MONASH University
Accident Research Centre

INTERSECTION STUDY
TASK 3 REPORT

DEVELOPMENT OF THE KINETIC ENERGY MANAGEMENT MODEL AND SAFE INTERSECTION DESIGN PRINCIPLES

Report prepared for VicRoads

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August 2010

Report No. 316c

MONASH UNIVERSITY ACCIDENT RESEARCH CENTRE
REPORT DOCUMENTATION PAGE

Report No.	Date	ISBN	ISSN	Pages
316c.	August 2010	0-7326-2386-3		62

Title and sub-title: INTERSECTION STUDY TASK 3 REPORT - DEVELOPMENT OF THE KINETIC ENERGY MANAGEMENT MODEL AND SAFE INTERSECTION DESIGN PRINCIPLES

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Sponsoring Organisations:
This project was funded by the Roads Corporation (VicRoads).

Abstract:
The Kinetic Energy Management Model (KEMM) was developed by MUARC as a conceptual model for defining and analysing the various factors influencing crash frequency and crash outcome severity. Five layers of "protection" are used to either prevent the crash (by deflecting energy) or mitigate its effects and limit the risk of serious injury to less than 10% (by absorbing energy). The KEMM concept is integrated with the four major risk areas in the Safe System: the human, the vehicle, the road and roadside, and system operation. In this study, the model was extended to analyse intersection crashes (model known as KEMM X) with the primary focus of better measuring the intrinsic safety of the intersection as a whole. The inner three layers of the KEMM-X, relating to the risk of serious injury or death, have been modelled mathematically to provide a tool for objectively quantifying the safety of individual conflicts within an intersection. Practical examples of risk reduction in each of the areas are provided.

Principles for safe intersection designs were then defined through the use of the model and are described in some detail in the body of the report:

1. Fewer vehicles;
2. Fewer intersections;
3. Fewer conflict points per intersection;
4. Impact speeds and impact angles constrained to biomechanically tolerable levels. i.e.,

a. For 90° collisions - impact (and, therefore, travel) speeds need to be less than 50km/h;
b. Where angle of impact can be somewhat reduced through layout design - impact speeds can be greater than 50 km/h but not greater than 70 km/h;
c. For conflicts between vehicles and unprotected road users (i.e. pedestrians, cyclists and motorcyclists), impact speeds should not exceed 30 km/h regardless of geometric layout, if pedestrian and cyclist risks of death are to remain below the nominated level of 10%;
d. Where the above speed and angle combinations cannot be met, crash risk must be reduced to a negligible level.

The subsequent stage of the long-term study is to assess existing intersection layouts in relation to the KEMM-X principles, and where possible embody the defined principles in to new, Safe System aligned intersection designs.

Key Words: Kinetic Energy, Intersection Safety, Kinetic Energy Management Model (KEMM), Safe System Intersection Designs, Intersection Design Principles, Biomechanical Tolerance

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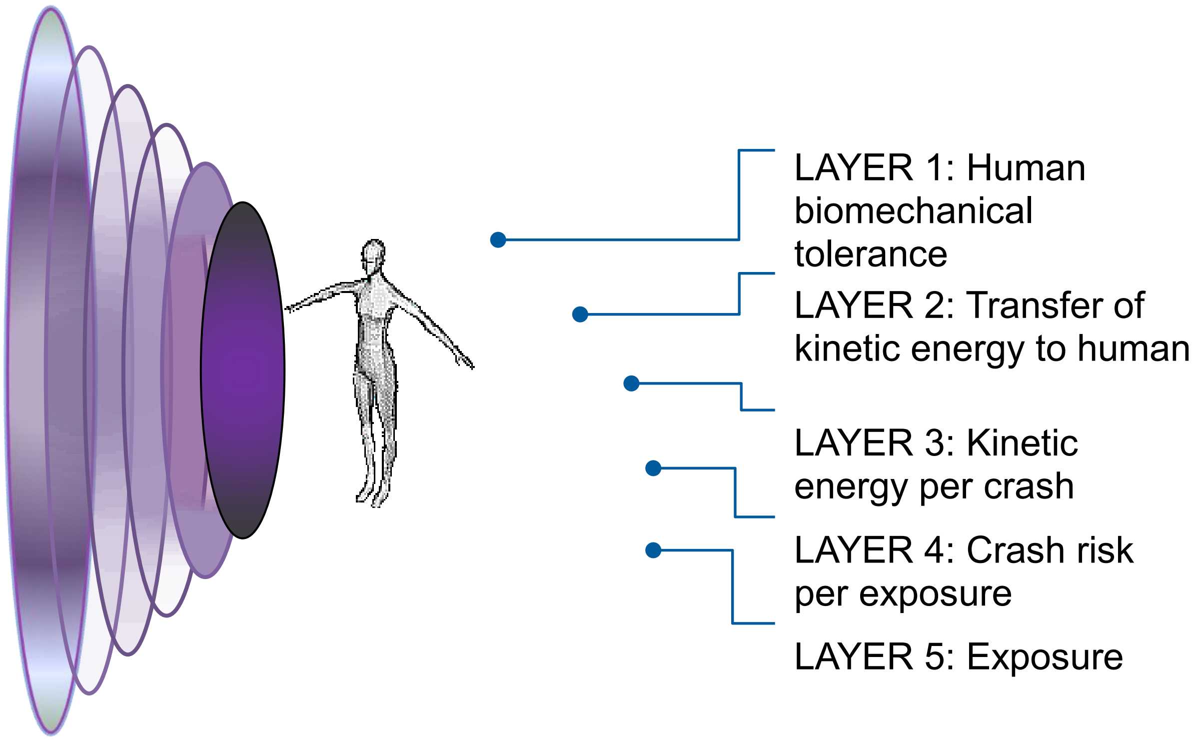
EXECUTIVE SUMMARY

Introduction

The primary goal of Task 3 is to develop design principles for Safe System performance of intersections, by developing an understanding of the Kinetic Energy Management Model and its potential to assist in evaluating fundamentally safer forms of intersection design, with injury prevention being the primary concern.

Kinetic Energy Management Model

The Kinetic Energy Management Model (KEMM) is introduced as a conceptual model for limiting the transfer of kinetic (motion) energy to the human to levels below those causing death or serious injury. Five layers of protection are used to either prevent the crash (by deflecting energy) or mitigate its effects (by absorbing energy).



- Layer 1, human biomechanical tolerance: minimisation of injury risk by understanding the tolerance of the human body to absorb energy. Intrinsic human tolerance levels vary primarily with age, health status, gender and stature.
- Layer 2, transfer of kinetic energy to human: management of the transfer of kinetic energy to the human during a crash. The effectiveness of this layer for a vehicle occupant is related predominantly to the performance of the energy-absorbing characteristics and safety features in modern vehicles.
- Layer 3, kinetic energy per crash: level of kinetic energy of the vehicle at impact during a crash. Lower travel speeds offer the greatest potential for

minimising levels of kinetic energy, with the reduction of mass also playing a role. Other relevant vehicle factors are braking effectiveness, and crash-avoidance systems, ABS-braking, brake-assist systems, and intelligent speed adaptation (ISA).

- Layer 4, crash risk given exposure: This layer and Layer 5 are targeted at crash risk reduction. Measures that influence the risk of a crash occurring are important to the performance of Layer 4, such as ISA and crash-avoidance systems. Changes to infrastructure can reduce crash risk by improving visibility, reducing complexity or reducing approach speeds.
- Layer 5, exposure: reduction in crash risk through reduced exposure to conflicts. Alternative intersection designs influence the performance of this layer, as well as initiatives at system level such as reductions in the number of intersections, or mode shifts from private motor vehicles to public transport. The use of advanced traffic control and management systems or traveller information systems can also be used to direct traffic along safer routes.

Layers 4 and 5 are not addressed in detail as the view has been taken that, while crash risk must be minimised whenever possible, the primary goal is to design intersections so that any foreseeable crash occurs below the biomechanically tolerable levels of humans. That is, the scope of Task 3 considers the inherent safety of an intersection in the event of a crash.

The KEMM concept is then integrated with the four major risk areas in the Safe System: the human, the vehicle, the road and roadside, and system operation. Practical examples of risk reduction in each of the areas are provided.

The inner three layers of the KEMM, relating to the risk of serious injury or death, have been modelled mathematically to provide a tool for objectively quantifying the safety of individual conflicts within an intersection. The model, known as KEMM-X, is introduced and the underlying relationships described, with the primary focus on better measuring the intrinsic safety of the intersection as a whole.

Design principles

The design principles have been developed within the context of the Safe System, Dutch Sustainable Safety and Swedish Vision Zero philosophies.

Based on the Victorian crash analysis and discussions with VicRoads, three intersection scenarios were selected for the focus of new designs:

a) signalised intersections of urban arterials;

b) sign-controlled intersections of urban arterials and local access roads and;

c) sign-controlled intersections between rural highways and low-volume side roads.

Four design principles were formulated and may be summarised as follows:

1. **Fewer vehicles** – by reducing the number of vehicles in use, fewer opportunities for collisions will arise;

2. **Fewer intersections** – by minimising the number of intersections within the road network, and concentrating more traffic movements at intersections with best-practice safety standards, fewer opportunities for high-risk conflict should arise;

3. **Fewer conflict points per intersection** – by simplifying intersections to produce fewer conflict points, the opportunities for crashes at a given intersection should fall. The resultant reduction in complexity should also have a positive effect on safety;

4. **Impact speeds and impact angles constrained to biomechanically tolerable levels** – by designing to create speed and angle combinations that result in a low risk of serious injury in the event of a crash. Analysis of the kinematics of traffic collisions shows that:

   - For 90° collisions, impact (and, therefore, travel) speeds should not exceed 50 km/h for vehicle-to-vehicle collisions. For conflicts between vehicles and unprotected road users (i.e. pedestrians, cyclists and motorcyclists), impact (and, therefore, travel) speeds should not exceed 30 km/h;
   - For intersections located in speed limits greater than 50 km/h and not greater than 70 km/h, vehicle-to-vehicle conflicts must occur at less severe angles than 90° to ensure that the biomechanical tolerances of humans are not exceeded. Regardless of geometric layout to influence impact angles, travel speeds in areas where pedestrian and cycle traffic is allocated high priority should not exceed 30 km/h if pedestrian and cyclist risks of death are to remain below the nominated level of 10%.
   - Where the above speed and angle combinations cannot be met, crash risk must be reduced to a negligible level.

Conclusions

These four principles will be applied in Task 5 and Task 6 of this study to guide the development of new designs and assess current designs. Designs will also be evaluated with the KEMM-X model to provide an objective level of safety for each.

ACKNOWLEDGEMENTS

The authors would like to thank the Victorian Government via VicRoads and the Transport Accident Commission for sponsoring this project and for the interest in this research.

MUARC would also like to acknowledge the collaboration with SWOV within the scope of the Memorandum of Understanding (MoU) between the two research. SWOV's investment in the project enabled Nicole van Nes to complete a one-year secondment at MUARC, which has been of great benefit to this project. We would also like to thank Prof. Kelwyn DaSouza from Hampton University for his contribution to this project during the sabbatical leave that he spent at MUARC.

Final thanks must go to Sujanie Peiris for her patience and diligence while spending many hours collating and incorporating the multitude of comments arising from the draft versions of this report.

1 INTRODUCTION

The primary goal of Task 3 is to develop a set of intersection design principles that meet Safe System aspirations. This was approached by gaining an understanding of the Kinetic Energy Management Model and its potential to assist in evaluating fundamentally safer forms of intersection design. Safety is of primary concern, with lesser emphasis on other design and operation considerations, although they are taken into account when appropriate.

1.1 Study background

A well-functioning road-transport system is vital to the well-being and prosperity of Australia. In the last decade, more than a quarter of a million serious injuries and approximately 17,000 fatalities have occurred on the roads in Australia (Department of Infrastructure, 2010). In 2009, there were 1,509 fatalities in Australia, of which 295 were in Victoria (Transport Accident Commission, 2010).

The crash data suggest that intersections are associated with a high proportion of the serious casualties that occur on the road network. Generally, intersections show a concentration of many types of frequently occurring conflicts, create threatening angles of impact and bring together a diverse range of road-user types and competing demands. Approximately 100,000 Australians have been seriously injured or killed in intersection crashes in the last decade. The data for Victoria suggest that slightly fewer than 50 per cent of all serious injury crashes occur at intersections (Vicroads, 2009). Intersection safety is now recognised as a major road safety concern not only in Australia, but also worldwide.

An intersection is, by definition, the area in which two or more roads or streets meet or cross at grade. Intersection design is a critical factor and can affect not only safety but also the capacity, general efficiency and operating costs of the traffic system or network. It is often suggested that the main goal of intersection design is to facilitate the safe and efficient movement of vehicles and road-users through the intersection. However, current approaches to intersection design and operation in most highly motorised countries are commonly driven primarily by capacity and performance considerations that prioritise vehicular traffic. Other objectives such as safety; the conservation of transport energy, the minimisation of harmful emissions and the needs of pedestrians and other vulnerable road-users are often given a lower priority.

Many of Victoria's long-standing Black Spot sites are intersections with a high standard of traffic signal hardware and operational software. This type of safety solution is often costly. Affording a higher priority to safe intersection design and operation at the outset would not only save lives and injuries, but would avoid the need to invest large amounts of public resources into accident Black Spot programs or other countermeasure strategies and programmes to rectify initial design deficiencies. Clearly there is a case for an urgent, fundamental review of safety in intersection design and operation.

Intersection safety is recognised as a major road safety concern, not just in Australia but worldwide. Quite recently, a number of countries have adopted a (new) approach to road safety that has the objective to prevent road crashes from happening, and where this is not feasible to reduce the incidence of (severe) injuries whenever possible. This can be achieved by a proactive approach in which human characteristics are used as the starting point: a user-oriented system approach. These characteristics refer on the one hand to human physical vulnerability and on the other hand to human (cognitive) capacities and limitations. People regularly make errors and are not always able to perform required driving tasks at an ideal level. Furthermore, people are also not always willing to comply with rules and violate them intentionally (e.g. speeding, red light running). By tailoring the environment (e.g. the road or the vehicle) to human characteristics, by preparing the road user for traffic tasks (by training and education) and by enforcing road rules, we can help build an inherently safe road traffic system.

In an inherently safe traffic system, provided driver compliance with the road rules is maximised, the responsibility is then on the organisations undertaking the design and operation of the traffic system.

The key principle is to redesign the transport system to accommodate human vulnerability, thereby making traffic safety an integral component of the road transport system (Racioppi, et al. 2004). This type of approach focuses specifically on the management and control of dangerous levels of kinetic energy and the effectiveness of measures that make the overall road transport system safer.

The project titled, "Intersection Safety: Meeting Victoria's Intersection Safety Challenge", has the following main objectives:

- To analyse key road safety problems at intersections ;
- To fundamentally improve intersection safety through innovation, including modification of existing infrastructure design and operation;
- To take a multifaceted and multidisciplinary approach to existing problems in order to find new sustainable solutions;
- To critically review existing intersection design and operation principles ;
- To develop, test, demonstrate and evaluate new intersection designs and based on useful and valid principles, concepts and philosophies; and integrate these into existing practices;
- To achieve sustainability: All transport system objectives must be considered (safety, traffic system performance and environmental impact);
- To help provide input to Australia's road safety strategy and the Victorian "arrive alive" strategy with regard to intersection safety based on Safe System principles.

This project currently comprises three main stages and ten key tasks. The tasks are intended to advance knowledge in ways that will assist VicRoads in achieving early implementation of the findings. The tasks within each stage have been described sequentially but may, in some cases, be carried out in parallel.

Table 1. Outline of Intersection Safety project

Stage 1	Task 1	Problem definition
	Task 2	Review of literature
	Task 3	Development and definition of design principles for safe intersections
	Task 4	Practitioner and stakeholder workshop 1
Stage 2	Task 5	Incorporate principles into practical intersection designs
	Task 6	Feasibility assessment and prioritisation
	Task 7	Practitioner and stakeholder workshop 2
Stage 3	Task 8	Performance Assessment of Design Principles
	Task 9	Trial Implementation, Demonstration and Evaluation
	Task 10	Information Dissemination

There are hold-points after a number of key tasks and at the end of each stage. Discussions regarding the work that has been carried out and the future direction of the project will be held between Monash University and VicRoads. Other stakeholders may be invited to attend these meetings.

So far Task 1 on the crash analyses and Task 2 on the literature review have been completed. A short summary of the main findings and conclusions of each of these tasks is provided, with the full reports available from MUARC upon request.

This report documents the findings of Task 3, which aimed to develop a set of guiding principles to achieve safe road traffic operation at intersections. These principles are based on scientific reasoning and sound research methods arising from relevant disciplines such as physics, psychology, biomechanics and traffic engineering.

