



The Five “I” Framework of crash investigation: Linking investigation practices to safety reform

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ARTICLE INFO

Keywords:

Crash causation
Prevention
Safe System approach
Post-crash
Crash investigation
Transportation safety

ABSTRACT

Crash investigation is vital to the advancement of road safety, and it is a foundation for determining effective countermeasures and interventions for true road safety reform. However, the way in which road crash investigations are conducted substantially influences the quality of understanding and the effectiveness of responses. In crash investigations, we traditionally focus first on the question: “What caused this crash?” when it would be more efficient to ask immediately: “What could have prevented this crash?” or better yet, “What are *all the ways* this crash could have been prevented?”

In this paper, we first explore a few common road crash investigation approaches where prosecution, retribution, or compensation are primary. We then examine investigation approaches where prevention is primary, especially investigations aimed at determining every point on the timeline preceding the crash where an intervention would have prevented the outcome, as illustrated by the Swiss Cheese Model. We draw from examples from the aviation industry, the occupational health and safety field, the U.S. National Transportation Safety Board (NTSB), and others, to identify strengths and weaknesses. We bring together good practices from several investigative approaches through the lens of diverse experiences in transportation safety and root-cause analysis to present a practical and proactive framework for road crash investigation. The Five “I” Framework provides guiding characteristics for prevention-focused safety investigations for road crashes: Immediate, In-Depth, Impartial, Independent, and Injury Prevention.

The Five “I” Framework is a practical guide for investigations to move beyond crash causation to crash prevention, aligning with the Safe Systems Approach, Vision Zero, and the public health perspective. Rather than focusing primarily on any single factor such as vehicle defect or driver error, it leads investigations to an array of countermeasures that involve collective action and systems change, and thus, to more effective road safety reform. Nevertheless, as a practical framework, it is the start (not the end) of discussions on how we can continue to move towards more multidisciplinary, collaborative, innovative, and ethical prevention efforts.

1. Introduction

Road safety reform commences with the quality of crash investigations. Accurate collection and analysis of crash investigation data is vital for driving the most effective approaches to reduce road user injury and implementing practical prevention policy. An impartial examination of crash and injury causation factors enables a better understanding about how the crash and injuries occur. As with any sound research practice, it is important to objectively collect all relevant evidence from a crash, including both proximal and distal risk factors and environmental concerns. Analysis of well-collected data can then lead to

policy changes for meaningful improvements in road safety.

In many jurisdictions, crash investigations play an important role in determining whether a breach of road laws has been committed whereby errant road users are punished legally and financially. Other jurisdictions focus on a compensatory regime for the victim or victim’s family. If there is a vehicle defect contributing to the crash, penalties may be imposed upon the owner or manufacturer. Moreover, if the road or road environment contributed to unsafe road manoeuvres, the road authority may be obliged to rectify the problem to prevent future road safety risks.

However, too often, crash investigations are concluded when

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<https://doi.org/10.1016/j.aap.2023.107296>

Received 31 May 2023; Received in revised form 12 August 2023; Accepted 7 September 2023

Available online 17 October 2023

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behavior or vehicle breaches of laws or regulations are identified, or compensation determined. This can result in a less-than-adequate analysis of crash and injury factors and no lasting advancements for safety.

This prosecutorial or compensatory focus for crash investigations leaves a critical knowledge gap in the foundational evidence for road safety reform. It is a serious system failure when the lead investigator is not mandated or challenged to report or determine crash prevention strategies. This belatedly becomes the responsibility of analysts, senior management, or researchers to interpret from the initial data sources. As the quality of the initial crash investigation is fundamental to reform, this failure strikes at the very heart of the Safe Systems Approach and the objectives of the Decade of Action for Road Safety 2021–2030 (United Nations General Assembly, 2020).

Road crash investigations internationally are largely shaped by the Haddon epidemiological model, where an examination is made of the injury causation factors present before, during and after the injury event - the crash (Haddon 1970, Haddon 1980). While some have argued that this is a systemic analysis, others have argued that Haddon's model is too static and looks at injury causation factors as discrete variables (Murray, W. et al, 2009, Stuckey, R. et al, 2007, Mooren et al., 2009). Moreover, it does not encourage analysis of broader or deeper systemic conditions. There is increasing support for the idea borrowed from occupational safety that a systems approach to analyzing road injury factors may help to explain the dynamic interaction of the risk factors within a work or driving process and the fact that the conditions built within the system can create risks that sometimes long pre-date the proximal unsafe act that finally resulted in an injury crash, e.g. inadequate brake maintenance, driver payment systems, etc. (Mooren et al 2009; Williamson and Friswell 2013).

Applying this thinking to road transport injury risks, the systemic preconditions can act to either prevent or exacerbate the injury event through the management of safety risk (Mooren et al., 2014). Risk management is most effectively applied when a thorough root cause analysis process informs safety management. That is, beginning with identifying behavioural, vehicle, environment, policy or other breaches or errors, crash investigators should then focus on why the breaches or errors occurred and how they could have been prevented.

