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# Can I Stop? Considering Opportunities to Influence Multidisciplinary Factors That Result in Crashes

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### Abstract

In previous decades significant gains were made in reducing the number of road traffic related fatalities in Victoria and Australia. However, in absolute terms this reduction started plateauing despite substantial investment in road safety countermeasures. This trend is not well aligned with the goal to achieve zero fatalities by 2050. Through practical traffic management experience, a study tour of nine countries and a literature review, we have gained valuable insights into the changing dynamics of roads. We have identified opportunities to improve road safety by adapting to larger/heavier vehicles, denser traffic, changing travel patterns and evolving demographics. These opportunities include: vehicle-centred crash avoidance in addition to crash consequence mitigation strategies; reduced traffic complexity; reduced cognitive workload; and targeted dynamic information of inclement weather and traffic conditions. Improved road surface friction, braking, tyres and vehicle stability can reduce crashes and their impacts. This article aims at stimulating broader discussions among experts for the development of next-generation road safety strategies.

### Key Findings

- Equal focus is needed on crash avoidance strategies and crash consequence mitigation
- Humans and vehicles have limitations that need to be acknowledged
- Improved road surface friction, braking, tyres and vehicle stability can save lives
- Opportunities exist for additional road safety measures in each safe system pillar
- Reducing crash occurrence is essential to achieve zero fatalities

## Introduction

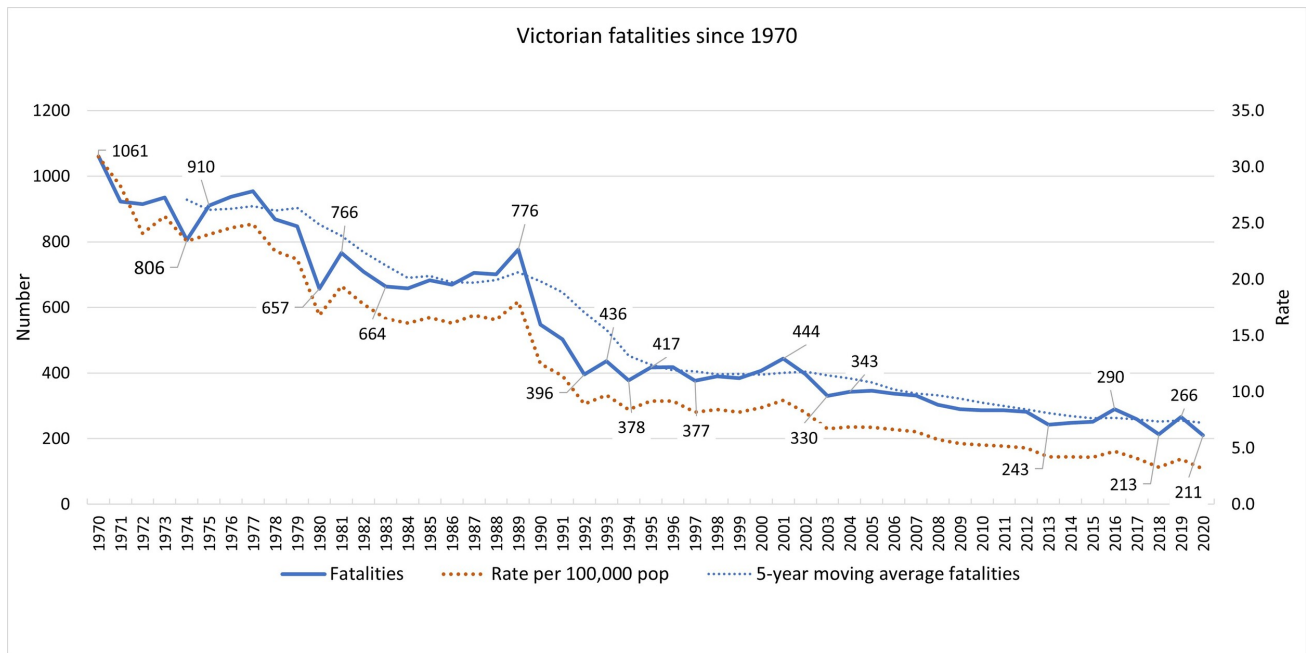
Significant gains have been made in reducing the number of fatalities in the state of Victoria and nationwide in Australia over recent decades. However, this has plateaued despite the substantial investment in road safety. Road safety strategies based on the Safe System approach have done much to improve safety but there is a gap between actual fatality and serious injury numbers and the targets. Victoria shows an almost continuous decline in fatal crashes on the road between 1970 and 1989, then a sharp drop from 1989 to 1992, followed by much slower reductions ([Figure 1](#)).

Based on analysis undertaken by BITRE (2018), hospitalisations from road crashes in Australia have increased from around 25,000 per annum between 1995 and 2000 to around 36,500 per annum in 2015 (an increase of close to 50%). They are predicted to increase further, to around 47,500 per annum in 2030 (under the ‘do-nothing’ scenario, with little change to current enforcement and few new road safety measures). This is a cause for concern.

The above trends are not aligned with the Victorian Government’s goal to achieve zero fatalities by 2050 (State Government of Victoria, 2020). An inquiry into the national road safety strategy highlights the ‘need for dramatic change in road safety management, given the inadequately

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**Figure 1. Fatalities from road crashes since 1970 (Victoria)**

Source: Internally developed based on DTP data and ABS data

acknowledged national road injury epidemic and the national costs to the economy now and in the next 30 years from road crashes' (Woolley & Crozier, 2018, p. 5).

The nature of road transportation has changed considerably over recent decades as road transport is simultaneously evolving, maturing and operating under more stress than at any other time in history (Gaffney & Hovenden, 2023). A whole-of-system approach is urgently needed to comprehend the consequences of these changes on road safety direction, including:

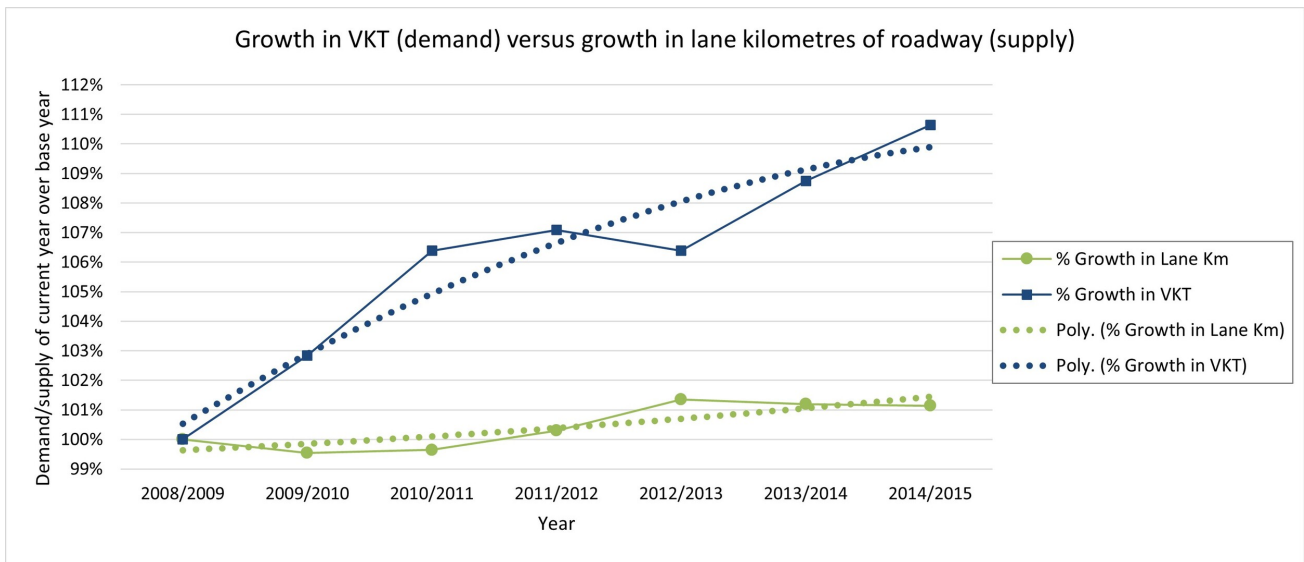
1. Increasing traffic density due to significant growth in the number of vehicles and Vehicle Kilometres Travelled (VKT) compared to the small growth in lane kilometres (Figure 2);
2. Growing vehicle size, mass, load and higher centre of gravity;
3. Changing trip purposes (on urban motorways, only around 20% are commuting and around 80% are linked to a service-based economy that includes 'roads as workplaces');
4. Progressive re-allocation of road space to other modes (pedestrians, bicycles, trams, buses);
5. Changing mode share (increased walking and cycling);
6. An increasingly aging society;
7. Rising affluence (more consumption of goods and services per capita delivered by roads).

