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Research article

Developing improved crash prevention approaches through in-depth investigation of motorcycle crash causation patterns

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A R T I C L E I N F O

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A B S T R A C T

Despite advancements in road safety, Powered Two-Wheelers (PTWs) remain a vulnerable group with disproportionately high crash rates. This paper presents an in-depth analysis of PTW crashes in six European countries, with a case study of Loss of Control in Curves (LoCC), to address the gap between crash causation and prevention. By examining crash causation factors and their linkage to prevention strategies, the study illustrates various approaches for connecting causes and countermeasures. These approaches, which are applicable to different crash scenarios, include looking forward in the crash causation chains, looking backward, looking at only the last cause (critical events), or the first cause, or following a systemic approach. The research introduces a set of guidelines following the safe system approach, aiming to enhance the understanding of crash prevention among policymakers. The systemic approach to countermeasures, bridges the shortcomings of traditional crash causation studies that may exhibit bias or a narrow focus on "root causes". The proposed approach emphasizes the need for a comprehensive view of crash scenarios (i.e., considering the entire crash causation chain or multiple causation chains) and ensuring that preventive measures address the full spectrum of the system. It also takes in to account external factors such as cost, benefits, and politics, leading to improved road safety outcomes. The study findings are significant for researchers, since it is a step forward in in-depth crash causation studies, as well as road practitioners and policymakers, in providing a strategic framework for more effective and efficient road safety interventions.

1. Introduction

The crash fatality rates worldwide are disproportionate and uneven across different road users, with vulnerable road user groups such as pedestrians, powered two-wheelers (PTW), and cyclists facing higher risks. According to recent statistics, PTWs account for 21 % of global road fatalities with figures reaching as high as 48 % in some regions [1]. While some regions like Europe have experienced a substantial decrease in the trends for car crashes over the years, the reduction in PTW crashes has only been marginal [2]. The majority of PTW crashes have been attributed to human errors or "looked but failed to see crashes" for both PTW riders and other road

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users' perspective [3–5].

Meanwhile, the population of PTWs (moped, scooter and motorcycle) is experiencing significant growth owing to their low purchase and running cost, light weight nature, and factors such as their flexibility and maneuverability during congested traffic. This population is also increasing, with new vehicle types emerging such as e-scooters and enhanced e-bikes which are closer to PTWs than bicycles, all of which are not well regulated currently. However, the trade-off to their weights and flexibility is the increase in crash exposure, injury severity, and other associated risk factors [6–8].

When navigating curves, Powered Two-Wheelers (PTWs) are challenging to maneuver, particularly at high speeds, which substantially increases the likelihood of losing control, leading to loss of control crashes. Michel et al. (2005), as referenced in Ref. [9], define motorcycle loss of control crashes as incidents where the crash results exclusively from the motorcyclist losing control of the vehicle, without the contributory involvement of other road users in the loss of control. This specific type of crash, when occurring in curves, is identified as Loss of Control in Curves (LoCC) [2]. Although studies specifically focusing on loss of control in curves (LoCC) are limited, existing research has emphasized the substantial risk associated with this scenario [9–12]. These findings underscore the urgent need for in-depth investigations into this particular crash scenario. Furthermore, different authors [9,13] have noted that while LoCC incidents may not always occur with high frequency, they tend to be disproportionately represented in serious or fatal crash statistics. In some case studies, the frequency of loss of control crashes is substantial [2,14] highlighting the critical need to prevent LoCC. This study is dedicated to exploring this particular crash scenario, addressing the substantial gaps in knowledge, especially in the context of prevention measures.

In-depth investigations of crash causation factors for PTW crashes are crucial for developing effective countermeasures to protect this user group. While numerous studies have been conducted to identify the causes, there has been limited discussion on the connection between causes and countermeasures. Establishing these linkages is challenging and requires clear definitions and thorough examination.

Therefore, the primary objective of this study is to employ theories and concepts related to crash causes and countermeasures and use a case study approach focusing on a specific scenario, in this case 'loss of control on a curve' (LoCC) for PTWs, to illustrate various approaches for linking causes and countermeasures. This examination will shed light on the potential variations in outcomes resulting from different approaches and determine the most effective strategies for preventing PTW LoCC crashes. The analysis focuses on the PTW perspective only. Additionally, the study introduces guidelines for attributing countermeasures to crash chains following the safe system approach. These guidelines and the various approaches discussed aim to contribute to the existing knowledge and enhance the understanding of crash prevention strategies among policy makers by providing empirical evidence derived from the chains of crash causation factors.

