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Utilising Human Crash Tolerance to Design an Interim and Ultimate Safe System for Road Safety

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Abstract: Many jurisdictions globally have adopted a zero road trauma target by 2050 and an interim target of a 50% reduction by 2030. The objective of this study was to investigate what the road system will need to look like in order to achieve these respective targets. Utilising human tolerance to injury as the key design factor, this study defined the combination of vehicle, infrastructure, and travel speed requirements to manage crash energy in order to: 1. prevent all fatalities and serious injuries by 2050 in an Ultimate Safe System scenario; and 2. significantly reduce fatalities and severe injuries by 2030 in an Interim Safe System scenario. Victoria, Australia and its Movement and Place (M&P) framework was employed as a case study. With the vehicle and infrastructure countermeasures currently available coupled with appropriate travel speeds it is possible to construct an Ultimate Safe System that can manage crash forces to achieve zero trauma and an Interim Safe System that can significantly reduce the most severe injuries in Victoria. This study has demonstrated a potential pathway from the current situation to 2030 and then 2050 that can achieve safety targets while meeting the core objectives of the transport system.

Keywords: vision zero; safe system; ultimate safe system; interim safe system; human tolerance; road safety strategy

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1. Introduction and Aims

In 2020, the United Nations (UN) General Assembly declared the timeframe between 2021–2030 the second Decade of Action for road safety and set the ambitious target for countries to achieve at least a 50% reduction in road fatalities and injuries by 2030 [1]. Governments and countries globally were encouraged to develop appropriate road safety strategies and actions to achieve this ambitious target. Governments have taken this one step further, and have committed to not just an interim target of a 50% reduction by 2030 but to zero fatalities and serious injuries by a set year. For example, the United States, Victoria in Australia, New Zealand, and the European Commission have all set a zero or near zero target by 2050.

It is commendable that jurisdictions are aiming for zero; however, current strategy development processes appear to be insufficient to support this ambition. Road safety strategies are often planned in 3–5 or 10 year cycles [2] attached to a set of interim casualty reductions targets without a concurrent long term plan on how to build a safe road system that can help ultimately achieve zero road trauma. While the ultimate goal of any road safety strategy is to reduce road trauma, in determining the ability of a road safety strategy in setting out a long-term pathway to zero, casualty reduction targets alone should not be the only measure of success. Rather than focus solely on short-term trauma targets, it is important to set out parameters of what a safe road transport system should look like and track its progress in obtaining that. However, many strategies focus on short to medium term goals without considering what is required to achieve this long-term zero objective.

It is clear that to achieve an interim 50% target and ultimately a zero target requires the development of a systematic and sustainable pathway of transformation from the current road transport system to a future safe road system that can ultimately prevent all serious road trauma. A sustainable pathway would involve gradually removing the underlying risk in the transport system by improving infrastructure and vehicles, along with appropriate speed limiting setting and management, to a stage where crash severity does not exceed human physical tolerance and without a strong dependency on road users always behaving appropriately due to the propensity for people to make mistakes as well as wilfully transgress. Job, Truong and Sakashita [3] defined '*a system in which people cannot be killed or seriously injured regardless of their behaviour or the behaviour of other road users*' as an Ultimate Safe System.

1.1. Ultimate Safe System—The Desirable Future State

In visualizing how to design a safe road transport system that is true to the moral imperative of achieving zero deaths and serious injuries, an Ultimate Safe System should, according to Job, Truong and Sakashita [3], be one in which:

- Road users are never exposed to forces which are not survivable or can create long-term debilitations even when they or others make mistakes, including deliberate risk-taking;
- the network incorporates road and vehicle features that are maintained, reliable, and effective, and can prevent deaths and serious injuries without being reliant on road user behaviour and compliance with laws;
- the network includes setting and achieving compliance with the speed limits through vehicle engineering without relying on drivers to choose to comply with limits.

There is no single initiative or road safety intervention that alone can accomplish the elimination of road trauma. Instead, research increasingly indicate a systemic approach to trauma reduction is required [4]; this thinking has been utilized in other industries to recognize that each part of the system has an important role to play and that even small changes in one area can make a significant difference to the effectiveness of the overall system [5]. In recent times, the Safe System approach is frequently used to guide the effective development of strategies to reduce road trauma [6,7]. While there may be issues with the interpretation of how the Safe System approach should be applied [3], it clearly highlights the need to take a systems perspective rather than a siloed approach when addressing road safety. Especially with the expanding development and availability of technologies such as electronic stability control [8,9], autonomous emergency braking [10], and lane keeping systems [11] that can help increase safety and decrease reliance on road user behaviour, there is a need to better understand the interactions and synergies between all parts that make up the transport system in order to effectively design a safe road system. In the future, as systems and technologies develop even further and interconnectedness becomes more prevalent, additional consideration will need to be given to supporting elements, such as the security of the system [12] and how to utilize these developments to enhance safety on the roads [13].

Fortunately, there is growing evidence as to what a safe road system needs to entail and the minimum requirements for roads, vehicles, and road users and how these components, together with speed, should interact to create safe traffic use [14]. Therefore, to achieve zero fatalities and serious injuries, it is necessary to define the joint requirements for vehicles, roads, and speed to achieve a future Ultimate Safe System. In an Ultimate Safe System, the system should be able to protect a road user from serious harm despite any unintentional mistakes or deliberate risk taking (e.g., drug driving). When a mistake or transgression occurs, an Ultimate Safe System should be able to guarantee safety through vehicle and infrastructure specifications in combination with speed setting and management to ensure the impact stays within acceptable injury tolerance levels. It is anticipated that these key elements will be able to help enforce most of the road user behaviors required, and thus there will be minimal reliance on road users to behave appropriately, due to their propensity to make mistakes. Nonetheless, road user compliance programs (e.g., police enforcement) will be very much required in the interim phase in the lead up to having a fully Ultimate Safe System.

Using a back-casting approach, one strategy might be to begin with defining an Ultimate Safe System before working backwards to define an appropriate Interim Safe System that can help meet any interim road safety target that has been set, and then to the current road safety situation. Back-casting works to determine the feasibility of that desirable future state, what policy measures would be required to reach that point, and highlight what the discrepancies are by testing alternatives based on existing risks [15]; this shifts the focus from prediction and likelihood to feasibility and choice [16].

1.2. Human Tolerance to Crash Forces

It is recognised that health losses are not randomly related to crashes and instead correspond to the amount of external forces to which one is exposed [17]. Therefore, to reduce road trauma it will be necessary to either prevent impact or mitigate the level of forces generated by an impact to a level that is within human tolerance and does not result in death or long-term health losses.

The human body has a predefined level of tolerance to external forces, varying with age, and becomes susceptible to injuries once the tolerance has been exceeded; this is known as the human tolerance to crash forces. To effectively reduce road trauma, the dissipation of kinetic energy within the road system needs to be controlled. Movement and access, i.e., travel speed, in this road system should be a function of the ability of roads and vehicles to effectively moderate crash forces to within human tolerance. Speed management thereby becomes the tool to regulate crash forces within the system by adapting the speed limit to the boundaries given by roads and vehicles.

The early Vision Zero system design principles were based on injury risk curves, i.e., the mathematical relationship between crash force and injury risk, where travel speed was used as a proxy for crash force [18]. Informed by risk curves on the likelihood of death and injuries by crash forces, the maximum possible travel speed for different crash types based on an inherently safe road system that will not result in deaths and serious injuries were refined to be:

- Locations with possible conflicts between pedestrians and cars = 30 km/h
- Intersections with possible side impacts between cars = 50 km/h
- Roads with possible frontal impacts between cars = 70 km/h
- Roads with no possibility of a side impact or frontal impact (only impacts with roadside infrastructure) = ≥100 km/h [19].

The Vision Zero design speeds were suggested based on best available evidence at the time, and allowed for at least a 10% risk of death. This has provided instrumental design guidance for rural and urban infrastructure and has been an important tool for justifying the transformations of the road transport system and in communicating with the community on the necessary changes. It is clear from reviewing road strategies around the world that the 30–50–70 km/h travel speed recommendation has been utilised from the late 1990s as a model of what constitutes a safe road transport system and is usually accompanied by indicative risk curves showing the exponential increase in risk with increased speed [20].

However, more recent research has shown that the early research around injury risk curves suffered from underreporting bias, overestimating the fatality risk for both pedestrians and car occupants [21]. While previous research suggested a 10% fatality risk for pedestrians at impact speeds of 30 km/h, Rosen and Sander [21] reported a fatality risk of only 2% at the same impact speed. However, Jurewicz et al. [22] estimated a 10% risk for a severe pedestrian injury (Maximum Abbreviated Injury Score 3+) to already be reached at a 20 km/h impact speed.

It can be concluded that travel speed alone is not a complete predictor of injury risk and that a change in velocity (delta-v) has a stronger connection to crash forces because of its dependencies on the acceleration level (negative) in the actual crash, and not only the travel speed prior to the crash. As travel speed in many crashes is not translated into the equivalent change in velocity, it can result in relatively flat risk curves compared to risk curves using delta-v, such as with the risk curve for single vehicle impacts [23].

While it can be a challenge to translate a risk curve using delta-v into advice on travel speed, it is necessary if the boundary conditions on human tolerance are to be translated into acceptable speed limits. A more precise relationship between crash forces and injury risk is given when deriving it as a function of closing speed, or the relative speed between two oncoming vehicles (e.g., for a car to pedestrian crash, impact speed and closing speed would be equal, while in a head-on crash the closing speed would be the sum of the impact speeds of the two approaching vehicles).

Even though this newer research indicates that while the previous advice on fatality risk as a function of travel speed might be somewhat misleading, the basic design speeds remain relevant if the scope is expanded to include the prevention of both fatal and serious injuries, especially when consideration is given to the older and more fragile segments of the population.

Under Vision Zero, the aim is to eliminate both fatalities and long-term health losses. While the earlier risk curves were concerned with only fatal injuries, new research considers the risk of serious injuries as well. To achieve zero, it will be necessary to determine this more precise relationship between delta-v and impact speeds to injuries for different crash types in order to be able to design a safe road system that is within the human tolerance and also meet the transport objective of the road system.

1.3. Safe Mobility and Accessibility

The main objective of a road network is to move people and goods. Many jurisdictions have in place a plan for safe and accessible mobility that details their approach to designing a transport system that meets the needs of those that use it, as well as the design purpose of each section of their road network [24]. Where available, these can be used to guide the types of safety interventions to be deployed to preserve the overall transport objectives of the system. Overlaying safety on an existing network plan can ensure that the countermeasures utilised are both safe and fit for the purpose of the different types of road environments and transport needs, and demonstrate how safe mobility can look in each network area. If safety is pushed forward without being able to sustain the movement function of the area this is less likely to be supported by government, as the transport objective of the network is not met.