These collectively have changed the context in which crashes occur. On urban motorways, the increasing proportion of multi-vehicle crashes is linked to higher traffic density whilst single vehicle crashes are proportionately declining (Figure 3).

Besides the changing context, looking at crashes from different perspectives provides additional information that can help shape and refresh strategies. Studies undertaken by the authors found that:

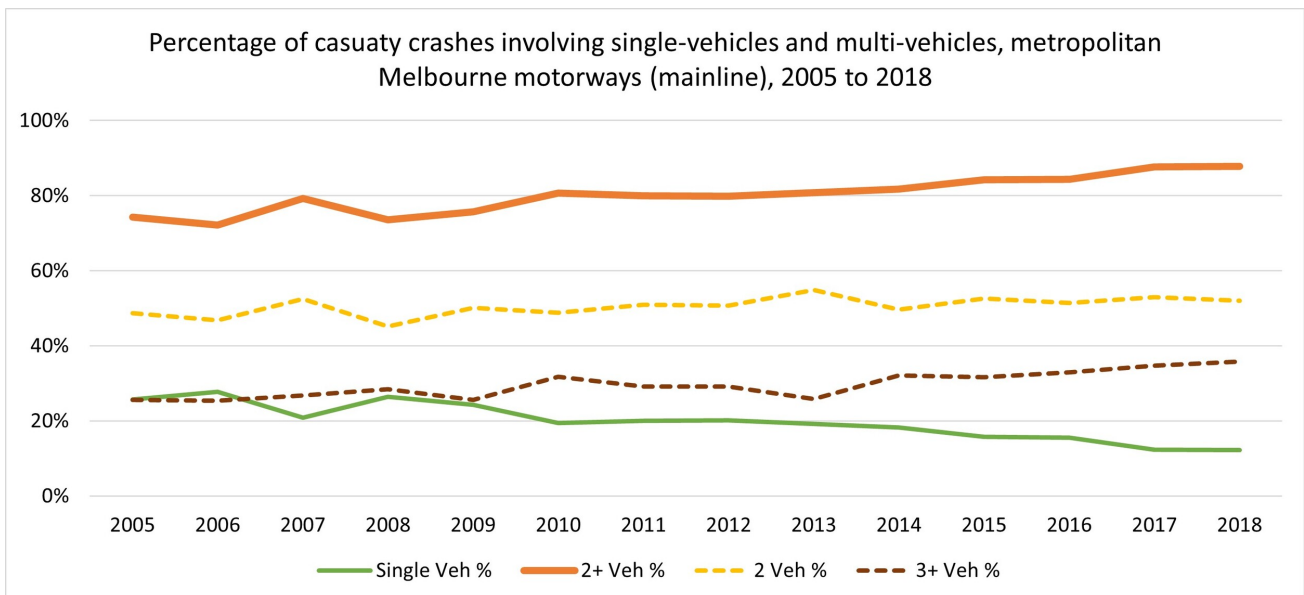
1. More than 40% of crashes involve contributing factors not normally considered in traditional road safety strategies and programs (these include congestion, animals and weather which involve elements of surprise, leaving virtually no time to react often beyond human and vehicle capability);
2. The majority of crashes are random in terms of their location (Hovenden & Liu, 2020);
3. The 'Swiss cheese model' of crash causation is inadequate for explaining situations such as crashes on high standard motorways, where the dynamic conditions such as shockwaves due to congestion, and the complex vehicle interactions cause many multi-vehicle crashes;
4. Traffic conditions, and climate/weather are important contributing factors affecting human behaviour and perception of risk;
5. Weather also affects vehicle and driver performance, modifying the road environment (road-surface friction and visibility).

Whilst traditional road safety approaches are still relevant, complementary holistic (systems) thinking and solution development are required to address the changing nature of crashes. All contributing factors must be understood and every opportunity for crash avoidance leveraged by managing the relationship between required and available road space. This paper focuses on stopping and the many factors influencing braking distance.



**Figure 2. Growth in VKT (demand) versus lane kilometres of roadway (supply)**

Source: Internally developed based on DTP data



**Figure 3. Percentages of casualty crashes involving single- and multi-vehicles**

Source: Internally developed based on DTP data

Given the breadth and depth of the topic, this is not meant to include a complete overview of current road safety work and strategies, but rather to identify additional areas of focus and investigation to further reduce fatalities and serious injuries. (For additional information see Gaffney et al., 2023). This paper does not undertake in-depth evaluation of context changes such as the increase in exposure and traffic density, nor does it evaluate road safety measures taken to date.

The existing Safe System approach as applied in Victoria and Australia to road safety includes the management of crash likelihood (described as crash avoidance in this paper) as well as exposure and crash severity. Safe System Planning tools such as Safe System Assessments apply equal

weighting to these three elements (VicRoads, 2018). This paper focuses on crash avoidance as, due to the complete avoidance of any damage, this should always have a higher weighting. However, tackling crash avoidance will also reduce severity should a crash occur.

## Background

A study tour of nine countries and a literature review were undertaken (Gaffney, 2018) including conversations with many key experts. Detailed crash analysis of ~400 casualty crashes on the Monash and Eastern Freeways also provided insights (Hovenden et al., 2020). Images and descriptions in crash records were reviewed in combination with minute-

by-minute “traffic-state” data. Recorded Department of Transport and Planning (DTP, Victoria) CCTV camera observations on Melbourne’s managed motorways also demonstrated impacts of weather variability and traffic flow complexity on crashes.

Findings from Japan and the United Kingdom suggest the largest part of the significant reduction in the number of fatalities in the past can be attributed not only to improved vehicle technologies but also to better access to emergency care, including the role played by the mobile phone (Noland, 2003, 2004; Oguchi, 2016). Other factors may also play a role in these countries. Japan focused on minimising crashes and has achieved declining numbers of fatalities and fatality rates for 20 years straight (2.25 per 100,000 population in 2020 compared to 4.3 in Australia), suggesting greater focus on crash avoidance is necessary in Australia.