The various approaches proposed in this study serve for the practical application of countermeasures, as there is a current gap in the literature regarding the concepts of crash prevention and its linkage to countermeasures for practical purposes. Embracing the proposed framework within this research allows independent practitioners to apply the same methodology, regardless of the crash scenario or type, in correlating crash patterns or chains with countermeasures. The use of the LoCC as a case study within this research is specifically intended to elucidate the proposed methodologies and is not an end in itself.

1.1. PTW crash causation studies

In recent years, there has been growing research aimed at understanding the different factors and patterns (i.e., recurring sequences or chains of events that lead to a specific type of crash) responsible for crashes involving PTWs. Previous analyses have been primarily based on epidemiological studies, which focus on crash data and a set of non-crash databases (geometry, traffic or vehicle parameters). A few analyses of crash causation studies (CCS) have focused on in-depth investigation of crash causation factors involving PTW based on subjective evaluations by experts. CCS delineates research endeavors that aim to uncover the origins of crashes by examining data collected from real crash incidents, typically conducted by a multidisciplinary team [15]. These investigations are also referred to as clinical in-depth studies [16].

To understand the crash causation factors for PTW crashes in Europe, the Association of European Motorcycle Manufacturers (ACEM) carried out a Motorcycle Accident In-Depth Study (MAIDS) of 921 PTW crashes occurring in five European countries [4]. A total of 200 variables were coded per crash, with a full reconstruction of the crashes involving several experts. The study observed that human error was the primary contributor to crashes, with the most frequent error being "failure to see the PTW" (by the other road user) due to lack of attention, sight distance or low conspicuity of PTW.

A European case study conducted an in-depth investigation of 245 PTW-car crashes involving only human errors extracted from the MAIDS database [17]. The authors identified five Merged Accidents Configurations (MACs) based on the kinematic behaviour of PTWs and cars prior to the precipitating event. This enabled the understanding of different characteristic behaviours in the event of a crash. The main human errors identified were perception, comprehension and execution failures, and the authors proposed rider assistance systems as effective means to address these errors.

A UK case study analyzed an in-depth dataset of 41 fatal or serious injury crashes involving a PTW and another vehicle at junctions [5]. The findings of the study indicated that the most prevalent causes of these crashes were "too high speed" or "too late action" on the part of the motorcyclist, and "too early action" by the other drivers involved. Moreover, a significant crash cause identified in the observed incidents was the phenomenon of “looked but failed to see”. However, the analysis was primarily focused on discussing the causes without establishing any connections to preventive actions.

A more recent European case study conducted an in-depth investigation of 500 crashes involving PTWs (77 %) and bicyclists (26 %) in six European countries [2]. The Driving Reliability and Error Analysis Method (DREAM) was used for analyzing the crash causes.[1] The study provided an analysis of different crash scenarios and identified various contributory factors to PTW and bicyclist crashes. The results indicated that the most prevalent crash causes for both PTW and bicycles were “looked but failed to see” incidents, with the actions of other vehicles being the most critical factors. Observation errors, distraction and sight obstruction, were identified as principal causation factors. These findings are consistent with other European studies [4,18]. However, despite investigating the crash causation factors for PTW, these studies are limited in establishing the linkages between the crash factors and preventive measures.

Another UK based study used a Human Functional failure model on an in-depth collision dataset to examine the behaviours of PTWs prior to a crash [19]. The model describes driving errors according to a series of cognitive steps that result in a driving action. The study analyzed 428 crashes using descriptive statistics and cluster analysis to identify interactions between rider, vehicle, and infrastructure factors, thereby developing different PTW crash scenarios. The authors argued that examining risk factors in combination and understanding the dynamics of pre-crash events provides insight on crash causation which is an initiation to the sequence of development involved in the selection of countermeasures. From the analysis, the authors observed that the common crash scenarios were “looked but failed to see” crashes and single-vehicle PTW crashes. The authors proposed that countermeasures should follow a systemic approach focused on improving rider behaviour, vehicle design, infrastructure design, and training programs for both riders and other road users. However, no specific details were provided on the application of this approach.