In Victoria, Australia, Movement and Place (M&P) is the framework used for transport planning [24]. It is used to identify which roads serve what purpose and to define and operationalise the strategic objectives of achieving place, movement safety, and environmental outcomes. The M&P framework aims to balance the accessibility needs of different road users across the network and considers the community needs and expectations for the streets and places where they live, work, and pass through.

The M&P framework acknowledges that there are different modal priorities in different parts of the road network. The needs, requirements, and interventions needed to safety proof the area vary and the boundaries on how to make different parts of the network safe would be different. The challenge, then, is how to relate back to the Vision Zero objective on mobility being a function of safety, and how to overlay safety on the M&P framework to effectively manage the energy to within human crash tolerance levels to create a system that can move people around safely without the risk of dying or sustaining a serious injury.

1.4. Aims

This paper had three aims:

1. To review the human tolerance to crash forces and compile a more precise relationship between delta-v and impact speeds and the level and risk of injury.
2. To define the operational boundaries of what could constitute an Ultimate Safe System in 2050 that is both trauma-free and fit for its strategic transport purpose by utilising

human tolerance as the key design factor. As many jurisdictions are aiming for zero by 2050 in their planning horizon, this was selected as the example year.
3. To define the operational boundaries of what could constitute an Interim Safe System able to reduce the most severe injuries and contribute to trauma reduction by 2030, utilising human tolerance as the key design factor. As the UN has set a target of a 50% reduction in fatalities and injuries by 2030, this was selected as the example year.

Under an Interim Safe System, the most severe trauma would be prioritised for treatment first and beyond that, the system would be built upon to address any remaining serious trauma to arrive at an Ultimate Safe System that can prevent all fatal and serious road injuries. Using the state of Victoria, Australia as a case study, this study used back-casting methods on the pathway from 2050 to 2030 to the present and considered the outlooks at each time horizon to understand how to build on the countermeasures deployed to design and build an Interim Safe System and eventually an Ultimate Safe System.

2. Methods

2.1. Approach

This paper used human tolerance to injuries as the key design factor to define the combination of vehicle, infrastructure, and travel speed requirements to (1) prevent all fatalities and serious injuries by 2050 in an Ultimate Safe System scenario, and (2) significantly reduce fatalities and severe injuries by 2030 in an Interim Safe System scenario for Victoria, Australia based on its Movement and Place (M&P) framework objectives.

To determine the specific components of an Ultimate Safe System and Interim Safe System, the following steps were taken:

1. Described the road trauma problem by crash types and road users in the different parts of the road network in the M&P framework for Victoria;
2. Described the human tolerance per crash type and road user;
3. Determined the infrastructure and vehicle countermeasures available to address the road trauma issues/crash types identified;
4. Consulted the human tolerance for different crash types and determined the combination of infrastructure and vehicle countermeasures in conjunction with a maximum travel speed which together would be able to prevent all fatalities and serious injuries in an Ultimate Safe System scenario for each of the M&P areas;
5. Consulted the human tolerance for different crash types and determined the combination of infrastructure and vehicle countermeasures in conjunction with a maximum travel speed which together would likely be able to significantly reduce fatalities and severe injuries in an Interim Safe System scenario for each of the M&P areas.

2.1.1. Identifying the Road Trauma Problem in M&P Network

Road trauma data for Victoria, Australia between the 2015/2016 and 2017/2018 financial years recorded in the Road Crash Information System (RCIS) online database were utilised to determine the road trauma problem in the different parts of the road network in the M&P framework. For this study, road trauma was limited to crashes involving motorised vehicles, thereby excluding single vehicle crashes with bicycles and micro-mobility devices such as e-bikes and e-scooters.

2.1.2. Compiling the Human Tolerance to Crash Forces

Currently, there is no globally accepted definition of what a serious road injury is, and this can create confusion in knowing what jurisdictions are aiming to prevent. To assist with defining the level of unacceptable serious injury to target, the type, severity, and length of injury were considered.

The Maximum Abbreviated Injury Score (MAIS) is often used as a measure of the level of injury sustained in a road crash, with a score of 0 to 6 where 0 is uninjured and 6 is considered a fatal injury. The group of MAIS 3+ injuries include more life-threatening injuries, such as severe brain injuries, amputations, paraplegia, quadriplegia, multiple rib fractures, complex fractures, and at the most severe end, injuries such as decapitation that guarantees a fatal outcome. Jurisdictions such as the European Union (EU) have identified MAIS 3+ injuries as the most essential consideration in trauma reduction and elimination in their interim targets [25]. However, when considering permanent health losses, injury types at the lower end of the MAIS, while not life threatening, can affect long-term quality of life. Injuries at the MAIS 2 level can include whiplash injuries, fractures, and concussions leading to cognitive issues and other injuries that can be debilitating and create a greater risk of long-term health impairment [26,27].

Based on these considerations, in this study a severe injury was defined as a life-threatening injury including any MAIS 3+ injury and/or any whiplash injury resulting in symptoms longer than six months in duration, and a serious injury was defined as any MAIS 2+ injury and/or any whiplash injury resulting in symptoms longer than one month in duration.

A review of the available research around the relationship between impact speed and injury, i.e., risk curves, was undertaken to understand the human tolerance boundaries to achieve a less than 10% risk of a serious injury for each of the crash types identified in the road trauma analysis in the M&P network under an Ultimate Safe System and a less than 10% risk of a severe injury under an Interim Safe System. The 10% was chosen on the basis of risk curves in general being challenging to interpret in the lower risk band due to the mathematical construction of the curve; thus, 0% was not a feasible choice.

2.1.3. Identifying Available Countermeasures

A list of currently available infrastructure and vehicle countermeasures that can address the crash types identified in the trauma analysis was developed based on a literature review and by reviewing available and upcoming New Car Assessment Programme (NCAP) protocols, technical specifications for vehicle standards, and manufacturers descriptions. This study only focused on currently available technologies and on preventing fatal and injury outcomes from the different crash types, rather than interventions that can address every identified risk factor.

According to Vision Zero principles, it is acknowledged that humans are fallible and thus any interventions that rely on human input and compliance lacks certainty and sustainability in achieving its intended effects. Countermeasures that are reliant on human input/compliance would require the user to execute some behaviour in order for the countermeasure to achieve its safety benefits. For example, a seatbelt reminder would only achieve its safety benefit if the occupant responds to its prompt by wearing the seatbelt; the vehicle could be driven regardless of the seatbelt wearing status. If the seatbelt was not worn despite a warning from the seatbelt reminder and a crash was to occur, the safety benefit of seatbelts would not be achieved. Similarly, while a tactile lane marking could alert a driver that they are departing the lane, it would require the driver's input to correct the vehicle and not hit any dangerous objects outside of its lane. Conversely, countermeasures that are not reliant on human input/compliance can either enforce for the required behaviour to achieve the safety benefit or be independent of human behaviour in achieving the safety benefit. For example, a seatbelt interlock would enforce for seatbelt wearing by not allowing the vehicle to be moved unless occupants are belted; thus, if a crash was to occur, the safety benefits of seatbelts would be achieved. Similarly, a wire rope barrier would physically ensure the vehicle will not hit any dangerous objects outside of its lane regardless of what the driver's behaviour may be.

Therefore, the countermeasures in this section were separated into two lists, those that rely on human input/compliance and those that do not, in order to achieve the intended safety outcome. To be included on the list, the countermeasures must be available and have demonstrated effectiveness in reducing real life crashes and injuries, or else have shown a potential in reducing injuries through simulations or predictive studies on their target crash population.

A literature review was conducted for each countermeasure on effectiveness in reducing road trauma. The design and boundary limitations of each countermeasure were documented as well.

- Vehicle Safety Countermeasures

The report 'In depth cost-effectiveness analysis of the identified measures and features regarding the way forward for EU vehicle safety' was commissioned by the EU to assess the benefit and feasibility of a range of vehicle safety technologies, which led to the amendment of the General Safety Regulations [28]. For the report, a comprehensive literature review was undertaken, with studies being included based on quality of research, quality of data, timeliness, and relevance. The review included studies from around the world and the level of effectiveness would be applicable to the Australian context. Where available in the EU report, the studies that were included as a part of the report's effectiveness assessment were used as the basis of effectiveness for vehicle safety technologies in this current study.

- Road Infrastructure Countermeasures

Austroads is the main organisation of Australasian road transport and traffic agencies and regularly publishes reports and guides to promote a nationally consistent approach to road design, maintenance, and operation. Literature reviews of effectiveness and parameters of operation (where available from Austroads) were used as the basis of effectiveness for road infrastructure countermeasures in this study.

For the remaining countermeasures, the databases Science Direct, EBSCOhost, and MEDLINE were utilised to search for research indicating the effectiveness of the countermeasure. A scan of the resulting articles was conducted, and the following criteria used to select the supporting article for this study:

- Utilise Australian based studies of effectiveness where available;
- Utilise meta-analyses of effectiveness where available;
- Utilise studies with real world data where available.

Related articles sourced from the primary article were reviewed where relevant.

An internet search was conducted to identify any relevant grey literature, and was limited to official reports and guidelines, conference proceedings, and information with credible sources and references.

2.1.4. Determining an Ultimate and Interim Safe System

To determine the combination of vehicle, infrastructure, and travel speed requirements for each part of the M&P road network to create an Ultimate Safe System in 2050 and an Interim Safe System in 2030, the following were considered:

- The transport function of the area;
- The key trauma issues of the area;
- The human tolerance boundaries.

The combination of vehicle and infrastructure measures were selected based on the different trauma problems in the area and whether the intervention was able to address the particular crash types in the area and to reduce the risk of injury to the tolerance levels specified in Table 1.

For an Ultimate Safe System, countermeasures were selected from the list that did not rely on human input or compliance (NRHIC) in order to guarantee the intended outcome as much as possible whenever there was an available and effective intervention for the crash type. Countermeasures were only selected from the human intervention or compliance required (RHIC) list if there were no viable alternatives available on the NRHIC list while ensuring, in combination with other NRHIC countermeasure and the travel speed, that any crash would be within human tolerance and not result in a fatality or serious injury. The threshold for injuries to be considered unacceptable was defined as a 10% risk of a serious injury (MAIS 2+ or whiplash injury greater than one month duration).

Table 1. Delta-v and Impact Speed with a 10% risk for serious and severe injury for different crash types.

Crash Type	10% Risk for Serious Injury		10% Risk for Severe Injury	
	Delta-v km/h	**Impact Speed km/h**	**Delta-v km/h**	**Impact Speed km/h**
Car to Pedestrian crash	No impact allowable	No impact allowable	20	20
Car to powered two-wheeler (PTW)	No impact allowable	No impact allowable	30	30
PTW to wide object	N/A	25	N/A	50
PTW to narrow object	No impact allowable	No impact allowable	No impact allowable	No impact allowable
PTW to ground	N/A	N/A	N/A	75
Car to bicyclists	No impact allowable	No impact allowable	20	20
Side Impact–Car to Car (of equal mass)	20	40	30	60
Side Impact–Heavy Vehicle into Car	20	20	30	30
Head On Impact–Car to Car (of equal mass)	25	25	50	50
Head on Impact–Car to Heavy Vehicle	25	10	50	25
Rear End–car to car	10	20	20	40
Rear End–heavy vehicle into car	10	10	20	20

Table based on risk curves on relatively modern vehicles and belted occupants, rounded to the nearest 5 km/h.

