APPLICATION OF A MODIFIED INTEGRATED SAFETY CHAIN USING IN-DEPTH CRASH DATA TO IDENTIFY FACTORS ASSOCIATED WITH SERIOUS INJURY CRASHES: A METHOD TO PRIORITISE CURRENTLY AVAILABLE ACTIVE SAFETY SYSTEMS AND TO IDENTIFY NEW OPPORTUNITIES TO ADVANCE VEHICLE SAFETY.

Michael Fitzharris
Mike Lenné
Sara Liu
Tandy Pok Arundell
Sujanie Peiris
Accident Research Centre, Monash University
Australia

Bruce Corben
Corben Consulting
Australia

Claes Tingvall
Accident Research Centre, Monash University
Australia

Chalmers University of Technology
Sweden

ÅFRY
Sweden

Diana Bowman
Arizona State University
United States of America

Andrew Morris
Loughborough University
United Kingdom

Paper Number 23-0156

ABSTRACT

Recognising the ambition of Vision Zero, vehicle safety will play a critical role in reducing the number of road users seriously injured globally. The objective of this research, therefore, was to identify currently available and required future countermeasures that will lead to the elimination of serious injury. To meet this objective a systematic approach to the analysis of in-depth crash data using case-by-case analysis linking contributing factors to safety countermeasures was developed.

In-depth crash investigation data collected as part of the MUARC-TAC Enhanced Crash Investigation Study (ECIS) was used. 400 drivers (MAIS 3+: 47%) admitted to a major trauma centre in Victoria, Australia, were included. Data sources included: driver or next-of-kin/family interview, ambulance and medical records, and police data. Vehicle and scene analysis was undertaken. Crashes were reconstructed using HVE and PC-Crash. EDR data was accessed where available.

Using a modified version of Tingvall's Integrated Safety Chain, contributing factors and safety countermeasures across the 10-phase crash chain were examined using a case-by-case approach. Contributing factors were those associated with crash occurrence and injury severity. An countermeasure library was established with each of the 278 countermeasures linked to a specific contributing factor. Countermeasures included those focussed on the driver, passive and active vehicle safety systems, road infrastructure and post-crash response. The efficacy and time-horizon of each was assessed and estimated for future active safety systems. All applicable countermeasures for each crash and injured driver were identified; these were considered to be sensitive to the countermeasure effect.

Driver distraction (48.8%), sudden sickness (10.0%), drowsy driving (24.5%), and impaired driving (19.8%) resulted in lane departure and cross-path vehicle movements; this, combined with low proportion of driver pre-crash braking (55%, 1.3 s) and exceeding the speed limit (27.0%) demonstrates the need for intervening safety systems (e.g., ISA, AEB). Intervening systems to correct lane deviations and intersection entry are also required.

The findings highlight the importance of in-depth data in establishing the use case for existing but relatively new systems as well as the identification of system capability limits in addressing current crash scenarios. These crash scenarios represent development opportunities for new standalone active safety systems. However, for full safety benefits to be realised, and to address the full range of driver performance and impairments, next generation systems that are fully integrated with one another are required (e.g., AEB + driver monitoring systems, DMS). Occupant status monitoring, on-board sensors, V2I and V2V enabled technologies linked to chassis control systems will be central to the future safety architecture of the vehicle.

The findings are relevant to passenger vehicle crashes where at least one driver was seriously injured and admitted to hospital. Other limitations associated with the sample and data collection methods must also be considered.

The analysis method represents a powerful approach to analyse in-depth crash data and to understand crash causation, injury occurrence and applicable countermeasures. Adoption of this method using other datasets is recommended so that the full range of countermeasure needs across jurisdictions and other road user groups can be understood.

INTRODUCTION

The use of crash data — whether it be large-scale administrative datasets based on police reports or in-depth investigation of a sample of crashes — to inform the development, selection, and implementation of safety countermeasures has a long history.[1, 2] The systematic analysis of crashes and adoption of an evidence-based approach to countermeasure implementation has translated to fewer traffic-crash related deaths, at least on a per-capita basis, in many jurisdictions.[1,2] Nonetheless, it remains the case that approximately 1.35 million people are killed and tens of millions are injured each year on the worlds roads.[3].

Frameworks for the analysis of crashes and the identification of safety countermeasures

A number of frameworks and approaches to the analysis of crashes and systematic identification of road safety countermeasures exist. These are briefly outlined below given their relevant to the present study.

The 3 E's of road safety. As early as 1923 road safety countermeasure opportunities were seen through the lens of education, enforcement and engineering; these are commonly referred to as the 3 E's of road safety.[4] Proposed by Harvey, this characterisation of the primary elements of safety, as described by Groeger in 2011, dominated road safety thinking for decades.[4] While succinctly defining the prospects for intervention. Groeger argued that a narrow interpretation of the original three E's limited the scope of each and their potential contribution to road safety. For instance, education was seen as having solely a driver skill-based learning focus and enforcement was undertaken by police to ensure drivers complied with the road rules; engineering was broader in that it included road design and quality (i.e., surface, geometry) as well as improvements in occupant protection, vehicle build quality and reliability. With advances in technology and the increasing inter- and interdisciplinarity required to achieve improvements in road safety, Groeger argued that the 3 E's can continue to remain a useful way of conceptualising road safety measures so long as a broader view of their application was adopted; Groeger did however identify four additional potential contributors to safety, these being exposure, emergency response, examining for competence, and evaluation.[4] Collectively, these 3 + 4 E's capture the range of measures across the road safety cycle. What the 3 E model did not do, however, was to highlight the interdependencies across the elements in what is today considered a systems-based approach.

Following this, it is notable that the dominant paradigm in road safety for many decades was a focus on driver behaviour as a means of reducing the number of people killed in crashes.[5,6] This was driven by the perspective that drivers were almost always responsible for crashes, a point lamented by Haddon.[7,8] Whether this stemmed from a narrow view of the analysis of crash factors and/or a narrow application of the original 3 E's is unknown.

The Haddon Matrix Taking key learnings from aviation safety and impact biomechanics, Haddon transformed road safety by arguing that greater focus ought to be given to 'crash packaging' and energy control, given the relationship of the latter to injury severity; this same concept forms the basis of modern occupant protection strategies and underpins *Vision Zero* and the *Safe System* approach.

In defining the *Haddon Matrix* [7,9], Haddon also argued for the objective study of crashes where the causes of injury and safety measures (i.e., countermeasures) were identified, rather than viewing crashes, or 'accidents' as commonly referred to, as 'chance' events. The systematic analysis of crash data was central to this objective. To facilitate this analysis, the *Haddon Matrix* (Figure 1) identified three factors in the road transport system (humans/driver, vehicle, environment) and three phases (pre-crash, crash, post-crash) in the sequence of events leading to injury, where '…causal factors are active and countermeasures can be undertaken' [7, p.1434]. While Haddon placed emphasis on energy management and injury control, post-crash care including rehabilitation and addressing driver-related factors – including broader person-based risk factors – were also seen to be important.