In summary, there is a large and long-standing problem of severe road trauma at intersections in Victoria. It appears that the opportunities to address this through current design and implementation approaches have been largely exhausted and that, to take a significant step towards the achievement of Safe System performance at intersections, a new way of thinking about intersection design is required. This project, and in particular Task 3, explores the opportunities to develop new design principles to assist Victoria to achieve a fundamentally safer road transport system. Nowadays, with the growth in motor traffic over recent decades and the relatively high speeds that continue to prevail, current approaches are no longer able to provide acceptable levels of safety.

1.2 Task 3 – Development of design principles

The aim of this phase is to generate a set of intersection design principles that meet Safe System aspiration by gaining a basic understanding of the Kinetic Energy Management Model (KEMM) and its potential to identify and resolve specific types of intersection safety problems, primarily through fundamentally safer forms of design. It is envisaged that fundamental changes in intersection design and operation can bring about major improvements in road safety through the reduction and eventual elimination of fatalities and serious injuries in the road transport system.

Safety is of primary concern in this report. The main focus is on the effectiveness of designs and safety improvement treatments. Less emphasis is given to implementation costs, mobility, accessibility and environmental sustainability, but they are recognised when appropriate. In a later stage, cost-benefit analysis could provide a means to identify important measures that maximise safety benefit while maximising system operation and keeping infrastructure investment costs to a minimum.

This report also aims to identify design principles for Safe System intersection designs by gaining an understanding of the KEMM as well as through analyses of existing intersection designs. These design principles are the starting point for the development of innovative intersection designs and new ways to operate the road-transport system with the potential to dramatically accelerate progress in intersection serious trauma reduction in Victoria.

1.2.1 The design process

A design process was adopted for the entire project that originated in the industrial design field, starting from the definition of the problem, moving to a problem analysis, establishment of design principles, through to the design itself, detailing, testing and implementation. It was recognised that the design process should be iterative, such that at each step the need for feedback be evaluated and, if necessary, earlier stages in the design process be revisited.

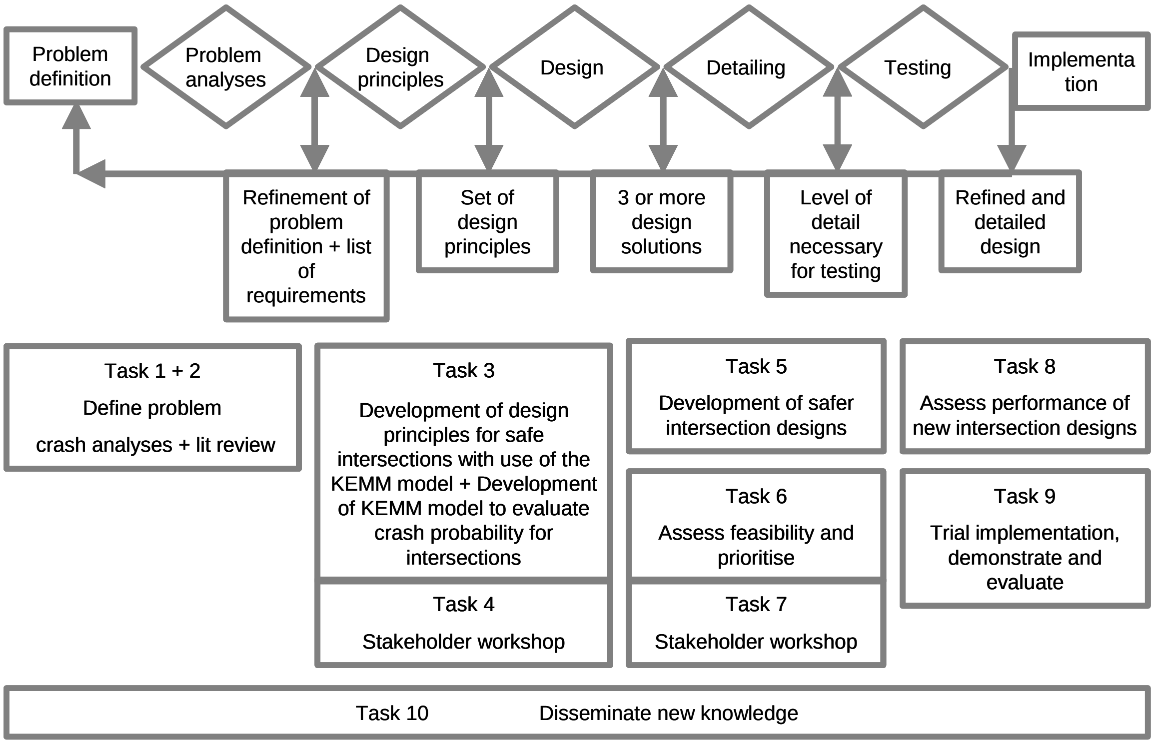


Figure 1. The design process, adapted for the Intersection Study.

Figure **Error! Reference source not found.** shows how the design process for this project integrates with the well-established process used in industrial design: the problem was defined and analysed in terms of the crash types and areas of intersection safety that require focus and the project aim was defined as identifying intersection designs that address these problems. In order to generate such designs, principles were established for safe design. Designs that adhere to these principles were then highlighted, with some level of iteration employed to ensure the design principles and designs remained compatible with the original problem definition. Detailed design and testing are to follow once trial designs are selected. This report, Task 3, constitutes the establishment of a set of design principles.

1.3 Report outline

This report attempts to capture the process required to systematically dissect the problem of crashes at intersections, using the Kinetic Energy Management Model (KEMM). It then presents outcomes of research identifying the key elements required to produce a road system that minimises the likelihood of a serious injury, given the occurrence of a crash.

The report will first provide a brief summary of Tasks 1 and 2 then introduce the KEMM in general terms, followed by a discussion of the application and modification of the KEMM for intersections. In Section 1 the mathematical modelling of the KEMM is described and modelling software KEMM-X introduced. Section 5 discusses the development of the design principles based on the KEMM-X together with a discussion of safety principles known from literature. The report concludes with a discussion of the results.

2 SUMMARY OF MAIN FINDINGS TO DATE

2.1 Task 1

Victorian casualty crash data for the period January 2000 to December 2007 were provided by VicRoads for use in this study. Due to changes in the Victoria Police crash data collection system, introduced in late 2005, a discontinuity in the data resulted which does not allow for the reliable comparison of trends in the period prior to December 2005 to the period post-December 2005. Therefore, the decision was taken to rely primarily on an analysis of data covering the period 2000 to 2005.

The broad aim of the analysis was to identify and obtain an overall indication of the extent of the problems associated with serious casualties resulting from intersection crashes. More specifically, the study examined the distribution of serious casualties by several variables including crash type (using the Definition for Classifying Accidents (DCA)), time-of-day, day-of-week, intersection type, traffic control type, road class, speed zone and locality (urban versus regional). These variables were examined at an aggregate (six-year) level using descriptive analyses and by looking at time trends over the six-year period. Injury distribution resulting from serious casualty intersection crashes compared to all crash types was also examined.

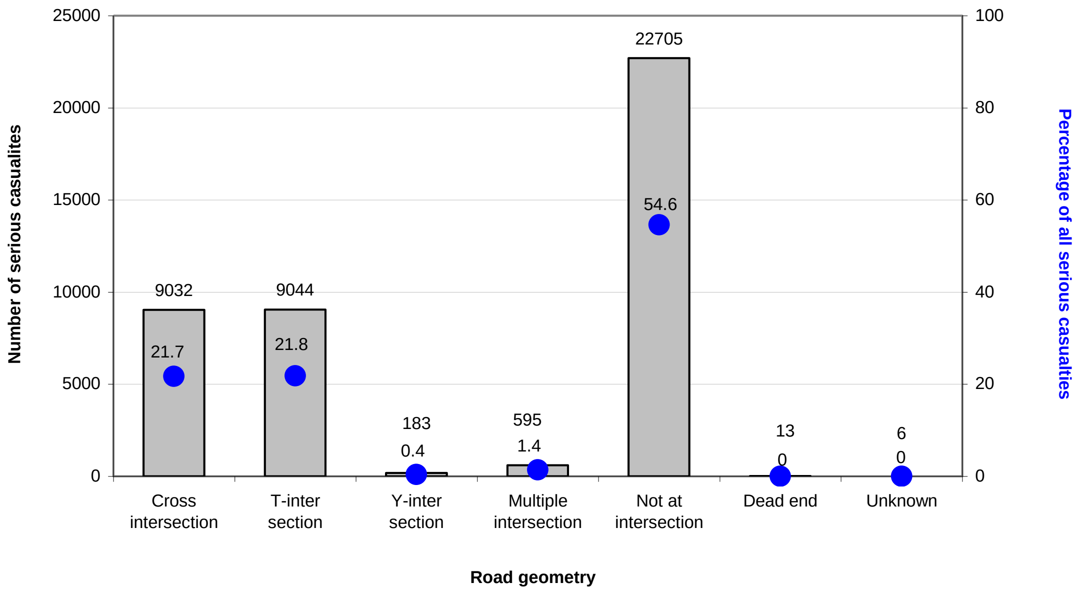


Figure 2(a). Number and percentage distribution of serious casualties at all road geometries, 2000-2005

Analysis of serious casualties in Victoria found almost 50% were killed or seriously injured at intersections and of these, similar proportions (around 20%) were distributed between cross-intersections and T-intersections. The remainder were at multiple-leg and Y-intersections (Figure 2(a)).

This proportion of serious casualties occurring at intersections has remained at around 45-46% over the five-year period between 2000 and 2005.

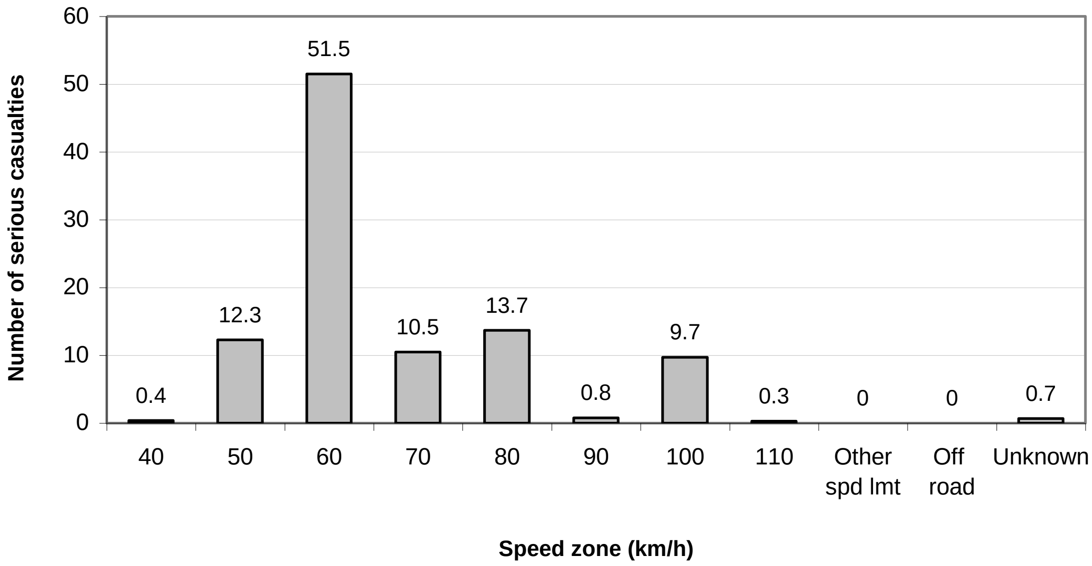


Figure 2(b). Percentage distribution of serious casualties at intersections across speed zones.

The largest proportion of serious casualties occurred in 60 km/h speed zones (invariably indicating an urban setting), with around half of all serious casualties at intersections occurring within this zone (Figure 2(b)). However, 60 km/h is also recognised as one of the more common speed zones in the road network, in terms of vehicle-kilometres travelled and, hence, is likely to be associated with a high number of crashes and serious injuries. Regardless of the reason for such a high proportion of serious casualties occurring along 60 km/h roads, these crashes are a major target for reduction. Similarly the "main roads" road classification, typically with speeds of 60 km/h, was associated with a greater proportion of serious casualties, followed by local roads and then highways. Almost half of the crashes occurred at intersections with "no controls", which were assumed in this project to include crashes at intersections where the type of intersection control was interpreted by the reporting police officer to be largely unrelated to the crash type being reported. For example, a single-vehicle collision at intersection signals may be interpreted as 'no control' given that signals may be viewed as irrelevant in controlling a single-vehicle collision. It was found that a quarter of serious casualties occurred at traffic signals.

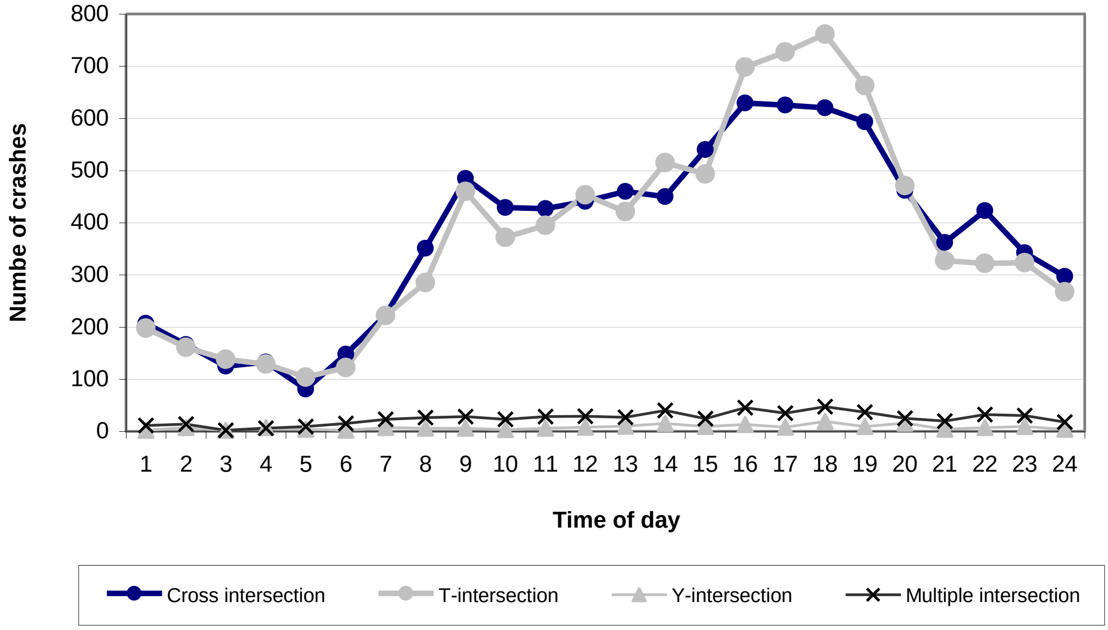


Figure 2(c). Percentage distribution of serious casualties at intersections by time of day

In terms of crash characteristics, Sundays had the lowest incidence of serious casualties, with this proportion increasing gradually over the week to peak on Fridays, Fridays having around a 40% higher crash incidence than Sundays. Peak time for crashes coincided with the afternoon peak period, regardless of intersection geometry, with the highest incidence of serious casualties occurring between 1600 and 1900 hours (Figure 2(c)).

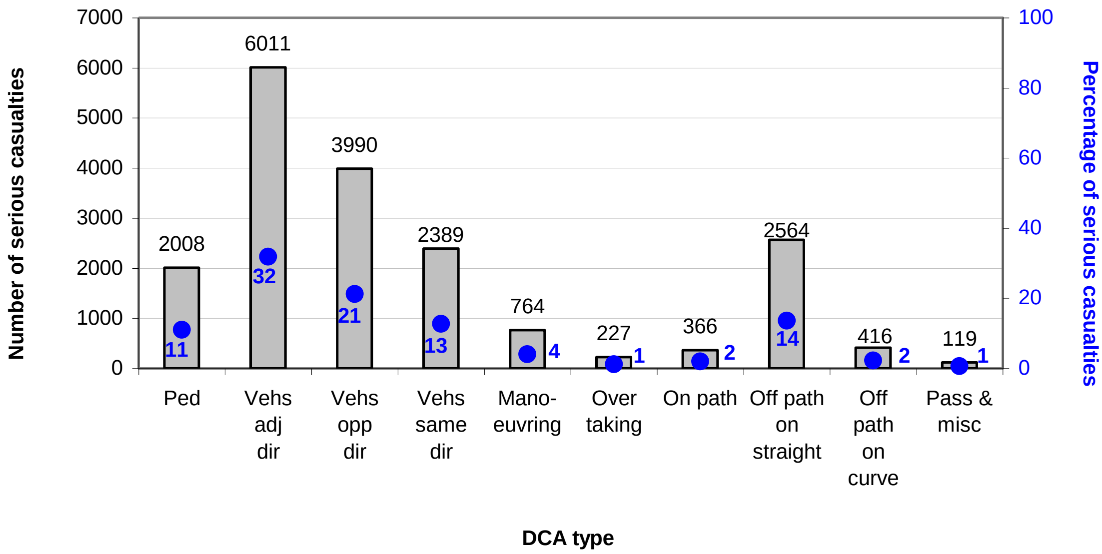


Figure 2(d). Frequency and percentage distribution of serious casualties by DCA type

The major crash types producing serious casualties were vehicles travelling from adjacent directions. Typically these were right-angle crashes, as well as drivers turning right from a side road and being hit by a vehicle on the main leg approaching from the right. It should be noted that in interpreting these results, traffic in Australia is required to travel on the left-hand side of the road. Next most common were vehicles from opposing directions, involving a driver turning right across the path of at least one oncoming vehicle. These two crash categories comprised half of all crashes producing serious casualties at intersections. The remainder included drivers losing control of vehicles at intersections, vehicles colliding while travelling in the same direction i.e., rear-end crashes, followed by pedestrian crashes (Figure 2(d)).

