency of pedestrian fatalities, of pedestrian serious injuries, or of pedestrian casualties are commonly used measures. Much of the published literature in this area reports percentage reductions in these outcome measures. In other literature, changes in speed may be reported as a surrogate for changes in crash or injury risk, and in some cases, additional analyses are carried out to translate changes in speed into estimated changes in the basic outcome measures.

4.2 KNOWN COUNTERMEASURES AND THEIR EFFECTIVENESS

This section lists a *sample* of pedestrian crash or injury risk countermeasures and, where readily available from a brief literature search, measures of effectiveness (refer to Table 4.1). The countermeasures listed here represent just a few candidates for implementation and can also be included in future work aimed at developing the mathematical capability of the VRM.

Table 4.1 Some Examples of Pedestrian Crash and Injury Countermeasures and their Effectiveness

Risk Factor Addressed	Countermeasure	Effect of Countermeasure	Countermeasure Target	Reference/Source
Layer Number 1 - biomechanical tolerance of humans to impact forces				
Human Factors	Human bio-engineering	not known		
Human Factors	Medical/health programs to restore/ preserve biomechanical tolerances	not known		
Layer Number 2 - attenuation of kinetic energy during a pedestrian crash				
Human Factors	Pedestrian suit or helmet	not known		
Vehicle Design Factors	Car bonnet lifting	0.9	Reduction in HIC	Fredriksson, Haland & Yang (2001)
Vehicle Design Factors	Car bonnet and bumper airbags	0.93	Reduction in HIC	Holding, Chinn & Happian-Smith (2001)
Layer Number 3 - minimisation of kinetic energy before impact in a pedestrian crash				
Human Factors	Speed reduction of 5 km/h from 60 km/h	0.32	Reduction in ped fatalities	McLean et al. (2004)
Road/Roadside Factors	Roundabouts	80%	Reduction in ped injuries	Dijkstra et al. (1988, cited in Oxley et al. (2003)
Road/Roadside Factors	traffic calming - raised cross-walks	6.5 km/h	Speed reductions	Huang & Cynecki (2001)
Road/Roadside Factors	Central reserve	57% to 82%	Reduction in crashes with crossing pedestrians	Jensen (1999)
Road/Roadside Factors	Combined traffic calming	0.5	Reduction in avg. crash rate/yr	Steinbrecher (1992, cited in Oxley et al., 2003)
System Operation Factors	15 km/h lower speed limits	0.63	Reduction in ped crashes	Jensen (1999)
System Operation Factors	Speed reduction of 0.5-18 km/h	17% to 92%	Reduction in all ped crashes	Jensen (1999)

Table 4.1 Some Examples of Pedestrian Crash and Injury Countermeasures and their Effectiveness Cont'd …