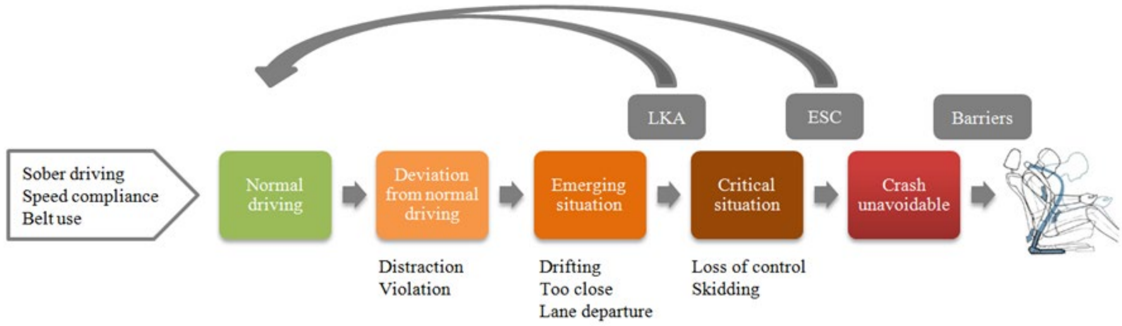
		FACTORS		
PHASE		HUMAN	VEHICLES AND EQUIPMENT	ENVIRONMENT
Pre-crash	Crash prevention	Information Attitudes Impairment Police enforcement	Roadworthiness Lighting Braking Handling Speed management	Road design and road layout Speed limits Pedestrian facilities
Crash	Injury prevention during the crash	Use of restraints Impairment	Occupant restraints Other safety devices Crash-protective design	Crash-protective roadside objects
Post-crash	Life sustaining	First-aid skill Access to medics	Ease of access Fire risk	Rescue facilities Congestion

Figure 1. An example of the Haddon Matrix with selected countermeasures.[1]

The influence of the *Haddon Matrix* on crash analysis and road safety cannot be overstated. Through the *Haddon Matrix,* Haddon provided the basis for the systematic analysis of crashes and the means to operationalise a preventative, population-based approach to preventing road trauma. Of particular note is that Haddon proposed two matrices, the first being the factors associated with crash events and injury, and the second being ways to address these factors. Haddon went further and suggested mathematical modelling to assess intervention choices in a systematic way. While the countermeasures identified through this process could arguably be classified within the 3 E's, the greater specificity provided a more robust basis from which to prioritise road safety countermeasures and shape road safety policy. It is for these reasons that the *Haddon Matrix* was used as a key starting point for the analysis of crashes and countermeasures in the present study.

The Integrated Safety Chain While a number of other frameworks and crash analysis methods have emerged since the *Haddon Matrix*, including for instance, the *Road Trauma Chain* [10], KEMM-X [11], AcciMAP [12], DREAM, [13] arguably the most prominent crash sequence model was the *Integrated Safety Chain* (ISC) first outlined by Tingvall in 2008.[14] (Figure 2) and subsequently applied by Lie [15], Strandroth [16], Rizzi [17] and Sunnevång [18]. The ISC provides a framework for understanding the role that individual factors play in the crash sequence and how to best intervene. The influence of the ISC is driven by its operational links to *Vision Zero* [19,20,21] and the Multi-dimensional (SRA) Model of a Safe Road Transport System [22,23].

The ISC is a time-based model of the driving process where the pre-crash phase is divided into discrete sub-phases leading up to a crash (Figure 2). Requirements to access the road transport system are described, as is crash protection and post-crash emergency care. This overlaps with Haddon's pre-crash, crash and post-crash phases. The key point of difference is in the pre-crash phase and once driving has commenced. Having set requirements for accessing the road transport system in order to facilitate *Normal Driving* (i.e., seat-belt used, compliance with speed limit, sober), and once the trip has commenced, the pre-crash phase is divided into three distinct phases where the intervention urgency escalates if the driver does not respond to *Normal Driving.* The intervention objective is to return a driver to the *Normal Driving* phase as quickly as possible.



Note: Arrows indicating a return to normal driving due to the influence of specific countermeasures; Lane Keep Assist [LKA] and Electronic Stability Control [ESC] shown as specific examples). Barriers shown as an energy management intervention in the crash phase.

Figure 2. The Integrated Safety Chain [14, 15, 16]

In addition to road user access requirement, measures to support and sustain *Normal Driving* include infrastructure and enforcement measures, as well as vehicle-based active safety systems. Indeed, the ISC is especially well suited to identifying relevant active safety measures given the emergence of new vehicle technologies that shape driver and/or vehicle response aimed at crash prevention, injury mitigation, or both. Indeed, it was this blurring of system functionality across the driver, vehicle and road environment across the pre-crash, crash, and post-crash phase [24] that transformed vehicle safety from 'passive' occupant protection crashworthiness measures toward dynamic integrated safety systems that linked driver responses to the vehicle, linked the vehicle to the road environment, better prepared the driver for the crash through optimisation of the drivers seating position, and automatically called emergency services post-crash. These systems gave rise to the idea that vehicle safety countermeasures could be placed on a timeline from the seconds to milliseconds before the crash, during the crash itself, and after the crash. It can be observed that as one moves closer to the crash the burden of preventing the crash moves further away from the driver toward the vehicle and infrastructure solutions.

For completeness, the prevention of serious injury once a crash occurs is the exclusive domain of passive vehicle safety measures and energy-control infrastructure measures; these sit within the crash phase of the ISC. This includes setting speed limits in line with the limits of protection offered by vehicles and foreseeable crash types given the road environment due to its link to impact speed. While emergency response is noted in Tingvall's original ISC [14], a distinct post-crash response phase was added by Rizzi, who also represented the ISC in a vertical manner.[17]

In addition to being a time-based model of the crash sequence, the ISC explicitly brings together primary prevention (i.e., crash prevention) and secondary prevention (i.e., injury mitigation) into a sequential and integrated model. With discrete phases, the ISC permits determination of where each risk factor sits within the crash sequence, and by extension, where specific countermeasures apply. To do so however requires a detailed understanding crash occurrence and injury severity risk factors in real-world crashes; for this reason, data collected using in-depth methods is ideal for this purpose.