The focus of crash investigation processes should be to learn as much as possible about the pre-conditions of the crash event in order to determine what could have changed to prevent or reduce the severity of the crash. It is through this learning that injury crashes can be avoided (Lukic et al., 2010, Njå and Braut, 2011). The key attributes from workplace safety, aviation, and current good practice in road crash investigation can be extracted to provide a more effective approach to determine crash prevention strategies. These attributes are then considered as the basis for all investigative approaches involving injury and death where precursor risks are identified, policy recommendations made, and reform implemented.

2. Methodology

This paper first examines the key approaches adopted within the road crash, occupational safety, and aviation industries to help define a practical way forward to achieve more structured and immediate preventative measures. It then analyses key approaches to road crash investigations globally, with different primary purposes, and identifies strengths and weaknesses of current systems. It draws upon the experiences of crash investigation practitioners, practical research analysis in transport safety, strategic management, and expertise from aviation investigation. The focus on injury prevention as a key outcome and a broader and more balanced systems view of crash investigation addresses the knowledge gap in the evidence base and aligns with the Safe System Approach (Shinar 2019), the Decade of Action for Road Safety (United Nations General Assembly, 2020), and Vision Zero (Tingvall & Haworth 1999).

This paper acknowledges the numerous models, standards and varieties of crash investigation processes existing globally ranging from rudimentary police investigations to sophisticated expert multi-disciplinary teams. Through evolution, resourcing restrictions or technological advancements, jurisdictions have developed their own models for expediency. This review (and the Five I Framework that emerges) is not intended to provide a comprehensive analysis of all approaches, but rather a conceptual observation of road crash investigations in select countries, analysed through the lens of 90 years of experience by the authors in road safety management, policing, research, policymaking, public health, and crash investigation. Road crash investigations have the potential to contribute to a reduction in road trauma by helping initiate safety reform, but it is difficult to accurately quantify their contribution. Representative examples were analysed with the goal of developing a practical framework for injury prevention-focused road crash investigations and contribute to discussions on how to effect true road safety reform.

3. Examination of three types of investigations

Safety investigations are crucial in preventing future incidents in many fields. Road crash investigations, workplace or occupational safety investigations, and aviation accident investigations are some of the key types of investigations and provide different perspectives on how investigations are conducted.

3.1. Road crash investigations

In most jurisdictions worldwide, operational police with a 24/7 response capability are, by default, the principal initial investigators for fatal and serious injury road crashes. Investigative skills vary widely. For example, the International Road Policing Assessment Program (IRPAP) classifies skills from Level One, basic cause and offender identification, to Level Five, a holistic process using 3D laser scans, event data recorder analysis, mobile phone analysis and full forensic investigation where every fatal crash investigation involves the same level of rigor, competence, and community accountability as for a homicide (Shuey 2013). These classifications were determined following an analysis of techniques adopted in ten high income countries in comparison with ten low and middle-income countries. Notwithstanding the level of sophistication, the investigations are biased towards offender detection and prosecution for criminal liability.

In Australia, for example, a coronial inquest follows all fatal collisions with an autopsy identifying any blood alcohol content or drug presence. All hospital admissions, 16 years and over, are required to have a blood sample for alcohol presence. All drivers involved in a crash are required to undergo a breath test for alcohol and, if relevant, a drug impairment test. Ideally, fatal crashes should be investigated by detectives from specialist units as qualified experts on 24/7 callout together with reconstruction experts with engineering qualifications undertaking forensic analysis. It is of note that collision investigators should have a collegiate association for sharing knowledge and experiences.¹

Mandated data requirements ensure officers assess numerous categories, classifications, data elements with up to 200 data entries (Shuey 2021). Investigating officers provide an opinion as to the crash cause and a narrative accompanies a recommendation. Safe System Approach considerations are an integral component inviting commentary on 'Safer Road Users', 'Safer Vehicles', 'Safer Speeds' and 'Safer Roads' (Victoria Police 2021).

Similar processes exist in the United Kingdom where *Standard Operating Procedures* are followed during any crash investigation

¹ Australian and South Pacific Association of Collision Investigators. <https://www.aspaci.org.au/membership/flier.pdf>.

including scene preservation, measurements, photography, isolation and interview of witnesses, interview of surviving offender(s) and follow-up inquest proceedings and court prosecutions. Experts are equipped with hi-tech investigation tools including 3D Laser Scanners, Event Data Recorder access as well as collision and trajectory reconstruction software. Contributory factor databases are being progressively implemented throughout Australia and the United Kingdom (Rolison 2020, Shuey and Myers, 2021).

Crash investigations are more likely to be biased or incomplete if their ultimate goal is not prevention, whether they are conducted by road authorities, police, insurance investigators, or others. For example, a 2016 fatal crash in a rural shire in Australia was attributed to speeding by the local road authority conducting the investigation, but other road factors such as tight curves, slippery conditions (reported by police), and lack of guardrails were not considered. In fact, the driver was travelling at 60 km/h on a road with a speed limit of 80 km/h (Mooren, 2017).