Risk Factor Addressed	Countermeasure	Effect of Countermeasure	Countermeasure Target	Reference/Source
Layer Number 4 - minimisation of the risk of a pedestrian crash				
Human Factors	Education in high-risk zones	0.14	Older adult ped crashes	Oxley et al. (2003)
Vehicle Design Factors	Audible Warning Device	0.34	Reduction in ped crashes	Jensen (1999)
Vehicle Design Factors	Rear collision warning	29% - 90%	Reduction in reversing encroachment crashes	Oxley et al. (2003)
Road/Roadside Factors	Automated Pedestrian detection	89%	Reduction in traffic conflicts	Bechtel, Geyer & Ragland (2003)
Road/Roadside Factors	Flashing Crosswalk lights	80%	Avg reduction in crashes	Bechtel et al. (2003)
Road/Roadside Factors	Raised cross-walks	6.5 km/h	Speed reductions	Huang & Cynecki (2001)
Road/Roadside Factors	Traffic calming - roundabout	46% to 89%	Reduction in all ped crashes	Jensen (1999)
Road/Roadside Factors	Guardrails on central reserve or sidewalk	20% to 48%	Reduction in all ped crashes	
Road/Roadside Factors	Pedestrian overpass	85%	Reduction in crashes with crossing pedestrians	Jensen (1999)
Road/Roadside Factors	Side road pedestrian refuge with kerb	-50% to 27%	Reduction in all ped crashes	Jensen (1999)
Road/Roadside Factors	Signalisation of junction	0% to 70%	Reduction in all ped crashes	Jensen (1999)
Road/Roadside Factors	Street lighting	0.45	Reduction of ped injuries	Jensen (1999)
Road/Roadside Factors	Zebra crossing at non-signalised junction	-127% to 35%	Reduction in crashes with crossing pedestrians	Jensen (1999)
Road/Roadside Factors	Zebra crossing on road link	-50% to 50%	Reduction in crashes with crossing pedestrians	Jensen (1999)
Road/Roadside Factors	Barriers	33%	Decrease in adult casualties	Stewart (1988, cited in Oxley et al., 2003)
System Operation Factors	Exclusive pedestrian signal phase	7% to 63%	Reduction in all ped crashes	Jensen (1999)
Layer Number 5 - minimisation of exposure to pedestrian crash risk				
Road/Roadside Factors	General traffic calming	5-40%	Speed reductions	ETSC (1995)
System Operation Factors	Vehicle free zones	45-67%	Decrease in injuries	Danish Road Directorate (1988, cited in Oxley et al., 2003)

5 SUMMARY AND RECOMMENDATIONS

This project has involved the development of the Visionary Research Model whose principal aim is to define the current state of the road-transport system and how it should look and operate so that death and serious injuries due to road traffic crashes can be prevented. A key focus of the assessment of the model concerns its ability to assist with the identification of research needs and priorities that, ultimately, will lead to major breakthroughs in generating and developing countermeasures that can change fundamentally the risk of serious trauma. While the model is being assessed for its generic applicability to all categories of road trauma, it has been developed within this study specifically for the car-pedestrian conflict scenario.

5.1 RESEARCH NEEDS AND PRIORITIES

With these general aims in mind, it is recommended that pedestrian safety research concentrates, during the immediate future, in the following areas:

Risk Factors	Research Area/Direction
Layer 1 - biomechanical tolerance levels	
Human	Investigation and assessment of the capacity for health-based approaches, such as nutrition, exercise and strengthening, to raise or restore human biomechanical tolerance levels.
Vehicle	None
Road and Roadside	None
System Operation	None

Risk Factors	Research Area/Direction
Layer 2 – attenuation of the transfer of kinetic energy to the human	
Human	None
Vehicle	MUARC to continue its current research effort into the relationship between car design and pedestrian injury risk, with the longer-term view to stimulating design and purchase of vehicles with high safety ratings with respect to pedestrian protection in crashes.
Road and Roadside	Quantify the extent to which pedestrian serious injuries or fatalities are the result of the pedestrian falling onto the road pavement or striking roadside hazards after being struck by a vehicle. Subject to the findings of this research, further research could be undertaken to develop and assess deformable, energy absorbing pavement materials (or less hazardous roadside objects) for possible use in areas of high pedestrian crash risk.
System Operation	None

Risk Factors	Research Area/Direction
Layer 3 – minimise kinetic energy to be managed in a crash	
Human	1. Continue to support research (e.g., scientific foundations for TAC “Wipe-off-5” campaigns) that results in drivers affording speed a higher level of respect, and understanding more accurately the true relationship between speed and crash and injury risk, especially for pedestrians, and research that leads to lower travel speeds in pedestrian areas. 2. Investigate whether driver perception-reaction-times (PRT) can be reduced, and if so, ways in which this can be achieved where there is a high risk of severe injury to pedestrians.
Vehicle	MUARC to continue its current research effort into the use of in-vehicle ITS applications such as intelligent speed adaptation (ISA). Other ITS applications that result in reduced driver perception-reaction-time, reduced vehicle “perception-reaction-time” (i.e., leading to more rapid and effective application of vehicle braking systems in the event of a pedestrian conflict), or both, should also be investigated.
Road and Roadside	1. In hazardous pedestrian areas, undertake demonstration projects to evaluate the combined effects of lower urban speed limits and infrastructure design that supports lower speed environments and provides more effective and comprehensive separation of vehicles and pedestrians, while meeting aesthetic and environmental goals for urban settings. 2. Of special value would be an investigation and countermeasure development study aimed at ensuring pedestrians benefit fully from the intrinsically safer operation of roundabouts (due largely to the lower vehicle speeds at roundabout-controlled intersections). Enhancements to roundabout design and operation for all vulnerable road users are envisaged.
System Operation	Undertake a meta-analysis of the national and international literature on the effectiveness of lower vehicle speeds in reducing serious pedestrian trauma. This research activity would also aim to identify the most effective means for realising any trauma savings found elsewhere or within Victoria.