A similar study based on a German in-depth crash database observed that most of the pre-crash scenarios linked to PTWs were losing control and looked but failed to see crashes [14]. The study also observed that the road surface was the most common injury source, and the leg and thorax injuries were the most represented. In the design of potential countermeasures, the authors proposed both preventive and protective countermeasures aimed at preventing the different crash scenarios and the associated severities based on the injury sources. Some of the proposed countermeasures were relevant to one or more crash scenarios, i.e., a countermeasure was linked to many crash scenarios. Overall, the countermeasures were proposed such that in 100 % of the crash scenarios, there was at least one countermeasure which addressed the scenario. However, while the approach used in this study to attribute countermeasures to crash causes may be relevant to the specific crash case, it may fail if there are initial biases in identifying the crash causes or may not be sufficient to stop future crashes of a different nature. Moreover, applying countermeasures to all crash cases does not justify their success, especially if all the crash causes were attributed to human factors and if a system approach is not considered. This concept is discussed in detail in section 4 where a more appropriate way of attributing countermeasures to crashes is proposed.

In addition to the key studies discussed above, Table 1 synthesizes findings from various studies on motorcycle crash causation, detailing the scope, methods applied, and main findings, including details on prevention measures. Generally, the common causes of crashes identified across studies include “looked but failed to see”, and “speed too high for conditions”. Although the studies underscore the importance of countermeasures, they often lack a detailed discussion on their implementation or linkages to causation patterns.

Furthermore, in most in-depth crash studies, the most common way of attributing countermeasures to crash causes is by stating some recommendations that could be implemented to eliminate or reduce the observed crash causation factors or events. However, this may not be the most appropriate way of attributing countermeasures, especially if the causes have not been adequately defined or identified. In the reviewed PTW in-depth studies, prevention measures are often briefly mentioned, and there is a general lack of systematic thinking to link prevention measures to crashes. In cases where a systemic approach is mentioned, there is no further discussion on the usefulness of this approach and how it can be applied to crash causation factors or chains. These limitations are covered in this study.

1.2. Crash causation theories and countermeasures

Theories on crash causations emerged since the 1930s from the work of Heinrich (1931), who proposed a model called the “domino theory” (cited in Refs. [21,23]). The model explains crashes as sequential chains of events, with each event dependent on the occurrence of the previous. The different stages of the events were social environment, the fault of the person, the unsafe act and the injury itself.

Over the years, other models (such as the Swiss cheese models, the Cognitive Reliability and Error Analysis Method (CREAM), Driving Reliability and Error Analysis Method (DREAM), the SafetyNet Accident Causation System (SNACS), HFACS (Human Factors Analysis and Classification Scheme), Human Functional failure models) have been developed linking crash occurrence to a set of conditions, factors or chains that must occur before a crash event can take place [18,19,21].

Generally, these models provide varying approaches, theories, and assumptions to understanding crash causation factors. They are important because they can clarify general issues of the causes of a particular crash type, describe the linkages between crash causes, and spell out their mediating processes to the occurrence of the crash. However, these models have something in common, which is their limitations in providing linkages between the causal factors and the possible prevention measures. This may be attributed to the fact that the causal factors identified using these models are most often not well defined or conceptualized from the perspective of

[1] The DREAM method is commonly used for analyzing car crashes but was first applied by Ref. [18] in a European study to carry our motorcycle in-depth investigation.

Table 1
Summary of Crash Causation studies on PTWs.