As a result of the analyses, described only in part in this paper, it was concluded that subsequent tasks in this research project should focus on intersections with one or more of the following crash types producing serious casualties:

- cross-traffic (including collisions involving at least one turning vehicle);
- right-turn-against;
- off- path on straight-alignment at an intersection;
- rear end crashes; and
- crashes involving pedestrians.

Based on this analysis the main focus of the project was on intersections in 60 km/h speed zones, intersections with cross- and T-geometries, and intersections controlled by traffic signals, stop signs or give way signs. Such a focus will potentially allow substantial reductions in the total number of serious casualties to be achieved, provided approved new designs can be developed and implemented.

2.2 Task 2

2.2.1 Current Research within Project Scope

Review of publications in the field suggests that creating safe intersections is recognised as an integral part of achieving overall road safety and most of the key international organisations appeared to be involved in some form of intersection safety research. However, there seemed to be little research related to the specific aims of this project. It is hoped that ongoing international collaboration will highlight any other related projects.

2.2.2 Existing Treatments

Findings fell into several categories, including policy changes, changes to geometry, speed reduction measures, crash prevention technology and measures to improve road user behaviour. Most treatments were not especially innovative, but are presented here as examples of treatments.

Among the proposed changes to safety policies were: discussions on the incompatibility of 90-degree geometries with the Safe System philosophy; general review of design guidelines required to better align long-established design aspects with current ‘best practice’ thinking; and challenging the existing operational and legal speeds on the road network.

The key role of speed limits in intersection safety was addressed in a wide variety of articles dealing with the influence of limits on driver speed choice. Kronqvist (2005) considered several scenarios for inducing speed reductions by drivers and found the placement of rumble strips in conjunction with reduced posted speed limits may be effective. Another study on speed found that transverse lines bordering traffic lanes can perceptually influence drivers into believing travel speeds are higher than actual (Fildes *et al.*, 1994, Mulvihill *et al*., 2008), though the longevity of this effect was questionable. A study by Ragnay (2007) found that reducing the speed limit by 10 km/h reduced mean travel speeds and crash occurrence. Driver warning systems were also found to be an effective means of addressing excessive speed (Winnett and Wheeler, 2002). A study incorporating a number of trials of fixed and vehicle-activated signs (VAS) found that the former were not as effective in reducing speed and VAS brought about speed reductions of around 4 mph (~6-7km/h). The findings did not suggest that the effect would diminish over time.

Many countries have tried a different approach to traditional traffic engineering, counter-intuitively removing all controls from a low volume intersection and evaluating its effect on driver behaviour. The Netherlands, Denmark, Belgium and Germany have trialled the 'shared space' concept where the onus is on the driver to take responsibility in negotiating the intersection safely. This involves removing signs, traffic controls, line-marking and forms of kerb delineation with the intention of making drivers more cautious, allowing individual road users to have eye contact with other road users and responsibly drive through an intersection. This form of operation contrasts with the belief that one stream of traffic has right-of-way, which may have the effect of legitimising the behaviour of drivers who proceed through the intersection without appropriate care. These redesigns are reported to generate more pedestrian and cyclist activity (Keuninginstituut, 2008).

Infrastructural means of inducing reduced speeds involved the standard roundabout, which aligns well with Safe System principles, as well as raised intersections and elevated stop-lines, where the road surface just before the stop-line is raised (refer to Figure 2). The use of "Intersection Speed Limits" was also considered (Candappa and Corben, 2006); in this case, at an appropriate distance before reaching the intersection, default intersection speed limits would be introduced in an attempt to ensure impact speeds, in the event of a crash, do not exceed biomechanically-tolerable levels, (i.e., approximately 50 km/h in a right-angle collision between two cars).

Some alternative roundabout designs were also identified. While the safety benefits of conventional roundabouts are well-established, the safety benefits of variants on the basic roundabout design have not been reported in the literature. The literature also shows that unless explicit attention is paid in the design to the needs of pedestrians and cyclists, these more vulnerable road users may be exposed to undesirable levels of risk (Fortuijn, 2003; Hels & Orozova-Bekkevold, 2007). One of the common concerns with roundabout operation is the effect of unbalanced flows where vehicle volumes are high. A Dutch variant of the roundabout, however, addresses concern that capacity and traffic movement will be affected detrimentally in some circumstances by roundabout construction. The 'Turbo' roundabout design is used increasingly in the Netherlands at roundabouts with more than one lane. The design involves vehicle paths for through, right-turning and left-turning traffic being separated and more clearly defined. This reduces confusion and hesitation among drivers and aids smooth flow through the intersection, while still providing the safety benefits of roundabouts. Moreover, the physical separation between circulating lanes within the roundabout impedes excessive travel speeds, otherwise of concern on multi-lane roundabouts.

A City of Port Phillip design in Melbourne, Victoria also looks at improving safety and convenience for the pedestrian at roundabouts by accentuating pedestrian crossings and providing right-of-way to pedestrians. An evaluation undertaken on this roundabout design found that both pedestrian safety and convenience could be expected to increase through utilisation of this enhanced design (Candappa et al., 2005). The literature review also indicated that staggered-T intersections were preferable to cross-intersections (Vadeby and Brude, 2006), though it should be noted that the staggered-T designs are not ideal from the viewpoint of Safe System principles, as at high speed, side impact crashes are still possible with this geometric configuration.

Crashes involving right-turners are among the most common and severe crash types at intersections in Victoria. Several designs exist that seek to minimise crash risk and, in particular, eliminate the need for a right turn (equivalent to a left-turn in the US and other countries where driving occurs on the right-hand side of the road). In theory, designs that eliminate the right-turn conflict are promising as they utilise some of the above concepts of more favourable (generally lower) conflict angles and lower speeds at the point of conflict. In practice, the designs require significant road space, and remodelling of the intersection which can impede their use in urban settings. One crash reduction approach used in the USA and Canada, but not in Victoria, is the All-Way Stops, which has the potential to reduce approach and impact speeds, and allows greater time for driver gap selection (FHWA, 2003). One means of minimising crash risk involves banning a movement, creating one-way roads and placing markers at evenly spaced intervals to provide guidance on the approach speeds of vehicles.

In-vehicle technology is gradually expanding the means by which drivers are provided with information that can better alert them to potential or imminent collisions, and assist drivers with negotiating an intersection or road length. The EU INTERSAFE Project, IP PreVent, has considered a number of technologies, including driver warning systems, traffic light assistance, turning assistance and right-of-way warnings (Fürstenberg & Rössler, 2006). No evaluations had been published at the time of the review. By alerting the drivers of hazards ahead, increased reaction time is provided allowing extended stopping distances or evasive action to be taken or, at worst, resulting in reduced crash impact speeds. Intersection Collision Warning Systems and Driver Safety Support Systems are other examples of this form of technology.

An important observation from the literature review is that there is little attention to the needs of road users other than vehicle drivers and occupants. Further, the review concluded that overall, there are few research projects currently in progress with similar aims and scope as this project. While there were a number of potential designs that were generated through the review, many designs appeared impractical because they required large areas for successful implementation or because of the need for extensive remodelling of the intersection. Some of the potential innovative measures included raised platforms, intersection speed humps, All-Way Stops signs, intersection speed limits and line-marking to aid driver gap selection.

3 THE KINETIC ENERGY MANAGEMENT MODEL FOR INTERSECTIONS

The Kinetic Energy Management Model (KEMM) is introduced as a conceptual model for limiting the transfer of kinetic (motion) energy to the human to levels below those causing death or serious injury. Five layers of protection are used to either prevent the crash (by deflecting energy) or mitigate its effects (by absorbing energy).

The KEMM concept is then integrated with the four major risk areas in the Safe System: the human, the vehicle, the road and roadside, and system operation. Practical examples of risk reduction in each of the areas are provided.

3.1 Conceptual description of the KEMM

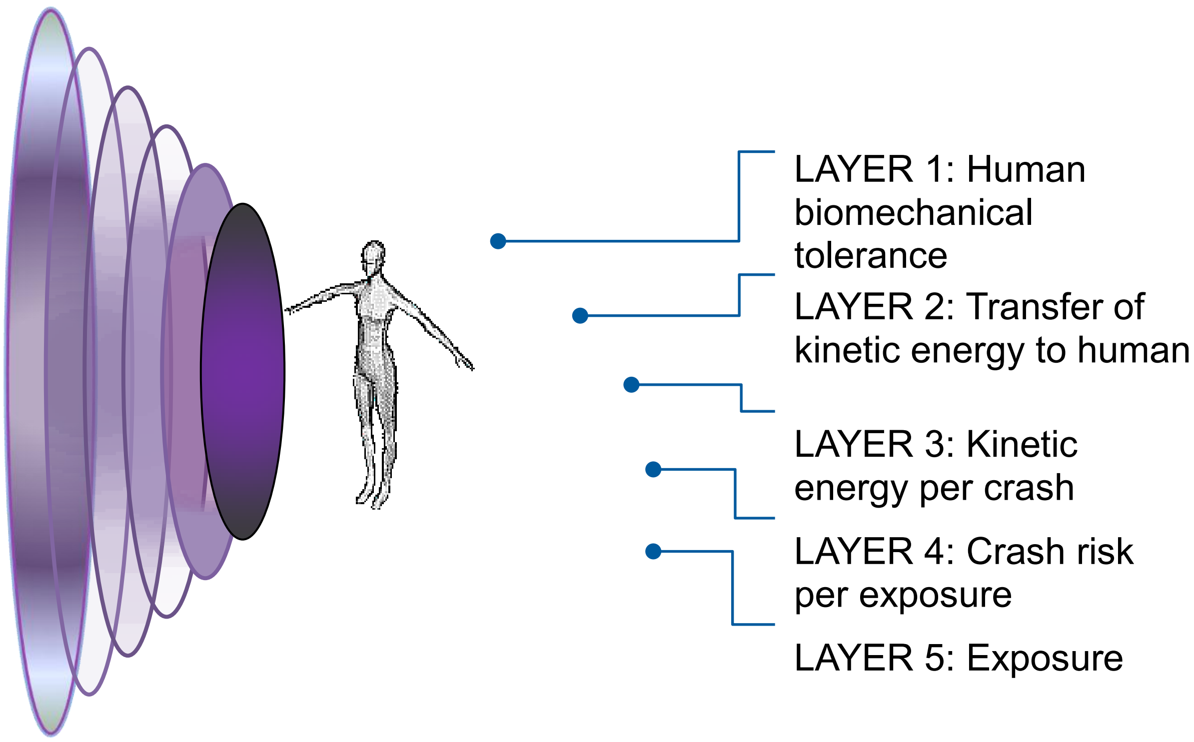


Figure 3. The five layers of protection of the KEMM

A unique and defining feature of the Kinetic Energy Management Model (KEMM) is the absolute requirement that the levels of kinetic energy to which a road-user is exposed should not exceed those that can be tolerated by the human body. The human is situated at the very centre of the KEMM and must be protected from serious injury or death, either by preventing the occurrence of a crash or, if a crash is unavoidable, by managing the transfer and exchange of kinetic energy upon impact. The KEMM introduces the notion of protective layers surrounding the human. These layers describe the types of crash and injury risk involved. A diagrammatic representation of the model is shown in Figure 3.

In the context of this project, the KEMM will be used to investigate particular types of intersection crashes and how design and operational factors might be configured to prevent or eliminate crash and injury risk. One of the strengths of the KEMM is its ability to quantify the safety levels of different intersection designs in order to be able to compare the safety performance of different designs. A specific aim of the KEMM is to show how crash and injury risk for road-users in specific types of conflicting situations at intersections might be fundamentally improved through specific countermeasures or alternative designs. The KEMM considers many of the practical issues faced by decision-makers and traffic planners and transport engineers.

The KEMM is perceived to have a number of general and more specific uses, including:

- Improving our understanding of the factors that influence crash and injury risk, the relative importance of these factors and how they might be moderated, or changed in a fundamental way, to enhance road-user safety;
- The ability to assess the effects, both qualitatively and quantitatively, of particular countermeasures and other interventions;
- To help gain a deeper understanding of the overall effects of applying two or more countermeasures simultaneously, in terms of combined and interactive effects;
- Enabling the safety effects of site-specific improvements to be assessed before they are implemented, thereby raising the cost-effectiveness of treatment programs;
- Enabling system-wide interventions to be assessed in terms of their general effects or the specific effects on high-risk categories of road-users, such as the young, the elderly or the intoxicated; and
- Generating research ideas and priorities, and identifying countermeasure development possibilities.

These benefits and others can be realised by ensuring that the KEMM has an appropriate structure that incorporates valid relationships between the various elements that are included. The model does not only incorporate a descriptive (qualitative) capability to facilitate an estimation of effective changes in crash and injury risk, but also a mathematical (quantitative) capability (Section 1).

3.2 The five protective layers of the KEMM

The KEMM consists of five concentric layers of protection around the centrally placed human. Consistent with the analogy of protective layers is the notion that thicker layers afford greater protection than thinner layers. The three layers located in the innermost zone of the KEMM represent attenuators of kinetic energy and/or other types of energy. Thicker layers imply greater energy attenuation properties and lower levels of kinetic energy that are eventually transferred or exchanged with the human on impact (i.e. lower injury risk). The two outermost layers represent crash probability in relation to exposure. Thicker layers again imply a greater level of protection, which in this case means lower crash risk.

The key aims of the five layers are summarised below:

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

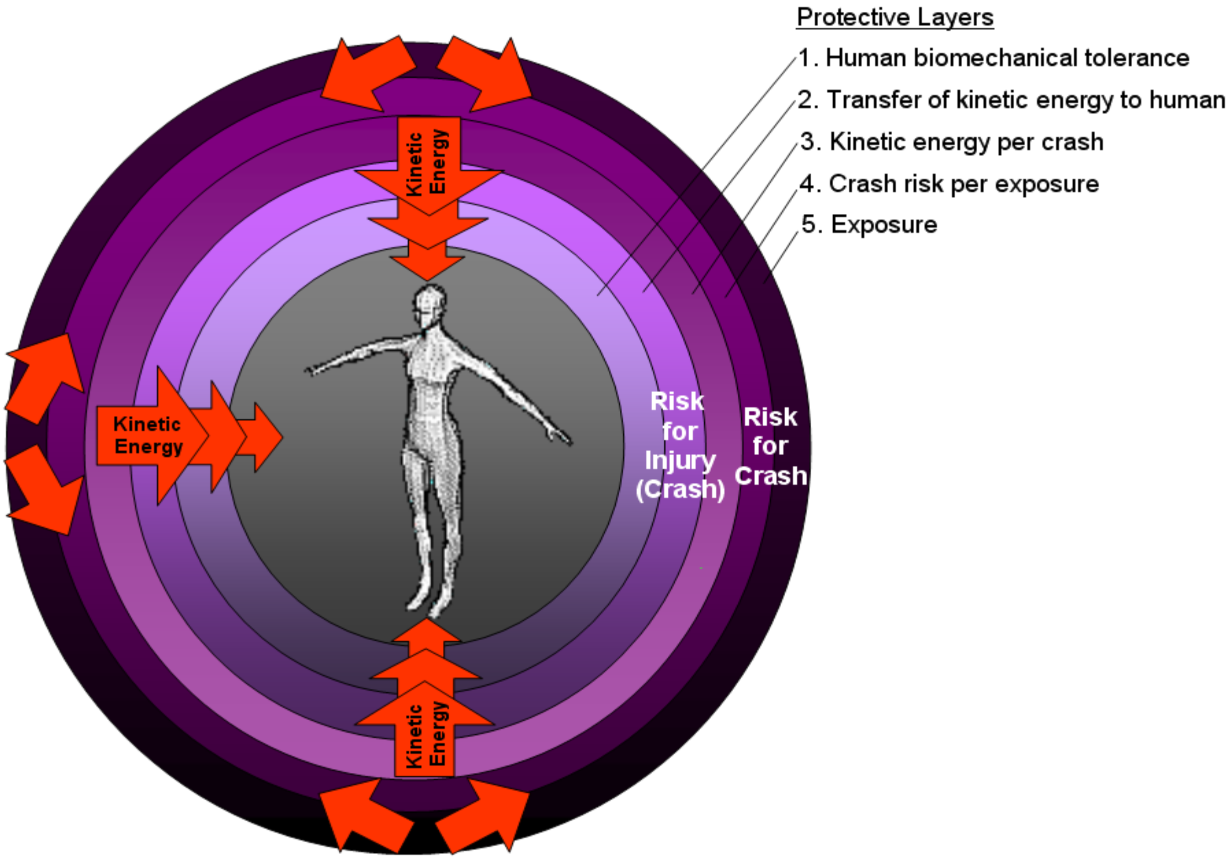


Figure 4. Kinetic energy and the five layers of protection in the KEMM

Within each layer, specific areas of protection can be identified that have the potential to be 'managed' to improve safety for the human. Figure 4 depicts the circumstance of a road user (vehicle occupant, pedestrian, etc.) threatened by the kinetic energy of an approaching vehicle and the layers of protection that must ensure that the kinetic energy reaching the person is below the level that leads to death or serious injury.