Risk Factors	Research Area/Direction
Layer 4 – minimise risk of a pedestrian crash for a given level of exposure	
Human	1. Continue to support research (e.g., scientific foundations for TAC “Wipe-off-5” campaigns) that results in drivers affording speed a higher level of respect and understanding more accurately the true relationship between speed and crash and injury risk, especially for pedestrians, and that leads to lower travel speeds in pedestrian areas. 2. Investigate ways of improving driver and rider compliance with speed limits through advances in the effectiveness of enforcement strategies and technologies. 3. Investigate whether driver perception-reaction-times (PRT) can be reduced, and if so, ways in which this can be achieved where there is a high risk of severe injury to pedestrians. 4. Review international and national literature on improving safe gap selection performance. 5. Review the literature on health-based opportunities for improving the performance of mobility-impaired pedestrians.
Vehicle	As per layer 3 for vehicle risk factors.
Road and Roadside	1. As per layer 3 for road and roadside risk factors. 2. Identify and assess all options for road-based ITS applications to achieve lower vehicle speeds in pedestrian areas. Potential of technology such as retractable speed humps, portable or fixed position speed indicator displays, variable speed limits and advisory travel speed displays should be assessed.
System Operation	1. As per layer 3 for system operation risk factors. 2. Undertake research aimed at strengthening Victoria’s overall approach to speed management, drawing upon the meta-analysis referred to above and to the basic laws of physics concerning vehicle braking distances and impact speeds with pedestrians. 3. MUARC to continue with Austroads-funded research aimed at reviewing and strengthening speed-zoning practices. 4. Evaluate the effectiveness of full-time 50 km/h speed limits in Victoria’s provincial cities and towns, and part-time 40 km/h speed limits in shopping strips of Metropolitan Melbourne and at schools throughout Victoria.

Risk Factors	Research Area/Direction
Layer 5 – minimise exposure to pedestrian crash risk	
Human	Review the published literature on health-based opportunities for developing safe alternatives to walking for people whose crash risk, injury risk or both are unacceptably high.
Vehicle	Investigate vehicle-based ITS to reduce exposure along pedestrian sensitive routes by encouraging or guiding drivers to suitable alternatives.
Road and Roadside	1. Prepare a state-of-the-art report on conventional and innovative approaches to land-use planning, with the potential to impact on pedestrian safety, positively or negatively. 2. Undertake a literature review of the effectiveness of by-pass routes constructed around provincial cities and towns, and other urban centres, with a view to quantifying their safety impacts, especially for pedestrians and other vulnerable road users.
System Operation	1. Investigate the potential for the innovative use of traffic signal control and linking strategies along selected routes to both promote traffic use on low risk routes and discourage traffic use on pedestrian-sensitive routes. 2. Undertake a literature review of congestion pricing schemes and their effects on traffic volumes using roads in congested cities of the world. Also assess the potential for applying such a strategy in Melbourne and its potential to reduce pedestrian crash risk. 3. Assess the potential for innovative, alternative modes of transport in major city centres, to reduce private vehicle use in these high pedestrian activity centres. A large-scale bicycle loan scheme funded by local government is one such example.