A more holistic approach can now be applied to heavy transport vehicle crashes, where the investigations delve into the contributing factors in the logistics supply chain. “Chain of Responsibility” culpability introduced in Australia from 2001 has enabled prosecution of trucking companies, consignors, customers, loaders, receivers, and equipment suppliers following a root cause investigation and analysis. While educational and customer awareness programs have been widely promoted, the prevention focus must have a higher profile. This conceptual approach must be applied to all injury crashes.

An example of how important it is to understand the chain of systemic safety risks is illustrated in Fig. 1 depicting trucking industry pressures that link risk and crash outcomes. This is supported by the findings of a review of the literature identifying gaps in safety and quality management accreditation, financial performance and worker characteristics (Mooren et al 2014).

In the case of truck transport safety, it is both an employer and government responsibility for providing a safe working environment for truck drivers. Fig. 1 reinforces the broader systemic risk factors for truck drivers. For effective prevention strategies, this conceptual in-depth investigative approach is necessary for all categories of crashes.

From the crash investigations, database analyses are undertaken to identify causation and contributory factors culminating in jurisdictional and national strategic plans. The Australian National Road Safety Strategy 2021–30 sets the direction for the next decade in Australia to reduce fatalities by 50% and serious injuries by 30% (NRSS, 2021). While a revitalized strategy, with an emphasis on a ‘social model’ and ‘priorities’, the achievements are yet to be realized, there being a 2.9% increase in fatalities in the first year of the strategy (BITRE, 2022), and a failure to achieve the targets of the previous Decade of Action for Road Safety 2011–2020 (World Health Organization 2011).

3.2. Workplace safety investigations

Workplace or occupational safety investigations are conducted to determine the cause of injury incidents that occur in a workplace setting. These investigations aim to identify the root cause of the incident, whether it is due to human error, equipment failure, organizational, or other factors. One of the most influential theorists in the field is James Reason. Starting from his early work on understanding human error (Reason 1990), Reason later argued and provided evidence that human error is not a cause, but rather a consequence of organizational shortcomings (Reason, 1997). As shown in Fig. 1, in some injury arenas, such as truck transportation, the chain of contributing injury factors can be long and complex and can stretch to industry conditions even beyond the organization.

By considering injury causation as management system failures, it is possible to devise organizational controls and defenses against active failures becoming injury events. As Reason (2000) states, “*We cannot change the human condition, but we can change the conditions under which humans work* (p.786).” However, safety researchers (Hollnagel, 2002; Hopkins 2000) have questioned a number of the common concepts that underpin safety management such as the idea that hazard barriers can be erected and embedded in a work system to block accidents from happening. Using the U.S. space shuttle programs as examples, Leveson et al. (2007) illustrated how building safety controls for making a complex and dynamic process resilient to accident risks requires an understanding that the systems involved in carrying out the work are fluid and feature continual interactions among people, social and organizational structures, engineering activities and physical components.

Hollnagel (2002) examined various methods of workplace accident investigation and analysis as to how safety professionals would choose a method, or methods, suitable for their particular work processes. He identified three types or models of accident analysis. However, he concluded that the *systemic models offered the best outcomes*. These models focus on variations of processes and conditions (compared with normal operations) associated with accidents that continually need to be monitored, controlled, or eliminated. This model assumes that humans behave in variable ways and that an understanding of how and why they behave can guide the development and maintenance of systemic safety measures. In other words, the system should be designed to suit the way humans interact with it. These models also call for continual examination of the interaction between human users and system performance.

3.3. Aviation accident investigation

Aviation accident investigation has long recognized the importance

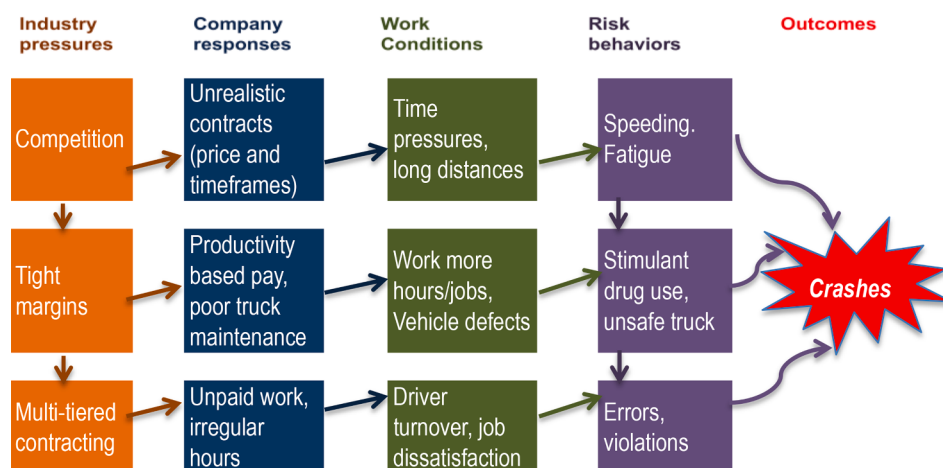


Fig. 1. Chain of factors leading to truck crashes (from Mooren, 2016).