The present study

The present study is set within the context of a broader *Enhanced Crash Investigation Study (*ECIS). The ECIS had two goals: 1. to identify the factors associated with serious injury crashes, and 2. to identify crash prevention measures and measures that would be effective in preventing occupants of vehicles being seriously injured once a crash occurs. The ECIS examined, in-depth, the crashes of 400 drivers admitted to a major trauma centre in Victoria, Australia.

The objective of this research paper is to demonstrate the application of an expanded ISC using defined crash scenarios to 1. prioritise currently available active safety systems, and 2. to identify opportunities to advance vehicle safety.

METHODS

Data

Crashes included in the ECIS program were those where a driver of a passenger vehicle was injured and admitted to one of two adult trauma centres in Melbourne, Australia (i.e., The Alfred Hospital; The Royal Melbourne Hospital).

Injured drivers, or their Next-of-Kin for the most seriously injured drivers, were required to give informed consent for participation in the study. The study was approved by The Alfred Hospital Research Ethics Committee (HREC, Project: 249-14), The Royal Melbourne Hospital HREC (Project: 249-14), and the Monash University HREC (CF14/2329-2014001254).

In total, 400 injured drivers were enrolled to the study (67% consent rate). Enrolled drivers were aged 18 – 93 years, 55% were male, and 37% of crashes occurred in non-metropolitan, regional areas of Victoria. These drivers were involved in 393 crashes, with two drivers injured in 7 crashes enrolled to the study. In total, these crashes involved 923 people, 18 of which died (in 17 crashes) and 547 people were hospitalised.

Comprehensive details of the crash were obtained. This included interviews with the involved driver, medical records, police reports, inspection of the vehicle, inspection of the scene and full crash reconstruction. Injuries were coded using the Abbreviated Injury Scale [25], with 'serious injury' being defined as a driver having sustained an AIS 3 or higher injury, referred to as MAIS 3+; injured drivers are referred to as MAIS 1+ injured drivers. The reader is referred to ECIS Reports 1,2,3, and 4 for detail [26,27,28,29].

Development of the expanded ISC for use in the ECIS program

Following Tingvall and others, a modified version of the ISC was created for use in the ECIS program. This forms the basis of the analysis of the ECIS data report here. The original ISC was modified after significant development work, including a review of conceptual models and application of the original ISC using ECIS case data across a series of workshops [28].

The modified version of the ISC used in the ECIS program is presented in Figure 2.

PHASE	DEFINITION AND INTERVENTION APPROACH	INTERVENTION GOAL
1. Threats to Normal Driving	• Driver (D), Vehicle (V), and Road Infrastructure/Environment (E) factors detrimental to *Normal Driving*, including factors that pre-dispose a driver to a crash or act to negatively impact driver ability to respond and avoid a crash. • D: intoxication and/or use of illicit drugs, abuse of prescribed medication; medical/health condition; experiential factors (new licence, presence of peers), offence/crash history; V: vehicle condition/roadworthiness including tyre tread and lighting systems; E: signage, road geometry, latent (in-built) risk by design. • The goal is to eliminate the presence or manage the influence of these threats.	**Measures to address human, vehicle & road environment factors detrimental to *Normal Driving***
2. Normal (Routine) Driving	• *Normal Driving* is characterised by the control of the vehicle by a driver in a manner that is responsive to the road environment, surrounding traffic and other road users such that a trip is successfully completed as planned and without conflict/incident. *Normal Driving* includes compliance with traffic laws. • Per the *Safe Driver* element of the *SRA Model of a Safe Road Transport System*[22,23], the prerequisites for *Normal Driving* are: seat belt worn (i.e., use of protective equipment); driving within the speed limit; non-use (handling) of mobile phone; BAC within limit for licence class; no illicit drugs used or abuse/non-prescribed use of benzodiazepines and/ or opioid-based analgesics; no excessive drowsiness.	**Measures to promote and return a driver to *Normal Driving***
3. Deviation from Normal Driving	• Driver (human) factors causing a shift from *Normal Driving*. In addition to the prerequisites of *Normal Driving* not being met (excluding impairment factors present prior to the commencement of driving (Phase 1: Threats), the driver/vehicle deviates from a safe travel path due to driver performance failure(s) (e.g., error), the effect of health and driver state factors, and/or non-compliant behaviour; these factors can result in a failure to recognise roadway cues and the presence of other road users/objects resulting in an *Emerging Situation* if not corrected. • Intervention approach: provide information and support (includes warning).	
4. Emerging Situation	• Vehicle is in a position sufficiently beyond *Deviation from Normal Driving* to be a direct threat to the driver (and other road users) if left uncorrected. • Movement depends on crash type: midblock/lane departure involves a drift/deviation/move from travel lane; intersection: lack of proper response to traffic control signal and/or on-coming vehicle. • Intervention approach: warning and intervention in driving.	
5. Critical Situation	• Crash event is imminent due to non-response or ineffective response to the threat of the *Emerging Situation*. • Trajectory of vehicle: in-path of other road user, entered shoulder/off-roadway, non-response to stationary vehicle. • Intervention approach: immediate and active correction.	
6. Crash Unavoidable	• Crash is imminent with the time-to-collision (and vehicle trajectory) so short as to make the crash unavoidable. • Intervention approach: preparation for the crash with a viewing of controlling the level of crash energy and optimising vehicle safety systems to minimise crash energy and preparing the driver/vehicle safety systems for impact.	**Energy reduction and injury mitigation measures**
7. CRASH	• Injury mitigation through the effective control and management of crash energy. • Intervention approach: measures aimed at vehicle crashworthiness and road engineering solutions to manage impact speed, energy transfer, and energy dissipation. Includes measures to prevent secondary impacts, the prevention of vehicle rollover events and/or impacts with non-frangible roadside objects.	**Injury mitigation measures/energy dissipation**
8. Ambulance & Hospital Care	• Emphasis is on systems, processes, and training to enable an optimal outcome for the injured driver to be achieved. • Intervention approach: stabilisation, extrication and transport of the injured driver and the provision of rapid and efficacious trauma care in the hospital setting.	**Immediate post-crash emergency care, retrieval, and acute hospital trauma care**
9. Rehabilitation, Recovery, Injury/other Insurance	• Care and access to services following acute treatment for injuries. • Intervention approach: processes and programs to facilitate recovery and achievement of optimal health, function, and re-integration to everyday life post-crash and beyond the hospital setting.	**Rehabilitation, supported recovery and community integration**
10. Crash Data Systems	• Vehicle (on-board) data systems to capture critical pre-crash and in-crash data, enabling understanding of crash circumstances, occupant injury risk factors and effects of safety systems. Data collected via in-depth crash investigation. • Integrated administrative crash data, emergency service and hospital-based data systems required to monitor system performance and monitoring of road trauma. • Required for the development of road safety strategy and action plans.	**Fitment, access, collection, and reporting**

Figure 3. The expanded Integrated Safety Chain adopted in the ECIS program [26,27]

Formulation of crash types/scenarios

Recognising that countermeasures will differ across crash types and according to specific vehicle movements, eleven (11) crash scenarios were identified (Appendix, Table A.1). Broadly, these were defined as Lane Departure crashes, Across Path crashes, Rear Impact crashes, and 'Other'; this latter category were characterized by complex vehicle movements that did not fall within the three principal crash types. Within each principal crash type, sub-types were also defined. For Across Path crashes, a further split was created based on the presence/absence of traffic lights.