Crash causation is complex with a multitude of pre-crash factors. Due to an (almost) unlimited number of permutations of contributing factors, all crashes are unique although appear similar when classified by a simple code. It is necessary to tackle all the contributing factors, rather than only some. In the technology space, little emphasis has been placed on leveraging relatively simple, proven technologies such as speed limiters, tyre pressure monitoring systems and real-time traffic and weather information.

Certain weather and traffic conditions, such as damp road surfaces or shockwaves progressing against the direction of travel, are often not always visible to the driver. These occur on all road types and can contribute to serious crashes due to prolonged Perception-Reaction Time (e.g., when the driver of a heavier vehicles could not stop before crashing into a lighter vehicle in front). This also included hazards in the surprise category (e.g., an animal jumping in front of a driver or rider). Due to surprise and/or other random elements, few casualty crash locations are statistically significant hot spots (Hovenden & Liu, 2020), making it difficult to reduce the crash problem using traditional approaches.

While it is possible to provide additional driver support through provision of dynamic information during times of elevated crash risk for weather and traffic conditions, this is not possible with all surprises. It is therefore essential that safety travels with the vehicle. This can be achieved through Safe Vehicles having the optimum braking and handling performance under all conditions to avoid crashes, and/or Safe People who are not exposed to distractions and who have been educated on unseen and unperceived risks. Greater uniformity of brake performance, including use of better tyres (a cheap solution) could contribute to avoidance of many crashes.

The counterpart to the reducing the braking distance approach is the provision of more road space approach. Universally mandating and enforcing truck-related minimum following distances between heavy vehicles (as is done in Germany; Gaffney et al., 2023) would reduce crashes, which are usually high severity and occur regularly on heavily trafficked roads.

A comprehensive approach to targeting the multiple factors contributing to a crash, based on robust science (e.g., in-depth investigation of crashes) needs to regularly occur utilising every opportunity for crash avoidance. Only when strategists consider the changing context (denser traffic, larger and heavier vehicles) and understand the variable influences of climate/weather and traffic conditions, can the current gap of reaching zero fatalities be closed.

## Safe System

Figure 4 shows the current Safe System architecture including the missing themes and gaps highlighted in red. This section presents new insights and opportunities for the expansion of current themes. Importantly there is a need to focus on the dynamic interconnections between pillars to form a holistic real-world system that addresses temporal conditions. Specifically, “Climate and Environment” and “Traffic Conditions” are constantly changing. They need to be continuously measured and the relevant information based on the measured data provided to the road users in near real-time for targeted risk awareness. Whilst there are some isolated real-time interventions (such as Side Road Activated Speeds), there is much more that can be done in this area, especially through a systematic application on all high-volume arterial roads and motorways. Real-time interventions need to be embedded across each of the five pillars to address the gaps in order to achieve zero fatalities and tackle growing serious injuries. Better use could be made of existing systems (e.g., Lane Use Management Systems and Traffic Signals) such as lowering speeds during inclement weather and congested conditions, and increasing the all-red phase of traffic signals at night-time and during inclement weather conditions.

## Can I stop? A matter of required and available space

### Required Space for Stopping

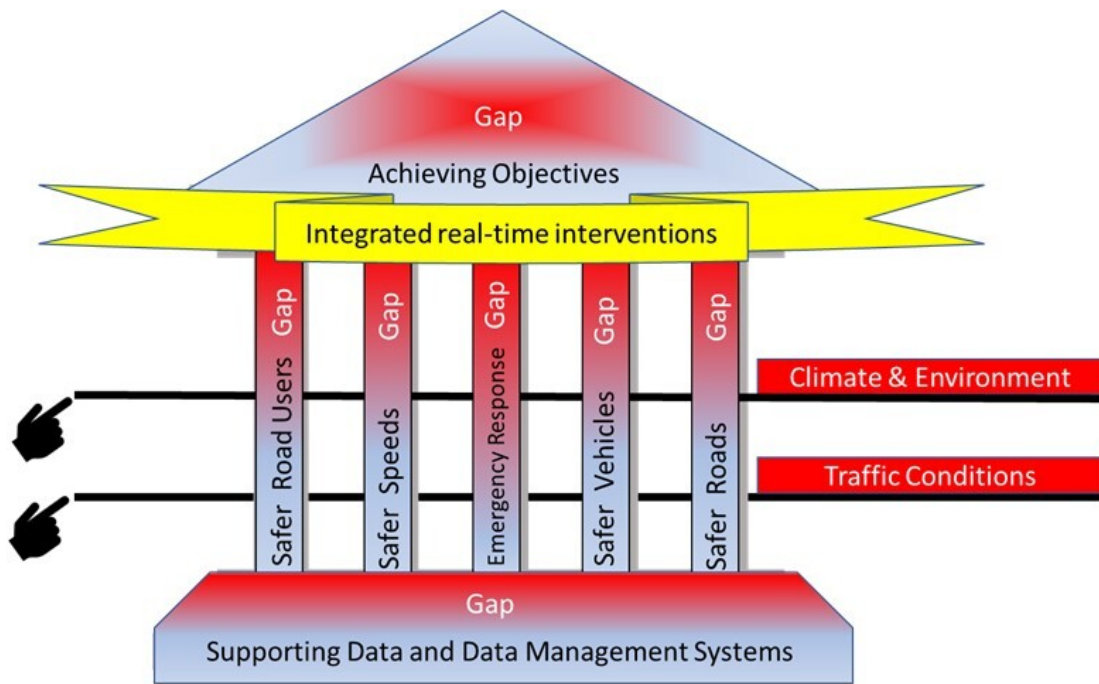
The simplified Equation (1) shows that stopping distance consists of two components: 1) perception and reaction, and 2) braking.

$$D_{Stop} = D_{P+R} + D_{Braking} = v * t_{P+R} + \frac{v^2}{2\mu g} \quad (1)$$

Where  $v$  = Vehicle speed (m/s),  $t_{P+R}$  = Perception (latent) + Reaction time (s),  $\mu$  = Friction (-),  $g$  = Gravity (9.81 m/s<sup>2</sup>).

Numerous extensions to this equation are possible, however including these makes the equation too complex for illustrative purposes. From this equation, understanding the influence of Vehicle speed  $v$  on stopping distance is straightforward. The same applies to Perception-Reaction time  $t_{P+R}$  and Friction  $\mu$  but these parameters are influenced by a multitude of dynamic factors, making it more complex. The factors of  $\mu$  include tyre/brake quality, pavement surface quality and geometry (slope, curve and super-elevation).

Table 1 provides an overview of the various factors impacting on stopping distance to stimulate thinking about where there might be opportunities to reduce the stopping



**Figure 4. Reinforcing the safe system where dynamic factors operate across the pillars**

Source: Internally developed based on information contained in the Victorian Road Safety Strategy 2021–2030 (State Government of Victoria, 2020) and gaps identified in this and other strategies

distance and lower crash likelihood. Some of these opportunities are described further below. Influencing any of these factors aimed at avoiding a crash would also help reduce the kinetic energy in the pre-crash phase and hence reduce the forces in an impact if a crash could not be avoided. This mitigates crash severity and injury.