To be able to define the various layers of protection in the KEMM required to ensure that a human has minimal risk of death or serious injury in a traffic crash, it is important to first define the specific elements posing a threat. Given the structure of the KEMM it is appropriate to begin by examining the crash phase and how energy is transferred or exchanged between a vehicle and the road-users involved in a crash situation. Road-users can include those inside the vehicle such as the driver or passengers, but also persons situated outside the vehicle such as pedestrians or cyclists. Generally, collisions are only likely to result in serious injuries to humans if there is a sufficient velocity (and resultant acceleration during impact) and mass involved. Injuries can be sustained even at low speeds, particularly if the road-user is especially vulnerable due to their age, stature, weight or physical health. Elderly road-users are often more frail than those of a younger age, and child pedestrians are often more vulnerable due to their smaller size in relation to the point of impact with a vehicle.

The KEMM has as its premise the vision of no crashes resulting in serious or fatal injury. The model then systematically specifies pre-crash and post crash conditions to achieve this vision. Initially, the KEMM defines the acceptable outcomes of a crash event and then operates in reverse to specify crash and pre-crash conditions that would, in most cases, generate an acceptable outcome. This somewhat non-intuitive order was selected to reflect the primary emphasis Vision Zero places on low severity crashes, as opposed to crash elimination.

As suggested by the deflected arrows in the outer layers of Figure 4, the kinetic energy potential of vehicles approaching conflicts rarely results in a collision – usually the kinetic energy possessed by vehicles by virtue of their speed continues without incident and their kinetic energy is maintained. Both of the outermost layers reduce the risk of a crash by reducing exposure (Layer 5) and/or by reducing the intrinsic risk of a crash for any given level of exposure (Layer 4). The proportion of kinetic energy harmlessly deflected away from a potential collision depends on the overall effectiveness of the measures that exist in Layers 4 and 5.

The protective nature of the outer layers minimises crash risk through various forms of traffic management and control, and by ensuring that the infrastructure is designed properly and that there is suitable lighting and good visibility. The protective value of the outer layer is enhanced when drivers are suitably trained and qualified and free from impairment (e.g., drugs or alcohol or fatigue). Even immediately prior to an impending collision (i.e. during the pre-crash phase), the protective nature of the outer layers can reduce or deflect kinetic energy from a collision course through innovative designs such as speed humps or rumble strips that warn the driver of the need to reduce speed, and perhaps provide a road surface friction that supports sudden hard braking. Crash risk can also be reduced through the use of various vehicle-based intelligent transport systems such as electronic stability control, brake-assist and collision avoidance.

In situations where the kinetic energy cannot be successfully deflected from the collision course and a crash becomes inevitable, the focus is shifted to kinetic energy attenuation and minimising injury risk within the three innermost layers. The inner layers attempt to reduce the kinetic energy at impact and the amount that is subsequently transferred to, or exchanged with, the human. At this stage in the process of the crash event, it is essential that the vehicle can absorb energy and properly restrain vehicle occupants from colliding with the interior surfaces of the vehicle. For pedestrians and cyclists situated outside the vehicle, the frontal design of the vehicle can also play an important role in minimising energy transfer and exchange. In the future, the innermost layer may also offer protection by heightening the biomechanical tolerance levels of humans to kinetic energy and other mechanical forces (though no practical opportunities have been identified to date).

3.3 The four risk factors

To ensure that the KEMM is comprehensive as an approach to traffic safety improvement at intersections, the characteristics of each of these layers of protection are considered systematically. Within each of the defined layers, it is helpful to define the components that represent the principal risk factors of the traffic system: the human, the vehicle, the road and roadside, and 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.

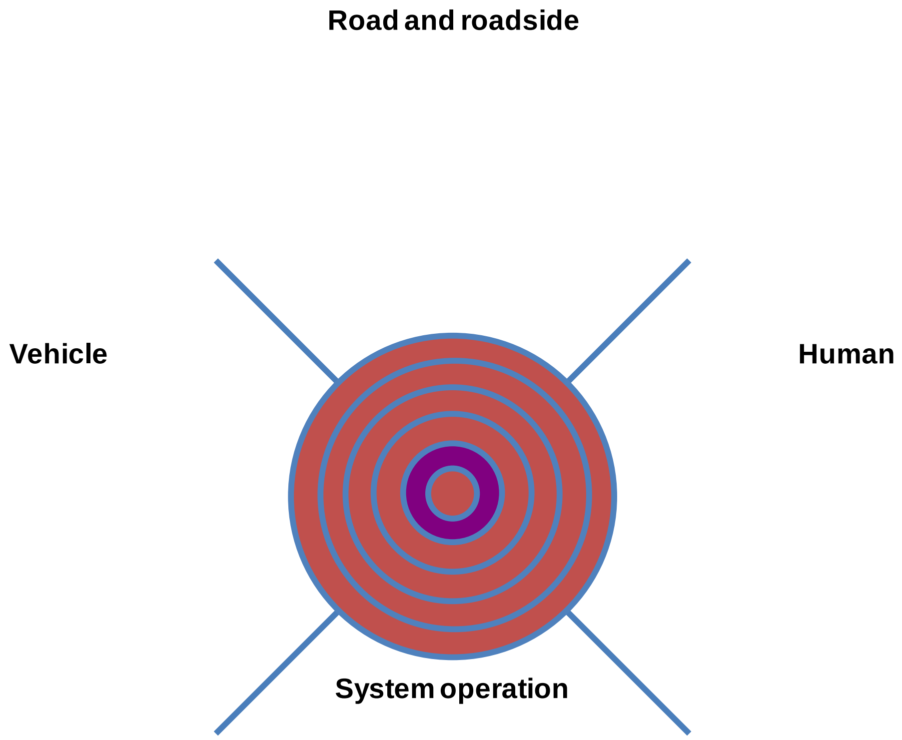


Figure 5. The four influencing factors in each layer of the KEMM

In the following sections, each of the protective layers of the Kinetic Energy Management Model is discussed in relation to the four risk factors. It should be noted that it is not meaningful to discuss risk factor groups other than those relating directly to the human for the innermost layer. (see Table 2).

Table 2. Matrix showing the KEMM protective layers and the risk factors.

Protective layer	Crash or injury risk factors			
	Road & road-side	**Vehicle**	**Human**	**System operation**
1: human biomechanical tolerance	×	×	✓	×
2: transfer of kinetic energy to human	✓	✓	✓	✓
3: kinetic energy per crash	✓	✓	✓	✓
4: crash risk per exposure	✓	✓	✓	✓
5: exposure	✓	✓	✓	✓

× signifies not applicable

In the description of layers that follows, the layers closest to the human are discussed first, along with measures that ultimately can attenuate the level of energy to which they are exposed. The outermost layers of the Kinetic Energy Management Model are discussed last and focus on ways in which crash occurrence can be reduced or avoided.

3.4 Layer 1: human biomechanical tolerance

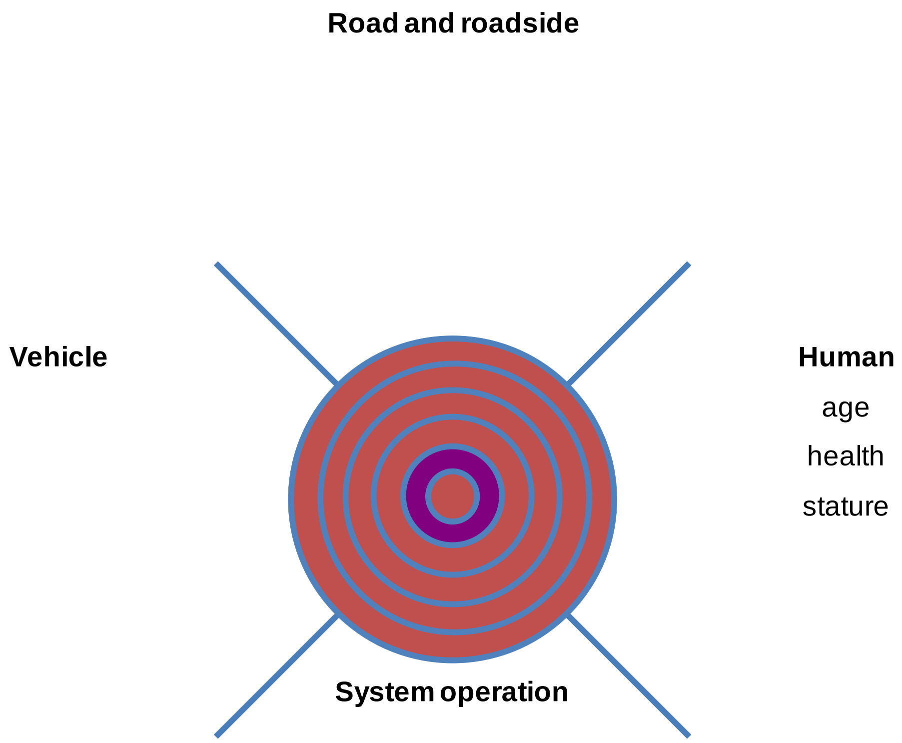


Figure 6. The first layer of protection: human biomechanical tolerance

The first layer immediately surrounding the road-user attempts to minimise injury risk by understanding and utilising knowledge about the biomechanical tolerances of the human to the energy dispersed in a crash situation. The intrinsic tolerance levels of humans vary with factors such as age, health status, gender, stature and possibly other factors.

3.5 Layer 2: transfer of kinetic energy to human

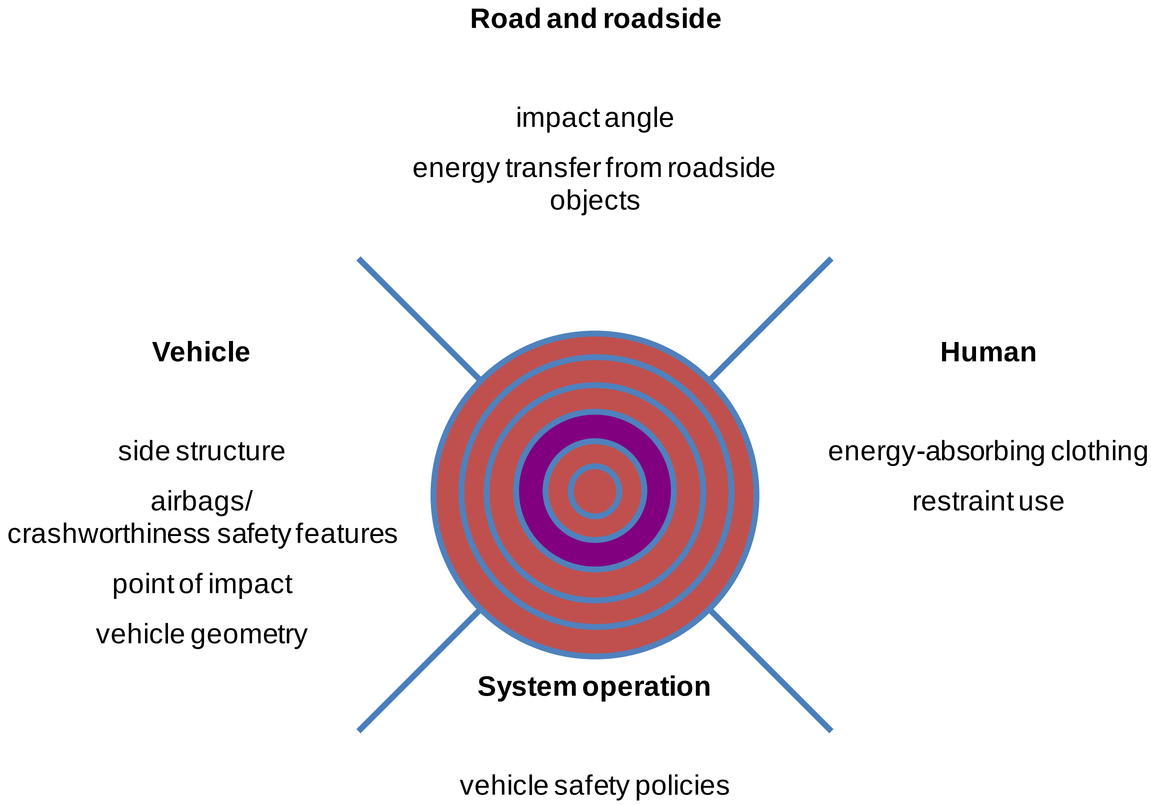


Figure 7. The second layer of protection: transfer of kinetic energy to human

In the second layer of protection the focus is placed on managing the transfer of kinetic energy to the human during the crash phase. The difference between this layer and Layer 1 is that the intention is to minimise kinetic energy transfer, for example through the deployment of energy-absorbing features and devices such as those found in modern vehicle designs.

This layer is not concerned directly with the prevention of specific types of injuries that result from biomedical human intolerances, but rather in managing and mitigating kinetic energy transfer in general by adapting human behaviour through restraint use, vehicle design and infrastructure design to ensure that only a tolerable residual amount of energy is eventually transferred to the occupant (or a struck pedestrian, bicyclist or motorcyclist).

3.6 Layer 3: kinetic energy per crash

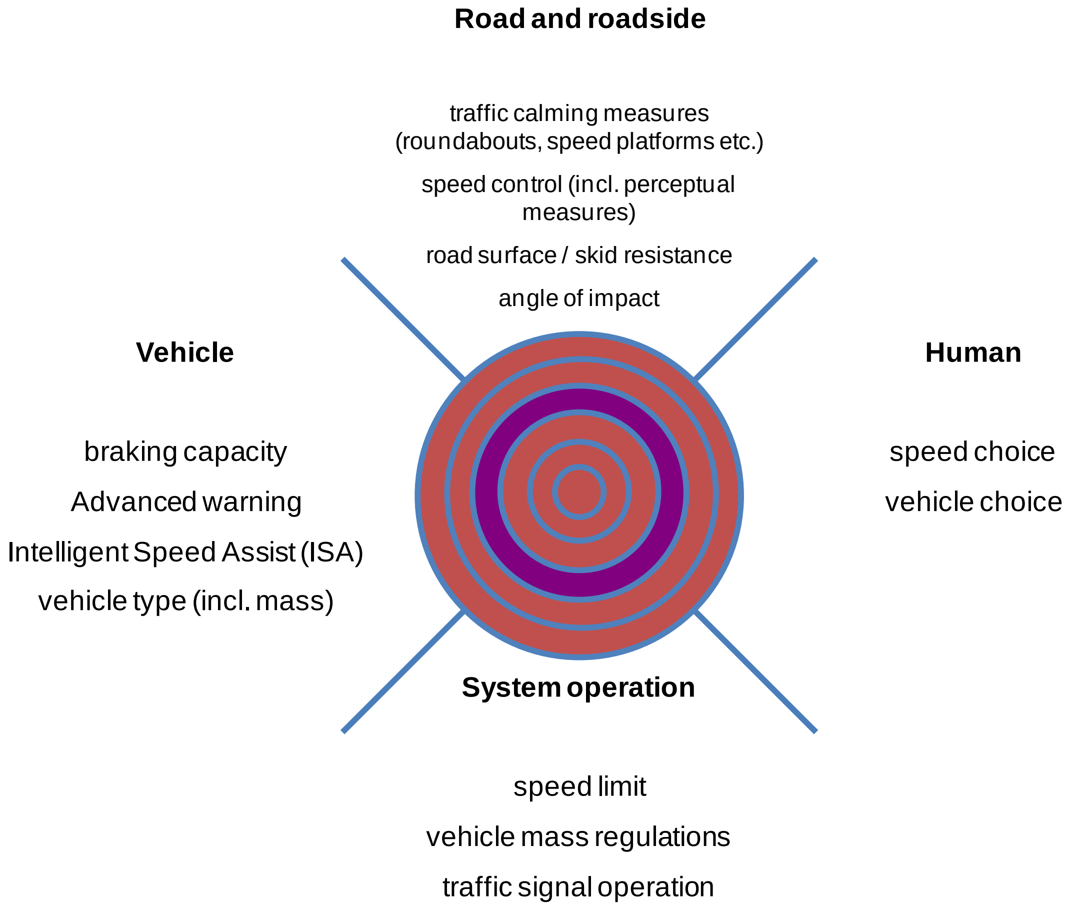


Figure 8. The third layer of protection: kinetic energy per crash

The third layer of protection aims to reduce injury risk by minimising the kinetic energy of the vehicle at impact during a crash situation. Kinetic energy is a function of the square of the speed and (half of the total) vehicle mass. Consequently, lower travel speeds offer great potential for minimising levels of kinetic energy involved in vehicle crashes. Also reducing mass is considered an important factor in minimising the kinetic energy involved in vehicle crashes. Other relevant vehicle factors include in-vehicle technologies such as pre-crash systems, ABS-braking, brake-assist systems and intelligent speed adaptation (ISA).