Risk factor identification and countermeasure library

Comprehensive data collection forms were created for use in the study. These included a Driver Interview form, including a truncated form where Next-of-Kin consent was required, a Vehicle Inspection form, and a Scene Inspection form. An *ECIS Contributing Factors Form* was also created; this was largely structured on the *Haddon Matrix,* informed by known risk factors based on the road safety literature and ECIS Investigator team expertise. In completing the *ECIS Contributing Factors Form* all available information was used. A distinction was made between the presence of a particular factor and whether it contributed to the crash and/or injury.

As stated, risk factors – also referred to as contributing factors – were aligned with a specific phase of the modified ISC. In a separate exercise, all possible countermeasures (278) associated with each contributing factor were identified, including future measures; this represents the countermeasure library. This was made possible through the input of an expert group where 40 cases were analysed individually using the integrated safety chain, while an additional 56 cases were individually discussed and countermeasure opportunities identified in 16 multi-disciplinary panels.

Each identified countermeasure was assessed for its likely efficacy in addressing the contributing factor given. A scale of low (<20%), medium (20% - 50%), and high (50%+) was adopted. This assessment was based on a number of parameters, including its function and technical limits (i.e., operational boundaries), effectiveness studies published in the research literature and technical reports/manuals, as well as expert opinion. For countermeasures not presently available and where no formal evaluations were available, expert opinion was used in the context of the crash scenario; while estimates of efficacy are given, these technologies will require testing and field evaluations to be undertaken.

For each crash, countermeasure applicability was assessed independently of one another, and no consideration was given to cost-effectiveness or other policy implementation considerations.

A countermeasure availability time horizon for each countermeasure was identified. For countermeasures under development, a short-term (within 5-years) or medium-term (> 5 years) availability time horizon was estimated based on best available information.

Countermeasure categories, based on their action and point of effect, were also defined [29]; these are not considered here for the sake of brevity.

Analysis approach and primary analysis outcome

Using the crash categories, a case-by-case analysis using the modified ISC and associated decision rules on risk factors and aligned countermeasures was performed.

The primary analysis outcome of interest was the proportion of serious injury crashes where each contributing factor is present and each associated countermeasure is applicable to the crash. Whether the crash was 'sensitive' to the countermeasure was based on the function and technical performance specifications of the countermeasure being considered.

RESULTS

The analysis of contributing factors highlights a broad array of driver, vehicle and road infrastructure factors that contributed to the occurrence of crashes and their severity. Driver distraction (48.8%), sudden sickness (10.0%), drowsy driving (24.5%), and impaired driving (19.8%; alcohol: 11.3%; illicit drugs: 12.8%) resulted in lane departure, cross-path vehicle movements and collisions with parked vehicles, fixed objects and rear impact crashes.

Driver performance failures also included looked but failed to see errors (20.3%), failure to detect parked vehicle/objects at roadway (4.3%), driving too close (7.8%), as well as non-compliance with traffic signals and directional yield signs (20.5%). Non-compliance with seat belt use was 6.8%.

The data also indicated that in only 55% of crashes did drivers apply the brakes, and when they did the time was short resulting in a small percentage reduction in vehicle speed at impact. Further, analysis indicated that in 27% of crashes, one (or more) of the involved driver(s) were exceeding the speed limit.

In addition to driver-based factors, infrastructure-related factors (e.g., pavement surface 6.3%) and vehicle-related factors (e.g., tyre condition, 4.8%) were also evident as contributing factors.

Linking these contributing factors back to the pre-crash phases of the modified ISC (Figure 3) and with reference to the established countermeasure library, a broad range of countermeasures are available either now (Table 1) or could be available in the future (Table 2) were identified.

From an implementation perspective, ideally priority is given to high efficacy countermeasures that are applicable to a high proportion of serious injury crashes. Notably, high efficacy measures are intervening technologies, while medium and low efficacy measures are generally warning systems that are dependent on drivers responding accordingly. However, from a technology acceptance perspective, warning-based systems may be preferable for many drivers. It is likely that the acceptability of intervening technologies among driver will evolve over time as systems as the safety and convenience benefits become clear.

It is also evident from Table 2 that a large number of countermeasure opportunities exist. These are either new systems entirely or are more advanced, intervening technologies than what are currently available. In some instances, significant research and development work would be required to bring these technologies to the vehicle fleet.

Table 1.

Identified (select) currently available countermeasures and the proportion of serious injury crashes to which they are applicable

System / countermeasure	**Contributing Factor being addressed**	**Applicable serious injury crashes (%)**		**ISC Phase**	**Efficacy**	**Horizon**
		MAIS 1+	**MAIS 3+**			
Intelligent Speed Assist (ISA) (intervening, retrofitted)	Traffic offence, within last 12-months	24.8%	23.4%	1	High	Now
Alcohol interlock	Impairing influence alcohol	11.3%	13.8%	1	High	Now
Seat belt reminder (SBR) systems (advisory)	Seat belt not worn	6.8%	7.4%	3-5	Medium	Now
Speed assistance - manual speed limiter	Non-compliance with posted speed limit	27.0%	36.2%	3-5	Low	Now
Speed assistance – speed sign recognition & warning	Non-compliance with posted speed limit	27.0%	36.2%	3-5	Medium	Now
Intelligent Speed Assist (ISA) (advisory)	Non-compliance with posted speed limit	27.0%	36.2%	3-5	Medium	Now
– Intelligent Speed Assist (ISA) (intervening)	Non-compliance with posted speed limit	27.0%	36.2%	3-5	High	Now
Attention Assist (warning)	Driver Inattention (all forms including driver state and sudden sickness)	66.8%	68.6%	3-5	Low	Now