### Pillar 1: Safe Speeds

Vehicle speed impacts on both parts of Equation 1, namely ‘Perception and reaction distance’ (proportional to speed) and ‘Braking distance’ (proportional to the square of speed). Influencing speed, especially inappropriate and excessive speed, is the most important means of reducing the stopping distance and thus lowering crash risk.

Analysis of data from vehicle detection technology on Melbourne’s motorways found that high to extreme speeding is not a rare event, with vehicles far exceeding the speed limit every day and in every location. For example, from infrared data loggers on DTP’s managed motorways, it was found that around two percent of vehicles were measured travelling more than 10 km/h above the posted speed limit (inbound section of Monash Freeway between South Gippsland Freeway and Heatherton Road). Although relatively low as a percentage, it is high in terms of number (around 1650 per carriageway per day) suggesting a re-think of current enforcement practices and alternative technical approaches are required.

#### *Speed management*

There is an opportunity in the Safe Speed pillar to deploy more point-to-point speed enforcement facilities, which

calculate and enforce average vehicle speeds between two points such that motorists cannot avoid being caught by slowing down at fixed camera locations.

Another opportunity is to work with international vehicle manufacturers on a national basis to limit the maximum speed at which vehicles can be driven. This has been implemented in other countries, including Japan and Germany (where heavy trucks are speed limited; Bundesministerium der Justiz, 2012), for many decades. The EU ruling that Intelligent Speed Assistance (ISA) technology will be installed in new vehicle models from May 2022 (and existing vehicle models from May 2024), creates the conditions that all vehicles can adapt to the posted speed limit or to a constant maximum speed (European Commission, n.d.-a). Such technology sends the correct messaging that excessive speed is not appropriate or safe on public roads. A beneficial side-effect of speed-limiters is that dangerous driving manoeuvres such as high-speed driving by unlicensed drivers (‘hoon races’), that often involve police pursuits in response, could be avoided.

Sale of after-market products to enhance speed, power and vehicle performance sends a wrong message to the community. Sale of products that increase a vehicle’s engine power and speed capability, departing from the original manufacturer’s specifications, should be controlled or prohibited. This is an important step towards changing the community’s perception of speeding.

There currently is conflict between personal freedom (the ability to choose travel speed) and the larger community and workforce right to live and work safely, which is a tension that needs to be addressed. A plan for the progressive introduction of speed limiting technology is outlined

**Table 1. Factors within Safe System pillars influencing stopping distance for crash avoidance**

| Safe System Element | Factors impacting on stopping distance (examples)                                                                                                                                                                                                                                                               | Contributing factor in Equation 1 |
|---------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------|
| Safe Roads          | Geometrical conditions (vertical and horizontal alignment, slope, crossfall)                                                                                                                                                                                                                                    | $v$                               |
| Safe Roads          | Intelligent Transportation System (ITS) such as variable speed limits, real-time warnings of hazardous pavement, traffic or weather conditions, also Cooperative ITS                                                                                                                                            | $v, t_{P+R}$                      |
| Safe Roads          | Distractions (roadside advertising, scenery)                                                                                                                                                                                                                                                                    | $t_{P+R}$                         |
| Safe Roads          | Visibility range / hazard conspicuity                                                                                                                                                                                                                                                                           | $t_{P+R}$                         |
| Safe Roads          | Pavement (general condition, roughness, wetness, dampness, temperature)                                                                                                                                                                                                                                         | $\mu$                             |
| Safe Roads          | Run-off area / distance to an obstacle / hazard (impacting on the available space to stop)                                                                                                                                                                                                                      | NA                                |
| Safe Roads          | Traffic conditions (avoidance of congestion and lane changing concentrations, impacting on the available space to stop)                                                                                                                                                                                         | NA                                |
| Safe Vehicles       | Advanced Driver Assistance Systems (ADAS) (Adaptive Cruise Control (ACC), Anti-Lock Braking System (ABS), Auto Emergency Braking (AEB), Electronic Stability Control (ESC), Lane Departure Warning (LDW) / Lane Keep Assist (LKA), Driver Drowsiness Detection (also impacting on the available space to stop)) | $v, \mu, t_{P+R}$                 |
| Safe Vehicles       | Brakes (general performance, braking power as is very relevant for trucks, temperature)                                                                                                                                                                                                                         | $\mu$                             |
| Safe Vehicles       | Tyres (width, pressure, profile, tread depth, age, temperature, failures e.g., punctures)                                                                                                                                                                                                                       | $\mu$                             |
| Safe Vehicles       | Manoeuvrability / handling, influenced by (inappropriate) loading (e.g., campervans (also impacting on the available space to stop))                                                                                                                                                                            | $\mu$                             |
| Safe Vehicles       | Brake pedal movement and force required                                                                                                                                                                                                                                                                         | $\mu$                             |
| Safe Speeds         | Desired speed                                                                                                                                                                                                                                                                                                   | $v$                               |
| Safe Speeds         | Speed limit (road related)                                                                                                                                                                                                                                                                                      | $v$                               |
| Safe Speeds         | Speed limit (vehicle type specific, e.g., 80 km/h for trucks $\geq 3.5$ tonnes in Germany (Bundesministerium der Justiz / German Federal Ministry of Justice, 2012))                                                                                                                                            | $v$                               |
| Safe Speeds         | Speed enforcement                                                                                                                                                                                                                                                                                               | $v$                               |
| Safe Speeds         | Maximum speed of a vehicle / speed limiter (vehicle related)                                                                                                                                                                                                                                                    | $v$                               |
| Safe People         | Experience / training level                                                                                                                                                                                                                                                                                     | $t_{P+R}, \mu$                    |
| Safe People         | Physical condition such as strength and size of driver (ability to activate vehicle braking power, see Safe Vehicles above)                                                                                                                                                                                     | $\mu$                             |
| Safe People         | Alertness: Alcohol/drug use                                                                                                                                                                                                                                                                                     | $t_{P+R}$                         |
| Safe People         | Alertness: Awareness (risk, changed conditions)                                                                                                                                                                                                                                                                 | $t_{P+R}$                         |
| Safe People         | Alertness: Distractions (conversations, listening, absence of mind, mobile phone use)                                                                                                                                                                                                                           | $t_{P+R}$                         |
| Safe People         | Alertness: Environmental conditions (e.g., sunglare)                                                                                                                                                                                                                                                            | $t_{P+R}$                         |
| Safe People         | Alertness: Fatigue/drowsiness                                                                                                                                                                                                                                                                                   | $t_{P+R}$                         |
| Safe People         | Alertness: Medical conditions (acute illness, physical health)                                                                                                                                                                                                                                                  | $t_{P+R}$                         |
| Safe People         | Alertness: Mental health and psychological distress                                                                                                                                                                                                                                                             | $t_{P+R}$                         |

below, noting that it is easier to introduce such new technologies by initially targeting non-compliant motorists (repeat offenders).

1. Target drivers with serious speed offences (e.g., re-cidivists, high speed offending) with a compulsory speed limiter installed in their vehicle and as a permanent condition on their licence;
2. Encourage Worksafe to require speed-limited business cars and commercial vehicles;
3. Permanent speed-limiters as an inclusion in ANCAP 5 Star vehicle safety rating;
4. Financial incentives for motorists to buy new cars with permanently fixed speed-limiters;
5. When the community is better informed of benefits and attitudes have changed, gradually introduce stronger policy settings.