of finding the risks that can be corrected in system design and operation, rather than focusing on who made a mistake, in order to prevent future accidents. The investigation may involve examining the wreckage of the aircraft including the cockpit data recorder, interviewing witnesses, and analyzing weather, scheduling, and other sources of information. The aviation industry often cites Reason's Swiss Cheese Model, which explains how accidents occur due to multiple layers of errors or failures (illustrated by the holes in the cheese slices lining up) and how to prevent them (Reason 1990).

In 1993, examining multiple aviation investigations citing root causes that could be traced to faulty system design and operation, the International Civil Aviation Organization (ICAO) Circular stated explicitly that "by determining why the accident occurred, it indicates what is wrong in the system and should be corrected rather than who made a mistake and should be punished. Blame and punishment have, in themselves, limited value as prevention tools" (ICAO, 1993). Rather than simply reporting the cause of a fatal accident as "pilot error," investigations ask what caused the pilot to make certain decisions and what system safeguards should have changed the wrong decision. *It is understood that pilot errors are not made in isolation but rather, in the context of an air transportation system.* This philosophical prevention-focused approach may be applied to road crash investigations, although it should be noted that aviation investigations are conducted under a very different regulatory and enforcement framework.

In the aviation industry, incident reporting and investigation "is performed to obtain information on actual or potential safety deficiencies, correct and learn from deficiencies in a timely fashion." (Airports Council International, 2016) This manual is guided by the occupational safety publications of Reason and calls for a forensic root cause analysis. Unlike many road crash investigation processes, its aim is prevention rather than culpability.

Root cause analysis is described by the practice of asking "why" five times when a contributing factor is identified. It advises, "Keep asking the question "Why?" to peel the layers of symptoms away until you reach the deepest level of root cause(s) which is still within the range of your organization's influence and is fundamental enough to prevent reoccurrence." (ACI, 2014, page 25). This focus on 'why' can be directly applied to road crash investigations.

3.4. Purposes of road crash investigations

Road crash investigations are carried out in different countries for different primary purposes. In some countries, investigations are conducted to determine legal responsibility for the crash, while in others, the primary purpose is to prevent future crashes. The approach taken can have a significant impact on the effectiveness of the crash investigation leading to road safety reform.

3.5. Primacy of prosecution and retribution

While compensation is a major factor in civil litigation investigations, many jurisdictions focus police investigations on a form of restorative justice, or retribution where an offender is judged on their deliberate, dangerous, or inconsiderate actions, which result in harm to others. In this case, the police may become both the investigator and the arbitrator, however, at scene or shortly thereafter, adjudication disadvantages both the vulnerable and the poor (Aeron-Thomas 2003). Importantly, system failures and contributory factors are rarely even considered.

Many Islamic Nations enshrine a legal structure of Qisas (retribution) and Diyat (compensation or blood money), whereby offences are determined against individuals rather than the State. This process requires the investigator to identify a percentage breakdown of blame to assist the judicial and/or out-of-court negotiations to be settled in benefit of the victims or legal heirs (Gottesman, 1991, Hakeem, 2003). The Diyat, as a minimum, may be applied strictly in some countries

(Pakistan) and may vary depending on the religious background of offenders/victims (Iran) or the wishes of the victim (Saudi Arabia). While criminal negligence and judicial sanctions may be imposed separately or in parallel, the foundational structure and processes are not attuned to prevention and road safety reform. The pervasive nature of culture and beliefs affects road user behaviors as well as having the potential to influence the performance of institutional governance, policing and road crash investigation (Kayani 2022, Kayani, King and Fleiter 2016).

While both the retributive punishment and the amount of Diyat are legislated, the choice between the two remains with the victim and additionally, offenders may be subjected to discretionary punishments (Ali, Saleem and Habib, 2015). The processes are further complicated by the acceptance of 'fatalism' as a causation factor in crashes in countries such as Pakistan (Kayani et al 2012).

In the jurisdictions mentioned above, all crash investigations are driven by the need to find liability for the road crashes and associated injuries. In Saudi Arabia, the primary focus, embedded in law, is determining and apportioning blame in order that the damage is paid by those at fault.

In Australia and the United Kingdom, the primary focus of road crash investigations by law enforcement is to prosecute those who played a part in contributing to the crash or injuries. The police lead crash investigations on behalf of State coroners. The focus is on determining breaches of traffic laws by road users. While there is some consideration of contributing factors that should be addressed by road authorities and others, the primary purpose of those investigation is prosecution of individuals.