System / countermeasure	Contributing Factor being addressed	Applicable serious injury crashes (%) MAIS 1+	MAIS 3+	ISC Phase	Efficacy	Horizon
Attention Assist (warning)	Inattention – distraction inside/outside of vehicle/phone use	48.8%	50.0%	3-5	Low	Now
	Drowsy driving	24.5%	26.6%	3-5	Low	Now
Advanced vehicle lighting systems (DRL / auto high beam / adaptive headlights)	Looked but failed to see vehicle or hazard / object (i.e., other road users, object)	13.5%	12.8%	3-5	Medium	Now
Object detection (including night vision assist & 360° surround view monitor with Head-Up Display (HUD)	Failure to detect parked vehicle / objects on side of roadway	4.3%	1.1%	3-5	High	Now
Braking systems – EBA fitment	Braking system fitted to crash-involved vehicle sub-optimal	78.5%	85.6%	3-5	High	Now
Braking systems – ABS fitment	Braking system fitted to crash-involved vehicle sub-optimal	48.5%	53.2%	3-5	High	Now
Braking systems – EBD fitment	Braking system fitted to crash-involved vehicle sub-optimal	74.0%	79.8%	3-5	High	Now
Forward collision warning (FCW, camera, radar, LiDAR)	On collision trajectory	67.0%	64.4%	4-5	Medium	Now
Autonomous Emergency Braking (AEB) – includes consideration of subtypes (e.g., junction AEB, high-speed AEB)	On collision trajectory	67.0%	64.4%	5	High	Now
Lane departure warning	Vehicle deviated (departed) from lane / beyond centre of lane	47.3%	53.7%	3-5	Medium	Now
Automated Lane Keep Assist (ALKS): intervening for oncoming traffic crash mitigation	Vehicle deviated (departed) from lane / beyond centre of lane	47.3%	53.7%	3-5	High	Now
Electronic Stability Control (ESC)	Loss of control causing departure from lane (i.e., out of control, not overtaking)	15.5%	15.4%	3-5	Medium	Now

System / countermeasure	Contributing Factor being addressed	Applicable serious injury crashes (%)		ISC Phase	Efficacy	Horizon
		MAIS 1+	MAIS 3+			
Traffic light alert (advisory, V2I)	Apparent failure to see / recognise /obey traffic signs at intersection	8.3%	7.4%	3-5	Medium	Now
Traffic sign display (in-vehicle)	Apparent failure to see / recognise /obey traffic signs at intersection	11.5%	12.2%	3-5	Medium	Now
Cross Traffic Alert (collision warning)	Enter intersection across path of vehicle [crash types F, H; refer Appendix]	19.3%	20.2%	3-5	Medium	Now
Turn Assist (collision) warning (intersections) / Right turn crash warning (in intersection and turning)	Turn across path of oncoming vehicle in intersection [crash type G; refer Appendix]	10.8%	8.0%	3-5	Medium	Now

Table 2.

Identified (select) likely available countermeasures in the short-term (within 5-years) and medium term (beyond 5 years), and the proportion of serious injury crashes to which they are applicable

System / countermeasure	Contributing Factor being addressed	Applicable serious injury crashes (%)		ISC Phase	Efficacy	Horizon
		MAIS 1+	MAIS 3+			
Vehicle ignition technology (e.g., smart key	Driver experience, indicated by driver behaviours and vehicle control.	8.0%	8.0%	1	Medium	Short-term
	Traffic offence, within last 12-months	36.0%	32.4%	1	Medium	Short-term
Telematics fitment and on-going monitoring as licensing requirement	Driver experience, indicated by driver behaviours and vehicle control.	8.0%	8.0%	1	Medium	Short-term
	Crash history – involved in injury crash last 5-years	11.0%	8.0%	1	Medium	Short-term
	Traffic offence, within last 12-months	36.0%	32.4%	1	Medium	Short-term
Vehicle ignition technology (e.g., smart key	Driver experience, indicated by driver behaviours and vehicle control.	8.0%	8.0%	1	Medium	Short-term
	Traffic offence, within last 12-months	36.0%	32.4%	1	Medium	Short-term
	Inattention – distraction inside/outside of vehicle	45.0%	45.2%	3-5	High	Short-term
Passive alcohol sensor (warning)	Impairing influence alcohol	11.3%	13.8%	1	Medium	Medium-term
Passive alcohol sensor with interlock (intervening)	Impairing influence alcohol	11.3%	13.8%	1	High	Medium-term
Drug interlock (intervening) via passive detection	Impairing influence illicit drugs	12.8%	17.6%	1	High	Medium-term
Tyre pressure monitoring system (TPMS)	Underinflation of tyres	4.5%	5.3%	1	Medium	Short-term
Tread warning	Poor type condition/low tread	4.8%	5.9%	1	Medium	Medium-term
Co-operative ITS enabled warning systems including speed advisory	Pavement surface having a negative impact on vehicle stability and friction	6.3%	5.3%	1	Medium	Medium-term
	Pavement surface conditions having a negative impact on vehicle stability due to foreign substances on road	4.5%	4.3%	1	Medium	Medium-term
Congestion alert (V2V / V2I enabled)	Dynamic, congested high volume traffic environment	7.5%	5.3%	1	Medium	Medium-term

System / countermeasure	Contributing Factor being addressed	Applicable serious injury crashes (%)		ISC Phase	Efficacy	Horizon
		MAIS 1+	MAIS 3+			
Seat belt reminder (SBR) systems (intervening)	Seat belt not worn	6.8%	7.4%	3-5	High	Short-term
Attention assist (warn) / Driver monitoring system (camera-based)	Driver Inattention (all forms including driver state and sudden sickness)	66.8%	68.6%	3-5	Medium	Short-term
	Inattention – distraction inside/outside of vehicle/phone use	48.8%	50.0%	3-5	Medium	Short-term
	Drowsy driving	24.5%	26.6%	3-5	Medium	Short-term
Attention assist (intervening with steer assist) / Driver monitoring system (camera-based)	Driver Inattention (all forms including driver state and sudden sickness)	66.8%	68.6%	3-5	High	Short-term
	Drowsy driving	24.5%	26.6%	3-5	High	Short-term
	Sudden sickness	10.0%	9.0%	3-5	High	Short-term
Attention Assist via DMS / OSM with vehicle takeover (steer, park) for a non-responsive driver)	Drowsy driving/asleep	11.0%	13.3%	3-5	High	Medium-term
	Sudden sickness	10.0%	9.0%	3-5	High	Medium-term
Intervening Headway / Following Distance System	Unsafe margin / follow too close	7.8%	4.8%	5	High	Short-term
Adaptive cruise control (ACC) [with Stop-Go & Traffic Jam Assist plus Steer / Collision Evade Assist]	Cruise control active and apparent failure to respond to intersection / correct lane deviation	2.8%	2.7%	3-5	Medium	Medium-term
Disengage cruise control linked to Attention Assist, using DMS / OSM	Cruise control active and assessed to be contributing factor for crash event and/or associated with injury severity	2.8%	2.7%	3-5	High	Medium-term
Autonomous Emergency Steer / Collision Evade Assist	On collision trajectory	67.0%	64.4%	5	High	Medium-term