For the Interim Safe System, countermeasures were selected from either list, and the threshold for injuries that could result in a permanent health loss was defined as a 10% risk of a severe injury (MAIS 3+ or a whiplash injury greater than six months duration).

To determine what was a safe travel speed, all the components of the system that controls crash forces and injury risk, both road infrastructure and vehicle, were considered. For example, with autonomous emergency braking (AEB) on vehicles the acceptable travel speed could be determined by the acceptable closing speed (or impact speed) plus the speed of which the vehicle can reduce by braking prior to impact. This approach was used by Eugensson et al. [29] to define the boundary conditions for a safe road transport system in 2020, and this is the approach used in this study when setting the boundary condition for the Ultimate and Interim Safe System as well. In addition, many vehicle and infrastructure measures are designed to be effective within certain travel speeds (e.g., lane-keeping assist activates at 60 km/h and above, traffic calming is designed for areas with travel speeds $\leq$50 km/h), and these boundaries of effectiveness for each countermeasure were considered when deciding which countermeasures to specify for an area and the appropriate travel speed to overlay on it.

The human tolerance boundaries in Table 1 were consulted when selecting the countermeasures and the speed to specify and again to confirm the final combination of vehicle, infrastructure, and travel speed requirements decided on to meet the desired tolerance levels.

3. Results

3.1. Road Trauma Problem in M&P Network

There are six street families under M&P, classed as civic hubs, city streets and city places, activity streets, local streets and connectors. In this paper, the street families were combined into three categories based on their safety need commonalities:

- Pedestrian priority areas = civic hubs, city streets and city places;
- Mixed traffic areas = activity streets;
- Vehicle priority areas = connectors and local streets.

Transport Function

The main transport functions for each of the street family categories according to the M&P are detailed below. It should be noted that the M&P currently does not specify a recommended or allowable travel speed in each movement area.

Pedestrian Priority Areas

The main transport purpose and function of pedestrian priority areas is to give priority to pedestrian movement and safety in a pedestrian friendly environment. There is high pedestrian movement and numbers and the objective is to support on-street activity and public life while connecting with the wider transport network. Pedestrians are encouraged to walk and move around freely and the aim is for them to both feel and be safe in doing so. While ideally this would be a vehicle-free zone, limited vehicle access for accessibility reasons (e.g., taxis, buses) may be required [24].

Mixed Traffic Areas

Mixed traffic areas have a high demand for movement and place that provides access to shops and services by all modes. There is a strong focus on supporting neighbourhood life and residential streets as well as businesses. There is a need to balance all these demands within the space that is available, and there are competing demands between vehicles and other road users [24].

Vehicle Priority Areas

The main transport function of roads and transport links in the vehicle priority areas is the efficient movement of people and goods between regions, and this necessitates a certain level of travel speed to achieve this function efficiently. It includes local streets that should foster a community spirit as well as local access [24].

Trauma Analysis

The analysis showed that 80.8% of all fatalities and serious injuries (FSI) (where serious injury is defined as hospitalisation by the Victorian Government) occurred in the vehicle priority areas, followed by 11% in mixed traffic areas and 4.6% in pedestrian priority areas. While vehicle occupants dominated the FSI in all areas, pedestrian FSI were most prevalent in the pedestrian priority areas by proportion (see Figure 1). All the identified crash types (pedestrians, intersection, head-on, rear-end, manoeuvring, overtaking, on path and run-off road) occurred in each of the street categories in different proportions, as seen in Figure 2.

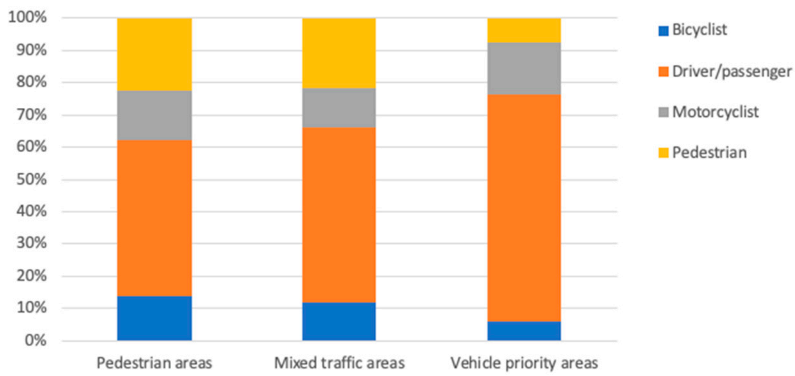

Figure 1. Road user FSI by M&P.

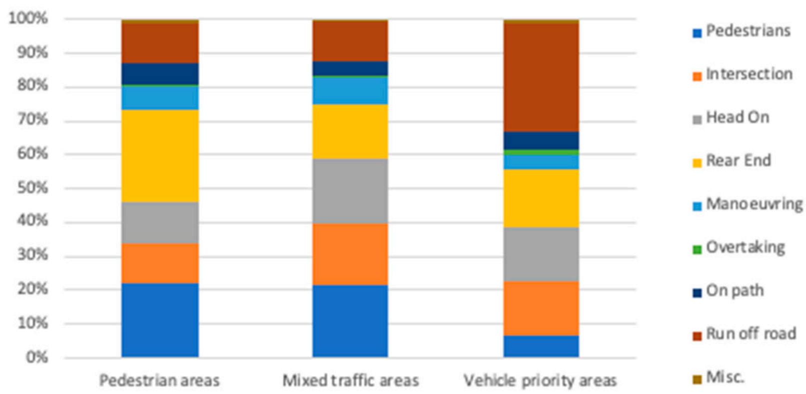

Figure 2. Crash types by M&P.

3.2. Human Tolerance for Fatalities, Severe and Serious Injuries

The results from the risk curve review are displayed in Table 1, showing the impact speed and delta-v for different crash types at which the road user would be subjected to a 10% risk of a serious or severe injury.

For pedestrians, Rosen and Sander [21] estimated that the 10% risk for an MAIS 3+ injury was at an impact speed of 30 km/h. However, if age was considered, Rosen [30] showed that for the age group 60 years and above, the 10% risk was estimated at 20 km/h. Jurewicz et al. [22] estimated the 10% risk for an MAIS 3+ injury to be at a 20 km/h impact speed. If a lower risk level is considered, it has been shown that even contact with the ground from a fall following a low-speed impact with a vehicle could result in a serious pedestrian injury. Hence, in an Ultimate Safe System, no motor vehicle and pedestrian collisions can be allowed. The same risk curves for pedestrians were assumed to be relevant for bicyclists.

For motorcycles, Ding et al. [31] derived risk curves for MAIS 2+, MAIS 3+ and fatal injuries as a function of impact speed for helmeted riders. The 10% risk of MAIS 2+ and MAIS 3+ injury for a crash into a wide object was estimated to be 25 km/h and 50 km/h, respectively, while risk of a serious and severe injury into a narrow object far exceeds 10% at any impact speed. The 10% risk level in a ground impact was only possible to estimate for MAIS 3+ injuries at 75 km/h.

With side impacts, more recent risk curves from the German In Depth Accident Study (GIDAS) [32] showed a 10% risk for MAIS 2+ and MAIS 3+ injuries at 20 km/h and 30 km/h lateral delta-v and 40 km/h and 60 km/h impact speeds, respectively. The risk was determined to be equal for car to heavy vehicles collisions regarding delta-v, which would naturally result in a lower allowable impact speed due to the mass difference.

For head-on frontal collisions, Doecke et al. [23] estimated a 10% risk of a MAIS 3+ injury at 53 km/h impact speed (half the closing speed) based on United States event data recorder (EDR) data. Autoliv [32] estimated the same 10% risk of a MAIS 3+ injury to be at 50 km/h delta-v, which would be the same as an impact speed in a head-on collision with a vehicle of equal mass. The same study using GIDAS data showed a 10% risk for an MAIS 2+ injury at 25 km/h delta-v. Similar results have been shown using Swedish and US EDR data [33,34]. The same logic was used to set the delta-v and impact speed for car to heavy vehicle frontal impacts as for side impacts.

For rear-end impacts the MAIS levels were not relevant, as the most dominant permanent impairing injury would be a whiplash injury as a result of mostly non-life-threatening injuries. Instead, the 10% risk of a serious and severe injury was based on symptoms for more than one month duration and symptoms for more than six months duration, respectively. Krafft et al. [35] showed a 10% risk of a serious whiplash injury to be approximately 10 km/h delta-v (20 km/h impact speed) and 20 km/h delta-v (40 km/h impact speed) for a severe whiplash injury. The impact speed in car to heavy vehicle crashes was divided by two in the case of head-on and side impacts.

There were no relevant risk curves for side impact into fixed narrow objects to estimate a 10% risk for a serious or severe injury. The Australasian New Car Assessment Programme carries out side impact pole tests for vehicles at an impact speed of 32 km/h [36], and thus 30 km/h was used as a proxy as the maximum allowable impact speed for a serious injury.

3.3. Available Countermeasures

The available countermeasures for infrastructure and vehicles, both reliant and not reliant on human input and compliance, are specified in Tables 2 and 3. Further information on the boundary conditions and literature of effectiveness for each countermeasure can be found in Appendix A.

Table 2. Infrastructure Safety Countermeasures by reliance on human input/compliance.

Infrastructure Safety Countermeasures	
Not Reliant on Human Input/Compliance	**Reliant on Human Input/Compliance**
• Bicycle Path—Separated • Flexible Wire Rope Barriers—Far and Near Side • Fencing • Flexible Wire Rope Barriers–median • Frangible Poles • Grade Separation • Left in Left Out • Pedestrian Fencing • Removal of Hazardous Objects	• Bicycle Lanes—Dedicated • Cameras—Speed or Red Light • Raised Intersections • Roundabouts • Signalised Intersection • Speed Humps • Tactile Lane Marking with Road Widening-Middle • Tactile Lane Marking with Road Widening-Side • Traffic Calming • Rumble Strips—Transverse • Wombat Crossing

Table 3. Vehicle Safety Countermeasures by reliance on human input/compliance.