Motorists tend to drive at the posted speed limit even when encountering adverse weather or environmental conditions such as fog (Hammit et al., 2019), damp pavement surfaces, wind, or at times when animals are likely to be on the road as they do not perceive the increased risk. There is also a cultural concern that when some motorists drive slightly below the speed limit (to adapt to current external conditions), they are considered 'slow drivers' (although they are often safer) and implicitly stigmatised as 'bad drivers' by faster drivers who do not regard speed limit as an upper threshold but as a 'target speed' applying to all conditions. Strategies should be developed aimed at turning such attitudes around. Educating drivers about consequences of not aligning speed with current conditions, combined with a recommendation to 'wipe off 10' under such conditions, can change culture by promoting the

speed limit as an upper threshold not suitable for certain traffic, weather and environmental conditions. This gives responsible drivers a justification to drive slower so that they do not get tailgated by other, less responsible drivers.

Dynamically reducing the speed limit by 10 or 20 km/h when there is risk of congestion or hazardous weather conditions is another opportunity. At a base speed of 100 km/h,  $t_{P+R} = 1.75$  and  $\mu = 0.7$ , according to Equation 1, these speed reductions would be equivalent to a reduction in the stopping distance of more than 15 percent or 30 percent respectively.

Road authorities understand the likelihood of congestion occurring. Traffic engineers can track in real-time the back of the moving shockwave, allowing traffic-related variable speed limits/recommendations and warnings to be implemented. In contrast, transferring meteorological data from Bureau of Meteorology (BOM) into meaningful geographic-based information requires involvement of meteorologists in road safety programs. This is being done in other domains and should be applied to road safety.

## Pillar 2: Safe People

Human factors (drivers' behaviour) are often stated as the main causes of crashes. For example, a media release from ANCAP (2015) states that '90% of crashes involve some form of human error'. This may be technically correct if based on a comparison of driver behaviour against legal regulations. However, the absence of human error (whilst complying with the law) requires that all humans are 'perfect' at all times. This is unrealistic due to variations in motorists' performance capability resulting from the dynamics of certain conditions which cannot be seen nor perceived. The latter, in complex surroundings such as multi-lane motorway carriageways with thousands of vehicles lane changes per km/h (Zurlinden et al., 2020), can suddenly and unexpectedly change the legal situation (e.g., when a lane changing vehicle halves the distance to the vehicle in front). This is not only challenging for humans but also for autonomous vehicles.

### *Human performance capability*

The distance a vehicle travels during perception of, and response to, a hazardous situation is proportional to the reaction time (refer to Equation 1). Reaction time comprises a large proportion (25-50%) of the total stopping distance. The greater the reaction time, the greater the stopping distance. Stopping distance is a function of human and mechanical processes involved in Perception, Reaction and Stopping times.

Perception and Reaction times (RT) vary greatly between the 'best' and 'worst' performing persons, both in real world and laboratory conditions (Zhuk et al., 2017). Age, fitness level, strength, driving practice or day-to-day fluctuations affect a person's reaction time. According to Zhuk et al. (2017), studies can underestimate reaction times (particularly laboratory studies), especially when surprise events occur. The driver's RT increases under complicated traffic conditions or when sudden changes occur. When the driver

is attentive and predicts the emergence of some danger or obstacles in advance, RT almost halves.

Individual drivers' capabilities and reaction times vary greatly. Neither the driver nor the vehicle will perform in a predefined way every time an emergency braking and precise steering or handling manoeuvre is required.

There is an opportunity for practitioners to help drivers have greater awareness of dynamic hazards and the means (including education) to respond to them. A true Safe System must also cater for those motorists with longer RT times (such as the elderly) and/or situations when good drivers have a bad day. A non-exhaustive list of opportunities to achieve this is:

1. Implement and evaluate technical solutions (e.g., incorporation of congestion and weather warnings into variable message signs or displayed inside vehicles);
2. Free roadsides from unnecessary distractions;
3. Educate drivers on why they need to keeping a safe distance to the vehicle in front;
4. Use 'nudge theory' to encourage good behaviours;
5. Educate drivers on the importance of driving practice (Langford et al., 2006; Vlakveld, 2005);
6. Include emergency stopping manoeuvres in the driver licence test to increase driver experience in reacting to suddenly occurring hazards;
7. Increase risk awareness of inappropriate speed and insufficient stopping distances under certain traffic, weather and environmental conditions, of poor tyre performance (e.g., age/tread depth/quality), of unstable vehicles and incorrect loading (e.g., caravans).

## Pillar 3: Safe Vehicles

Current road safety strategies aim to improve the vehicle fleet, ensuring that vehicles using the road network are the safest available (Commonwealth of Australia, 2021; State Government of Victoria, 2020). This can be achieved in part through the increased uptake of Advanced Driver Assistance System (ADAS) technologies to improve the vehicle's ability to protect the car's occupants and to some extent pedestrians. This is also included in the ANCAP vehicle safety star rating methodology, but not to its full potential. Whilst crash avoidance is also a benefit of ADAS, the focus is not on braking and vehicle stability.

There is a risk of over-reliance and over-confidence by consumers and practitioners in such technologies for crash avoidance. This has led to overestimating the benefits and resulted in risk compensation, where the road user has a 'tendency to engage in riskier driving as a result of a perceived Intelligent Transportation Systems (ITS) related safety gain' (PIARC, 2011, p. 115).

There are also limitations with these technologies, for which the road user may be unaware. The AEB test for a car driving into the back of another vehicle is at a maximum speed of 50 km/h (Hulshof et al., 2013), however on urban motorways and highways vehicles travel at much higher speeds with increasingly complex traffic conditions. Peak-hour headways are very small and drivers often change lanes into these small gaps, further reducing them. This can

coincide with a sudden lock-up (nucleation) and a shock-wave can quickly move upstream, requiring risk anticipation by drivers without visual cues. Since AEB can only detect slow or slowing vehicles immediately in front of them, there is an urgent need to develop strategies to avoid lock-ups and shockwaves, and warn drivers of the risk unfolding further ahead.

Despite all ADAS listed above,  $D_{\text{Braking}}$  in Equation 1 ultimately comes down to the relationship between speed and friction where the latter is directly dependent on the quality and condition of tyres, brakes and the road surface. Tyre and brake performance impacts friction  $\mu$ . Braking distance is inversely proportional to  $\mu$  (doubling  $\mu$  means halving braking distance). Insufficient emphasis is given to promoting high performing classical crash avoidance components such as maintaining pavement surface friction, high-quality tyres, better brakes and improved stability.

### ***Better tyres (across their lifetime)***

Tyres are used over many years and during tens of thousands of kilometres. Before their replacement, drivers will encounter continuous reduction of tread depth (wear) and rubber deterioration (aging). Safety on wet or damp roads is a major concern for drivers braking in an emergency. A few extra metres in braking distance can make a substantial difference to outcomes. Wet grip tyre labelling has been implemented in the EU and gives consumers reliable information on stopping distances. Tyre labelling regulations include wet grip tyre rating ranging from A (shortest) to E (longest) braking distance. The difference in stopping distance between each category is around 3-6 metres (European Commission, n.d.-b).