System / countermeasure	Contributing Factor being addressed	Applicable serious injury crashes (%)		ISC Phase	Efficacy	Horizon
		MAIS 1+	MAIS 3+			
Autonomous Emergency Steer / Collision Evade Assist linked to DMS/OSM for non-responsive drivers	On collision trajectory	10.0%	10.6%	5	High	Medium-term
Emergency Lane Keep Assist (ELKS) to manage non-responsive drivers (intervening, linked to DMS/OSM)	Vehicle deviated (departed) from lane / beyond centre of lane	15.0%	17.0%	3-5	High	Medium-term
Active Brake Assist with cross-traffic function / Junction AEB (optimised with sensor based on V2V)	Enter intersection across path of vehicle [crash types F, H; refer Appendix]	19.3%	20.2%	3-5	High	Short-term
Intelligent Traffic Light Assist (haptic feedback of accelerator pushback + braking, V2V / V2I)	Driver failed to obey a red light at intersection, entered	8.3%	7.4%	3-5	High	Medium-term
Brake-hold with roll warning	Drift / roll into intersection (from stationary)	0.8%	1.6%	3-5	Medium	Medium-term
Autobrake – forward (linked to DMS-OSM for non-responsive drivers)	Drift / roll into intersection (from stationary)	0.8%	1.6%	3-5	High	Medium-term

While a range of passive vehicle safety measures were identified as being applicable to the serious injury crash sample, these were not the focus of this paper. These measures relate to Phase 6 (*Crash Unavoidable*) (e.g., pre-safe) and Phase 7 (*Crash*)(e.g., airbags; crashworthiness indicated by NCAP star-rating; impact speed relative to vehicle safety) of the modified ISC. Here it is worth noting the AEB has both a collision avoidance function and if successful the driver can return to *Normal Driving* from a *Critical Situation,* otherwise AEB can play a role in injury mitigation by reducing the impact speed where the time-to-collision allows (Phase 7, crash). As none of the vehicles involved in the crashes examined has AEB fitted, AEB was considered applicable to 67% of all serious injury crashes in the sample; however, to bring the impact speed with the safety design window of the vehicle given its NCAP star rating, AEB would be applicable to 43% of crashes.

The role of post-crash notification technology and on-board vehicle data systems are important to note. Due to the severity and location of a subset of crashes, eCALL/AECS technology must be considered to be a vital safety technology, particularly as timely treatment is critical to survival following injury. While technically applicable to all of the crashes in the sample as all required emergency care, based on crash location, road type and traffic volume, eCALL/AECS would be applicable to 43% of crashes. Taking an even narrower perspective, eCALL/AECS would be highly applicable to 5.5% of serious injury crashes where the delayed notification of emergency medical services and/or difficulty in locating the crash was apparent.

On-board vehicle data systems, including Event Data Recorders (EDR) and Data Storage Systems for Automated Driving (DSSAD), are an essential crash investigation and research tool. The data collected by these systems will be essential in evaluating driver engagement, the efficacy of both active and passive safety systems, and more broadly, assessing the influence of road safety policies over time. The global adoption of regulations concerning the fitment, data points, and access of these systems is essential. It is worth noting that within the ECIS sample, EDR data was available and accessible in only 9.8% of ECIS driver vehicles.

DISCUSSION

Using recently collected crash data, this paper set out to demonstrate the application of an expanded form of the Integrated Safety Chain (ISC) using pre-defined crash type scenarios to identify the potential of currently available active safety systems to reduce serious injury crashes. A further objective was to identify crash-relevant technologies not currently available but likely to be of value given the observed range of driver behaviours and associated vehicle movements pre-crash. The primary analysis outcome was the proportion of hospitalisation crashes where each currently available or future identified countermeasure would be applicable.

As a starting point, modifications were made to Tingvall's original ISC [14], in addition to those made by other researchers [15-18]. Expansions to the ISC included the addition of a number of phases in the crash sequence, specifically as they relate to *Threats to Normal Driving* and further splitting the *Post-crash phase* into two distinct phases. A final phase, *Crash Data Systems* was added given the value of on-board data collection systems. Further innovations included defining crash and injury relevant contributing factors that align to each crash phase, defining the intervention approach specific to each crash phase, and the formulation of relevant decision-making heuristics. A conceptual and operational definition of *Normal Driving* was also articulated. The basic principles of Tingvall's ISC remain the same however, these being that each phase represents an intervention opportunity to promote safe driving or to protect occupants from serious injury in the event of a crash.

Analysis of the ECIS serious injury crash data highlighted the broad range of factors that contribute to both crash occurrence and injury severity, once a crash occurs. By making explicit the nature of *Threats to Normal Driving*, it is evident that there are a range of driver, vehicle and road infrastructure factors that need to be addressed, even before a driver enters the vehicle to commence their trip. Intervening safety systems play a key role in addressing these threats. The need for systems that monitor occupant status and impairments are clear.

As described, drivers shift from *Normal Driving* due to performance failures (e.g., error), the effect of health and driver state factors, and intentional or unintentional non-compliance with relevant road laws. These deviations cascade into *Emerging Situations* and *Critical Situations* that are characterised by the vehicle moving toward, and ultimately a position of conflict, with another vehicle, road user or fixed object. Active safety systems can play key role in addressing these shifts from *Normal Driving,* from warning drivers through to intervening when drivers fail to respond accordingly. A range of active safety measures in the form of Advanced Driver Assistance Systems (ADAS) were identified. It is likely that convergence of multiple active safety systems will provide the most benefit in the future. For example, occupant status or driver state monitoring linked to braking systems and cross-traffic alerting systems offer immense promise in preventing inattentive drivers from entering intersections into the path of other vehicles, pedestrians and cyclists, for instance. The efficacy of such systems will be further enhanced through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technologies.

Application of the modified ISC also highlights the need for advanced post-crash, automated response systems in the form of eCALL / Accident Emergency Call System (AECS). Similarly, there is a key role for the universal fitment of crash data collection systems, including Event Data Records and Data Storage Systems for Automated Driving (DSSAD).

While recognising the prior work of other researchers that have use the ISC, the analysis method presented in this paper represents a powerful approach to analyse in-depth crash data and to understand crash causation, injury occurrence and applicable countermeasures. This work differed from earlier work by using an expanded crash sequence model across the full range of serious injury crash scenarios. Adoption of this method using other datasets is recommended so that the full range of countermeasure needs across jurisdictions and other road user groups can be understood.