Vehicle Safety Countermeasures	
Not Reliant on Human Input/Compliance	**Reliant on Human Input/Compliance**
• Alcohol Interlock • Autonomous Emergency Braking (AEB)—Bicyclist • AEB Head-On • AEB Intersection (Cross Traffic & Front Turn Across) • AEB Interurban • AEB Pedestrian • AEB Rear End • Back over avoidance • E-Call • Emergency Lane Keeping • Intelligent Speed Asssistance (ISA)—Limiting • Lane Keep Assist • Seatbelt Interlock • Truck Underrun—Front • Truck Underrun—Rear • Truck Underrun—Side • Vehicle Crashworthiness	• Blind Spot Monitoring • Electronic Stability Control (ESC) • Fatigue/Driver Monitoring • Intelligent Speed Assistance (ISA)—Advisory • Lane Departure Warning • Motorcycle Anti-lock Braking System (ABS) • Motorcycle Daytime Running Lights • Reversing Cameras • Seatbelt Reminder System

3.4. Designing an Ultimate and Interim Safe System

3.4.1. Pedestrian Priority Areas

The key trauma focus in pedestrian priority areas was car to pedestrian impacts. From Table 1, it is understood that no level of impact is considered safe for pedestrians if aiming to eliminate serious injuries. In a vehicle free zone, the possibility of conflict, and thus the risk of any injury, is eliminated. However, if vehicles are allowed the risk will need to be managed through the deployment of safety countermeasures. The combination of vehicle and infrastructure interventions in conjunction with travel speed limits must be able to eliminate the risk of serious injury altogether in an Ultimate Safe System (refer to Table 4).

AEB pedestrian is currently being assessed by NCAPs on their ability to avoid impact with a pedestrian at speeds up to 40 km/h and ability to reduce impact speed by at least 20 km/h at travel speeds up to 60 km/h [37]. The vehicle's ability to avoid a pedestrian collision is, however, dependent on the Time To Collision (TTC), which is the time it takes the AEB system to detect the pedestrian. TTC would vary depending on the environment. In a longitudinal setting, where a vehicle is approaching a pedestrian in the same direction without sight obstruction, a Forward Collision Warning needs to be issued before a TTC of 1.7 s for the vehicle to be awarded points in the NCAP assessment [37]. Where the vehicle is able to detect and brake with a TTC around 2 s, it is assumed that a travel speed of at least 40 km/h is possible without the risk of a pedestrian collision. However, in a highly pedestrianised area or in an environment with many potential obstructions the TCC will be much lower. For example, a child running into the traffic lane from behind a parked vehicle would result in a TTC of less than 0.5 s. With such a low TTC, AEB will at most be able to remove 10–15 km/h off the impact speed in normal conditions on dry asphalt.. Therefore, it will be necessary to set the maximum travel speed limit at 10 km/h to guarantee crash avoidance with a pedestrian in pedestrian priority areas. Road surface friction that can guarantee effective performance of AEB under all weather conditions including ice and snow will be required under all circumstances.

Table 4. Ultimate Safe System in 2050 for Pedestrian Priority Areas.

	Vehicles Requirements	Infrastructure Requirements	Maximum Travel Speed Requirements
Vehicle free zone	N/A	Off road separated lanes not in pedestrian areas for bicycles and micro-mobility devices	N/A
Vehicles allowed No motorcycles	AEB pedestrian AEB bicyclist ISA limiting or geofencing for speed control Front, side and rear underrun protection for heavy vehicles	Off road separated lanes not in pedestrian areas for bicycles and micro-mobility devices	10 km/h

To ensure the speed is complied with, the vehicle should be equipped with limiting Intelligent Speed Assistance (ISA). From an infrastructure perspective, fully separated lanes for bicycles and micro-mobility devices (e.g., e-bicycles and e-scooters) outside of pedestrianised areas will remove conflict between vehicles and bicyclists/micro-mobility devices. These measures together will create an environment that has less than a 10% risk of a serious injury for all road users. For all the other crash types identified in Figure 2, even without additional vehicle features, a travel speed of 10 km/h, enforced by limiting ISA will not create forces that exceed the human tolerance in any scenario in an Ultimate Safe System.

In an Interim scenario (refer to Table 5), a higher level of injury is accepted, and thus even with less stringent requirements, such as higher travel speeds and advisory ISA in combination with traffic calming measures, could still greatly reduce the risk of severe injuries to 10%, but not be able to remove the risk of a serious injury altogether. However, limiting ISA would still be preferable in an interim scenario, as it can enforce for the maximum speed even without additional infrastructure support. AEB rear-end was added because while a travel speed of 30 km/h would be within the tolerance levels of a severe injury if a crash was to occur, compliance with the travel speed requirement cannot be ensured with only advisory ISA and traffic calming measures. Therefore, additional vehicle technologies are required to help decrease the risk of a severe injury in a rear end impact if ISA limiting is not in use. A travel speed of 30 km/h was set and if complied with, and if any of the crash types identified in Figure 2 were to occur, they would not exceed the human tolerance for a severe injury.

From the crash data, motorcycle to pedestrian crashes were rare and there were no risk curves that could be used to estimate the level of risk, therefore it is assumed that motorcycle to pedestrian crashes can be reduced in the Interim scenario with the combination of measures specified.

Table 5. Interim Safe System in 2030 for Pedestrian Priority Areas.

	Vehicles Requirements	Infrastructure Requirements	Maximum Travel Speed Requirements
Vehicle free zone	N/A	Off road separated lanes not in pedestrian areas for bicycles and micro-mobility devices	N/A
Vehicles & Motorcycles Allowed	AEB pedestrian AEB bicyclist AEB rear-end (if ISA advisory is in use instead of ISA limiting) ISA limiting/or advisory Alcohol interlocks Driver monitoring Motorcycle ABS Motorcycle Daytime Running Lights	Off road separated lanes not in pedestrian areas for bicycles and micro-mobility devices Traffic calming (if ISA Advisory is in use instead of ISA Limiting)	30 km/h

3.4.2. Mixed Traffic Areas

The key trauma risks in mixed traffic areas were identified as car to pedestrian impacts, head-on crashes and side impact crashes at intersections. While the M&P framework does not specify speed limits for the street areas, other urban street design guides (e.g., Global Designing Cities Initiative) provide guidance on speed limits for safety and liveability. For urban areas, it is recommended that the speed limit does not exceed 40 km/h [38]. To ensure that a speed of 40 km/h is within human tolerance in an Ultimate Safe System, vehicles will need to be equipped with AEB pedestrian, AEB head-on, AEB rear-end, limiting ISA and other technologies. AEB pedestrian will be able to effectively prevent a collision with a pedestrian if the TTC is 2 s or greater with no obstruction to sightline; this can be achieved in combination with pedestrian crossings with a travel speed of 10 km/h and limiting ISA to ensure the speed is complied with (refer to Table 6).

Table 6. Ultimate Safe System in 2050 for Mixed Traffic Areas.

	Vehicles Requirements	Infrastructure Requirements	Maximum Travel Speed Requirements
Mix of road users No motorcycles or heavy vehicles	AEB bicyclist AEB pedestrian AEB rear-end AEB intersection AEB head-on ISA limiting or geofencing Seatbelt interlock Front, side and rear underrun protection for heavy vehicles	Off road separated lanes not in pedestrian areas for bicycles and micro-mobility devices Pedestrian crossings with 10 km/h speed zone Frangible narrow roadside objects/and or removal of hazardous narrow roadside objects 5 m distance from sidewalk to road lane/or pedestrian fencing	40 km/h BUT 10 km/h at pedestrian crossings 20 km/h at intersections

If a pedestrian was to cross outside of the designated pedestrian crossing, their risk of a serious injury must be eliminated under an Ultimate Safe System. To do this, sidewalks must be designed with sufficient distance from the closest road lane to ensure AEB pedestrian can detect and react to a pedestrian attempting to enter the road lane. In a worst-case scenario with a running pedestrian, a distance of around 5 m would be required for a vehicle at 40 km/h to avoid impact (assuming a running speed of 10 km/h and that the car would require approximately 1.5–2 s to stop from a speed of 40 km/h). Otherwise, pedestrian fencing can be considered to ensure no pedestrian access outside of the designated pedestrian crossing areas. However, in a mixed traffic area where liveability and accessibility for pedestrians is a priority, consideration will have to be given to whether fencing would fit within the type of environment the transport objectives would prefer to achieve for the area.

Frangible narrow roadside objects/and or removal of hazardous narrow roadside objects will be required to ensure any side impact into narrow objects are either avoided or the impacted object is frangible so the impact is less than 30 km/h due to unexpected events such as a tire puncture.

To ensure side impact collisions in an Ultimate Safe System are within the tolerance level of an impact speed and delta-v of 20 km/h to protect against serious injury, speed at intersections must be reduced to 20 km/h and enforced by limiting ISA. Fully separated lanes outside of pedestrianised areas will need to be provided in order to help remove conflict between vehicles and bicyclists/micro-mobility devices.

In an Ultimate scenario, heavy vehicles cannot be accommodated in the mixed traffic area if the travel speed needs to be preserved at 40 km/h due to the movement function of the road. At this travel speed, head-on crashes involving heavy vehicles will exceed the tolerance limit and therefore alternate route planning for heavy vehicle through traffic via vehicle priority areas will be required.

Under an Interim Safe System scenario (refer to Table 7), the higher accepted injury threshold would enable some less stringent requirements as compared to the Ultimate Safe System, which include:

- Advisory ISA instead of limiting ISA, although limiting ISA would still be the preference where possible;
- A minimum of 2 m distance from sidewalk to closest road lane to avoid high severity car-to-pedestrian collisions based on a person running into traffic or pedestrian fencing to prevent access;
- 30 km/h for pedestrian crossing instead of 10 km/h;
- Utilising roundabouts to reduce impact angle severity and to slow vehicles down to the tolerance level for severe injuries in side impact crashes;
- Addition of traffic calming measures to encourage higher levels of speed compliance.

Table 7. Interim Safe System in 2030 for Mixed Traffic Areas.

	Vehicles Requirements	Infrastructure Requirements	Maximum Travel Speed Requirements
Mix of road users Motorcycles and heavy vehicles allowed	AEB bicyclist AEB pedestrian AEB rear-end (if ISA advisory is in use instead of ISA limiting) AEB head-on AEB intersection Seatbelt reminder ISA limiting or advisory Alcohol interlock Driver monitoring Front, side and rear underrun protection for heavy vehicles Motorcycle ABS Motorcycle Daytime Running Lights	Off road separated lanes not in pedestrian areas for bicycles and micro-mobility devices Roundabouts at all intersections Pedestrian crossings with 30 km/h speed zone 2 m distance from sidewalk to road lane/or pedestrian fencing Frangible narrow roadside objects/and or removal of hazardous narrow roadside objects Traffic calming to ensure maximum travel speed of 30 km/h at pedestrian crossings (if ISA Advisory is in use instead of ISA Limiting)	40 km/h BUT 30 km/h at pedestrian crosings

For both the Ultimate and Interim Safe System, the defined vehicle, infrastructure and speed requirements will be able to effectively manage the energy in the system to the defined acceptable tolerance levels for the remaining crash types identified in Figure 2.