Worn tyre performance cannot be derived from new tyre performance as the level of degradation (which affects braking) is different for different combinations of tyre models and wear (Todoroff et al., 2019). [Figure 5](#) shows that in damp conditions, base tyre friction as well as tyre wear vary greatly between given pairs of tyres, with some worn tyres outperforming some new tyres.

Education of consumers about wet braking tyre performance is not a focus when purchasing new tyres, nor are consumers routinely made aware of the significant deterioration that occurs over the tyre's life even though regulatory requirements are met. The differences in braking distances between dry, damp and wet pavement may catch motorists unaware. Drivers who become accustomed to normal driving and normal braking conditions, may get caught out when extreme braking is required on damp or low-friction pavements, especially when tyres and brakes are cold.

Although consumers spend thousands of dollars on the purchase of a vehicle (including latest safety features), often this does not include tyres that perform optimally under all conditions, nor proven technologies like tyre pressure monitoring systems, run-flats and self-sealing tyres (allowing the damaged car to be driven to a safe environment for repair rather than changing a wheel on the roadside). These are important as tyre blow-outs are common on freeways (Martin & Laumon, 2005), especially for vans.

Martin and Laumon (2005) found that tyre blow-outs causing casualties almost always involved rear tyres which get less wear and are less frequently replaced. Practices such as replacing front tyres with rear ones and mounting the new ones on the rear wheels are beneficial. Reporting tyre condition by police for Police-attended crashes (age, air-pressure, after-crash state) is important to understand tyre involvement in crashes.

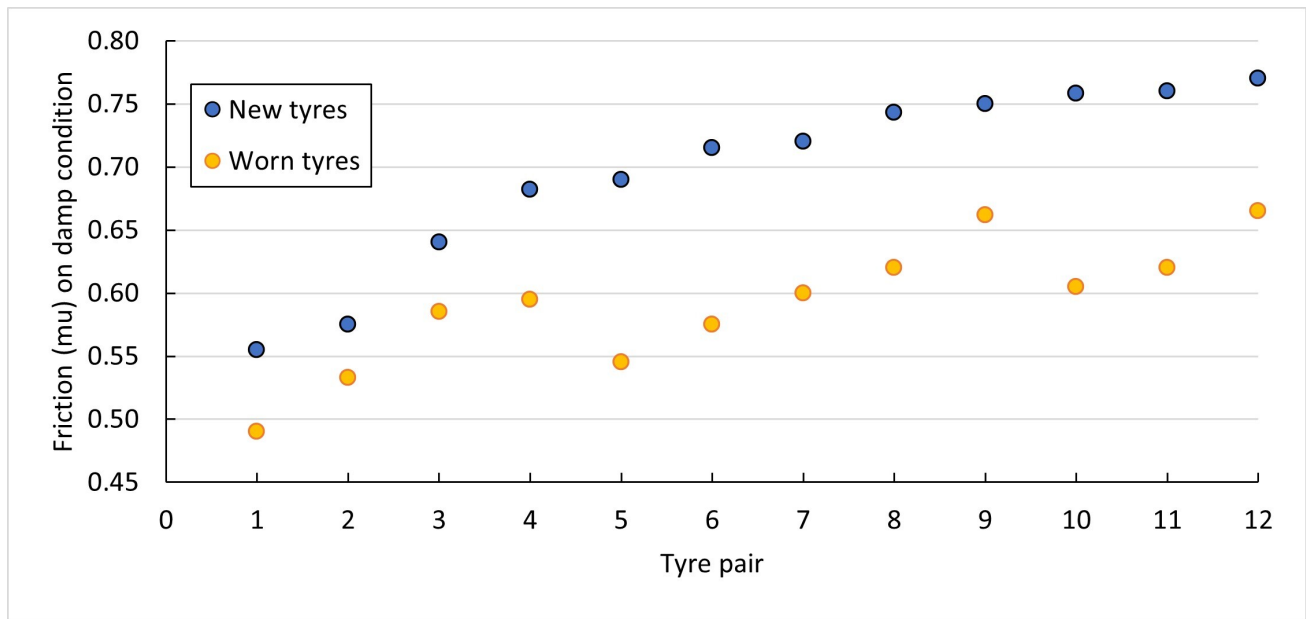
Yet tread depth and age influence a vehicle's stopping behaviour, especially in damp, wet or rutted pavements. The tread depth of new tyres is around 8mm and in Victoria, the minimum legal tread depth is 1.5mm (VicRoads, 2021). Some motoring associations recommend tyres be replaced when the tread depth is 3mm. Tread depth makes a considerable difference to a vehicle's handling, cornering and stopping ability, especially in wet conditions. In these conditions the stopping distance can be 18.6m more for tyres with minimum tread compared to new tyres (Gaffney et al., 2023). This difference is equivalent to reducing the speed by almost 10 km/h (based on Equation (1) with speed 80 km/h,  $t_{P+R}$  1.75s,  $\mu$  0.6) for new tyres. Some vehicle manufacturers recommend tyre replacement after six years due to hardening and breakdown of rubber, lowering braking friction and increasing risk of catastrophic failure. It is likely that motorists are not familiar with these minimum requirements for the tyres on their motor vehicle, nor the risks associated with tyres worn below the recommended tread depths.

### ***Better brakes across the vehicle fleet***

The current vehicle fleet is bigger, heavier, has a higher centre of gravity leading to longer braking distances and in some cases reduced handling compared to the past (Gaffney & Hovenden, 2023). Australian vehicles now have larger wheels (rim and tyre diameters) and lower profile tyres, with significantly higher operating tyre pressures which reduce fuel consumption by decreasing rolling resistance. However, this decreases braking friction as less tyre is in contact with the pavement surface (Srirangam et al., 2015), creating tension with the need for shorter braking distances in increasing traffic density. This is a major context change which has been given little attention.

There are significant differences in braking performance between vehicle makes, models and classes and it is likely that most consumers are unaware. For example, data from Bartlett (2021) showed that stopping distances for different passenger vehicles categories (at ~100 km/h) varied between 36.6m to 43.6m (Gaffney et al., 2023). A test of the top 50 best-braking cars has shown stopping distances of 30.7m to 33.5m (Brembo, n.d.). The difference between the best and worst in these examples is 12.9m. An unsuspecting motorist changing between similar weight and size vehicles (e.g., a private and a work vehicle) may not be aware of the difference in braking performance.

Stopping distances vary both with travel speed and road surface condition. Heavy vehicles have longer stopping distances (2-4 times) than lighter vehicles, and are incompatible in emergency stopping/braking situations. Road surface type, vehicle loading and road geometry (e.g., downhill or



**Figure 5. Friction  $\mu$  on damp condition for some pairs of new and worn tyres (dots represent different tyre models)**

Source: Recreated from chart in Todoroff et al., 2019

tight curvature) can also affect braking capability, exacerbating these differences.

### **Better stability and handling**

Vehicle rollovers are still a significant part of the crash problem. Richardson, Reznitzner and Grzebieta (2003) found that a vehicle's Stability Factor (SF) and the rate of real world rollovers were linked, indicating that apparent noise within the data is due to the vehicle's unique handling capabilities. Similar vehicles have different stability performance. However, many consumers are not aware of this. Unfortunately, some of the worst performing vehicles such as the Toyota Hilux and Toyota RAV4 (Overdrive, n.d.; Teknikens Värld, n.d.) are amongst the most popular ones in Australia, although since the initial "Moose Tests", improvements have been made to these vehicles. Although rollover tests are undertaken by ANCAP, additional tests for resistance to rollover (stability) and vehicle control under emergency braking and steering are needed.