Limitations

There are a number of assumptions and limitations that need to be considered when interpreting and applying the findings presented in this paper. First, the study examines passenger vehicle crashes where at least one involved driver was admitted to hospital for at least 24 hours. While drivers included in the study were age 18-93 and approximately half were female, the sample is biased toward MAIS 3+ injury crashes (47%).

Second, crashes were those that occurred in Victoria, Australia, in the 2014 – 2016 period. While vehicle turnover is slow, at approximately 2 – 3% per annum, the entry of newer vehicles due to attrition through vehicle age or crash-involvement may impact the proportion of crashes to which the fitment particular vehicle safety systems would be relevant. The extent to which the impact of COVID-19 will impact this vehicle replenishment rate is currently unknown. This is relevant to understanding the proportion of the crash population that has the potential to be influenced by vehicle safety systems.

Third, it is also noted that while the crash reconstruction process and attribution of contributing factors was conducted in a systematic manner with multiple checks and balances, it is recognised that the interpretation is that of the ECIS Crash Investigation team and ECIS Program Investigators.

For a full exposition of the limitations of the ECIS program and impacts on interpretation, the reader is referred to available reports [26,26,27,28].

CONCLUSIONS

Using a modified crash sequence model, this paper highlights the significant potential of active vehicle safety systems in reducing serious injury road trauma. The findings can be used to promote the uptake and adoption of these systems through government and fleet road safety action plans, as well as being useful in informing consumers on the protective role of these technologies in preventing crashes, mitigating serious injury, and in promoting timely emergency care once a crash occurs. In addition, the findings can be used to promote targeted investment in research and development of new vehicle technologies. From a conceptual perspective, the modified ISC when linked with specific crash scenarios offers a viable systematic method to analyse crashes across the entire crash sequence, from before drivers enter the vehicle through to recovery from the crash.

Finally, it is important to note that other non-vehicle related countermeasures that were identified as being applicable to these crashes. These countermeasures included driver-based measures and infrastructure-based measures. While not included in this paper for reasons of space and the focus on active safety systems, addressing the range of risk factors through implementation of these measures remains critical, as is the need to implement countermeasures at each part of the crash sequence. Doing so is necessary as each countermeasure addresses a specific risk factor that exerts its influence at a particular part of the ISC, and no single countermeasure is 100% effective 100% of the time.

ACKNOWLEDGEMENT

The Enhanced Crash Investigation Study (ECIS) was funded by the Victorian Transport Accident Commission (TAC). The authors acknowledge the contribution of The Alfred Hospital and The Royal Melbourne Hospital, as well as Victoria Police in the conduct of the study.

REFERENCES

[1] Peden M, Scurfield R, Sleet D, Mohan D, Hyder AA, Jarawan E, et al. (Eds.). World Report on road traffic injury prevention. Geneva: World Health Organisation; 2004.

[2] Shinar D. Traffic Safety and Human Behavior: Second Edition. UK: Emerald Publishing Limited; 2017.

[3] World Health Organisation. Global status report on road safety 2018. Geneva: World Health Organization; 2018.

[4] Groeger JA. Chapter 1 - How Many E's in Road Safety? In: Porter BE, editor. Handbook of Traffic Psychology. San Diego: Academic Press; 2011. p. 3-12.

[5] Muir C, Johnston IR, Howard E. Evolution of a holistic systems approach to planning and managing road safety: the Victorian case study, 1970–2015. Injury Prevention. 2018;24(Suppl 1):i19-i24.

[6] Johnston I. Beyond "best practice" road safety thinking and systems management – A case for culture change research. Safety Science. 2010;48(9):1175-81.

[7] Haddon W Jr. The changing approach to the epidemiology, prevention, and amelioration of trauma: the transition to approaches etiologically rather than descriptively based. American Journal of Public Health. 1968;58(8):1431-38.

[8] Haddon W, Jr. On the escape of tigers: an ecologic note. American Journal of Public Health. 1970;60(12):2229-34.

[9] Haddon W Jr. A logical framework for categorizing highway safety phenomena and activity. Journal of Trauma. 1972;12(3):193-207.

[10] Cameron MH. Vehicle crashworthiness ratings, preliminary report. Monash University Accident Research Centre; 1990, cited in Cameron MH. Statistical evaluation of road trauma countermeasures. Clayton: Monash University; 2000.

[11] Corben B., Senserrick T., Cameron M., Rechnitzer G. Development of the Visionary Research Model – application to the car / pedestrian conflict, Report 229. Clayton: Monash University Accident Research Centre; 2004.

[12] Salmon PM, Cornelissen M, Trotter MJ. Systems-based accident analysis methods: A comparison of AcciMap, HFACS, and STAMP. Safety Science. 2012;50(4):1158-70.

[13] Thomas P, Morris A, Talbot R, Fagerlind H. Identifying the causes of road crashes in Europe. Annals of Advances in Automotive Medicine. 2013;57:13-22.

[14] Tingvall C. Distraction from the view of governmental policy making. Subsection of the chapter: Government and Industry Perspectives on Driver Distraction. In: Regan M, Lee J, Young K, editors. Driver distraction: Theory, effects, and mitigation. Melbourne: CRC Press; 2008.

[15] Lie A. Managing traffic safety: an approach to the evaluation of new vehicle systems. Stockholm, Sweden: Karolinska Institute; 2012.

[16] Strandroth J, Sternlund S, Tingvall C, Johansson R, Rizzi M, Kullgren A. A new method to evaluate future impact of vehicle safety technology in Sweden. Stapp Car Crash Journal. 2012;56:497-509.

[17] Rizzi M, Strandroth J, Tingvall C. The effectiveness of antilock brake systems on motorcycles in reducing real-life crashes and injuries. Traffic Injury Prevention. 2009;10(5):479-87.

[18] Sunnevång C. Characteristics of nearside car crashes – an integrated approach to side impact safety. Umeå, Sweden: Umeå University 2016.

[19] Tingvall C. The Zero Vision a road transport system free from serious health losses. In: von Holst H, Nygren Å, Thord R, editors. Transportation, Traffic Safety and Health — The New Mobility: First International Conference. Brussels, Belgium: Springer Berlin Heidelberg; 1995, Published 1997. p. 37-57.

[20] Tingvall C, Lie A. The implications of the Zero Vision on biomechanical research International Research Council on the Biomechanics of Injury (IRCOBI); Dublin; 1996.

[21] Tingvall C. The Swedish 'Vision Zero' and how parliamentary approval was obtained. Road Safety Research, Policing and Education Conference; Wellington, New Zealand; 1998.