3.4.3. Vehicle Priority Areas

The key crash types in vehicle priority areas were head on, run off road, rear end, and side impact crashes. Head on and run off road crashes can be managed with full continuous flexible side and mid barriers to remove the risk of these resulting in a serious injury risk. In an Ultimate Safe System (refer to Table 8), vehicle technologies such as lane keep assist and emergency lane keeping alone or even in combination with other infrastructure measures such as a centre line would not be sufficient to ensure safety due to the possibility of tire punctures and other unexpected events that can result in unintentional lane departure and loss of control, which exceeds the boundaries of what the technologies were designed to address. In addition, head on crashes with heavy vehicles can only tolerate a very low delta-v; barriers can effectively prevent this conflict.

Table 8. Ultimate Safe System in 2030 for Vehicle Priority Areas.

<table>
<tr><th></th><th>Vehicles Requirements</th><th>Infrastructure Requirements</th><th>Maximum Travel Speed Requirements</th></tr>
<tr><td>Urban arterial–high movement link between local streets and freeways</td><td rowspan="4">AEB bicyclist
AEB pedestrian
AEB rear-end
AEB intersection
AEB head-on
ISA limiting
Lane Keep Assist
Emergency Lane Keeping
ESC
Seatbelt Interlocks
Front, side and rear underrun protection for heavy vehicles</td><td>Pedestrian grade separation
Off road separated bicycle lanes not in pedestrian areas with soft asphalt
Grade separation at all intersections if no speed limit reduction
Full continuous flexible side barriers
Full continuous flexible mid barriers
Barrier/fencing to prevent pedestrian access</td><td>60 km/h
BUT
20 km/h at intersections (if no grade separation)</td></tr>
<tr><td>Unsealed, undivided roads–very low movement, no improvements will be made to road or infrastructure</td><td>Close road and reroute to safer route
Or
One way travel only</td><td>30 km/h</td></tr>
<tr><td>Undivided sealed roads–low to high movement</td><td>Full continuous flexible side barriers
Full continuous flexible mid barriers
Pedestrian grade separation
Barrier/fencing to prevent pedestrian access near built up areas
Grade separation at all intersections if no speed limit reduction
Left in Left out with acceleration lanes
Off road separated lanes not in pedestrian areas for bicycles and micro-mobility devices</td><td>80 km/h or 100 km/h with good road alignment for good sight lines
BUT
80 km/h for heavy vehicles *
20 km/h at intersections (if no grade separation)</td></tr>
<tr><td>Divided multi lane roads with a physical median</td><td>Full continuous flexible side barriers
Full continuous flexible mid barriers
Grade separation at all intersections
Barrier/fencing to prevent pedestrian access
Off road separated lanes for bicycles and micro-mobility devices</td><td>100 km/h
BUT
80 km/h for heavy vehicles *</td></tr>
</table>

* unless there is a barrier that is tested and can withstand a higher speed.

Similarly, with side impact crashes at intersections grade separation can remove the conflict altogether and thus the injury risk. Otherwise, the installation of roundabouts with a speed limit of 20 km/h at intersections, enforced with limiting ISA can ensure any crash impacts are within human tolerance for a serious injury.

For unsealed roads where authorities are not motivated to make any infrastructure improvements due to the low volume of traffic, vehicle technologies alone will not be sufficient to ensure safety from serious injury without a significant reduction in travel speed in an Ultimate Safe System. For example, AEB head-on can reduce closing velocity by 30 km/h on average [39]; however, with lower friction on unsealed roads the effectiveness would be significantly reduced. To prevent head on serious injury risk, the maximum travel speed needs to be 30 km/h or lower to allow AEB head on, as well as other AEB technologies for other crash types, to work effectively. Otherwise, the alternative will be to close the road and re-route traffic to other nearby safer roads where safety can be guaranteed.

Where pedestrians and bicyclists are allowed access, pedestrian grade separation and off-road bicycle paths need to be provided.

Motorcyclists are inherently vulnerable due to the lack of protection and currently cannot be safely accommodated with other vehicles in the mixed traffic area in an Ultimate Safe System due to no available countermeasure that can guarantee the use of a motorcycle helmet. Without a helmet, the risk will exceed the human tolerance and motorcyclist safety cannot be assured. In an Interim scenario, dedicated motorcycle routes away from other vehicles could reduce their risk of severe injury to within tolerance levels, assuming helmets are worn and enforced for.

In an Interim scenario (refer to Table 9), barriers will still be needed to reduce the risk of a severe injury due to the high-speed environment necessitated by the M&P function. Where continuous barriers cannot be motivated, continuous line markings coupled with lane keep assist/emergency lane keep, with targeted flexible barriers at high-risk locations (e.g., where hazardous objects such as trees, cliffs, mountains in close proximity to the road) will be a necessary minimum to keep crash energies to within a severe injury tolerance. For side impact crashes, well designed roundabouts or raised intersection platforms will be required to bring any impacts to within the tolerance level if grade separation is not used.

Table 9. Interim Safe System in 2050 for Vehicle Priority Areas.

	Vehicles Requirements	Infrastructure Requirements	Maximum Travel Speed Requirements
Urban arterial–high movement link between local streets and freeways	AEB bicyclist AEB pedestrian AEB rear-end AEB intersection (for other access points) AEB head-on ISA limiting/advisory Lane Keep Assist/Emergency Lane Keeping ESC Seatbelt Reminder Alcohol Interlocks Front, side and rear underrun protection for heavy vehicles	Off road separated bicycle lanes not in pedestrian areas with soft asphalt Pedestrian grade separation or pedestrian crossing at roundabouts Traffic calming to ensure traffic speed is 30 km/h or less at pedestrian crossing (if not grade separated) Roundabouts at all intersections and/or raised intersection platforms or grade separation Frangible narrow roadside objects/and or removal of hazardous narrow roadside objects Continuous line markings	60 km/h BUT 30 km/h at pedestrian crossing (if no pedestrian grade separation)
Unsealed, undivided roads–very low movement		No requirements for road or infrastructure	60 km/h *
Undivided sealed roads–low to mid movement		Targeted flexible side barriers at high risk locations **/or frangible narrow roadside objects/and or removal of hazardous narrow roadside objects Continuous line markings plus sufficient shoulder for recovery Pedestrian grade separation Roundabouts at all intersections or grade separation Left in Left out with acceleration lanes Off road separated lanes not in pedestrian areas for bicycles and micro-mobility devices	80 km/h
Undivided sealed roads–high movement		Full continuous flexible side barriers or Targeted flexible side barriers at high risk locations */Frangible narrow roadside objects/and or removal of hazardous narrow roadside objects Full continuous flexible mid barriers Pedestrian grade separation Roundabouts at all intersections or grade separation Left in Left out with acceleration lanes Off road separated lanes not in pedestrian areas for bicycles and micro-mobility devices	100 km/h 80 km/h for heavy vehicles ***
Divided multi lane roads with a physical median		Full continuous flexible side barriers Full continuous flexible mid barriers Grade separation at all intersections Barrier/fencing to prevent pedestrian access Off road separated lanes for bicycles and micro-mobility devices	100 km/h 80 km/h for heavy vehicles ***
Separated Motorcycle Only Routes ** Motorcycles prohibited from other routes**	Motorcycle ABS Motorcycle Daytime running lights	Motorcycle rub rails on identified prioritised motorcycle only routes with a high number of motorcycle riders	75 km/h

* while 60 km/h exceeds the tolerance level in Table 1, data analysis indicate head on collisions on gravel roads are very rare and thus negligible in an Interim scenario; ** high risk location where hazardous objects e.g., trees, cliffs, mountains are in close proximity to the road; *** unless there is a barrier that is tested and can withstand a higher speed **** requires helmet usage.

3.5. Minimum Vehicle Requirements for the Fleet in 2030 and 2050

To achieve zero road trauma and a reduction in the most severe injuries by 2050 and 2030, respectively, the overall fleet must comprise of vehicles equipped with certain safety features that can help prevent or mitigate injuries.

From the combination of vehicle, infrastructure, and travel speed requirements defined for the pedestrian priority, mixed traffic, and vehicle priority areas to achieve an Ultimate and an Interim Safe System, the minimum vehicle technology requirements at 2030 and 2050 are as shown below in Tables 10 and 11.

Table 10. Minimum vehicle technology requirements at 2030.

Technology	Passenger Vehicles	Heavy Vehicles	Powered Two-Wheelers
AEB Bicyclist	✓	✓	N/A
AEB Head-On	✓	✓	N/A
AEB Intersection	✓	✓	N/A
AEB Pedestrian	✓	✓	N/A
AEB—Rear End	✓	✓	N/A
Alcohol Interlocks	✓	✓	N/A
Electronic Stability Control	✓	✓	N/A
Emergency Lane Keeping	✓	✓	N/A
ISA—Advisory (with a preference for ISA Limiting where possible)	✓	✓	N/A
Lane Keep Assist	✓	✓	N/A
Motorcycle ABS	N/A	N/A	✓
Motorcycle Daytime Running Lights	N/A	N/A	✓
Seatbelt reminder	✓	✓	N/A
Underrun protection for heavy vehicles—front, side, rear	N/A	✓	N/A

Table 11. Minimum vehicle technology requirements at 2050.

Technology	Passenger Vehicles	Heavy Vehicles
AEB Bicyclist	✓	✓
AEB Head-On	✓	✓
AEB Intersection	✓	✓
AEB Pedestrian	✓	✓
AEB Rear-End	✓	✓
Electronic Stability Control	✓	✓
Emergency Lane Keeping	✓	✓
Geofencing	✓	✓
ISA—Limiting	✓	✓
Lane Keep Assist	✓	✓
Seatbelt Interlocks	✓	✓
Underrun protection for heavy vehicles—front, side, rear	N/A	✓

In addition to the vehicle safety technologies specified for 2030 and 2050, the crash protection features of the vehicles need to be of a high standard, and as a minimum, meet all the priority vehicle safety regulations set out under Target 5 of the UN Global Road Safety Performance Target for vehicles, which states:

- Target 5–By 2030, 100% of new (defined as produced, sold or imported) and used vehicles meet high quality safety standards, such as the recommended priority UN Regulations, Global Technical Regulations, or equivalent recognized national performance requirements [40].

The recommended priority UN regulations include:

- UN Regulation 94 Frontal Impact
- UN Regulation 95 Side Impact
- UN Regulation 140 (GTR 8) Electronic Stability Control
- UN Regulation 127 (GTR 9) Pedestrian Protection
- UN Regulation 16 Seat Belts
- UN Regulation 14 Seat Belt Anchorages
- UN Regulations 44/129 Child Restraints
- UN Regulation 78 (GTR 3) Motorcycle ABS

Currently, the only priority regulation Australia is lacking is for pedestrian protection [41]. These minimum regulations need to be regulated for by the target dates. For maximum protection, all vehicles and specified technologies must be of a 5-star ANCAP safety standard according to 2030 and 2050 assessment protocols. In addition, heavy vehicles including buses and trucks should not be allowed to raise the height of the vehicles or fit bull-bars in order to further increase the safety for all road users.