There are also infrastructure treatments such as high-friction road surfaces, traffic-calming measures (e.g., roundabouts, road-narrowing and speed-humps), speed control measures and treatments that define the angle of impact and influence driver speed choice and impact speed. In some crash types, such as vehicle to pedestrian impacts, the angle of impact has little or no influence on the kinetic energy at impact. However, in the case of vehicle to vehicle collisions at intersections, the angle of impact can effectively moderate the amount of kinetic energy available to be transferred to the occupant in Layer 2 (see below). In practical terms, 90-degree collisions represent the highest injury risk configuration, so by altering the impact angle, the effective velocity relative to the worst-case condition is reduced.

Influencing factors at system operation level are the speed limit, regulation of vehicle mass of the fleet and traffic signal operation.

3.7 Layer 4: crash risk per exposure

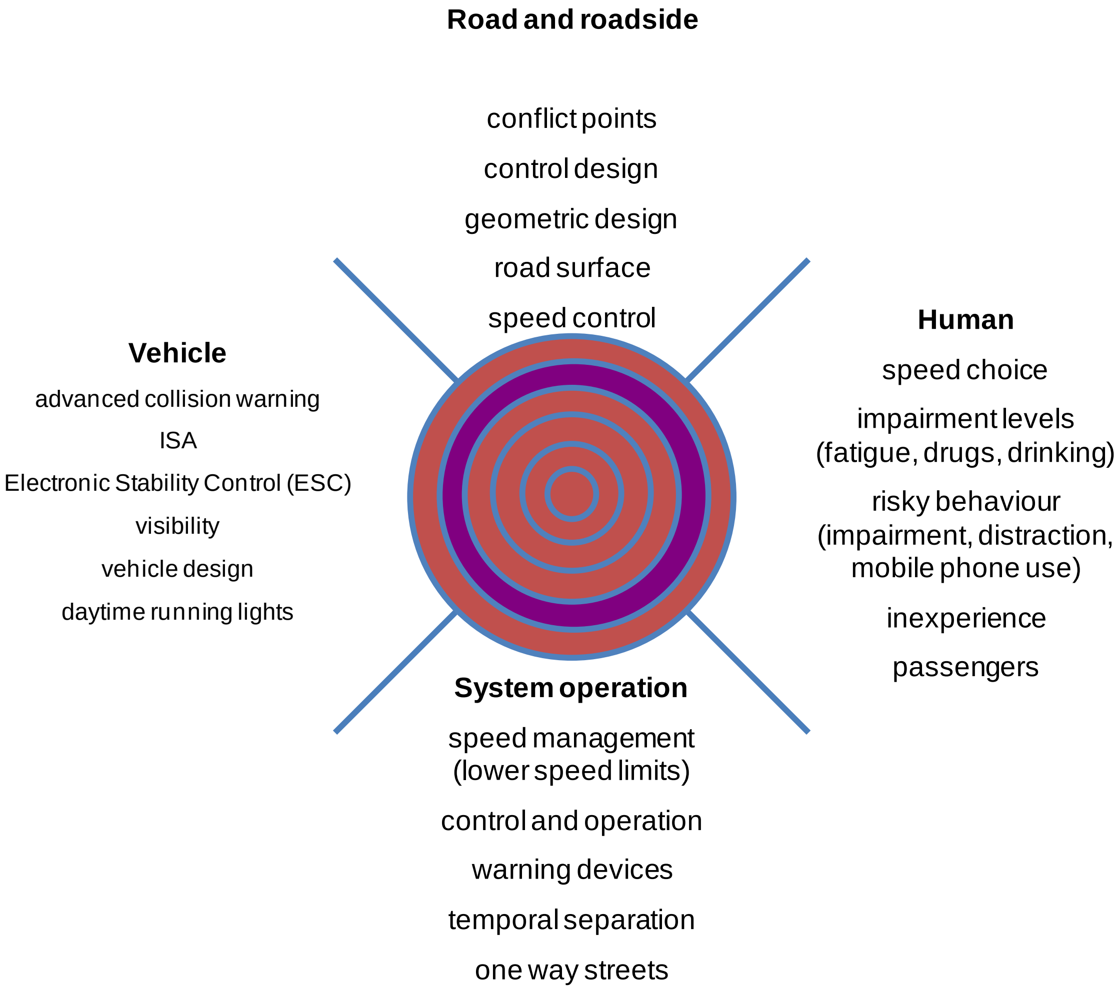


Figure 9. The fourth layer of protection: crash risk per exposure

The fourth layer is the first of two that aim to reduce crash risk. In this layer the intention is to reduce crash risk for a given level of exposure. Some of the countermeasures that are applicable to the third layer are also applicable to this level. This is because measures such as ISA not only result in a lower speed and therefore less kinetic energy in the event of a crash, they also influence the likelihood of a crash occurring (i.e. the crash risk that is determined by the relationship between a given level of exposure and the number of crashes). Changes to the infrastructure, such as the introduction of a roundabout rather than a four-legged intersection, can eliminate certain types of crashes (e.g. right-turn across the oncoming stream of traffic) and therefore also exposure (Layer 5), as well as reducing crash risk in other interactions by improving visibility or reducing complexity (Layer 4). At the same time a properly-designed and implemented roundabout may reduce approach speeds and the angle of impact in the event of a crash, thereby reducing injury risk as described in relation to Layer 3.

3.8 Layer 5: exposure

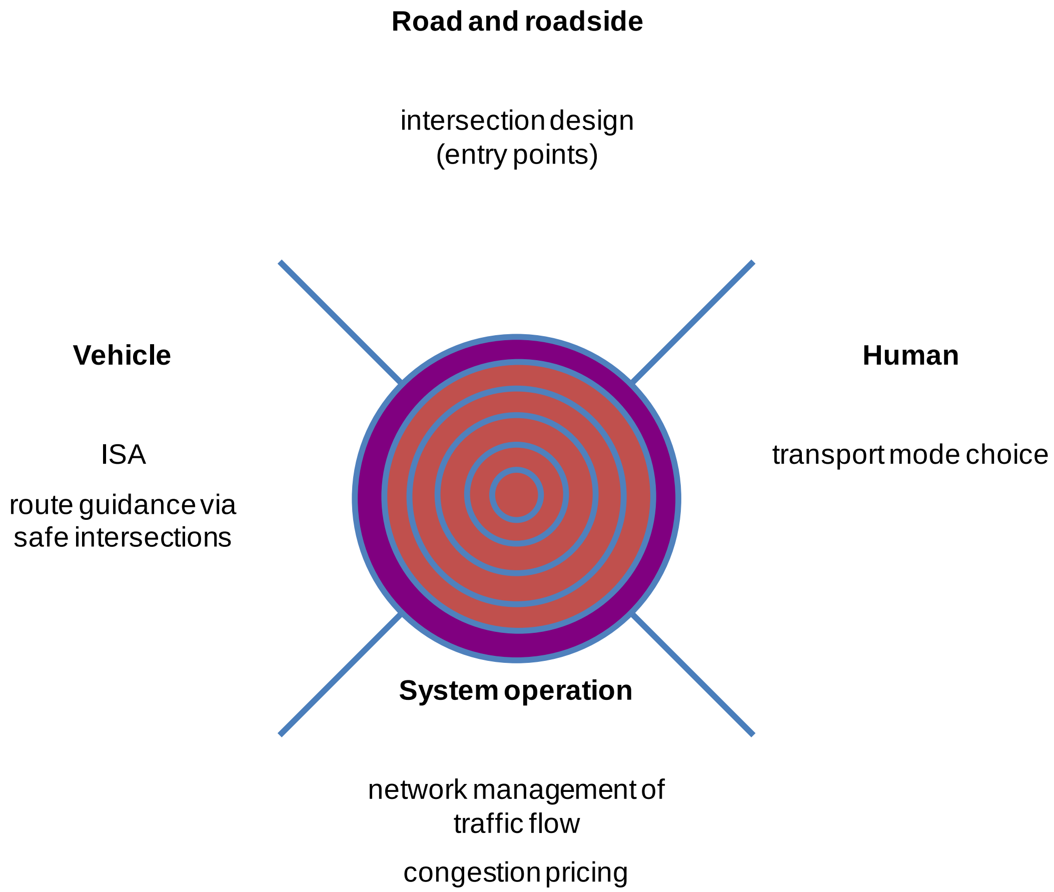


Figure 10. The fifth layer of protection: Exposure

The fifth and outermost layer of protection focuses on exposure as a method to reduce crash risk. Exposure can be defined in terms of, for example, the numbers of specific types of interactions in a given traffic situation; by the relative volumes of road-users and vehicles, by the number of intersections encountered, or by types of intersection controls. Exposure to a specific type of interaction can be eliminated or reduced through alternative forms of design (as described in Layer 4). It can also be reduced at the system level through disincentives for private-car use or incentives for public transport use. The use of advanced traffic control and management systems or traveller information systems can also be used to direct traffic along safer routes.

3.9 Overview of all five layers

A summary of the risk factors identified at each of the five layers is provided in Table 3.

Table 3. Summary of the risk factors identified at each of the five layers.

Protective layer	Crash or injury risk factors			
	Road & roadside	Vehicle	Human	System operation
1: human bio-mechanical tolerance	×	×	age, health, stature, gender	×
2: transfer of kinetic energy to human	impact angle energy transfer from roadside objects	Vehicle side structure airbags/crash-worthiness safety features point of impact vehicle geometry	energy absorbing clothing restraint use	vehicle safety policies
3: kinetic energy per crash	angle of impact road surface / skid resistance speed control (incl. perceptual measures) traffic calming measures (roundabouts, speed platforms etc.)	braking capacity advanced collision warning ISA vehicle type (incl. mass)	speed choice vehicle choice	speed limit vehicle mass regulations traffic signal operation
4: crash risk per exposure	conflict points traffic control design geometrical design road surface speed control road user composition	advanced warning ISA ESC visibility vehicle design daytime running lights	speed choice impairment levels (fatigue, drugs, drinking) inexperience risky behaviour (impairment, distraction, mobile phone) passengers	speed management (lower speed limits) control & operation warning devices temporal separation one way streets
5: exposure	Intersection design (entry points) Vehicle volumes	ISA route guidance via safe intersections	transport mode choice	network management of traffic flow congestion pricing

3.10 Kinetic energy as an indicator of traffic safety

The KEMM uses the kinetic energy levels that are likely to be generated during a crash to provide an indication of the levels of energy transfers that may occur. This in turn, can be used as a measure of potential injury outcome and hence safety levels. Often, other measures of road safety such as road audits, and road-users' perceptions of safety levels can be subjective and consequently, poor indicators of true safety. Other road safety indicators such as crash numbers and time to collision present the *likelihood* of a crash, and generally not the injury risk. Kinetic energy calculations, however, use speed, the primary indicator of a safe design, to demonstrate how impact speeds can influence final injury.

The KEMM seeks to apply the best knowledge and scientific evidence available from empirical and theoretical research in order to estimate crash and injury risk. The success of the KEMM depends to a large extent on its simplicity, including its ability to utilise the least number of physical or probability measures required to generate sufficiently accurate estimates of absolute or relative risk. From a practical perspective, the KEMM has been developed to allow changes in crash or injury risk to be examined in detail at different conceptual levels. Qualitative and quantitative assessment also makes it possible to determine objectively whether a particular measure has had a desired effect. The model also provides insights into the mechanisms through which it is possible to effectively reduce risk. As a measure of injury risk, the amount of kinetic energy dispersed at the moment of impact is recognised as an indicator that has good predictive value in relation to crash outcome severity (i.e. injury and/or fatality risk).

Unless a crash actually occurs, the kinetic energy potential of a vehicle, which is determined by its mass and velocity, is never realised, meaning that Layers 4 and 5 may not be suited to quantification in terms of kinetic energy. For the two outer layers of the KEMM it is more appropriate to consider crash risk in terms of the number of unsafe events (crashes or near-crashes) in conjunction with a level of exposure for a particular manoeuvre or location (e.g. conflict point, roadway intersection, mid-block section, pedestrian crossing). The probability of a crash, given exposure could then be applied to the kinetic energy of the vehicle or system to determine the average potential for energy to be released.

With regard to the inner three layers, injury risk data can only be obtained through the analysis of in-depth crash databases and is subject to the influence of a wide range of variables relating to the characteristics of vehicle occupants, vehicle safety performance and real-world crash configurations; or through extensive field trials that involve driver monitoring and data logging, and advanced simulation techniques.

The quantitative capability may also be based partly or fully on previous research findings. This may be empirically-based taking the form of quasi-experimental, before-after evaluations of implemented measures (singly or in combination), or theoretically-based studies based on physical laws of motion and energy. When suitable methodologies have been established it is envisaged that the KEMM will allow a variety of theoretical scenarios to be assessed prior to implementation. An important challenge in the future development of the model is to determine how high-level research findings are manifested at the fundamental level of changes in kinetic energy.

Over time, and with practical experience in using and developing the model as well as more detailed analyses of real-world data, it may be possible for refinements to be introduced through the identification of better injury risk variables, improved differentiation of vehicle safety performance and more effective segregation of individual crash types.

4 KEMM-X: A MATHEMATICAL MODEL FOR INTERSECTION SAFETY

The inner three layers of the KEMM, relating to the risk of serious injury or death, have been modelled mathematically to provide a tool for objectively quantifying the safety of individual conflicts within an intersection.

The model, known as KEMM-X, is introduced and the underlying relationships described. The primary focus is on better measuring the intrinsic safety of the

4.1 Conceptual basis

The primary goal of the mathematical modelling process was to develop a practical tool based on the outcomes of real-world crashes for evaluating the probability of death or serious injury for existing intersection designs and proposed Safe System designs. Model development to the end of Task 3 has reached the stage where the probability of a serious casualty outcome can be estimated for a single collision within an intersection. In order to achieve this, the mathematical model, known as KEMM-X (Kinetic Energy Management Model for intersections), models the transfer of kinetic energy from Layer 3 to Layer 1 in accordance with the KEMM principles described in Section 3 and shown in Figure 11.

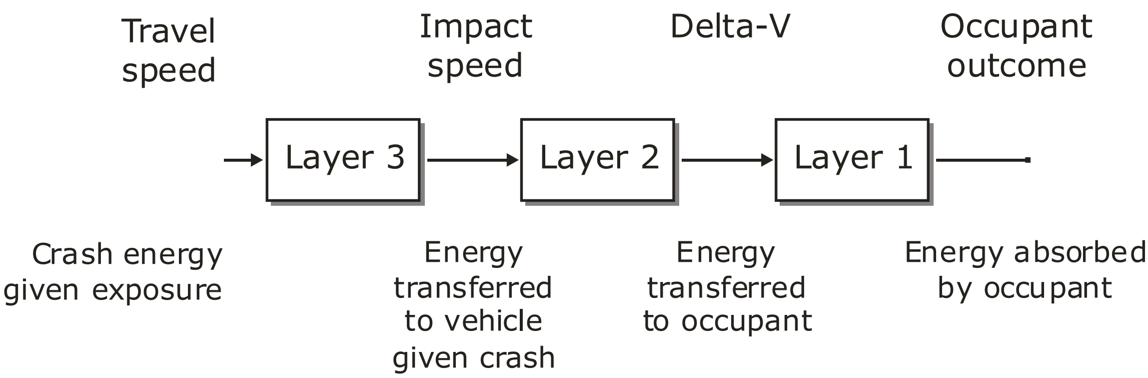


Figure 11. Conceptual basis of the KEMM-X model.

The conceptual energy flow described on the lower portion of the figure is that proposed by the KEMM principles from Layer 4 through to the human at Layer 1. Since it is not practical to quantify such energy flows in actual crashes, the top row in Figure 11 shows the proxy flow used, which determines occupant outcome (killed or seriously injured) from pre-impact travel speed. The model uses a stepwise calculation approach for a range of distances-to-collision.