[22] Tingvall C, Lie A, Johansson R. Traffic Safety in Planning - A Multidimensional Model for the Zero Vision. In: von Holst H, Nygren Å, Andersson ÅE, editors. Transportation, Traffic Safety and Health — Man and Machine: Second International Conference. Brussels, Belgium: Springer Berlin Heidelberg; 1996, Published 2000. p. 61-9.

[23] Stigson H. A Safe Road Transport System - Factors Influencing Injury Outcome for Car Occupants. Stockholm Sweden: Karolinska Institute; 2009. The SRA Model of a Safe Road Transport System operationalises the Vision Zero Multi-Dimensional Model for Safe Travel.

[24] Kanianthra, J. Re-inventing safety: Do technologies offer opportunities for meeting future safety needs? SAE Technical Paper 2006-21-0009; 2006.

[25] Association for the Advancement of Automotive Medicine (AAAM). Abbreviated Injury Scale (AIS) 2005 – Update 2008. Chicago: AAAM; 2015.

[26] Fitzharris MP, Corben B, Lenné MG, Pok Arundell T, Peiris S, Liu S, Stephens A, Fitzgerald M, Judson R, Bowman DM, Gabler HC, Morris A, Tingvall, C. Overview and analysis of serious injury crashes – crash types, injury outcomes and contributing factors, ECIS Report 1. Monash University Accident Research Centre, Report 346; Clayton; 2022.

[27] Fitzharris MP, Corben B, Lenné MG, Peiris S, Pok Arundell T, Gabler HC, Liu S, Stephens A, Bowman DM, Morris A, Tingvall C. Speed, crash risk and injury severity, ECIS Report 2. Monash University Accident Research Centre, Report 344; Clayton; 2022.

[28] Fitzharris MP, Corben B, Lenné MG, Liu S, Peiris S, Pok Arundell T, Stephens A, Bowman DM, Morris A, Tingvall C. Understanding contributing factors for serious injury crashes using crash chain analysis, ECIS Report 3. Monash University Accident Research Centre, Report 345; Clayton; 2022.

[29] Fitzharris MP, Pok Arundell T, Corben B, Lenné MG, Liu S, Peiris S, Stephens A, Bowman DM, Morris A, Tingvall C. Identification of countermeasures to address serious injury crashes, ECIS Report 4. Monash University Accident Research Centre, Report 346; Clayton; 2022.

APPENDICES

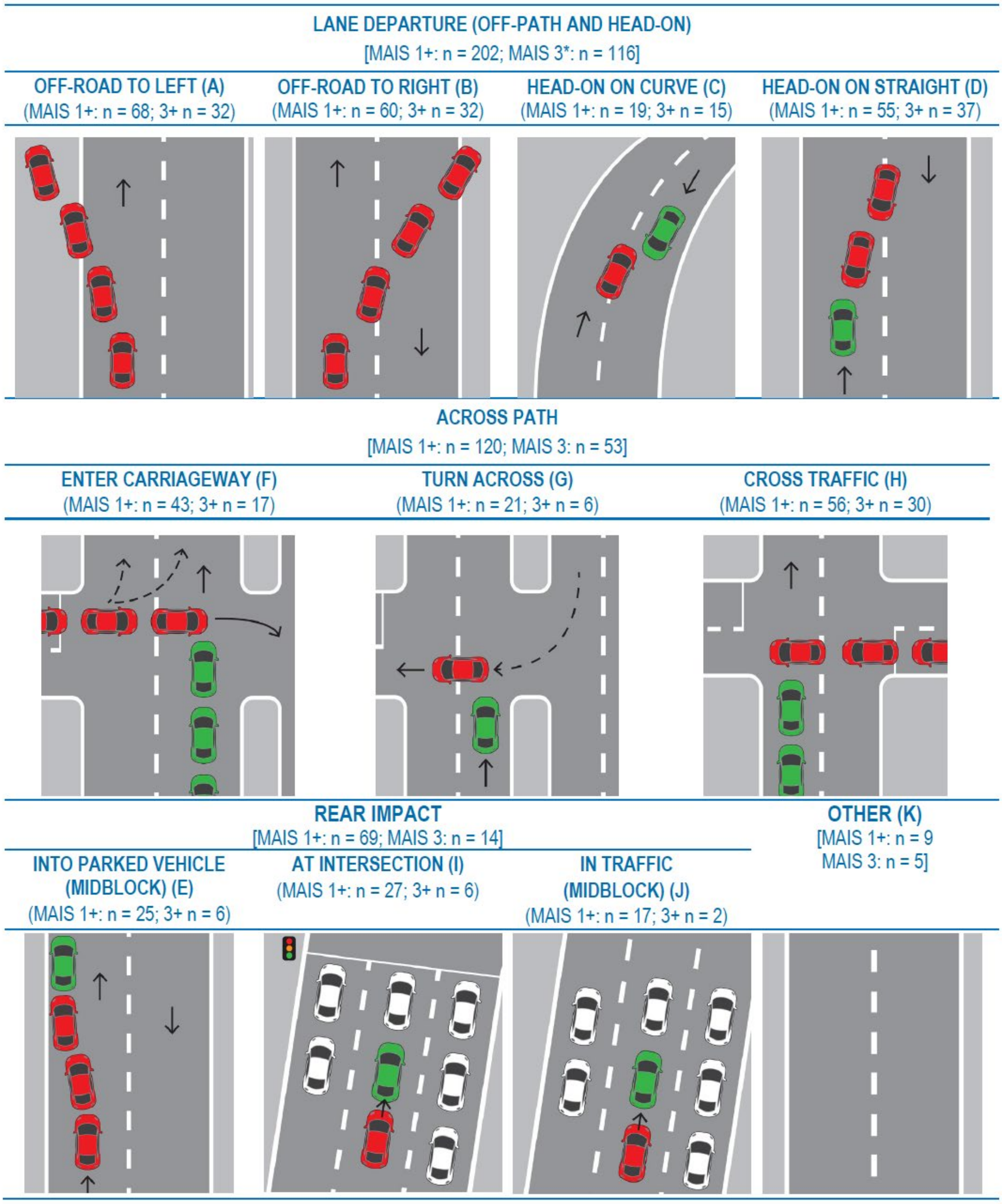


Figure A.1 Defined crash types and number of injured ECIS case drivers

Key: Vehicle (red): signifies the critical pre-crash vehicle movement; Vehicle (green): signifies that vehicle travelling in its normal path (or is stationary, rear impact - parked) and involved in the crash; Vehicle (white): vehicle (stationary or moving) in proximity of rear-impact crash but not involved. The ECIS driver can be the occupant of either of the crash-involved vehicles in each of the crash type scenarios. Note: * 3+ refers to MAIS 3+ injury severity. (letter) denotes crash type identifier.