Author	Country	Study period	Sample size	Crash investigation method	Analysis method	Comments on study
[4]	France, Germany, Netherlands, Spain and Italy.	1999 to 2000	921 crash cases 923 non crash cases	In depth investigation	Descriptive analysis	Most frequent crash cause was "failure to see the PTW". Provided recommendations for countermeasures based on identified causes but no critical discussion provide on aspects of the safe system.
[19]	United Kingdom	2000 to 2010	428 crash cases	On scene in depth investigation	Descriptive and cluster analysis	Looked but failed to see crashes identified as main concern. Proposed a systematic approach to prevention but provided no details on application. These were also not linked to causation patterns.
[2]	France Greece Italy Netherlands Poland United Kingdom	2015 to 2017	385 crash cases	On scene and retrospective in-depth investigation	DREAM	Looked but failed to see crashes was identified as main concern. No countermeasure analysis.
[20]	South Australian	2014 to 2017	117 crash cases	at-scene in-depth investigations.	Descriptive analysis	Speed too high for conditions and road visibility identified as most common crash causes. Proposed a systematic approach to prevention but provided no details on application. These were also not linked to causation patterns.
[21]	Germany Finland Italy Netherlands Sweden United Kingdom	2006 to 2008	178 crash cases	in-depth investigations	Descriptive analysis	Timing and speed error were the most common errors that led to crashes for motorcyclist. Timing was most frequent for all vehicle type. No countermeasure discussion.
[14]	Germany	1999–2014	332 serious injury crashes	Crash reconstruction	Descriptive analysis	Loss of control and looked but failed to see were most frequent contributory factors. Covered prevention measures but did not acknowledge the safe system.
[5]	UK	2010 to 2016	41 fatal and serious injury crashes	In depth investigation plus police investigation	Descriptive analysis	The most frequent crashes were too high speed or too late action for the motorcyclist and too early action for other driver. No discussions on prevention actions considered.
[22]	USA	2011 to 2016	351 crash cases, 702 control	On scene investigation	Case-control analysis	Lack of motorcycle rider conspicuity associated with higher risk, while riders with partial helmet coverage have lower crash risk. Suggested the need to develop countermeasures with some listed countermeasures but provided no insights on a systemic approach.
[17]	France, Germany, Netherlands, Spain and Italy.	1999 to 2000	245 crash cases	In depth investigation	Descriptive analysis and grouping	Perception, comprehension and execution failure were main causative factors. Suggested a list of countermeasures but provided no insights on a systemic approach.

prevention actions, especially those factors linked to human factors. Nonetheless, linking causal factors and conceptualizing them to prevention actions is not simple as it may entail chains of direct and indirect effects of countermeasures which may be linked to one or several causes.

Countermeasures theories in the literature are generally limited compared to causal theories. A review by Vingilis [24] highlights two types of countermeasures models; the intervention's change theory (how and why an intervention could "cause" specific outcomes) and the intervention's action theory (identifies theoretical basis and evidence of intervention effectiveness). Vingilis explained two commonly used methods for evaluating the countermeasure theories, which are the causal chain and the program logic model:

> "The causal chain represents a series of steps of causal assumptions along a continuum that reflect the change theory underlying the intervention … The focus of the causal chain is on the recipient of the intervention and reflects the process of change to positive outcomes that is assumed to occur with the person or system (if the system is the recipient of the intervention). The focus of the program logic model, on the other hand, is on the intervention inputs, activities, and outputs that are expected to

occur to cause change to each of the steps of the recipient's causal chain for the short and longer outcomes. Program logic models present a schema for understanding how resources for an intervention are used to implement key strategies and activities and how their implementation contributes to expected short and longer-term outcomes".

The author concluded that using these methods for evaluating countermeasures can improve the interpretation of outcomes and enhance causal attribution of prevention actions.

A study by Elvik [25] explained some of the theories of crash causation regarding the mechanisms by which risk factors affect the probability of crashes. Elvik proposed some laws of crash causation aimed at explaining the existence of certain risk factors and the shape of their statistical relationship with crash rates. These laws are summarized in Table 2. Elvik related these laws to practical examples and case studies and also demonstrated instances where the laws could be falsified. However, Elvik's work was limited to crash causation as he did not link these laws to the expected countermeasures. It is expected that crash causation theories should have a natural link to the possible theories of countermeasures to make them useful. The laws may be self-explanatory but the linkages with countermeasures should be made. Otherwise, it may become meaningless to define a crash cause when no countermeasure can be derived from it. So, the question to ask is how countermeasure theories could be derived from the laws of crash causation proposed by Elvik? Table 2 below provides some possible implications of the crash causation laws to countermeasures.

Elvik recounted that each of the crash causation laws are related and suggested the need for further reduction to a smaller number of mechanisms. However, simplifying the mechanisms may inadvertently obscure the effectiveness of prevention measures. Nevertheless, this interrelationship amongst the crash causation laws presents an advantage in terms of countermeasures, emphasizing that countermeasures derived from each crash law should not be implemented in isolation, but complementarily if the goal is to eliminate crashes. In isolation, the countermeasures from the laws are not useful. For example, even if a driver possesses a high mental capacity dedicated to driving due to possible interventions that reduces distraction, a crash can still occur if the driver is taken by surprise by rare events or becomes confused by complex road conditions.