There is now a strengthening movement towards the primacy of prevention even in countries, such as Iran and the UK, that historically focused on retribution or prosecution.

Iran is currently formalising an in-depth crash investigation process, whereby the National Road Safety Commission (NRSC) undertakes special criteria investigations, (three fatalities, one fatality plus four injuries, eight injuries, or crashes involving public transport, hazardous materials or those with social consequences). While investigating police are responsible for gathering primary information at the scene, a multi-disciplinary team will undertake the investigation and the findings will be discussed at a Safety Taskforce meeting involving all sixteen safety organisations with recommendations as to make sure that such a crash would not happen again. A pilot project in three provinces will focus directly on crash prevention strategies with an Expert Review Team led by the NRSC to fully analyse causation factors and ensure appropriate interventions are actioned (Ranjbar et al 2022). This independent oversight by an Expert Review Team provides a more holistic and collaborative approach to ensure collective ownership and reform occurs.

In June 2022, the British Government initiative established the UK's first multi modal independent Road Safety Investigation Bureau (RSIB), to analyze certain road crashes and provide independent recommendations for road safety policy (UK Department for Transport, 2022), with a focus on new technologies (Ito and Kester, 2022). This followed a review of International Crash Investigation Approaches (Jeavons & Runacres 2020).

3.6. Primacy of prevention

Throughout the aviation and occupational safety industries, the primary purpose for investigations is to determine a way to prevent the incident from recurring. The aim is to fully understand the circumstances preceding the incidents so that a positive approach can be taken to prevent the development of those circumstances.

A focus on prevention is often a requirement among independent multimodal (air, rail, maritime, road) government transportation investigation agencies, including all the members of the International Transportation Safety Association (ITSA). Some, but not all, ITSA members also conduct road crash investigations. One such member, is

the U.S. federal agency, the National Transportation Safety Board (NTSB).²

The NTSB is charged by the U.S. Congress with investigating every civil aviation accident in the United States, as well as certain accidents³ in other modes of transportation, with the purpose of making recommendations to prevent future crashes, deaths, and injuries. In addition to investigating disasters in the fields of aviation, highway, marine, railroad, pipeline and hazardous materials, the NTSB has the additional charge of coordinating assistance to the families of victims.

The NTSB's process involves a series of steps which include: identification of a crash, launch decision, deployment of the investigative team (called a Go Team), on-scene multidisciplinary investigation, continued collection of factual information through research or an investigative hearing, communication with families and the public, and in-depth analysis of the factual information to identify safety improvements. Investigative teams may also designate outside parties to provide technical information. The final report for major incidents is generally completed in about one year. It contains safety improvement recommendations and is presented by staff in a public meeting to NTSB Board Members for discussion and vote. The independent NTSB Board Members approve and sign (or dissent from) the final report containing safety recommendations that are issued to entities ranging from private companies, diverse types of organizations, and federal, state, and local governments.

It must be noted that a clear goal of road safety programs is preventing injuries. One argument for conducting safety investigations, rather than investigations solely for prosecution, is to understand crash survivability. The NTSB focuses on a range of survival factors when conducting their investigations. Survival factors investigators document the wreckage with an eye toward survivable space. This information is cross referenced with injury information to provide a view of what may have caused the injuries that occurred during the crash. Many of the safety improvements in vehicles today such as air bags, seatbelts, and child passenger seats are the result of thorough survival investigations. These improvements have proven to prevent or reduce injuries and have prevented fatalities. In some instances, while significant damage occurred to the vehicles, individuals have been uninjured. Survivability is critical, as demonstrated in rollover crashworthiness testing, where governments must mandate occupant protection mechanisms against roof crush for causal injuries to seat-belted occupants (Grzebieta et al 2008).

Weaknesses in the NTSB approach include the delay from crash to recommendation to reform,⁴ the small number of road crashes investigated (due to both budget constraints and the focus on aviation when the agency was established), and a strong bias towards fatal, multi-vehicle, and larger vehicle (buses, trucks) crashes. Strengths include: the

independence of the agency, Board Members, and investigation; the immediacy, transparency and thoroughness of the investigation examining pre-crash, crash, and post-crash response; the strong safety and prevention-oriented focus; and the ability of the agency to advocate for safety improvements. Despite its lack of regulatory power, the agency is able to accomplish the adoption of recommendations through effective communication with victims, public officials, and the public. These strengths of independence and transparency would be beneficial to all road crash investigations globally.

In Australia, the Centre for Automotive Safety Research (CASR), is an example of a non-government road safety research organization conducting selective investigations. Located at the University of Adelaide, South Australia, CASR conducts in-depth, at-the-scene crash investigations, using multidisciplinary "call-out" teams for select criteria road crashes (Baldock et al 2009). While acknowledging the role of human error in crashes, CASR investigators and researchers generally propose infrastructure treatments and vehicle technologies as their recommendations for eliminating or mitigating crashes (Doecke et al 2020).