### **Pillar 4: Safe Roads**

To achieve safer roads, current strategies focus on locally retro-fitting the infrastructure such as through the installation of flexible roadside and centreline barriers and tactile edge-lines. Whilst this is needed to tackle head-on or run-off road crashes on (rural) high speed roads, there is also a need for other infrastructure-based measures that consider dynamic or short-term risks resulting from changes in traffic and weather conditions.

### **Smart Infrastructure**

Opportunities exist in ITS or Smart Infrastructure space to address dynamic traffic and weather conditions. There is already Managed Motorway technology in place in Victoria (including telecommunications, gantries and variable message signs) which can be easily expanded to include dynamic speed reductions as well as traffic and weather condition warnings (refer to Figure 6 which shows an example from Germany). This has a direct impact on  $v$  and  $t$  P+R in Table 1.

This approach could be gradually expanded to cover lower volume roads such as peri-urban or rural motorways and potentially other roads. While high-cost infrastructure elements cannot be realised everywhere, a technology called Virtual Managed Motorway (with reduced Managed Motorway functionality) can use vehicle-generated speed and event data or BOM weather data to communicate warnings to direct to vehicles with minimal additional roadside infrastructure.

### **Distraction-free infrastructure**

Much emphasis has been placed on discouraging mobile phone use while driving, and this is an important element of ensuring full driver attention at all times. However, there are many other sources of distraction that are mentioned in police crash records. Roadside advertising/billboards are one such source of distraction (Gitelman et al., 2019). Given the existence of traffic state phenomena that can lead to traffic suddenly stopping and thousands of lane changes per kilometre per hour of urban motorway (Zurlinden et al., 2021), safe mobility and crash avoidance requires motorists to pay full attention at all times. However, the increase in crash numbers due to the distraction of billboards



**Figure 6. Managed Motorway technology in Frankfurt am Main, Germany, the VMS attached to the gantry pillars capable of displaying warnings of congestion and adverse weather conditions**

(Gitelman et al., 2019), means that millions of dollars in annual government revenue per highway section from such signage is required to cover the additional community social costs of the increased crash risk. Removing billboards from high volume urban motorways is critical.

### **Pavements**

Braking distance is greatly affected by pavement surface friction and maintenance intervention levels. Friction is not uniform across the network and varies with pavement type, condition, weather, and temperature. There can be differences in performance of 30-50 percent in the wet (e.g., rain, dew) between different pavement types and these variations can catch motorists by surprise. Many pavement surfaces are subject to rutting (affecting vehicle stability in lane changing) and pooling water (affecting drying time and braking friction). The melting of the binder in hot weather can result in bituplaning which is like braking on oil. Due to the importance of pavement surface friction on stopping distance, minimum standards for surface friction must be developed for Australia as a priority especially on roads with high density traffic.

### **Conclusion**

The rate of progress in road safety in Australia and internationally in the number of fatalities has plateaued. A system approach to road safety needs to consider current context of traffic conditions, variability of the environment, and factors that enable a vehicle to safely stop and avoid a crash.

Safe speed can be achieved through a range of measures such as technically limiting maximum vehicle speed, appropriately and dynamically setting speed limits, and various forms of intelligent enforcement such as point-to-point speed cameras.

Safe people can be achieved with more positive approaches, not just aggressively targeting non-compliant behaviours such as speeding, drink-driving or distraction. Approaches must acknowledge limitations in human capability, assisting drivers to respond instantaneously and correctly to suddenly occurring, unforeseen and unperceived hazards. This includes provision of targeted climate and weather information, and warnings of unstable traffic conditions and weather-related hazards.

Safe vehicles can be achieved through encouraging the uptake of crash avoidance technologies such as better brakes, tyres and handling performance. ANCAP rating scores need to include emergency braking and handling performance of vehicles as a key component of crash avoidance.

Safe roads can be achieved through smart ITS based infrastructure, greater use of dynamic speed management when headways are small and the avoidance of distractions such as roadside advertising in high-speed environments.

Closing these gaps in current road safety strategies brings us closer to achieving the ambitious goal of zero fatalities. A comprehensive system approach targeting the multiple factors contributing to crashes needs to be developed to break the chain of events, based on robust science and a return to the fundamentals. Emergency response has been a gap in safe system thinking and must be considered for a complete system approach.

A system approach must consider the changing context (denser traffic, larger and heavier vehicles), acknowledge and understand human limitations (perception and reaction time) and vehicle limitations (braking and stability), and understand the variable influences of climate/weather on visibility and pavement surface friction. Safety needs to travel with the vehicle and we need to utilise every opportunity to avoid crashes, in addition to the current focus on minimising harm to realistically achieve zero fatalities.

## Disclaimer

This paper is based on the authors' research and may not represent the current view of the Victorian Department of Transport and Planning.

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## Author Contributions

Hendrik Zurlinden, John Gaffney and Elizabeth Hovenden conceived this manuscript, undertook the data collection, data analysis and manuscript writing. All three authors revised the manuscript critically for intellectual content and have read and agreed to the published version of the manuscript.

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## Human Research Ethics Review

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## Conflicts of interest

The authors declare that there is no conflict of interest.

## Data Availability Statement

The authors have included all relevant materials, data, and protocols associated with the publication in the text.