Hauer [15] provides valuable insights into crash causation and prevention and places emphasis on the importance of understanding the causes of crashes in order to develop effective prevention strategies. The author also highlights the biases that can affect clinical crash causation studies. Hauer argues that knowledge of crash causes is important because it directs the mind to consider potential prevention actions. Knowing the frequency with which various causes arise in crashes is necessary for determining the promise of potential prevention actions. Using an example of an intersection crash and other case studies, Hauer provided clarity on the definition of a "cause" and "prevention action". The author argued that cause should be defined as "a circumstance or action that, were it different, the frequency of crashes and/or their severity would be different". On the other hand, Hauer identifies prevention actions as: "crash prevention actions change causes aiming to reduce the frequency of future crashes and/or to improve their severity

Table 2
Elvik Crash Causation Laws and possible implications on countermeasure.

Crash Causation Law	Possible Linkage of Law to countermeasure
The universal law of learning: the ability to detect and control traffic hazards improves continuously as a result of exposure to these hazards.	Countermeasures that encourage retraining programs and enhance familiarity with road hazards and risk factors can be effective in reducing crash rates as it increases the predictability of these factors. Continuous training and retraining program to novice drivers and road users in hazard perception and risk factors awareness can improve their ability to detect and effectively manage risks leading to improved road safety outcomes. Concepts such as graduated driving license programs could be effective in reducing the number of crashes, if drivers are gradually exposed to more complex situations as they become more experienced.
The law of rare events: the more rarely a certain risk factor is encountered, the larger is its effect on crash rate.	Certain countermeasures may hold greater importance in preventing crashes than others, even if they are associated with only a small portion of the overall risk factors. For instance, if a road has fewer crash barriers in more than 50 % of its length but has one or two sharp curves, which may be considered rare, preventive measures to correct the sharp curve may lead to a higher crash reduction compared to the equivalent crash barriers because drivers were already accustomed to the absence of crash barrier than the absence of sharp curves. Hence, countermeasures should also focus on eliminating rare but impactful risk factors.
The law of complexity: the more units of information per unit of time a road user must attend to, the higher becomes the probability that an error will be made.	Countermeasures should aim to create self-explanatory traffic environments to reduce the cognitive loads on drivers. This can be achieved through measures such as the removal of conflicting signs, provision of clear and standardized signage, construction of self-explanatory road designs, and improvements in Intelligent Transportation Systems (ITS). Introducing new Advanced Driver Assistance Systems (ADAS) could also reduce the cognitive load on drivers. Policymakers could consider strategies to particularly reduce the cognitive load on inexperience drivers, for example mandating that they should not carry multiple passengers which provide a distracting effect.
The law of cognitive capacity: the more cognitive capacity approaches its limits, the higher the crash rate.	Countermeasures focused on cognitive capacity management and addressing mental loads, such as driver assistance systems and warnings mechanism can decrease crash rates.

distribution". Hauer explains that crash causes and prevention are naturally linked, and a cause becomes useful only if it contains clues on the prevention actions, otherwise, it is not.

Based on the definitions of a crash and what prevention action should be, Hauer highlights some of the biases common with clinical studies that need to be considered for these studies to be effective in providing prevention actions. These biases include "but-for", "Not-Cause-if Absent" and "Not-Cause-if-Normal". The latter two biases refer to crash causation studies (CCS) not considering as "crash causes" what is absent (on crash scene) or what complies with the norms. The "but-for" bias does not recognize events that do not make crashes inevitable. For example, the presence of trees (which can obstruct sight) may not be recorded as a cause in CCS, as it does not make the crash inevitable. However, this practice would obscure possible crash causes and associated prevention measures. Another researcher, Hopkins [26] also recognizes a shortfall of preventive measures based on but-for analysis. He argued that the but-for analysis only provides evidence of how we may avoid future identical crashes, but in principle, crashes are always dissimilar. Consequently, there are limitations in providing prevention measures through CCS, which often focus solely on critical events or the final cause, often attributed to human errors.

A paper by Shinar [16] highlights some of the most common misperceptions and false assumptions about crash causes and countermeasures. This is rooted in the notion that since approximately 90 % of crashes are due to human errors, then the prevention must be directly linked to road user errors. The author provides a critical analysis of several case studies and examples and underlines several biases often made in defining a cause which makes it difficult to establish prevention actions and countermeasures.