In each of the subsequent sections, a brief description of the calculations behind each of the layers is provided, from the outer layers towards the inner to reflect the 'flow' of energy defined by the Kinetic Energy Management Model. For more detailed calculations, refer to Appendix A.

4.2 Assumptions and limitations within in KEMM-X

The basic assumptions made within KEMM-X are as follows:

- The only crash event considered is a vehicle-vehicle collision. Secondary impacts, whether involving another vehicle, a collision between the subject vehicle and roadside furniture or a rollover are not accounted for;
- Early in the development process, the model assumed the two vehicles to be travelling at right angles to one another, such that the subject or 'struck' vehicle sustains a side impact and the other vehicle ('striking') sustains a frontal impact. The current iteration of the model now supports impacts at any angle;
- Only injury/fatality risk to struck vehicle occupants is considered. This assumption held true when the struck vehicle was the subject of a right-angle side impact, but is still considered to hold for other impact angles.
- The crash configuration currently under consideration is a cross-intersection crash, with two vehicles approaching on adjacent paths;
- Only injuries or fatalities to occupants of the target vehicle are considered;
- The risk of fatality or serious injury is independent of the number and seating positions of target vehicle occupants;
- Transfer of kinetic energy between the colliding vehicles is estimated by the delta-V of the struck vehicle, , derived from conservation of momentum during the collision between two vehicles
- Occupant response to delta-V is based on probabilistic work of Evans (1994)

4.3 Layers 4 and 5 – risk of crash occurrence

The definition of an intersection design that complies with Safe System principles has been taken to be measured by the estimated risk of a fatality or serious injury in the event of a crash. The current focus on Layers 1, 2 and 3 address this. If, however, the definition of a Safe System intersection were extended to also focus on reducing crash risk, further development of KEMM-X would be required. Part of the collaboration between MUARC and SWOV has identified the opportunity to incorporate mathematically Layers 4 and 5 into an overall model of intersection safety. This would potentially involve the use of micro traffic simulation modelling of a defined traffic network as a means of quantifying, for individual intersections and crash types, the probability of conflicts for an assumed pattern of traffic movements and volumes (Archer, 2005; Young and Archer, 2009). While such an extension would undoubtedly be valuable, it is currently not seen as critical to the task of measuring the intrinsic safety of individual intersection designs.

4.4 Layer 3 – determination of impact speed given travel speed

Layer 3 determines the impact speed of the two vehicles, given their initial travel speeds. There are three distinct event types, as shown in the stopping distance curve in Figure 12. If the impact occurs in Region 1, the striking vehicle has not braked and the impact speed, v_i, will be the same as the initial travel speed. This is the worst-case outcome. In Region 2, the driver of the striking vehicle has detected an impending crash and begun to brake. The impact speed in this region is a function of initial speed, perception-reaction time, friction coefficient and the distance from the conflict point that the crash was perceived. The boundary between Regions 2 and 3 represents the point at which the striking vehicle driver brakes to a halt as the crash occurs and therefore also represents the conceptual boundary between Layers 3 and 4. Two main assumptions are made for the calculations in this layer: (a) maximum braking is applied once decision to stop has been made and; (b) both vehicles are travelling at constant speed prior to braking and constant deceleration occurs subsequent to the initiation of braking.

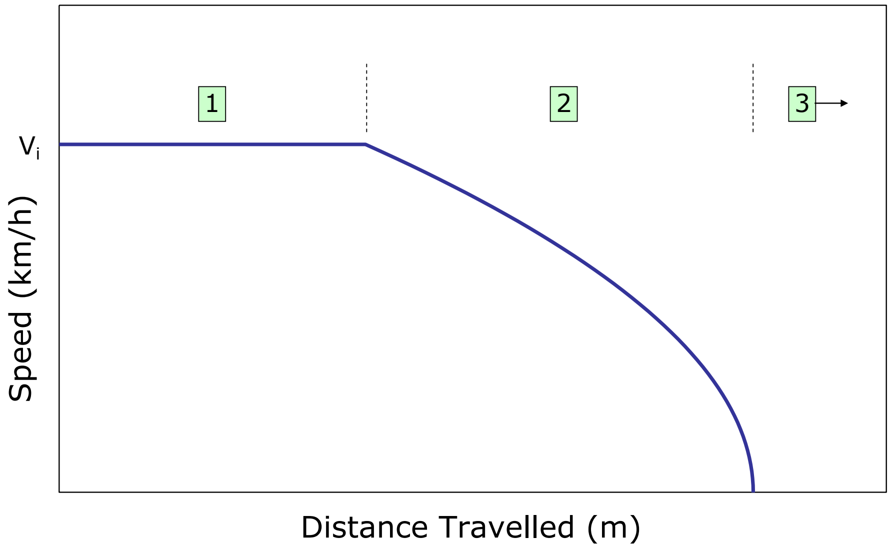


Figure 12. Conceptual relationship between speed and distance for Layer 3.

4.5 Layer 2 – attenuation of kinetic energy of crash by vehicle

Ideally, the calculations involved in this layer would determine how much of the kinetic energy embodied in both vehicles at the point of impact is transferred to the occupants of the target vehicle. In practice, this energy transfer is dependent upon a number of variables including vehicle structure, deformation, restraint system fitment and performance, many of which are difficult to quantify. As a result, the calculations for this layer yield delta-V*, which was selected as the most relevant parameter representing energy transfer. This parameter is also used by Evans to quantify the relationships used in Layer 1, so its use here facilitates the calculations from Layer 2 to Layer 1.

Figures 13 and 14 show schematically the vehicle to vehicle interaction in a generalised side impact crash. The angle of impact is defined as the angle between the travel direction of the target (struck) vehicle and the path of the sticking vehicle. Therefore, a head-on crash would

* Delta-V represents the change in velocity of the subject vehicle from the point of initial contact between the vehicle and collision partner to the point at which they separate at the end of the collision.

be at a contact angle of zero degrees, while the contact angle for a side impact would be either 90°or -90°.

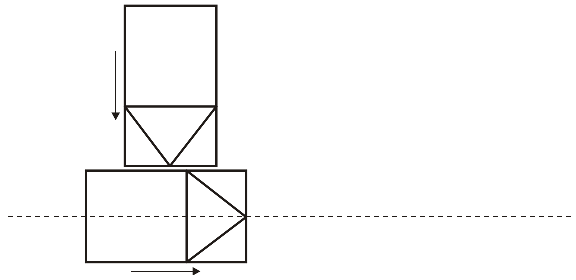


Figure 13. Car-to-car impact between struck and striking vehicles.

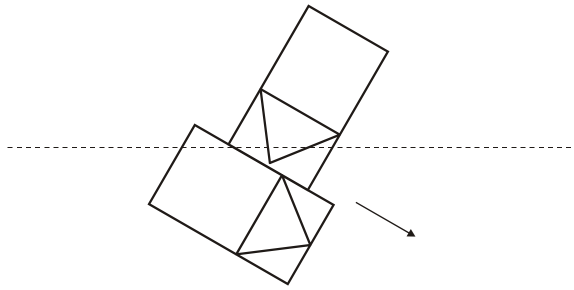


Figure 14. Vehicle motion, post-impact

Conservation of momentum, resolved along a set of orthogonal axes, is used to calculate the vectorial velocity change of the struck vehicle. Consistent with the crash reconstruction methods upon which the calculations in this Layer are based, the two assumptions are made that the crash is perfectly inelastic, meaning that the vehicles move together as one immediately post-crash and also that the centres of mass of the two vehicles are co-linear during the collision and therefore no significant rotation occurs. This latter assumption infers a collision with the passenger compartment and therefore a typically more severe outcome for the occupants due to the high levels of intrusion or occupant contact with the vehicle interior, striking vehicle or roadside object.

4.6 Layer 1 – kinetic energy absorbed by vehicle occupant

Layer 1 evaluates the probability, *P*, of a serious injury or fatal outcome for a vehicle occupant, based on the delta-V of the vehicle during the crash. In effect, this calculation is a combination of Layers 2 and 1. Leonard Evans (Evans, 1994) used weighted NASS data to determine an empirical relationship between the probability of fatal and serious injury outcome and crash severity, delta-V. Evans noted a number of limitations with this work, as documented in the paper. At present, however, it is the best relationship known to be available.

Evans fitted curves of the form:

$$P = \left(\frac{\Delta v}{\alpha}\right)^k \quad \text{for } \Delta v \le \alpha \qquad (1a)$$

$$P = 1 \quad \text{for } \Delta v > \alpha \qquad (1b)$$

Where:

Δv is the change in velocity of the vehicle during the crash event

For fatalities (belted occupants only):

$$\alpha = 69.18 \text{ mph}, \ k = 4.57 \pm 0.25$$

For serious injuries (belted occupants only):

$$\alpha = 67.43 \text{ mph}, \ k = 2.62 \pm 0.17$$

The confidence intervals around *k* are narrow and not taken into account in the numerical implementation of the model. The main limitations of Evans' work are first, that it was not possible to disaggregate by impact type and second, that there is clearly not a one-to-one relationship between delta-V and probability of a serious injury or fatal outcome, as some vehicles will afford greater protection than others. Also, the vehicle sample used by Evans comprises US vehicles manufactured between 1982 and 1991. This should result in a conservative estimate of risk, given the improvements in vehicle safety since that time.

For application to side impacts, the parameter, α, was converted to metric form and scaled such that the delta-V resulting from a side impact crash at 50 km/h corresponded to a probability of fatality of 0.1 (10%), resulting in the following new coefficients for side impact:

For fatalities (belted) $\alpha = 60.0$ km/h

For serious injuries (belted) $\alpha = 58.5$ km/h

This yielded a risk of serious injury of 29% at a delta-V of 36.3 km/h, which corresponds to a right-angle collision between two vehicles of equal mass at 50 km/h. This correlated well with the commonly-accepted Safe System limit for a vehicle in a side impact. The resulting curve is shown in Figure 15. These values of α imply a 100% risk of fatality at a delta-V of 60 km/h in a vehicle-vehicle side impact, which would correspond to an impact speed of around 80 km/h.

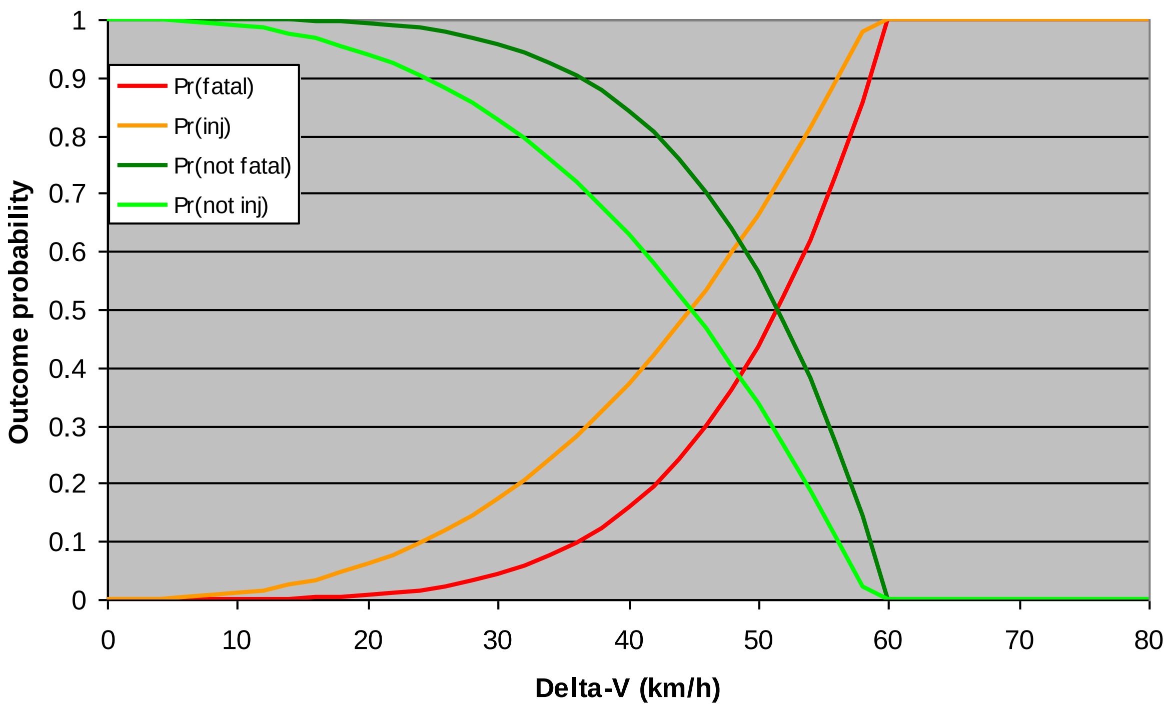


Figure 15. Probability of fatal and serious injury outcome vs delta-V.

The probability of non-fatal, 1-Pr(fatal), and non-serious, 1-Pr(serious), injury outcomes are also shown, anticipating a desired focus of the KEMM on survivability.

4.7 Model Implementation

The model is implemented in a Microsoft Excel spreadsheet that computes the probability of a fatality and serious injury for each of the possible distances from the collision point (closest) to the point at which a collision would not occur (farthest – see Region 3 of Figure 12, p. 29). The values of controlling variables are set by means of drop-down boxes embedded onto the output charts. The primary model output is the risk of a fatality or serious injury for a struck vehicle occupant against the distance from the collision point of the striking vehicle.

Future program development will include the ability to assess either the cumulative or worst-case risk of all of the conflict points within an intersection rather than the risk of injury or death of a single impact, given selected input perception-reaction times, vehicle-road friction coefficient, angle of impact and travel speed.

5 DEVELOPMENT OF DESIGN PRINCIPLES

The design principles have been developed within the context of the Dutch Sustainable Safety and Swedish Vision Zero philosophies.

Based on the Victorian crash analysis and discussions with VicRoads, three intersection scenarios have been selected for the focus of new designs: (a) signalised intersections of urban arterials; (b) sign-controlled intersections of urban arterials and local access roads and; (c) sign-controlled intersections between rural highways and low-volume side roads.

The four key principles of fewer vehicles, fewer intersections, fewer conflict points and optimised impact speeds and angles are developed and a practical level of Safe System performance nominated.

5.1 Guiding philosophies

5.1.1 The Dutch road safety vision: Sustainable Safety

"Sustainable Safety" is a Dutch Safety philosophy that recognises that the design of the road can have a significant influence in creating a level of road safety that is sustained in the long term. Sustainable Safety goals include creating a road system that functions effectively without exposing the road user to unacceptable levels of risk of a serious injury crash occurring. As per the Dutch research institute's website states that, "Sustainable Safety aims at (producing) road safety measures that intervene as early as possible… by intervening in the system as early as possible, unsafe actions are made minimally dependent on the individual road user's choices."[1] The philosophy identifies five principles of safe design:

1. *Functionality* of the road: the main purpose of the road needs to be clearly defined and where practical maintain a road of single function.

2. *Homogeneity* within vehicle mass, speed and direction produces greater safety design;

3. *Road User Expectation* through recognisable, predictable road design;

4. '*Forgivability*' of the road environment: the potential for a road user to err while negotiating the road and yet proceed unscathed;

[1] http://www.swov.nl/uk/research/kennisbank/inhoud/05_duurzaam/goal_and_starting_points.htm

5. *State of Awareness* of the road user is also considered an important aspect of safe road and intersection design.

However, Sustainable Safety requires that road users must be sufficiently capable and experienced to use the road system, and must also be able to perceive both what is expected from them as well as what they should expect from other road users. Sustainable Safety encompasses this in the 'Predictability Principle', achieved through consistency and continuity in road design. This means that the overall design of the road should support the user's expectations and every component of the design should be in line with these expectations.

People sometimes unintentionally make errors, but may also exhibit dangerous behaviour by intentionally violating road rules. While the original Sustainable Safety vision did not take this type of road user behaviour into account, the current version of the vision does so. It is important that the normative behaviour of road users should be to obey the traffic rules. In order to achieve this, the regulations should be appropriate for the traffic environment and road users should be educated in the logic and usefulness of the traffic rules. This supportive approach is coupled with a level of enforcement such that road users have the perception of a reasonable chance of being caught in the event of non-compliance.

An important element of the advanced vision is that the road system should be sustainably safe for everyone, as opposed to the 'average road user' alone. This is defined through the balance of task requirements and task capabilities. Fuller (2005) defines a road user's net task capability as the difference between the sum of their task capacities and the sum of their impairments, the latter being due to fatigue, alcohol, drugs and the like. For safe road use, the level of task capability of the road user should exceed the task requirements of the road environment as well as those imposed by the road user themselves, such as travel speed. Sustainable Safety also requires that road users are able to self-assess their capability for safely participating in traffic. This is important as individual task capability varies widely as a result of inexperience, age, fatigue, substance use and physical impairment. Generic road safety measures are alone insufficient to guarantee a safe traffic system for all road users at all times and it is therefore necessary to supplement these with specific measures aimed at specific groups or situations. These fall under the areas of regulation, education, enforcement and technology (such as Intelligent Transport Systems).