4. Discussion

A number of jurisdictions globally have set a zero road fatalities and serious injuries target by 2050 and an interim 50% reduction in road trauma by 2030. This study set out to investigate how the road system would need to look in order to achieve this, and whether such a safe system is possible to construct with currently available road safety measures. This was achieved by defining the operational boundaries of what could constitute an Ultimate Safe System able to eliminate road trauma in 2050 and an Interim Safe System able to reduce the most severe trauma in 2030 by utilising the known human tolerance to crash forces as the key design factor.

Utilising a back-casting approach, the vehicle, infrastructure and travel speed requirements were defined to effectively manage crash energy to within the human tolerance to achieve an Ultimate Safe System. It is acknowledged that the design boundaries of an Ultimate Safe System in its entirety are very far from where the current Victorian road transport system is, and the transformation required to achieve an Ultimate Safe System is significant. However, it was important to define the Ultimate Safe System free from considerations of political will, willingness to invest, cost, pragmatism, and community acceptance, as this step was to determine whether an Ultimate Safe System that can achieve its objective of zero trauma is actually feasible with the currently available countermeasures. This allowed for more creative thinking based on the desired end goal and available evidence rather than being restricted by present limitations. The result of this process clearly defined how such a system would need to look and the likely effort needed in order to achieve zero road trauma. Discussions on willingness to invest and build such a system can then be well-informed and based on a clear understanding of the scale of work that needs to be undertaken.

The results from this study demonstrated that by using human tolerance as the key design factor, with the vehicle and infrastructure countermeasures currently available coupled with appropriate travel speeds it is possible to construct an Ultimate Safe System that can manage crash forces to achieve zero trauma in Victoria, Australia. While these results will require further validation, indications are that there is no need for jurisdictions to await further technological advancements such as autonomous vehicles to reduce and even eliminate road trauma. Developments such as autonomous vehicles and connectivity may show promise in helping reduce trauma, however, the penetration of these features can take up to 30 years from the year of regulation [42], and is thus too slow to make a significant difference in the fleet to help achieve any targets set for 2030 or even 2050. With only the currently available interventions listed in this study, jurisdictions can already make significant changes to the road network to systematically remove risks and begin building an Interim Safe System to reduce the most severe trauma before moving towards building an Ultimate Safe System that can achieve zero; however, substantial implementation of known measures is currently lacking. With strategy planning often occurring in cycles of 3–5 years, the politics of committing to a zero goal is difficult when key decision makers do not expect to be in power when the results of the strategy are due. A long-term transformational plan to move towards zero trauma, as demonstrated in this study, has the value to leverage long-term commitment to ensure that actions are undertaken promptly.

To move from a mainly casualty reduction-based strategy to a transformational strategy may be considered too optimistic by jurisdictions without a bridging step. Therefore, this study back-casted from an Ultimate Safe System to an Interim Safe System that is able to reduce the most severe injuries in the system by 2030. In this pathway, the most severe injuries and fatalities will be addressed first from the current state up to 2030, before continuing to transform the system to an Ultimate Safe System that will eventually be able to eliminate the remaining fatalities and serious injuries by 2050. This approach demonstrated the stages and interventions required for a systematic and sustainable pathway from the current road trauma to an interim stage and finally to the ultimate goal of zero trauma.

It is important to note the combination of measures specified under the Ultimate and Interim Safe System was considered from a system perspective and must be implemented as a package in order to derive the intended trauma reduction/elimination outcome. The combination of vehicle and infrastructure treatments selected along with the maximum travel speeds have a synergistic effect, and if one measure exceeds the boundaries set it will affect the effectiveness of the other measures specified as well. For example, if the travel speed is too high, this might exceed the envelope of effectiveness for AEB and the technology will not work as intended. The safety outcome in an Interim Safe System scenario cannot be guaranteed due to the use of less stringent vehicle and infrastructure measures that are in part reliant on human input/compliance (e.g., seatbelt reminder systems) to achieve the intended safety outcome. Therefore, in an interim scenario, road user programmes such as police enforcement will still be required to motivate compliance with road rules.

Movement and Place was used in this paper as a tool for implementation and determination of which countermeasures would be relevant where in the road network. The Vision Zero principle of movement as a function of safety has long been used as an argument to reduce speed limits where the infrastructure is not adequately designed to protect road users. Alternatively, safety can be achieved by keeping the speed limit constant on roads with a high movement function by implementing infrastructure improvements. However, jurisdictions rarely have the resources to make transformational changes to the majority of the road network. Hence, guidance is needed on where to prioritise investments. The results of this study showed that by being clear on the movement or place function in different areas in the road network and adopting safety solutions targeting the modal priority it is possible to achieve a safe system for all modes of transport. It is therefore recommended that jurisdictions that plan to achieve zero fatalities and serious injuries should adopt available tools for transport and land use planning, followed by a clear definition of how safety is guaranteed in each of the areas of the transport network by utilising human tolerance as the key design consideration.

Ideally, a safe road system will be able to safely accommodate all modes of road users. In this study, it proved difficult to ensure the safety of motorcyclists, and thus their inclusion in an Ultimate Safe System. Motorcyclists are inherently vulnerable due to their lack of protection and their ability to travel at high speeds, and there are currently a limited number of countermeasures that can effectively improve their safety. The risk curves of injury risks for motorcyclists are for helmeted riders, with the assumption that injury for non-helmeted riders would far exceed the tolerance levels specified for serious injuries. As there is currently no intervention that can guarantee helmet wearing, and thus ensure crash forces will be within human tolerance levels for a serious injury, at this point in time motorcyclists cannot be safely accommodated in an Ultimate Safe System. In an Interim Safe System, motorcycle-dedicated routes to reduce car to motorcycle conflicts, as well as enforcing helmet wearing and protective clothing, would be needed in order to help reduce motorcycle trauma. However, a large gap in knowledge exists on how to move from an Interim scenario to an Ultimate scenario where motorcyclists can be safely accommodated, and further research and innovative measures in this area are needed.

Similarly, in an Ultimate scenario, heavy vehicles cannot currently be safely accommodated in the mixed traffic area. However, alternate route planning for heavy vehicle through traffic via vehicle priority areas can still allow heavy vehicle access. In regards to delivery of goods to businesses in the mixed traffic area, alternate vehicle choices such as light duty vehicles may need to be considered.

4.1. Implications for Road Safety

The Global Plan [6] published as a guiding document for the second Decade of Action for Road Safety sets out the recommended actions for jurisdictions in the coming decade, however, it does not provide guidance on the prioritisation of actions for the short or long term to achieve trauma reduction. The guidance is necessarily broad rather than specific due to the global audience of the document, and the results and processes undertaken from this study can be a useful accompaniment to the Global Plan for jurisdictions that would prefer a more detailed pathway to trauma reduction.

The results from this study set out a clear pathway from the current road trauma problem to an Interim Safe System that can reduce the most severe injuries by 2030 to an Ultimate Safe System that can achieve zero road trauma by 2050. It was based on the Victorian trauma problem and its overriding M&P transport plan. It is acknowledged that what would constitute an Ultimate and Interim Safe system in other jurisdictions with different trauma profiles and transport priorities might be different. However, the steps taken in this study to arrive at an Interim and Ultimate Safe System are equally applicable to other jurisdictions, as the human tolerance to injuries compiled is universally applicable, as are the majority of the specified countermeasures. Jurisdictions can undertake a similar process to determine the short- and long-term system requirements to achieve their desired targets and begin implementation to close the gap between their current road safety situation and their defined Interim and Ultimate Safe Systems.

4.2. Limitations

Currently, there is no clear definition of what a serious injury is. This is a limitation for global strategy development as well as for this study, as it is unclear exactly what it is that jurisdictions are aiming to prevent. The specification of human tolerance and the Ultimate Safe System are both dependent on having a clear definition. This paper defined a serious injury as a 10% risk of a MAIS 2+ injury or an injury with symptoms sustained for longer than one month duration. This is likely to be a conservative estimate, as the Ultimate Safe System aims to prevent all MAIS 2+ injuries regardless of whether the injury is permanent or not. Further research on where and how these injuries occur would allow for system designers to more effectively safeguard the system against them. Any adjustment in the definition of a serious injury would also adjust the Ultimate Safe System and the combination of measures required to construct the ultimate scenario.

There is a gap in the literature regarding the risk of injury for motorcycle to pedestrian crashes, single bicycle crashes, single micro-mobility device crashes, and crashes between these groups of road users. Without the relevant risk curves and profiles, it was not possible to specify an Ultimate Safe System or Interim Safe System that can systematically reduce their risk of injury. This paper only focused on preventing motorised vehicle-related crashes; however, as more research becomes available, the systems can be evolved to also incorporate the safety of these types of crashes.

The vehicles, infrastructure and travel speed requirements set for the Ultimate and Interim Safe Systems were based on the human tolerance to crash forces before the risk of serious, severe, and fatal injuries increase. It assumed that the interventions are effective within the limits of their boundary conditions. However, if the boundaries change or are exceeded, the risk levels will change. One example would be the friction available for braking on roads covered with snow and ice, or sensor performance in foggy and rainy conditions. This needs to be accounted for either by the road agency guaranteeing certain conditions, or more likely, by vehicles adapting their speed to the current conditions. Technological advancements are expected to be made in the near future, especially in regards to vehicle technologies. Where newer specifications are available, the boundaries and specifications of the system can change. For example, if AEB systems can automatically detect whether there are pedestrians at a crossing, the vehicle can automatically slow to 10 km/h or continue at the speed limit if there are no pedestrians present, rather than specifying a blanket 10 km/h requirement at all pedestrian crossings at present. As newer specifications become available, the system requirements can be updated.

Currently, the vehicle and infrastructure measures specified are assumed to be 100% effective for a particular crash type if all the boundary conditions are met (see Appendix A). However, there may be gaps in effectiveness based on real world data that would necessitate further technological developments to ensure effectiveness. In the Interim scenario, compliance is assumed rather than strictly enforced for, unlike the Ultimate scenario; thus, the trauma reduction outcome would only be achieved if the system requirements specified are complied with. Additional measures such as police enforcement may be required in the interim stage to further secure the target trauma reduction desired. Further validation of this study utilising real-world data is required to identify any gaps in the technical specifications. Modelling how closely the specified systems match the intended targets and identifying any residual trauma not already addressed in the system are additional requirements.

4.3. Next Steps

The next step will be to validate the specifications from this study by using a sample of real-world crashes to model how close the systems specified here are to the intended targets, identify any residual trauma in the system not already addressed, and plan how to optimally implement the systems.

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Appendix A. Currently Available Infrastructure and Vehicle Countermeasures

Table A1. Infrastructure and vehicle countermeasures not reliant on human input/compliance.