Other research bodies in Australia include Monash University Accident Research Centre (MUARC), Centre for Accident Research & Road Safety Queensland (CARRSQ), the Australian Transport Safety Bureau, the Australian Road Research Board and other semi-private organizations. While they contribute to crash investigation analysis and research, as with CASR, they do not have the charter, resources, or capability to undertake real-time investigations for all fatal crashes.

Similarly, many other multi-disciplinary organizations exist globally, although most are not independent agencies. Some examples not previously mentioned include Denmark's Road Accident Analysis Group, South Africa's Road Traffic Management Corporation Crash Investigation Unit, China's Traffic Management Research Institute in Wuxi, the Malaysian Institute of Road Safety Research, the Swedish Accident Investigation Authority, and the French Land Transport Accident Investigation Bureau.

An exemplar model of primacy of prevention in crash investigation for a national infrastructure is Finland where approximately 20 multi-disciplinary teams comprising 300 members are coordinated through the Finnish Crash Data Institute (OTI, 2023). Expert teams comprise representatives from police, engineering, medicine and public health, vehicle technology, road maintenance, behavioral sciences, and other special branches as required. The teams attend all 350–400 fatal road and off-road traffic crashes annually, providing non-identified data for scientific and statistical research as well as road safety interventions. They do not assess fault, guilt, prosecution, retribution or compensation, thus ensuring that prevention is the key focus.

The general goal of the Finnish strategy is to prevent crashes from happening again and reduce serious consequences by learning from crashes (Salo et al, 2006). This philosophical approach directly aligns with other research promoting both in-depth analysis and immediacy, being key factors identified in the Five I Framework. This approach is admirable for a nation with a population of 5.5 million, a road network of 78,000 km, and a fatality rate of 4 per 100,000 population (International Transport Forum, 2021). Replication of a cohort of similar experts for countries with larger populations, land masses and/or higher proportions of crashes is a serious challenge and difficult to sustain as a resourcing commitment. Because prosecution and retribution are not addressed, additional and separate resources would be required if these other factors are to be pursued. This concept of the primacy of prevention is a foundational philosophy in our approach.

Strengths of most of these approaches include the immediacy and thoroughness of the investigation examining pre-crash, crash, and post-crash response; and the strong safety and prevention-oriented focus. They usually comprise a multi-disciplinary and forensic specialist team with access to modern hi-tech investigative and reconstruction equipment. However, a critical weakness is that most assess a small proportion of crashes meeting set criteria (Larson 2004) and some do not have

² The National Highway Traffic Safety Administration (NHTSA) is another a U.S. federal agency that conducts road crash investigations but, as part of the U. S. Department of Transportation, it is not considered independent and therefore is not a member of ITSA. NHTSA's Model Minimum Uniform Crash Criteria (MMUCC) Guideline provides State and Local agencies with a standard set of motor vehicle traffic crash data variables they should consider collecting, an important contribution to crash investigation. MMUCC is currently in its fifth revision since it was developed in 1998 and anticipates publication of the MMUCC Guideline 6th Edition in 2024 (NHTSA 2023).

³ Although the term "accidents" is now rarely used for road crashes at the NTSB, it should be noted that in the original statute US Code 49 U.S.C. § 1133, NTSB is given the authority to investigate "a highway accident, including railroad grade crossing accident".

⁴ Although most NTSB investigations take approximately one year to complete, there is the opportunity (and duty) to make "urgent recommendations" more quickly if investigators identify a safety issue they believe to be so critical to the safety of the traveling public that a recommendation cannot wait. As with other recommendations, these are put forward to the 5-member Board for consideration.

complete independence from other organizations. Additionally, while recommendations for reform may follow investigations, the linkages to the broader national databases are not always clear and therefore the impact on overall trauma reduction is difficult to quantify. However, substantial benefits may ensue if the same philosophical approach (i.e. injury prevention focus) to investigations could be applied to the broader span of crashes within the jurisdictions in which they operate.

4. Discussion

In most jurisdictions, traffic police are first on scene to investigate fatal and serious injury road crashes and determine the main factors present before, during and after the crash. Sometimes the analysis is carried out in more detail, including a crash reconstruction process and often undertaken with the deployment of a multi-disciplinary expert team. The results of this process become the basis for reformative actions and crash prevention measures. It is therefore critical that this overall process is practical and has the highest integrity for effective road safety reform.

Much can be learned about risk management and injury prevention by adopting a holistic approach to crash investigation in considering the key attributes and policy directions from workplace safety and the aviation industry. The lack of systemic analysis of injury factors is more prevalent in the road transport incident investigations than in occupational injury events (Rollenhagen 2010), and the primary focus of aviation crash investigations involves a systematic analysis to prevent future tragedies.