In the event that a crash occurs, Sustainable Safety provides guidelines for safe travel speeds that would generally not exceed the biomechanical limits of vulnerable road users or vehicle occupants. To deal with the issue of vulnerability in an anticipatory fashion, Sustainable Safety requires that controls are placed on factors that may intensify the severity of a crash, including differences in speed, direction and mass. These controls form the foundation of the *homogeneity principle*, which states that, where vehicles or road users with significant differences in mass are desired to operate within the same road space, speeds should be sufficiently low that, in the event of a crash occurring, the most vulnerable of the collision partners should not sustain fatal injuries. In addition, where traffic is moving at high speeds, road users should be physically separated from one another. The advanced Sustainable Safety vision proposes safe speeds for different situations (Table 4).

Table 4. Safe speeds for various crash situations; from Sustainable Safety.

Road type/allowed road users	Safe speed (km/h)
Roads with potential conflicts between cars and unprotected road users	30
Intersections with potential transverse conflicts between cars	50
Roads with potential frontal conflicts between cars	70
Roads with no potential for frontal or transverse conflicts between road users or road users and roadside objects	≥100

Safe interaction speeds for some road user types have not yet been defined on a firm scientific basis, the most significant of these being motorcycles and heavy vehicles. The ideal solution for these two groups would be physical separation from other traffic, however this is currently not practical. The principle of physical forgiveness of roadsides is also an important element that contributes to reducing injury severity in crashes.

Relating Sustainable Safety to intersections, a number of insights may be gained:

- Recognise that the main function of an intersection is to cater for vehicles that need to change direction, not for through traffic. Consider alternatives for providing for through traffic;
- Where feasible, minimise interaction between non-homogeneous road users through separation;
- Where feasible, minimise interaction between non-homogeneous speeds by reducing speeds to a common intersection speed;
- Recognise that speed is the key element in relation to the crash frequency and outcome, as well as the forgiving nature of the intersection in the event of a crash.

5.1.2 Vision Zero

Sweden is widely recognised as a world leader in road safety, and often displays what is regarded as world's best practice in road safety and road trauma reduction. In 1997, the Swedish Parliament formally adopted the concept of "Vision Zero". Subsequently, the then Swedish National Road Administration (now Swedish Transport Administration, STA) began to implement the ethically-based 'Vision Zero' philosophy, with the primary goal to, "…ensure a socio-economically efficient transport system that is sustainable in the long term for individuals and industry throughout the country" (Brewer et al, 2001). To achieve this goal, five sub-goals have been identified, including: high accessibility, high transport quality, a good fit to the environment, promotion of regional development and, most importantly, no fatalities or serious injuries. Vision Zero emphasises the provision of inherently safe infrastructure, where it is desirable for vehicle speeds to be high, or lower speed environments where it is neither practical nor affordable to provide inherently safe infrastructure (Tingvall, 1999). In many urban areas, where vehicle interactions at intersections are very common, lower speed settings will frequently be the outcome of applying Vision Zero principles. Another key requirement of Vision Zero is that road users behave legally and responsibly while using the system (e.g., Tingvall, 1998). Given this provision, the road transport system should be designed and operated in such a way that it is tolerant and accepting of human error.

A new philosophy towards road trauma reduction is vital to assist social change among those who design, operate and use the road-transport system, so that safe choices become natural choices and health is no longer traded for mobility. 'Vision Zero' appears to offer such a philosophy and therefore its potential to enhance road trauma reduction is high.

The Vision centres on an explicit goal, and develops into a highly pragmatic and scientifically-based strategy which, in effect, challenges the traditional approach to road safety by asserting that mobility and safety cannot be traded against each other, and thus mobility becomes a function of safety rather than the other way around. It is noteworthy that common definitions of the concept of sustainability are expressed in terms that imply accessibility is the more important indicator of mobility than travel time in the road-transport system. Speeds should be managed at levels commensurate with the inherent safety of the road system, contrasting with the more conventional approach which values human life, mobility and other impacts in monetary terms and therefore encourages trade-offs between these factors. Speed limits on the road-transport system should be determined by the technical standard of vehicles and roads so as not to exceed the human body's energy absorption capabilities. The safer the roads and vehicles, the higher the travel speeds that can be accommodated safely.

The "Vision Zero" philosophy, when translated into practice for intersections, gives explicit recognition to the heightened vulnerability of pedestrians in traffic and vehicle occupants in the event of 90 degree, side-impact collisions between vehicles. The recognition of this vulnerability, derived principally from the levels of biomechanical tolerance of humans to violent forces in traffic, highlights the critical need for separating pedestrians from vehicular traffic or, alternatively, ensuring that vehicle speeds present a low crash and serious injury risk for pedestrians in the event of a crash. The latter aspect is of particular importance within the "Vision Zero" concept. A similar philosophy applies to vehicle occupants though the tolerable impact speed is higher than for pedestrians.

While the "Vision Zero" notion might suggest either no traffic crashes or, no crashes involving death or serious injury, this is not viewed by the Swedes as a realistic outcome, at least not in the short- to medium-term future. However, the pursuit of this highly ambitious goal is ethically essential and, in general, will generate the energy needed for action and innovation. Superior solutions result than if one accepts the traditional approach based on achieving incremental improvements. That is, adoption of the inspiring goal of no deaths or serious injuries in traffic will more often lead to countermeasures and strategies for operating the road-traffic system in a way that *fundamentally* changes the risk of serious injury or death.

Wramborg (2003) described the process developed and being implemented by the Swedish Road administration (SRA) and local government to meet the present and future needs and desires of its people for urban traffic systems in Sweden. The process, termed "The New Approach", emphasises three basic goals for urban areas, namely those of accessibility for all (including children, the elderly and the mobility impaired); safety; and a good environment.

These basic goals must be achieved within the framework of the "Vision Zero" concept of no deaths or serious injuries, provided users of the system comply with road rules.

Furthermore, three fundamental premises were formulated in relation to how the streets and roads of urban areas should perform. These premises, set out below, derive directly from recognising the basic physiological needs and limits of humans, and by embracing "… the humanistic view that power can only be legitimised through caring about human life" (Wramborg, 2003). Though not clear in the original text, it is assumed that Wramborg refers here to the *power* of the society (and hence of elected governments) to meet and respect the most basic needs of human beings.

Accordingly, the traffic system is undergoing a fundamental transformation that is founded on the vulnerability of the road user under certain crash conditions, such that:

- If there is a risk of head-on collision, or of driving into a rigid object, the maximum permitted vehicle speed is 70 km/h.
- If there is a risk of side-impact collision, the maximum permitted vehicle speed is 50 km/h.
- If there is a risk of hitting a pedestrian or cyclist, the maximum permitted vehicle speed is 30 km/h.

Thus, a sacrosanct regard for human life and a scientifically-based recognition of the limits of human biomechanical tolerance to violent forces are the two central issues in the way in which the road-transport system will operate in the medium to long-term future in Sweden.

In urban areas, all roads are classified according to the function they are intended to perform. There are five broad categories:

- Through Traffic Route (70/90 km/h roads, but sometimes 50 km/h)
- 50/30-Street (Main Street)
- 30-Street (Residential Street)
- Walking Speed Street (*Woonerf* – a Dutch word signifying that vehicles must not be driven at speeds exceeding walking pace)
- Car-free zones

Each of these functional categories is described and defined in terms of the length of journeys being undertaken, the types of areas through which the road or street passes and the speed goals. In this way, conflict possibilities are recognised explicitly within the road/street, as are the crashworthiness limits of the road-transport system, traffic volumes and the importance of transport efficiency (Wramborg, 2003). The imperatives of "Vision Zero" ensure that the lives and health of people using the system or living in urban settings are not compromised to achieve transport efficiency or other goals of society.

For each functional classification of roads and streets, "The New Approach" also describes the behaviour expected of individual users and what individuals can expect of other system users. Here, the focus is on permissible speeds for each street category, established on the basis of the intrinsic vulnerability of pedestrians and cyclists, the mobility impairments of older pedestrians and cyclists, and others suffering functional impairment, especially at the locations where conflict tends to occur. Thus, permissible speeds tend to be specified in relation to intersections, where side-impact and pedestrian crashes often occur, and between intersections where head-on and fixed object crashes are more common.

Finally, having established the functional classification of a road or street in an urban area, and the behaviour that is expected of road users, design elements for the achievement of these functional and behavioural goals are set. Important design considerations include the degree of “urban-ness” of areas through which roads and streets pass, the alignment of the road, whether or not the road should be divided, the number of lanes needed to meet the intended function, the needs for crashworthy separation of opposing directions of traffic and for crashworthy roadsides, and the extent to which pedestrian and cyclist traffic will be accommodated in the design (Wramborg, 2003). For example, design features can prohibit use of Through Traffic Routes by pedestrians and/or cyclists, provide safe separation of vehicles from pedestrians and cyclists or low vehicle speeds at locations of conflict on 50/30 km/h streets, or actively promote walking and cycling through the design of walking speed streets (and car free zones).

5.2 Scope of design principles

Insights gained from reviewing the principles defining Sustainable Safety and Vision Zero have guided the principles for safe intersection designs. Three high-priority trauma categories have been identified through the crash analysis component of the project as well as through consultation with VicRoads. These are elaborated upon below.

5.2.1 Traffic signals in urban areas

Traffic signals were identified in the crash analysis as being involved in at least 25% (and probably considerably more) of the serious casualties at intersections. One of the key factors in traffic signal intersection design contributing towards a significant proportion of serious casualties is incompatible or non-homogeneous speeds at intersections. Signals operate by allowing one or more streams of traffic to proceed through the intersection within the posted speed, but with no requirement to reduce speed. Should an error occur, there is limited opportunity to avoid a collision and a high probability of injury occurring to occupants if a crash occurs. It is necessary then to define design principles for this particular context, as a large proportion of vehicle km’s travelled in Victoria utilise traffic signals as the main form of control.

5.2.2 Sign-controlled side roads intersecting with urban arterials

The category of sign-controlled side roads intersecting with urban arterials was considered a high priority, as it incorporates several high risk components. One such component is a likely difference in operating speeds, with the side road often being a local road and therefore sign-posted at 50 km/h, and the arterial, with its function of transporting traffic, would generally have a speed limit of at least 60 km/h and up to 80 km/h. Secondly, sign-posted intersection control relies solely on appropriate driver gap selection, which is correspondingly reliant on driver “state of awareness”, levels of cognitive and physical functioning, intersection design factors such as sight distance; with any of these potentially contributing to a crash. Sign-posted intersections are also likely to be cross intersection or T-intersection in geometry, involving severe angles should a crash occur.

5.2.3 Sign-controlled side roads intersecting with rural highways

Sign-controlled rural roads intersecting with highways are selected for further focus as they again involve interaction at non-homogenous speeds and so can result in high severity crashes. This category is also common in rural areas as the volumes on side-roads are insufficient to warrant another type of intersection control, leaving the driver to select a suitable gap in traffic approaching at 100 km/h or 110 km/h.

This provides some context for exploring the key principles to safe intersection design. Details of designs are provided in the Task 5 report.

5.3 Key principles governing Safe System intersection design

The central focus of Task 3 was to develop a set of design principles for achieving 'Safe System' performance of intersections in Victoria. This section summarises and describes the principles developed to ensure that the probability of fatal injuries in the event of a crash does not exceed about 10%.

To be true to the ambitions of the Safe System – that there will ultimately be no deaths or serious injuries within the road-transport system, assuming full compliance with key road laws – a more stringent set of principles would be needed. This increased stringency would seek to meet two specific aspects, namely:

- the probability of death, given a crash at or below legal speeds by all involved road users, would be much lower than 10% and, in strict terms, zero;
- not only death but also serious injury would be prevented.

Given current speed limit setting practices in Victoria, it seems unrealistic to recommend design principles today, that meet the full spirit of the Safe System vision. Therefore, in order to be both practical and to achieve substantial reductions in serious casualty risk at intersections, and so move *towards* the aspiration of eventually eliminating death and serious injury, the more pragmatic criterion of not exceeding a 10% probability of death, given a crash, will be adopted for the remainder of the project.

Four key principles have been developed during the course of Task 3, though the first two of these are outside the scope of this project. All four of these principles are presented here, with the first two discussed briefly because together they provide a more complete view of what is needed to reduce very substantially, trauma at intersections. Furthermore, unless included here, their importance is less likely to be recognised for future consideration and refinement as a legitimate and potentially powerful means of reducing intersection-based trauma.

The four principles are:

1. **Fewer vehicles** – by reducing the number of vehicles in use, fewer opportunities for collisions will arise;

2. **Fewer intersections** – by minimising the number of intersections within the road network, and concentrating more traffic movements at intersections with

best-practice safety standards, fewer opportunities for high-risk conflict should arise;

3. **Fewer conflict points per intersection** – by reducing intersection complexity to produce fewer conflict points, the opportunities for crashes at a given intersection should fall. The resultant reduction in complexity should also have a positive effect on safety;

4. **Impact speeds and impact angles constrained to biomechanically tolerable levels** – by designing to create speed and angle combinations that result in a low risk of serious injury in the event of a crash. Analysis of the kinematics of traffic collisions shows that:

- For 90° collisions, impact (and, therefore, travel) speeds should not exceed 50 km/h for vehicle-to-vehicle collisions. For conflicts between vehicles and unprotected road users (i.e. pedestrians, cyclists and motorcyclists), impact (and, therefore, travel) speeds should not exceed 30 km/h;
- For intersections located in speed limits greater than 50 km/h and not greater than 70 km/h, vehicle-to-vehicle conflicts must occur at less severe angles than 90° to ensure that the biomechanical tolerances of humans are not exceeded. Regardless of geometric layout to influence impact angles, travel speeds should not exceed 30 km/h if pedestrian and cyclist risks of death are to remain below the nominated level of 10%.
- Where the above criteria cannot be met, the design should ensure that crash risk is negligible.

The relationship between conflict angle and travel speed (impact speed) to avoid intersection designs with a probability of death in a vehicle to vehicle collision that remains below about 10% is presented below:

Maximum impact speed (km/h)	Maximum acceptable conflict angle
40 and below	All OK
50	90°
60	52°/128° (from KEMM-X)
70	0°/180°
80 and above	None feasible

NOTE: 0° and 180° in the above table indicate a head-on and rear-end collision respectively.

Finally, to ensure that Safe System designs in accordance with the above principles perform to intended standards of safety, design attributes must be provided to the highest standards. This would entail, for example, high standard signing, line markings, lighting, pavement surfacing, etc. This 'fine-tuning' process should be applied within each of the four design principles and, while important to safe performance, is of secondary importance compared with the fundamental intersection design principles.

These principles, and in particular Principles 3 and 4, will be applied in Task 5 to generate new intersection designs and to assess existing designs using the Safe System aspiration as a point of reference.

The following sections describe each of the four principles in greater detail.

5.3.1 Fewer vehicles

An overarching principle in creating safer roads is to minimise the exposure of the road user to a crash. Each vehicle crossing the path of another vehicle or a pedestrian is exposing the involved road users to a possible crash. While it is acknowledged that reducing the number of vehicles may in fact increase the likelihood of vehicles being driven at higher speeds, and hence in term may diminish the speed reduction effects which traffic congestion may bring about, reducing vehicles overall, has the added benefit of reducing the chances of a collision occurring. That is, reducing the total number of vehicles passing through reduces exposure to a crash and hence increases overall safety. For example, few vehicles might traverse through some rural intersections. Regardless of the condition of this intersection however, if there are few conflicting vehicles present, the potential for a cross traffic crash is reduced. For this reason, road safety statistics are often compared in terms of number of vehicles and provide a standard means of comparing one site with another.

This principle can be addressed by assessing the road network and considering alternative routes for traffic, to improve efficient travel through the network, preventing traffic diverting along routes that are not designed to cater for high vehicle volumes and directing traffic to routes with improved safety features. Further, restricting heavy vehicle routes to minimise the potential of collisions occurring between vehicles of considerably different mass is also an active means of improving intersection safety. In eliminating or minimising the risks of collisions involving heavy vehicles, higher driving speeds can be achieved with the accompanying safety benefits. While the importance of this principle is acknowledged, given that this principle is outside the scope of the project, it will not be explored in further detail, although there are certainly a number of opportunities for benefits to be gained.