Infrastructure Intervention	Description	Crash Type	Applicable Vehicle Type *	Boundary Conditions	Effectiveness
Barriers–wire rope/flexible Far and near side	A cable barrier on the edge of a road to prevent lane departure	Lane departure crashes	M1, M2, M3, N1, N2, N3	• Impact angle <25 degrees at higher speeds of 100km/h • Heavy vehicle (HV) only in shallow angle (<5 degrees) and speed <80 km/h • Exclude rollovers prior to impact with barrier • Exclude unbelted occupants	• An overall crash risk reduction of 44% for run-off road and head on crashes, and 79–86% for individual routes [43]
Barriers–wire rope/flexible Median	A cable barrier on the median of a road to prevent lane departure	Head on crashes Lane departure crashes	M1, M2, M3, N1, N2, N3	• Impact angle <25 degrees at higher speeds of 100 km/h • HV only in shallow angle (<5 degrees) and speed <80 km/h • Exclude rollovers prior to impact with barrier • Exclude unbelted occupants	• An overall crash risk reduction of 44% for run-off road and head on crashes, and 79–86% for individual routes [43] • 98.1% success in preventing cars from crossing the median [44] • 95.5% success in preventing light trucks from crossing the median [44]
Bicycle Path/Track–separated or protected	Formally allocated road space for cyclists and provides a physical separation (e.g., by a barrier or median) between cyclists and motor vehicles	Bicycle crashes	M1, M2, M3, N1, N2, N3, L	• There must be physical separation from motorised vehicles [45]	• Reduces collisions and injuries [45]
Fencing	Fencing to direct people away from traffic and guide them to designated pedestrian crossings	Pedestrian crashes	M1, M2, M3, N1, N2, N3, L	N/A	• Fencing can reduce unwanted access by 94.6% [46]
Frangible poles (e.g. for street lighting and road signs)	A pole that is designed to break away when struck	Lane departure crashes into fixed objects	M1, M2, M3, N1, N2, N3, L	• There must be no other fixed objects along the route that can be impacted with (e.g., tree)	• Reduces injury and fatal crashes by 30% and 40%, respectively [47]
Grade Separation	The alignment of an intersection at different heights to eliminate conflict	Intersection crashes	M1, M2, M3, N1, N2, N3, L	N/A	• Resolves conflict points and eliminates safety threat posed by other vehicles [48] • An estimated crash reduction of 50% for all severities, but low confidence [49] • According to the Highway Safety Manual of American Association State Highway and Transportation Officials (AASHTO), converting an intersection and a signalised intersection to a grade separation reduces injury crashes by 57% and 28%, respectively [48]

Table A1. *Cont.*

Left in/left out	A junction that only allows vehicles to enter and exit from the left	Intersection crashes Side impact crashes	M1, M2, M3, N1, N2, N3, L	N/A	• Improves safety by reducing the number of conflict points [50]
Removal of hazardous objects (e.g., trees, poles)	The permanent removal of any objects that pose a danger if impacted with	Lane departure crashes into fixed objects	M1, M2, M3, N1, N2, N3, L	• There must be no other fixed objects that can be impacted with (e.g., fence) • There must be a systematic removal of the hazardous object along the route	• A 50% reduction in crashes when pole density was reduced from 38 per km to 13 per km [51]
Vehicle Intervention	**Description**	**Crash Type**	**Applicable Vehicle Type ***	**Boundary Conditions**	**Effectiveness**
Alcohol interlock	An electronic breath testing device that prevents a vehicle ignition from starting if it detects the presence of alcohol. It will also request intermittent breath tests during the trip	Alcohol impaired related crashes	M1, M2, M3, N1, N2, N3	• Vehicle transgressing is fitted with the alcohol interlock	• Application of EU wide alcohol wide interlock program for hard core drink drivers can reduce road fatalities by 7.3% annually for passenger vehicles and 1.3% for commercial vehicles by 2020 [52] • A 90% reduction in recidivism [53]
Autonomous emergency braking (AEB) bicyclist	A technology that utilises cameras, radars or optical sensors to detect any impeding cyclists and automatically applies the brakes to avoid/and or mitigate a crash if the driver does not react–designed to specifically detect bicyclists	Cyclist crashes	M1, M2, M3, N1, N2, N3	• Travel speed not greater than 45 km/h. The impacting vehicle must be equipped with the technology • Excludes night time crashes	• A 35–59% effectiveness for fatalities and 14–54% for serious injuries [54]
Autonomous emergency braking (AEB) city	A technology that utilises cameras, radars or optical sensors to detect any imminent crashes with vehicles travelling in the same direction and automatically applies the brakes to avoid/and or mitigate a crash if the driver does not react–operates in low speed environments	Rear end crashes	M1, M2, M3, N1, N2, N3	• Travel speed not greater than 50 km/h • The impacting vehicle must be equipped with AEB • No obstructed lines of sight if time to collision is <2 s	• A 38% reduction in rear end crashes for vehicles fitted with low speed AEB [55] • Forward Collision Warning with AEB reduced rear end crashes by 39% [56] • Similar effectiveness for N1 vehicles assumed [57]
Autonomous emergency braking (AEB) head-on	A technology that utilises cameras, radars or optical sensors to detect any imminent crashes between vehicles travelling in opposite directions and automatically applies the brakes to avoid/and or mitigate a crash if the driver does not react	Head-on crashes	M1, M2, M3, N1, N2, N3	• Technology on one or both vehicles	• Technology on heavy vehicles and passenger cars in frontal collisions can reduce closing velocity by 18km/h if technology on heavy vehicle only and by 30 km/h if technology on both vehicles [58]
Autonomous emergency braking (AEB) Intersection	A technology that utilises cameras, radars or optical sensors to detect any imminent crashes with vehicles when turning and automatically applies the brakes to avoid/and or mitigate a crash if the driver does not react.	Intersection crashes	M1, M2, M3, N1, N2, N3	• Travel speed not greater than 20 km/h for turning vehicle • Travel speed not greater than 55km for straight through vehicle • 120–180 degree field of vision required. • The impacting turning vehicle must be equipped with AEB	• Effectiveness of 33–59% for the turning vehicle [59] • Effectiveness of 11–26% for straight vehicle [59]

Table A1. *Cont.*

Autonomous emergency braking (AEB) interurban	A technology that utilises cameras, radars or optical sensors to detect any imminent crashes with vehicles travelling in the same direction and automatically applies the brakes to avoid/and or mitigate a crash if the driver does not react–operates in high speed environments	Rear end crashes	M1, M2, M3, N1, N2, N3	• Travel speed between 30–80 km/h • The impacting vehicle must be equipped with AEB • No obstructed lines of sight if time to collision is <2 s	• A 38% reduction in rear end crashes with frontal impact [60]
Autonomous emergency braking (AEB) pedestrian	A technology that utilises cameras, radars or optical sensors to detect any impeding pedestrians and automatically applies the brakes to avoid/and or mitigate a crash if the driver does not react–designed to specifically detect pedestrians	Pedestrian crashes	M1, M2, M3, N1, N2, N3	• Travel speed not greater than 60 km/h	• A 40% effectiveness in reducing pedestrian fatalities in frontal collisions with cars [61] • An 11% effectiveness for head injury protection for speeds up to 60 km/h, in daylight, with pedestrians in direct vehicle path [62]
Back-over avoidance/Rear automatic braking	A technology that utilises cameras, radars or optical sensors to detect any imminent crashes with obstacles when reversing and automatically applies the brakes to avoid/and or mitigate a crash if the driver does not react.	Reversing crashes, driveway crashes	M1, M2, M3, N1, N2, N3	• Travel speed not greater than 40 km/h	• Adding rear automatic braking to rear vision camera and rear parking assists further reduced the rates of backing crash involvement by an additional 62% [63]
E-Call	A technology that will automatically notify emergency services after a serious crash and provide the vehicle's GPS location	Crashes in which those involved would have survived if they received immediate care	M1, M2, M3, N1, N2, N3	• Occupants were still alive after the crash. • Emergency services were not already contacted immediately • Internet service available in location	• Effectiveness rate of up to 3.8% for all road fatalities and up to 4.6% for only passenger vehicle occupants [64]
Emergency Lane Keeping	A technology that will apply a large steering input to prevent a vehicle from running off the road or into oncoming or overtaking traffic when a collision is imminent	Lane departure crashes without loss of control	M1, M2, M3, N1, N2, N3	• Vehicle travelling above 70 km/h • Can detect road edge, solid lines, dashed lines, oncoming and overtaking vehicles	• A 53% reduction in injurious head on and single vehicle crashes and a 30% reduction in all head on and single vehicle crashes for M1 vehicles [11] based on effectiveness of LDW systems
Geofencing	A virtual boundary set up for a geographical location	Speed related crashes	M1, M2, M3, N1, N2, N3	• N/A	• Based on effectiveness of ISA limiting
Intelligent Speed Assist (ISA) limiting	A speed detection device that utilises cameras and/or an in built GPS map to determine the speed limit of the road to limit the speed of the car to the detected speed limit.	Speed related crashes	M1, M2, M3, N1, N2, N3	• Require speed sign recognition or in built digital speed limit map	• A reduction of 28.9% of injury crashes based on 100% penetration of technology [65,66]
Lane Keep Assist	A technology that prevents a vehicle from unintentionally departing from its lane when the turn signal is not engaged	Lane departure crashes without loss of control	M1, M2, M3, N1, N2, N3	• Vehicle travelling above 60 km/h • Roads must have at least one visible line marking • Excludes heavy rain and snow	• A 53% reduction in injurious head on and single vehicle crashes and a 30% reduction in all head on and single vehicle crashes for M1 vehicles [11] based on effectiveness of LDW systems • Similar assumption made for N1 vehicles [57]

Table A1. *Cont.*

Seatbelt interlock	A technology that prevents a car ignition from starting if the sensors in the seats detects an occupant and the seatbelt is not engaged.	Unbelted occupant crashes Crashes involving vehicle occupants that were not wearing a seatbelt but would have otherwise survived if they were wearing a seatbelt	M1, M2, M3, N1, N2, N3	• The seatbelt remains in place for the duration of the trip and not disengaged after the ignition of the car was started	• Gearstick interlock increased seatbelt use by 16% [67]
Truck underrun–front	A technology that can prevent smaller vehicles from being lodged underneath the front of a truck in a truck to car rear end collision	Crashes involving a truck rear ending a passenger vehicle, cyclist or motorcyclist	N2, N3	• N/A	• A 28% reduction in injury severity for vehicles involving heavy vehicles [68]
Truck underrun-rear	A technology that can prevent smaller vehicles from being lodged underneath the back of a truck in a car to truck rear end collision	Crashes involving other vehicle rear ending the truck	N2, N3	• N/A	• A 22.6–34.1% effectiveness for fatalities and 52% for serious casualties [69]
Truck underrun-side	A technology that can prevent smaller vehicles from being lodged underneath the side of a truck in a side impact collision	Crashes involving cyclists, pedestrians or motorcyclists where they get thrown under the truck from the side Vehicle side impact crashes into truck	N2, N3	• N/A	• A 50–74% reduction in fatalities and 3–9% for serious casualties for heavy vehicle crashes with cyclists; 17–27% for fatalities and no effect for serious casualties for crashes with pedestrians [70] • A 28% reduction in injury severity for vehicles involving heavy vehicles [68]
Vehicle Crashworthiness	The ability of a vehicle to protect its occupants in a crash	Crashes involving car occupants that would have survived in a newer car (e.g., 7 years, 10 years) due to better crashworthiness	M1, N1	• Exclude unbelted occupants	• Improvement of 26% in fleet safety if all vehicles in a market group performed as well as existing safest benchmark vehicle [71] • A one star ANCAP rating improvement is associated with a 20–25% reduction in the risk of serious injury to the driver [72] • 5 star Euro NCAP rated cars have a 69% lower risk of fatal injury than 2 star rated cars, and 23% lower risk for fatal and serious injuries [73]

* Vehicle type based on European definitions [74].