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## References

- ANCAP. (2015). *ANCAP Quick Fact: 90% of all crashes involved some form of human error*. <https://www.anca.com.au/media-and-gallery/media-releases/089566>
- Bartlett, J. S. (2021). *Cars, SUVs, and Trucks With the Best and Worst Braking Distances*. <https://www.consumerreports.org/car-safety/best-and-worst-braking-distances-a2960086475/>
- BITRE. (2018). *Information sheet – Modelling road safety in Australian states and territories*. [https://www.bitre.gov.au/sites/default/files/is\\_94.pdf](https://www.bitre.gov.au/sites/default/files/is_94.pdf)
- Brembo. (n.d.). *From 100 to 0 km/h: the 50 best-braking cars*. <https://www.brembo.com/en/company/news/50-special>
- Bundesministerium der Justiz. (2012). *Straßenverkehrs-Zulassungs-Ordnung (StVZO)*. Section 57c(2). [https://www.gesetze-im-internet.de/stvo\\_2012/StVZO.pdf](https://www.gesetze-im-internet.de/stvo_2012/StVZO.pdf)
- Commonwealth of Australia. (2021). *National Road Safety Strategy 2021-30*. <https://www.roadsafety.gov.au/sites/default/files/documents/National-Road-Safety-Strategy-2021-30.pdf>
- European Commission. (n.d.-a). *Intelligent speed assistance (ISA) set to become mandatory across Europe*. <https://road-safety-charter.ec.europa.eu/resources-knowledge/media-and-press/intelligent-speed-assistance-isa-set-become-mandatory-across>
- European Commission. (n.d.-b). *Tyre Label*. [https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/energy-efficient-products/tyres\\_en](https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/energy-efficient-products/tyres_en)
- Gaffney, J. (2018). *The Study of Road Safety on Urban Motorways*. Churchill Trust. <https://www.churchilltrust.com.au/fellow/john-gaffney-vic-2016>
- Gaffney, J., & Hovenden, E. (2023). *New Understanding of Motorway Crash Risk From Newly Available Metrics*. *Journal of Road Safety*, 32(2). <https://doi.org/10.33492/jrs-d-22-00027>
- Gaffney, J., Hovenden, E., & Zurlinden, H. (2023). *Supporting Notes for Can I Stop Article*. [https://www.researchgate.net/publication/369589190\\_Supporting\\_Notes\\_for\\_Can\\_I\\_Stop\\_Article\\_29Mar2023](https://www.researchgate.net/publication/369589190_Supporting_Notes_for_Can_I_Stop_Article_29Mar2023)
- Gitelman, V., Doveh, E., & Zaidel, D. (2019). An examination of billboard impacts on crashes on a suburban highway: Comparing three periods—Billboards present, removed, and restored. *Traffic Injury Prevention*, 20(sup2), S69–S74. <https://doi.org/10.1080/15389588.2019.1645330>
- Hammit, B. E., James, R., Ahmed, M., & Young, R. (2019). Toward the Development of Weather-Dependent Microsimulation Models. *Transportation Research Record*, 2673(7), 143–156. <https://doi.org/10.1177/0361198119844743>
- Hovenden, E., & Liu, G.-J. (2020). Use of spatial analysis techniques to identify statistically significant crash hot spots in metropolitan Melbourne. *Journal of Road Safety*, 31(4), 36–58. <https://doi.org/10.33492/jrs-d-19-00249>
- Hovenden, E., Zurlinden, H., & Gaffney, J. (2020). Safety on Heavily Trafficked Urban Motorways in Relation to Traffic State. *Journal of Road Safety*, 31(1), 51–65. <https://doi.org/10.33492/jrs-d-19-00247>
- Hulshof, W., Knight, I., Edwards, A., Avery, M., & Grover, C. (2013). Autonomous Emergency Braking Test Results. *23rd International Technical Conference on the Enhanced Safety of Vehicles*. <https://cdn.euronc.ap.com/media/1384/aeb-test-results-esv-2013-0-a837f165-3a9c-4a94-aefb-1171fbf21213.pdf>
- Langford, J., Methorst, R., & Hakamies-Blomqvist, L. (2006). Older drivers do not have a high crash risk—A replication of low mileage bias. *Accident Analysis & Prevention*, 38(3), 574–578. <https://doi.org/10.1016/j.aap.2005.12.002>
- Martin, J. L., & Laumon, B. (2005). Tire Blow-Outs and Motorway Accidents. *Traffic Injury Prevention*, 6(1), 53–55. <https://doi.org/10.1080/15389580490510174>
- Noland, R. B. (2003). Traffic fatalities and injuries: the effect of changes in infrastructure and other trends. *Accident Analysis & Prevention*, 35(4), 599–611. [https://doi.org/10.1016/s0001-4575\(02\)00040-4](https://doi.org/10.1016/s0001-4575(02)00040-4)
- Noland, R. B. (2004). A review of the impact of medical care and technology in reducing traffic fatalities. *IATSS Research*, 28(2), 6–12. [https://doi.org/10.1016/s0386-1112\(14\)60103-5](https://doi.org/10.1016/s0386-1112(14)60103-5)
- Oguchi, T. (2016). Achieving safe road traffic — the experience in Japan. *IATSS Research*, 39(2), 110–116. <https://doi.org/10.1016/j.iatssr.2016.01.003>

Overdrive. (n.d.). *Why New Cars Keep FAILING the Moose Test*. <https://www.youtube.com/watch?v=qIN8CyhYREM>

PIARC. (2011). *Taking advantage of Intelligent Transport Systems to improve road safety*. PIARC Technical Committee 3.1 Road Safety. [https://www.piarc.org/ressources/publications/6/11638,2011R03\\_WEB.pdf](https://www.piarc.org/ressources/publications/6/11638,2011R03_WEB.pdf)

Richardson, S. A., Reznitzer, G., & Grzebieta, R. H. (2003). A methodology for estimating vehicle rollover propensity that combines stability factor and handling metrics. *Proc. 18th International Technical Conference on the Enhanced Safety of Vehicles, Nagoya, Japan*.

Srirangam, S. K., Anupam, K., Kasbergen, C., Scarpas, A., & Cerezo, V. (2015). Study of Influence of Operating Parameters on Braking Friction and Rolling Resistance. *Transportation Research Record*, 2525(1), 79–90. <https://doi.org/10.3141/2525-09>

State Government of Victoria. (2020). *Victorian Road Safety Strategy 2021–2030*. [https://www.tac.vic.gov.au/\\_data/assets/pdf\\_file/0020/502166/RoadSafetyStrategy\\_DEC2020.pdf](https://www.tac.vic.gov.au/_data/assets/pdf_file/0020/502166/RoadSafetyStrategy_DEC2020.pdf)

Teknikens Värld. (n.d.). *Results in Teknikens Värld's moose test*. <https://teknikensvarld.expressen.se/algtest/>

Todoroff, V., Paupy, S., Biesse, F., & Le-Chenadec, Y. (2019). The mechanisms involved during the wet braking of new and worn tires. *Vehicle System Dynamics*, 57(11), 1601–1620. <https://doi.org/10.1080/00423114.2018.1535126>

VicRoads. (2018). *Safe System Assessment Guidelines*. <https://www.vicroads.vic.gov.au/business-and-industry/technical-publications/technical-publications-a-to-z>

VicRoads. (2021). *Vehicle Standards Information 16 - Tyre maintenance and repair*. <https://www.vicroads.vic.gov.au/registration/modify-or-build-a-vehicle/vehicle-standards-information>

Vlakveld, W. P. (2005). *Jonge beginnende automobilisten, hun ongevalsrisico en maatregelen om dit terug te dringen* (SWOV report R-2005-3). In Dutch, summary also available in English. SWOV, Leidschendam. <https://www.swov.nl/publicatie/jong-e-beginnende-automobilisten-hun-ongevalsrisico-e-n-maatregelen-om-dit-terug-te-dringen>

Woolley, J., & Crozier, J. (2018). *Inquiry into the National Road Safety Strategy 2011–2020*. [https://www.roadsafety.gov.au/sites/default/files/2019-11/nrss\\_inquiry\\_final\\_report\\_september\\_2018\\_v2.pdf](https://www.roadsafety.gov.au/sites/default/files/2019-11/nrss_inquiry_final_report_september_2018_v2.pdf)

Zhuk, M., Kovalyshyn, V., Royko, Y., & Barvinska, K. (2017). Research on drivers' reaction time in different conditions. *Eastern-European Journal of Enterprise Technologies*, 2(3), 24–31. <https://doi.org/10.15587/1729-4061.2017.98103>

Zurlinden, H., Baruah, A., & Gaffney, J. (2020). Towards linking driving complexity to crash risk. *Journal of Road Safety*, 31(1), 66–80. <https://doi.org/10.33492/jrs-d-19-00070>

Zurlinden, H., Hall, M., & Gaffney, J. (2021). Applying New Methods for Assessing the Impact of Weaving and Lane Changing Intensity on Motorway Capacity. *100th TRB Annual Meeting*.