As has been evident in the discussion of various countermeasures, there is sometimes the possibility of unintended effects from the application of some countermeasures, in certain circumstances. For example, reducing pedestrian exposure to crash risk may involve eliminating extraneous traffic from some routes, which can lead to higher average travel speeds, as a result of less congestion. Higher travel speeds will generally lead to higher crash and injury risk, especially for pedestrians. However, the net effect of these two influences is difficult to determine objectively.

It is recommended, therefore, that the scope of any research projects should include, where relevant, assessment of both intended and unintended effects of potential countermeasures. Well-designed evaluation studies of implemented countermeasures will normally be capable of capturing the overall effect of a countermeasure (i.e., the combination of the intended and unintended effects), though estimating their individual effects may not be possible in many cases.

5.2 COUNTERMEASURES FOR EARLY IMPLEMENTATION

The VRM not only defines how the road-transport system should "look and operate" and identifies research needs and priorities to achieve its ambitious goal, but has an ability to identify new countermeasures and approaches, and assist in understanding more comprehensively how they work. The VRM indicates the direction of countermeasure effects, in some cases enabling the magnitude of these effects to be estimated, either singly or in combination with other countermeasures.

In relation to countermeasures and approaches that could be applied in the immediate future, the following options are believed to be capable of reducing, in a fundamental way, the risk of serious injury to pedestrians:

- Lower vehicle speeds, using a variety of road infrastructure, system operation (e.g., reduced speed limits in pedestrian areas), enforcement and other behaviour change programs, and in-vehicle technology such as intelligent speed adaptation. It is clear from this study that reduced vehicle speed can have a major effect on crash risk and a dramatic effect on injury risk. The chief reason for this vital relationship between speed and pedestrian safety lies in the basic laws of physics, as articulated mathematically in the second-power relationship between speed and the kinetic energy of a moving object (i.e., kinetic energy = $\frac{1}{2} mv^2$).

- Road infrastructure that provides both effective separation between pedestrians and vehicles, and vehicle speeds of around 30-40 km/h. Because of the spatially dispersed way in which pedestrian crashes tend to occur along arterial roads in shopping centres and other environments in which pedestrian mix with vehicles, it is important that countermeasures are comprehensive in their spatial coverage. Lower speed limits have this quality and, when applied in combination with other measures (which reinforce lower speeds, and provide comprehensive spatial coverage while improving separation between vehicles and pedestrians), synergies can be expected.

- Exposure reduction in the form of measures described above to reduce vehicle travel speeds, as well as initiatives to divert traffic to inherently safer alternative routes.

- Promotion of pedestrian protection features for vehicles.

5.3 FURTHER DEVELOPMENT OF THE VRM

Overall, the model, at its conceptual scale, is believed to offer great potential for accelerating progress towards a new, fundamentally safer road-transport system for pedestrians. With further development of its mathematical capability, the VRM will have the potential to predict quantitatively and qualitatively the effects of countermeasures and other interventions on the crash and injury risk for pedestrians in conflict situations with vehicles. Where there are important gaps in information and knowledge, the VRM will highlight the gaps and direct future research needs and priorities.

On the basis of progress made with this initial study, it is recommended that:

- Further work be carried out to develop and validate the quantitative capabilities of the model to enable changes in pedestrian crash risk, injury risk or both to be estimated as a result of countermeasures or other interventions;

- The model be applied in its present form to assist in understanding better the nature of crash and injury risk for pedestrians, including the identification of risk factors which offer the greatest potential for short- and medium-term gains;

- The VRM be applied to other categories of serious road trauma, such as side-impact, vehicle-to-vehicle crashes at intersections or crashes involving single-vehicles leaving the road and striking roadside hazards. Work to date on the VRM for pedestrian-car conflict suggests that the model has generic qualities that would enable it to be successfully applied to many other, if not all, categories of road trauma. Countermeasures to protect pedestrians reduce crash and injury risk for all road users, especially where reductions in travel speeds can be achieved.

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