Table A2. Infrastructure and vehicle safety countermeasures reliant on human input/compliance.

Infrastructure Intervention	Description	Crash Type	Applicable Vehicle Type *	Boundary Conditions	Effectiveness
Bicycle lanes-dedicated	Formally allocated road space for cyclists and provides a spatial separation between cyclists and motor vehicles	Bicyclist crashes	M1, M2, M3, N1, N2, N3, L	• Exclude impaired drivers/riders	• Bicyclists are at 3–4 times higher risk on road segments without bicycle lanes than ones with [75]

Table A2. *Cont.*

Cameras-Speed or red light	Traffic cameras to detect vehicles travelling above the posted speed limit or disobeying a red stop light signal	Multiple	M1, M2, M3, N1, N2, N3, L	• Exclude impaired drivers/riders	• A 30% crash reduction for fixed overt speed cameras in rural and urban environments [49] • A 5% crash reduction crash reduction for red light cameras at intersections for all environments [49] • An 18% reduction in crashes [76]
Raised Platforms/Pavements (raised intersections)	Speed management treatment to reduce the maximum operating speed of a vehicle–includes platforms on the approach to an intersection or midblock and raising the entire intersection	Urban Intersection crashes in ≤60 km/h zones	M1, N1, L	• Exclude impaired drivers	• Non fatal and serious injury crash reduction of 63% [77] • A 7.5 km/h speed reduction in a 60 km/h zone [77]
Reduced speed limit with police enforcement	A reduction in the posted speed limit in combination with enforced compliance via road policing	Multiple	M1, M2, M3, N1, N2, N3, L	• Exclude impaired drivers/riders	• A 15% crash reduction when a speed limit is reduced from 100 km/h to 80 km/h [49] • A 20% crash reduction when a speed limit is reduced from 80 km/h to 60 km/h [49] • A 20% crash reduction when a speed limit is reduced from 60 km/h to 50 km/h [49]
Roundabouts	An intersection treatment designed so that vehicles deviate from a straight travel path to navigate a circular island in order to control the speed of vehicles through an intersection	Intersection crashes	M1, M2, M3, N1, N2, N3, L	• Exclude impaired drivers/riders • At 100 km/h, drivers require an unobstructed view of the approaches for approx. 170 m to ensure drivers have time to see it, recognise it and slow to a safe approach speed [78]	• An 85% percentile speed reduction of 46% or 24 km/h at the treatment and 15% at midpoint between treatments for local roads [79] • The zone of influence of a local roundabout on the free speed was 60–80 m on the approach and 100–120 m on departure [79] • A crash reduction factor of 55% for urban roundabouts [49,79] • A crash reduction of 70% for rural roundabouts [49] • A crash reduction of 70% for roundabouts in all environments [49]
Rumble Strips–Transverse	Raised pavement markings that extend across traffic lanes to alert drivers they are approaching a dangerous intersection	Speed crashes at intersections in ≥70 km/h zones	M1, M2, M3, N1, N2, N3	• Exclude impaired drivers • Flush transverse lines have limited influence on travel speeds [80]	• A 20–50% reduction in crashes at intersections [49]
Signalised intersection	An intersection with traffic signals to control the flow of traffic	Urban intersection crashes	M1, M2, M3, N1, N2, N3, L	• Exclude impaired drivers/riders • At 100 km/h, drivers require an unobstructed view of the approaches for approx. 170 m to ensure drivers have time to see it, recognise it and slow to a safe approach speed [78]	• A 40% and 45% crash reduction for traffic signals with and without turn signals, respectively for metro environments [49] • A 35% and 75% crash reduction for traffic signals with and without turn signals, respectively for rural environments [49]

Table A2. *Cont.*

Speed humps/road cushions/flat top road humps	Raised vertical deflection treatments to reduce vehicle travel speed	Pedestrian and cyclist to vehicle crashes in ≤60 km/h zines	M1, N1, L	• Exclude impaired drivers	• Speed humps reduce speed by 21.1 km/h [81] • A 27% reduction in 85th percentile speed in vicinity of road cushions [82] • A 24% reduction in 85th percentile speed in vicinity of flat top road humps [82] • Speed humps/road cushions/flat top road humps reduces speeds, traffic volume and crash risk; road cushions and flat top road humps also increase bicyclist safety [82] • A 37.5% reduction in car collisions with child and adolescent pedestrians [83] • A 22% reduction overall in pedestrian crashes; 26% reduction on local roads; 43% reduction for 0–15 years [84]
Tactile lane markings with road widening-middle	Raised profile lines on the centre of an undivided road that provides tactile and auditory warnings to alert drivers of lane departure combined with wide centre lines that create a greater separation between opposing lanes of traffic	Unintentional lane departure crashes	M1, M2, M3, N1, N2, N3,	• Speed and road space allows sufficient time and space to correct trajectory of vehicle (1.5 s and minimum of 0.5 m for alert drivers and 3 s and 1 m for fatigued drivers) • Exclude impaired drivers	• A 15% crash reduction [49]
Tactile lane markings-side	Raised profile lines on the edge of a road that provides tactile and auditory warnings to alert drivers of lane departure	Unintentional lane departure crashes	M1, M2, M3, N1, N2, N3,	• Speed and road space allows sufficient time and space to correct trajectory of vehicle (1.5 s and min of 0.5 m for alert drivers and 3 s and 1 m for fatigued drivers) • Exclude impaired drivers	• A 23% crash reduction [49]
Traffic calming E.g., chicanes/Lane Narrowing/Kerb Extensions/slow points [85]	Road treatments used to reduce vehicle speeds, especially in permanent lower speed urban environments	Speed related crashes in ≤50 km/h zones	M1, M2, M3, N1, N2, N3, L	• Exclude impaired drivers/riders	• A 20% crash reduction for all environments [49]
Wombat Crossing	A raised flat top pavement marked for pedestrian crossing and are commonly used at school crossings	Pedestrian crashes on crossings in ≤50 km/h zones	M1, N1, L	• Exclude impaired drivers/riders	• Fatal and serious injury crash reduction of 67% [77] • A 6.5 km/h speed reduction in a 50 km/h zone [77] • Reduces speed, traffic volume and crash risk and increases pedestrian and cyclist safety [82]
Vehicle Intervention	**Description**	**Crash Type**	**Applicable Vehicle Type ***	**Boundary Conditions**	**Effectiveness**
Blind Spot Monitoring	A vehicle technology that alerts the driver to objects in the driver's near and far side blind spots	Lane change crashes into other vehicles and VRUs in blind spot	M1, M2, M3, N1, N2, N3	• Exclude impaired drivers	• A 14% reduction in crashes in vehicles with technology than without [86]

Table A2. *Cont.*

Electronic Stability Control	An anti-skid technology that can help prevent loss of control crashes by reducing engine torque and braking individual wheels to bring the vehicle back on course	Loss of control crashes	M1, M2, M3, N1, N2, N3	• Driver must have made an attempt to steer/avoid the crash	• Effectiveness of 21.6% for serious and fatal crashes; 56.2% for serious and fatal loss of control crashes; 44.4% for single vehicle serious and fatal crashes [8] • A 49% reduction in single vehicle crashes; 13% reduction in head on crashes; 32% reduction in multi vehicle fatal crashes [9]
Fatigue monitoring/Driver Monitoring–audio and haptic warning	A technology that can detect a change in the driver's attention such as from fatigue or distraction and provides a warning	Lane departure due to fatigue/distraction	M1, M2, M2, N1, N2, N3	• Exclude impaired drivers • Strong winds and rutted surfaces can provide false warnings [87]	• An estimated 1.5–7% reduction in all road fatalities and 1–4.9% for all injured road casualties, based on full fleet fitment for passenger and commercial vehicles [88] • A 66% reduction in fatigue events in commercial vehicles [89]
Intelligent Speed Assist (ISA)–Advisory	A speed detection device that utilises cameras and/or an in built GPS map to determine the speed limit of the road to provide warnings to the driver if the detected speed limit has been exceeded	Speed related crashes	M1, M2, M2, N1, N2, N3	• Can be overridden • Require speed sign recognition or in built digital speed limit map	• For M1 and N1 vehicles, a reduction of 2.7% of injury crashes based on 100% penetration of technology [65,66]
Lane departure Warning	A technology that provides warnings when a vehicle starts to unintentionally depart from its lane when the turn signal is not engaged	Lane departure crashes	M1, M2, M3, N1, N2, N3	• Vehicle travelling above 60 km/h • Roads must have at least one visible line marking • Excludes heavy rain and snow • Excludes impaired drivers	• A 30% reduction in all head on and single vehicle crashes [11] • A 86% lower involvement rate in fatal crashes and 24% in injury crashes [90]
Motorcycle ABS	A motorcycle technology that can prevent wheel lockup, increase motorcycle stability and decrease stopping distance	Motorcycle loss of control during braking crashes	L	• Exclude impaired riders	• Reduction of 34–42% for severe and fatal crashes for all ABS equipped motorcycles [91] • Reduction of 22–27% of crashes involving ABS equipped scooters (at least 250 cc [91])
Motorcycle Daytime Running Lights	Dedicated low beam headlights for the daytime to increase visibility of the motorcycle to other road users	Motorcycle to vehicle crashes	L	• Automatically switched on with ignition	• Have the potential to reduce fatalities and injuries by 7–13% less fatalities and injuries [92,93]
Reversing Cameras	A camera mounted on the rear of the vehicle and shows the view behind the vehicle, including at ground level	Back over crashes	M1, M2, M3, N1, N2, N3	• Travel speed below 40 km/h	• Reduced odds of 0.59 of backover injuries [94]
Seat belt reminder system	A technology that provides a warning when the seatbelt in an occupied seat is not worn	Crashes where car occupants would have survived if they were wearing a seatbelt	M1, M2, M2, N1, N2, N3	• Exclude impaired drivers • Child seats are not covered by the seatbelt reminder system [95]	• A 47% reduction in in occupants being unrestrained during the trip; a 96% reduction in total travel time where an occupant was unrestrained [96]

* Vehicle type based on European definitions [74].

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