Shinar described the link between cause and countermeasure and argues that using the medical model to find "cures" cannot be applied in crash causation and prevention studies. The medical model assumes that to provide a cure (countermeasure), we need to find the cause (e.g., the behaviour of road users) and then find a way to kill it or eliminate its breeding ground. Shinar explains that this way of preventing crashes may be misleading as it would imply that human errors may be completely changed by either killing the source or eliminating it. He advises that a more nuanced solution is to use causes as clues to environmental or vehicular prevention measures to kill the cause or eliminate its breeding ground, with road user solutions as a last resort. The author emphasizes that these causes may be killed or eliminated by several countermeasures, not necessarily the ones derived from them. In a similar way, the same countermeasure may be linked to several causes. The author recommends the safe system concept as a more subtly and promising way forward to crash causation as it recognizes that crashes are caused by multiple factors interacting within a complex system rather than being solely attributable to individual driver behaviour or other specific causes.

Shinar emphasizes that most CCS fail to define causes in terms of potential countermeasures as they mostly focus on identifying conditions and behaviours preceding a crash. These conditions, while useful, usually give no clue to the type of countermeasures and as Hauer also argued, they cannot be considered causes if they are irrelevant to prevention, or especially if the cause cannot be changed by a countermeasure.

A synthesis of the crash theories explained above suggests that to develop effective countermeasures and policies, the disconnection between countermeasures and crash causes must be bridged. This can be done by:

(i) Accurately defining what a crash cause is and what a crash cause is not. A crash cause is an event which can be changed or altered with one or several countermeasures not necessarily derived from the crash cause.
(ii) Considering a broader systemic approach to crash prevention which considers both immediate countermeasures (applied on what may be defined as critical events or primary causes for CCS) and extended countermeasures (other non-related factors, which may be environment, road, vehicle, traffic or post-crash).

2. Data and methods

An instrumental case study approach is used to understand the role of crash causes in defining road safety countermeasures. The following subsections present the crash sample and data collection procedures adopted, the methods for crash causation analysis for a target crash scenario, and approaches for developing countermeasures from crash causation.

2.1. Sample and data collection

The data used for this study is from the SaferWheels EU project, which gathered in-depth data on 500 crashes that occurred during 2015–2017. Out of these, 385 (77 %) involved Powered Two-Wheelers (PTWs), and 130 (26 %) involved bicycles, with some crashes involving both PTWs and bicycles. The data was collected across six EU countries and analyzed to identify the main types of crashes and their causal factors. Among the PTW cases, 32 related to LoCC [2].

There were two ways to gather information from crash investigations: On-scene and Retrospective methods. Teams in SaferWheels could use either method or a combination of both. The on-scene approach involved attending the crash scene with necessary equipment to gather data, while the Retrospective method allowed more efficient use of time by grouping investigations by location and selecting cases according to the sampling plan.

In selecting the crashes to be included in the sample, the utmost care was also taken to achieve a random selection procedure as far as possible. However, factors such as traffic jam, team availability, data privacy issues, refusal by involved parties, etc., all provided practical restrictions to the ideal selection. This somewhat affected the data representativeness of the crashes that occurred in the studied regions. Retrospective crash investigation methods were adopted if relevant differences were found in the comparison of the sample and local crash population.

The data collection system for crash investigations is based on the DaCoTA European research project and is fully described, together with the methodology used for data collection in the investigation manual [27].

It includes about 1500 potential variables per case. Although teams are required to collect a set of core variables, additional variables may be collected where possible. No single crash case would contain all the variables listed in the protocol. A detailed methodology guideline is provided online, with variables viewable through a web browser or by accessing the database. The variables are divided into categories such as crash, road, road user, vehicle, and analysis, with examples of variables listed for each category.

2.2. Crash causes identification and coding

Upon completion of data collection, a crash causation analysis was conducted utilizing the DREAM method as described by Ref. [28]. The analysis method encompassed variables pertaining to the road, environment, vehicle(s), and road user(s), sourced from in-depth crash investigations, police reports, and interviews with involved road users and witnesses, where feasible.

The DREAM classification system employs "phenotypes" (a description of the observable behaviour or outcome of the accident) and "genotypes" to analyze crashes, as expounded by Refs. [18,29]. DREAM incorporates six general phenotypes (timing, speed, distance, direction, force, and object) and ten specific phenotypes (e.g., Timing phenotype is split into Too-early action, Too-late action, and No action). Genotypes are factors which may have contributed to the phenotypes. There are 51 general genotypes, each linked with one or more specific phenotypes, categorized into broad classifications - driver, vehicle, traffic environment, and organization - with further subcategories outlined in Table 3.