5.3.2 Fewer intersections

The safe negotiation of the road network is heavily dependent on the road user. However, if the number of intersections that a driver passes through is minimised, driver exposure to intersection crashes is clearly reduced. It is noted that reducing the number of intersection may overburden the existing, SS compatible intersections given the higher volumes of traffic which these intersections accommodate; however, this principle considers the need for an intersection and whether there is an alternative to providing an intersection at a particular location. Consolidation of intersections is one means by which intersection numbers can be reduced. For example, along a high speed rural road, it may be preferable to create a service lane or other alternative and produce one access point onto the highway for an entire stretch rather than at each desired location. This principle is best implemented using a comprehensive network perspective and is beyond the scope of this project.

5.3.3 Fewer conflict points

Conflict points at an intersection are the specific locations where two road users have the potential to collide should both movements occur concurrently.

The number of conflict points varies between road geometries as well as the permitted movements at each intersection. Figure 16 presents the 32 vehicle-vehicle conflict points conflict points at a standard one lane cross intersection. If pedestrians are taken into consideration, then the number of conflict points and their complexity rise markedly.

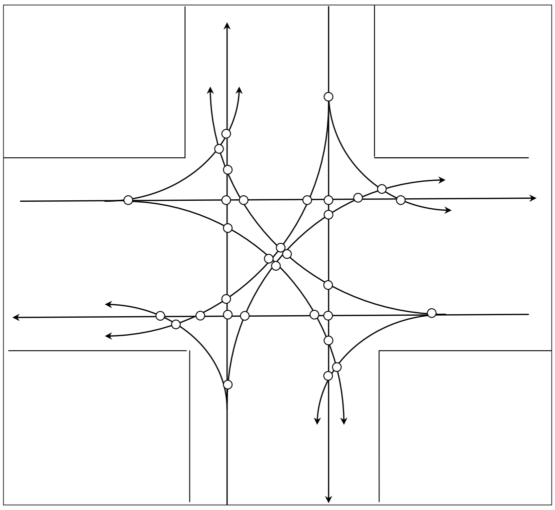


Figure 16. Standard conflict points for vehicle interactions in a simple cross-intersection.

Intersection designs that reduce the number of conflict points then reduce the potential for a crash. Therefore, reducing the number of conflict points is a key principle in increasing safety at intersections.

Some conflicts can produce more severe outcomes than others and targeting these is likely to improve safety. Conflicts involving unfavourable impact angles and speeds, as described in Principle 4, should become a high priority for elimination.

5.3.4 Impact speeds and impact angles constrained to biomechanically tolerable levels

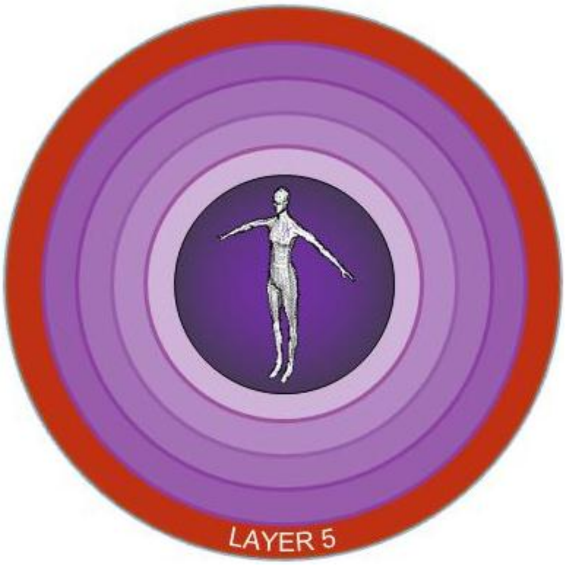
Given the importance of kinetic energy in determining crash and injury risk, this principle focuses on ensuring that speed is managed to levels that do not exceed the biomechanical tolerances of humans, recognising the ability of the vehicle to absorb energy during the crash. Scientific evidence shows that right-angle collisions produce the highest risk of severe injury to the occupants of the struck vehicle due to the high potential for intrusion and limited vehicle structure available to dissipate energy effectively. It is an inherent assumption of this principle that vehicle fleets over time become fully equipped with better in-built protection and safety features such as ABS, ISA, Stability control, curtain airbags for example, and hence become more compatible with the Safe System vision.

This principle focuses primarily on managing kinetic energy in right-angle collisions, with the key assumption being made that if adequate protection can be afforded to the occupants in vehicles involved in such collisions, then all other crash types will be also satisfactorily addressed. The extent to which speeds and/or angle can be managed to meet Safe System principles determines the intrinsic level of safety of a particular intersection design. International expert consensus states that when two vehicles collide at right-angles at speeds in excess of 50 km/h, the risk of severe injury rises rapidly with increasing impact speed.

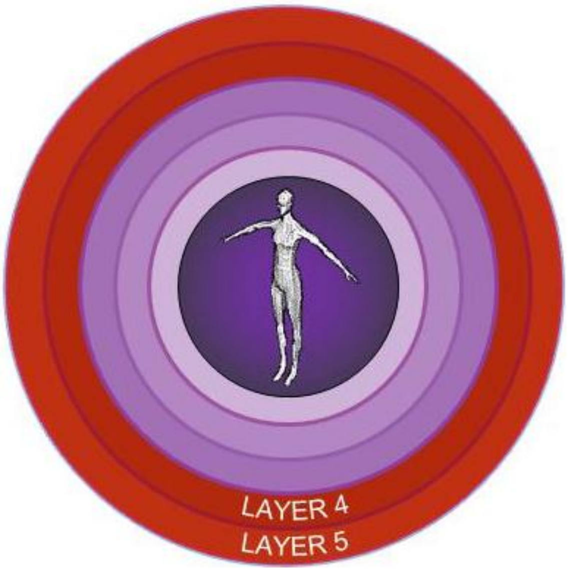
Where it is essential for travel speeds to exceed 50 km/h, fatal injury risk can be managed by moderating impact angles up to a maximum of 70 km/h before Safe System principles are violated. Where travel speeds exceed 70 km/h, it is not possible, through geometric design, to provide intersections that meet Safe System standards. In such circumstances all that remains is to reduce crash risk to negligible levels, a situation rarely achievable in present-day conditions.

5.3.5 Relationship between design principles and KEMM concept

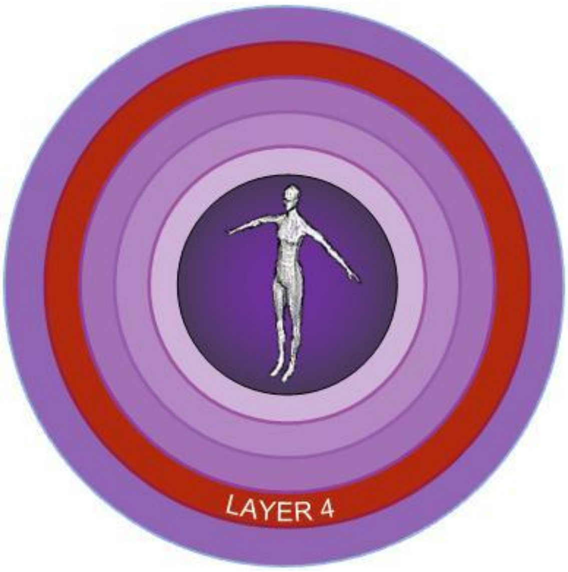
The four principles are the result of applying the thinking embodied within the Kinetic Energy Management Model. As a way of ensuring they are fully compatible with the KEMM concept, their relationships with the KEMM layers of protection are shown in Figure 17.



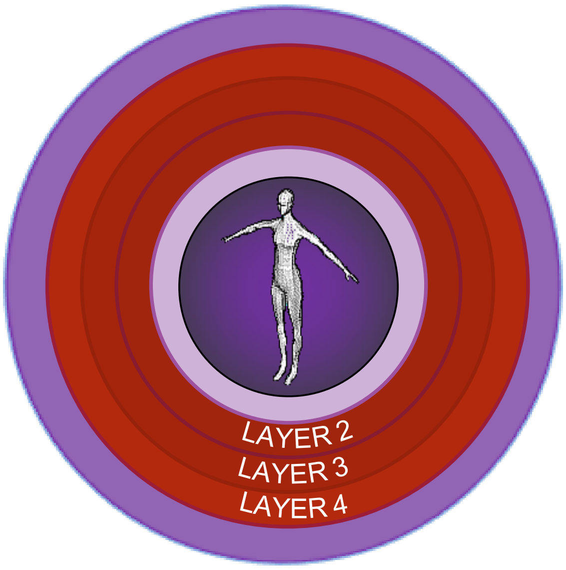
Principle 1: Fewer vehicles



Principle 2: Fewer intersections



Principle 3: Fewer conflicts



Principle 4: Lower speeds, more favourable impact angles

Figure 17. Relationship between design principles and KEMM layers.

Principle	Principle No.	Affected Layer
Fewer vehicles	1	Layer 5
Fewer intersections	2	Layers 4, 5
Fewer conflicts	3	Layer 4
Lower speeds/favourable angles	4	Layers 2, 3, 4

Principle 1, which involves reducing the numbers of vehicles passing through intersections, contributes to the level of protection offered by Layer 5 of the KEMM. This increased protection is the result of reduced exposure. Principle 2 encompasses fewer intersections and contributes to the level of protection available from the combination of Layers 4 and 5. This theoretical safety benefit is gained through reductions in both the opportunities for crashes and the likelihood of crashes for a given level of exposure. Principle 3 entails reducing the number of conflicts per intersection and consequently contributes to greater protection through Layer 4, which seeks to reduce crash risk for a given level of exposure. Finally, Principle 4, which concerns the management of speed and angle, contributes to enhanced protection through strengthening the protective capabilities of Layers 2 through 4. This is achieved by lower speeds reducing the likelihood of crashes (Layer 4); in conjunction with lower speeds and more favourable angles thereby reducing the amount of kinetic energy at impact (Layer 3) and reducing the risk of transfer of unacceptable levels of kinetic energy to the occupant or vulnerable road user during impact (Layer 2). This discussion helps to confirm the compatibility of the four design principles with the concept of the Kinetic Energy Management Model.

6 CONCLUSIONS

The purpose of Task 3 was to develop a set of intersection design principles concordant with the aspirations of Australasia's Safe System vision. This report presents the key findings of a scientifically-based analysis of the risks of death or serious injury in the event of an intersection crash.

A model based on the Kinetic Energy Management Model and also on Newtonian mechanics was developed and applied to high-priority crash types characterising Victoria's intersection crash problem. This model enables existing and future designs to be quantitatively assessed to estimate the risk of a fatal or serious injury outcome as a function of key design features. It was concluded that impact speed and angle are the primary determinants of intersection safety and that designers must focus on these two variables in order to achieve large and sustained gains in intersection safety.

Four design principles were formulated and will be applied in Task 5 of this study to guide the development of new designs and, where applicable, to assess current designs. These four principles may be summarised as follows:

1. **Fewer vehicles** – by reducing the number of vehicles in use, fewer opportunities for collisions will arise;

2. **Fewer intersections** – by minimising the number of intersections within the road network, and concentrating more traffic movements at intersections with best-practice safety standards, fewer opportunities for high-risk conflict should arise;

3. **Fewer conflict points per intersection** – by simplifying intersections to produce fewer conflict points, the opportunities for crashes at a given intersection should fall. The resultant reduction in complexity should also have a positive effect on safety;

4. **Impact speeds and impact angles constrained to biomechanically tolerable levels** – by designing to create speed and angle combinations that result in a low risk of serious injury in the event of a crash. Analysis of the kinematics of traffic collisions shows that:

   - For 90° collisions, impact (and, therefore, travel) speeds should not exceed 50 km/h for vehicle-to-vehicle collisions. For conflicts between vehicles and unprotected road users (i.e. pedestrians, cyclists and motorcyclists), impact (and, therefore, travel) speeds should not exceed 30 km/h;
   - For intersections located in speed limits greater than 50 km/h and not greater than 70 km/h, vehicle-to-vehicle conflicts must occur at less severe angles than 90° to ensure that the biomechanical tolerances of humans are not exceeded. Regardless of geometric layout to influence impact angles, travel speeds in areas where pedestrian and cycle traffic

is allocated high priority should not exceed 30 km/h if pedestrian and cyclist risks of death are to remain below the nominated level of 10%.

- Where neither of the above criteria addressing combinations of speed and angle can be met, crash risk must be reduced to negligible levels through other means.

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APPENDIX A: KEMM-X MATHEMATICS

Layer 3 calculations

This layer determines impact speed from travel speed, utilising the standard kinematics equations relating distance to speed at constant acceleration; namely, $v^2 = v_i^2 + 2ad$. The conceptual form of this speed-distance relationship is shown in Figure 12 (p. 29).

There are, however, three sections to the graph: (1) Constant speed, where a collision is about to occur, but the driver of the target vehicle is yet to react; (2) Constant deceleration, where the target driver is applying maximum braking and; (3) The target vehicle has stopped and is impacted by the bullet vehicle while at rest. The corresponding relationships are shown in Equations 2 to 4 below.

$$v = v_i \text{ for } d \le v_i PRT \qquad (2)$$

$$v = \sqrt{v_i^2 - 2\mu g(d - v_i PRT)} \text{ for } v_i PRT < d \le \frac{v_i^2}{2\mu g} + v_i PRT \qquad (3)$$

$$v = 0 \text{ for } d > \frac{v_i^2}{2\mu g} + v_i PRT \qquad (4)$$

Where:
v is vehicle speed (ms^{-1});
v_i is vehicle initial speed (ms^{-1});
d is distance from collision (m)

Layer 2 calculations

Figures 13 and 14 (p. 30) show schematically the vehicle to vehicle interaction in a generalised side impact crash. The angle of impact, θ, is defined as the angle between the travel direction of the target vehicle and the path of the bullet vehicle.

The pre- and post-collision situations are represented vectorially in Figure 18.

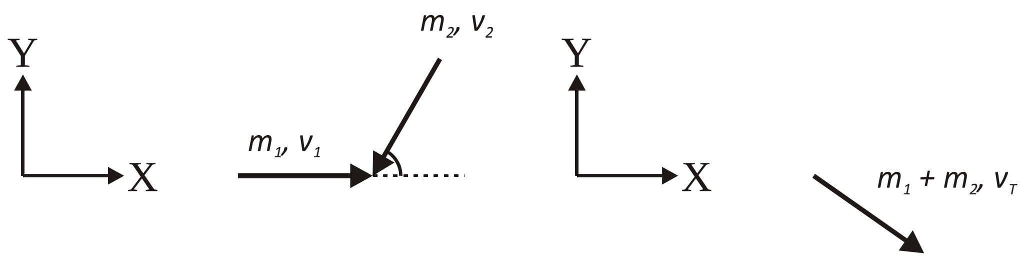

Figure 18. Pre- and post-crash vector diagram.

The purpose is now to determine the delta-V of the collision, defined as:

$$\Delta\vec{v}_1 = \vec{v}_{T,1} - \vec{v}_1 \qquad (5)$$

where:
$\Delta\vec{v}_1$ is the delta-V velocity vector for the target vehicle (kmh^{-1});
$\vec{v}_{T,1}$ is the combined post-crash velocity of the bullet and target vehicles (kmh^{-1});
$\vec{v}_1$ is distance from collision (m)

Applying conservation of linear momentum along each of the X- and Y-axes we then have:

$$m_1 v_{1,X} + m_2 v_{2,X} = (m_1 + m_2) v_{T,X} \qquad m_1 v_{1,Y} + m_2 v_{2,Y} = (m_1 + m_2) v_{T,Y} \quad (6)$$

$$\therefore v_{T,X} = \frac{m_1 v_{1,X} + m_2 v_{2,X}}{m_1 + m_2} \qquad \therefore v_{T,Y} = \frac{m_1 v_{1,Y} + m_2 v_{2,Y}}{m_1 + m_2}$$

Substituting
$v_{1,X} = v_1$ and $v_{2,X} = -v_2 \cos\theta$ $\qquad$ $v_{1,Y} = 0$ and $v_{2,Y} = -v_2 \sin\theta$

$$v_{T,X} = \frac{m_1 v_1 - m_2 v_2 \cos\theta}{m_1 + m_2} \qquad v_{T,Y} = \frac{-m_2 v_2 \sin\theta}{m_1 + m_2} \quad (7)$$

Now,

$$\Delta v_{1,X} = v_{T,X} - v_{1,X} \qquad \Delta v_{1,Y} = v_{T,Y} - v_{1,Y}$$

$$\therefore \Delta v_{1,X} = \frac{m_1 v_1 - m_2 v_2 \cos\theta}{m_1 + m_2} - v_1 \qquad \therefore \Delta v_{1,Y} = \frac{-m_2 v_2 \sin\theta}{m_1 + m_2} \quad (8)$$

Finally

$$|\Delta v_1| = \sqrt{\Delta v_{1,X}^2 + \Delta v_{1,Y}^2} \quad (9)$$

This is evaluated numerically in the model.

Layer 1 calculations

The calculations used in Layer 1 are included in Section 4.6 (p. 30).