A differential recognized in workplace safety is a high proportion of large organizational workplace and management controls which can be affected across a broad range of workplaces/industries in contrast with road safety law applicable to millions of individual road users and subject to training, self-discipline and law enforcement. For example, neither the Aviation Industry nor Workplace Safety tolerate alcohol/drug impairment or unsafe speeds and have put in place safeguards to reduce these activities, which collectively account for more than 50% of road trauma worldwide (Høye, 2020, Elvik 2013). This highlights the critical need for prevention and system-focused strategies in road safety and further highlights the need for 'systems-based reform' in the behavioral management of road users.

4.1. The 5 "I" Framework of crash investigation

Shuey and Myers (2021) outlined the 3A Approach (Acquire, Analyse, and Action) to crash investigation reform from the road policing practitioner perspective, with a fresh focus on the role and voice of the investigator. The critical issue raised was for every investigation, individually and collectively, to determine "How can the risk of a crash of this nature be prevented in the future?" reinforced by an Expert Review Team. The 3A Approach provides the structure for the process of crash investigations and this paper complements that approach with a conceptual framework for organizations conducting such investigations for the purpose of safety reform. The Five "I" Framework emerged organically from our analysis and review of crash investigation practices, coupled with our experience in diverse areas of road safety. The Five "I" Framework provides key guiding characteristics of safety investigation for road crashes with the mnemonic: In-Depth, Impartial, Immediate, Independent, and Injury prevention.

4.1.1. In-depth

The importance of road crash investigations being in-depth is well-known and acknowledged (Baldock et al, 2009; Salo et al, 2006; Poland and Bruce, 2017). Investigators create a complete and detailed timeline for before, during, and after the crash (including emergency response). Risk factors and similarities to previous crashes are identified and analyzed. An in-depth, multidisciplinary investigation provides the most accurate and complete safety data, leading to the most

comprehensive safety recommendations for the purpose of preventing and mitigating road crash injuries. This increases equity by ensuring policymaking is based on complete, unbiased information.

4.1.2. Impartial

The characteristic of impartiality is required to conduct a safety investigation effectively and accurately. Impartiality applies to the people involved in an investigation and means that investigators do not have a biased approach to crash investigations and consider all possible contributing factors to road crashes and injuries. Further, impartiality avoids pre-emptive findings such as speed or brake failure prior to an assessment of all contributory factors. Investigators must be impartial gatherers and analysers of information, without any affiliation or financial ties with manufacturers, insurance, or other involved parties. Nevertheless, these involved parties can, and should, provide technical information to the investigators as a validation of facts surrounding the event. The technical information provided by outside sources is examined neutrally and scientifically. In addition, an impartial group of experts should provide oversight and endorsement of the resulting safety recommendations even if it is impractical for the entire investigative process to be conducted by an independent entity. Investigators and experts providing oversight must recuse themselves from an investigation if they have financial, personal, or other ties, to avoid biased assessments.

4.1.3. Immediate

The importance of immediate (as soon as reasonably possible) road safety investigations has also been established (Baldock et al, 2009; Salo et al, 2006; Poland and Bruce, 2017). The prompt, at-the-scene attendance of crash investigators allows for effective collection of perishable data, better recall by witnesses, and better opportunity to build rapport with other public safety responders to the disaster. Timely investigations means both prompt data collection and prompt data analysis. Investigators secure and analyse the scene, interview witnesses, collect data (especially perishable data), consult and inform parties (such as victims, survivors or family members). Immediate use of data and prompt, accurate issuance of safety recommendations leading to *immediacy of reform* are also critical to this conceptual approach and aligns directly with prevention strategies for future crashes of a similar nature.

4.1.4. Independent

Independently conducted investigations and independent oversight are both required to effectively conduct a safety investigation. Independence applies to organizations and means that the investigative agency is not obliged to reflect the views of any outside person or entity in identifying causes, contributing factors, or safety recommendations. Independence lends credibility to the outcomes and prevention-based strategies. Safety recommendations are viewed as more trustworthy if they originate from an independent body or are endorsed by an independent source. An independent group of experts should provide oversight and endorsement of the resulting safety recommendations even if it is impractical for the entire investigative process to be organizationally or financially independent of governments or sponsors. In some rare cases, such as the U.S. NTSB, the agency conducting the investigation is entirely independent, both organisationally and financially, from all other government and non-government entities.

4.1.5. Injury prevention

Injury prevention as a primary purpose is the characteristic that clearly sets a prevention-focused safety investigation apart from other crash investigations. The intent of every safety investigation should focus on risk management; that is, to determine how to prevent future similar crashes from occurring and to prevent or mitigate injury crashes. Notwithstanding the fact that police have an initiating role for prosecution or retribution, prevention must have the highest priority in all investigations, particularly those initiated by police in their sworn duty

to protect life and property. Prevention must be of paramount importance over prosecution, retribution, or liability in order for the crash investigation to result in practical safety recommendations leading to safety reform.

By clearly establishing why the collision occurred, reforms can be implemented to prevent a similar tragedy from happening again. Survivors, families, the public, local officials, the media, and others involved in the crash should be informed and aware that safety is a



Fig. 2. The Five I Framework.

major goal of the investigation. This clear communication of the safety intent will lead to a more effective investigation, better cooperation from all involved, and potentially faster implementation of safety recommendations due to a more positive public perception. Injury prevention as an investigative outcome clearly aligns with the objectives of the safe system policy framework.