The analysis starts by choosing a phenotype for each driver/rider/pedestrian involved in a crash and then by identifying underlying genotypes, which are the causes leading to the observable behaviour of the drivers/pedestrians involved. The output is a DREAM chart, which can be formulated by establishing causal factors with directional links, connecting genotypes to phenotypes or interlinking genotypes. This visual representation elucidates how a causation factor can function as either a consequence or a precursor to another, forming a series of interconnected chains. For example (see Fig. 1), one such chain might illustrate a sequence where inadequate skills or knowledge of a rider leads to an overestimation of abilities, resulting in a misjudgment of the situation and subsequently causing a speed error. A single DREAM chart will often contain multiple chains, describing all the factors relating to that road user, and a chart is produced for every contributing road user in the crash. Chains may also split into multiple branches part way through the chain. Through this comprehensive method, a particular crash scenario can be fully delineated. Furthermore, through the analysis of aggregating multiple DREAMS charts, the most common or frequent patterns within them can be identified.

2.3. Crash causes aggregation and countermeasures definition

The study specifically focuses on Loss of Control in Curves (LoCC) as a case study and proposes various approaches for connecting crash causation factors to prevention strategies.

Starting from an aggregation of DREAM charts referring to the LoCC crash scenario, five countermeasure allocation approaches are discussed. For example, attributing countermeasures by looking at the phenotypes only, or by looking backwards from the phenotypes towards the first or root causes. The analysis method aims to identify a robust approach to crash prevention by understanding the linkages between crash causes and countermeasures.

3. Results - causation patterns for PTW LoCC crashes

Several crash scenarios (15) were identified within the European in-depth study of motorcycle crashes but the most common crash scenarios responsible for PTW fatal and serious injuries for two-vehicle crashes were: (1) opponent vehicle turning to the left, crossing the PTW path with the PTW coming from opposite direction riding straight (16 %); (2) PTW driving straight with an opponent vehicle crossing the PTW path from the right side (13 %); and (3) the PTW loses control on a curve and crashes an opponent vehicle (9 %). Regarding single PTW vehicle crashes resulting in fatal and serious injuries, it was found that 64 % of these cases involved a LoCC. This substantial prevalence of LoCC incidents, particularly in rural settings, among both single and multiple PTW vehicles, has prompted the selection of this specific crash type as the primary focus of analysis in this study. Moreover, limited attention has been devoted to investigating this particular crash scenario in the existing literature, underscoring the need for further examination [9]. Therefore, the present research is centered on PTW LoCC as the principal subject matter, with the results and discussions tailored accordingly.

Fig. 2 below represents the results of aggregating DREAM charts for the riders in the LoCC crashes in rural areas. The chart starts from the left with genotypes which explain other genotypes, then the phenotypes represents the observable effects of the crash. The thickness of the arrows represents the frequency of the occurrence of the preceding genotype or phenotype (i.e., for how many drivers this specific link was present). As an example of how the pattern works, inadequate road maintenance (O2) led to reduced friction (L2) which led to a misjudgment of the situation (C2), that in turn led to the observed effect (i.e., Force error), which is the last cause of the crash. In practical terms, this pattern can be explained as: the roads were poorly maintained, it rained, and the road was wet, hence reducing the friction. The PTW rider while traveling within speed limits misjudged the situation (of a wet surface) and applied the brakes too harshly leading to loss of control and skidding. The specific real-life events for the genotypes involving the PTW LoCC has been explained in Appendix.

The results of Fig. 2 shows that the most frequent phenotype or observable effect which led to the crash was speed (frequency = 18) followed by force (11; the force with which an action is conducted, i.e., surplus or insufficient force). It means it was as a result of the speed error of the rider or the force error that ultimately made the crash unavoidable. The most frequent antecedents of these phenotypes, which are the genotypes, are "misjudgment of situation"(15), "under the influence of substance"(2) or "late observations" (2).

Table 3
The main genotypes proposed by the DREAM methodology version 3.2

Genotype			
Driver	Vehicle	Traffic environment	Organization
B: Observation C: Interpretation D: Planning E: Temporary personal factors F: Permanent personal factors	G: Temporary HMI problems H: Permanent HMI problems I: Vehicle equipment failure	J: Weather conditions K: Obstruction of view due to object L: State of road M: Communication	N: Organization O: Maintenance P: Vehicle design O: Road design

Note: letters A, B, C, etc. are the codes used to name them.