Each of the five guiding principles are outlined in the Five “I” Framework infographic (Fig. 2). Informing parties involved (such as families, officials, and the community) can be considered a sixth “I” which, although external to the technical investigation process, is an ethical imperative (and a legal requirement, in some jurisdictions). This type of communication may also assist investigators in obtaining more accurate and complete information through building collaborative relationships with the parties involved.

4.2. Implementing the Five “I” Framework

The Five “I” Framework emerged from this research as a practical solution to begin to address the knowledge gap and fundamental system deficiency in the evidence base. By globally accepting the tenets of a robust investigation methodology targeting prevention, a more holistic and systematic reform approach can be achieved.

In crash investigations, we traditionally focus first on the question: “What caused this crash?” The Five “I” Framework directs the investigator to ask “What could have prevented this crash?” or better yet, “What are *all the ways* this crash could have been prevented?” But how is this accomplished? In seeking answers to these questions, there must be data collection for the many factors that may have influenced the crash and subsequent injuries. Knowledge of crash causes is important because it directs us to consider potential actions to prevent the crash and its related injuries (Hauer 2020).

The critical element required is the *independent oversight* or review from a multi-disciplinary perspective. This process is designed to strengthen and validate the investigation integrity. The immediate impediment is the vast number of fatal and serious injury crashes daily in every country combined with the scarce skill base of multi-disciplinary experts. A step-process to achieve this criterion is recommended tailored for individual jurisdictions to focus on prevention-based reform. This process can be initially graded from desktop reviews to multi-disciplinary real-time investigations. The first step is to mandate the initial investigator or review team to assess data from the investigation and make conclusions and recommendations about the incident on the basis of “How can the risk of this type of crash be prevented in the future?”.

Supplementary training, as provided in most police organizations, could ensure that a prevention-oriented framework is incorporated in all police crash investigations. The investigations also might be conducted by trained non-officers, which would have the added benefit of freeing up more of the law enforcement personnel.

There will be challenges in how to define systemic risks and “system management solutions” to address these risks. It has been suggested that the original idea behind the Swedish Vision Zero policy was that the road traffic system should be conceived as a “workplace” where road authorities/governments must manage the system to keep it free of injury risks. Indeed, the Safe System Approach calls for design and management of this system to make roads and roadsides more intrinsically safe for human use, as well as, to actively manage the way in which humans use the system to prevent serious harm to road users. Any “systems” approach for crash investigation must also be enshrined with an analysis of human behaviors where relevant, especially when behaviors such as speeding are triggered by or contingent upon characteristics of the road or environment.

The Five “I” Framework outlining in-depth, impartial, immediate investigations, with multi-disciplinary independent oversight and a primary focus on injury prevention, will lead to system-focused prevention strategies designed directly to reduce road trauma. Professional

review processes will ensure continuous improvement. The framework is intended to provide the foundation for investigations that may be adapted for different jurisdictional circumstances and cultures, but share a common philosophy that will lead to quicker and more effective safety reforms.

5. Conclusions

The Five “I” Framework can help move crash investigation beyond crash and injury causation to crash and injury prevention. It is timely, aligning with the Safe Systems Approach, Vision Zero, the public health perspective, and the Global Plan for the Decade of Action for Road Safety 2021–2030. Rather than focusing on any single factor such as individual behavior or vehicle defects, it directs investigations to an array of contributing factors and countermeasures that involve collective action and systems change, and thus, to more effective road safety reform. Nevertheless, as a practical framework, it should be considered the start (and not the end) of discussions on how we can continue to move towards more multidisciplinary, collaborative, innovative, and ethical prevention efforts. All jurisdictions are urged to adopt this crash investigation framework as a foundation for road safety reform.

With the renewed interest in the Safe System Approach worldwide, multidisciplinary prevention-oriented road crash investigation is a practical tool that jurisdictions can use to determine, communicate, and implement a wide range of safety measures for pre-crash prevention, injury mitigation during a crash, and post-crash emergency care. Using the Five “I” Framework, jurisdictions have a guide to creating an effective crash investigation process, focused on prevention, with the ultimate goal of saving lives.

Funding

This research did not receive any specific funding from agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr. Tho Bella Dinh-Zarr was employed by the FIA Foundation and the Traffic Injury Research Foundation (TIRF) as a senior advisor during the writing of this manuscript.

Data availability

No data was used for the research described in the article.

Acknowledgments

The authors thank the individuals who discussed their road crash investigation strategies, and we regret not being able to include a description of every organization. The authors also thank our reviewers who improved the manuscript with their insightful comments. The authors thank Jennifer Hall of the Traffic Injury Research Foundation (TIRF) for her assistance with the Five “I” Framework infographic.

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