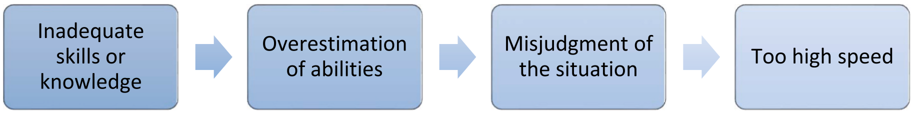

Fig. 1. Example of a DREAM causal chain.

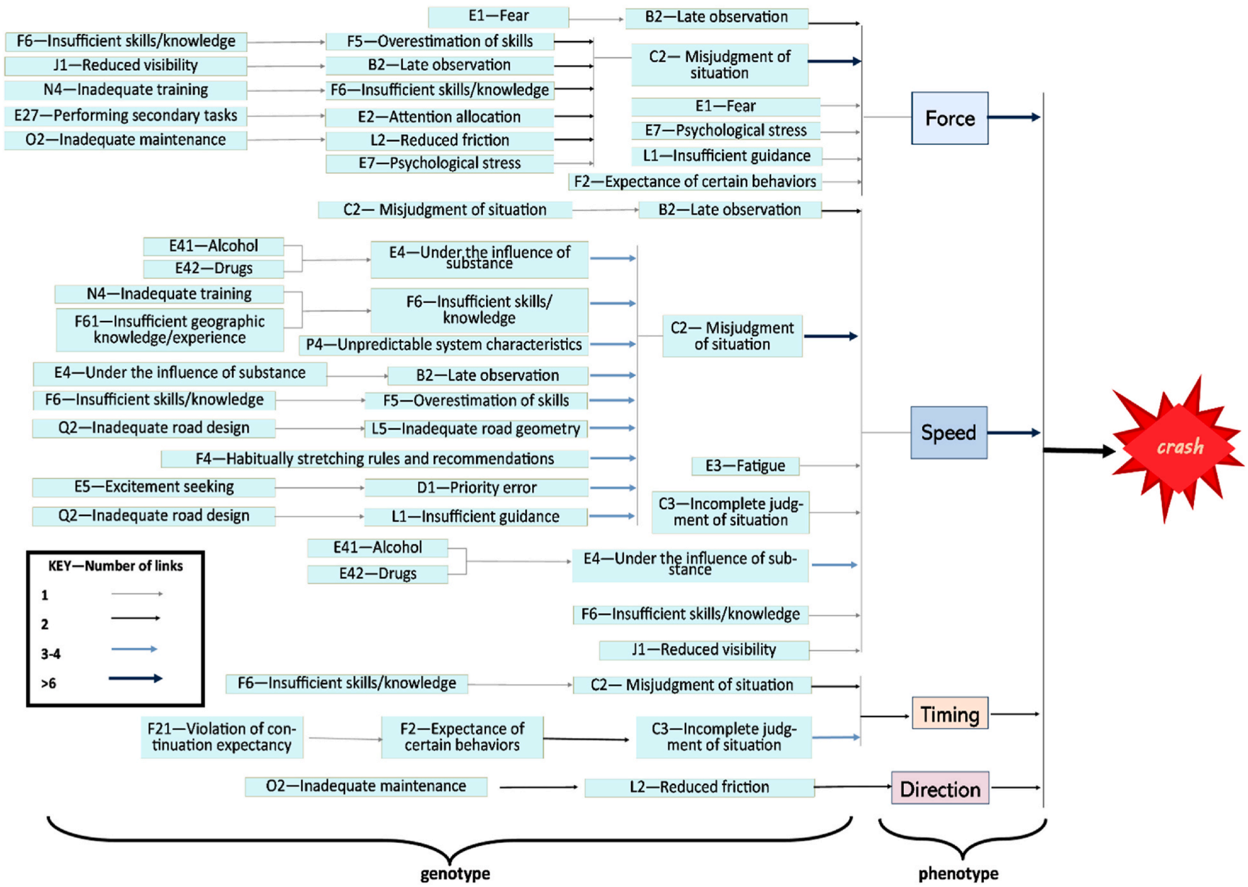

Fig. 2. Aggregated Dream chart for 32 riders in Loss of Control on Curve crashes - Rural roads.

Within the misjudgment category, insufficient skills/knowledge (5) was most frequent reason in explaining the misjudged situation.

4. Discussion on causes and countermeasures

4.1. Deriving crash causes from crash causation patterns (e.g DREAM chart)

In-depth analysis may not always define/identify crash causation factors from the perspective of prevention measures i.e., identifying a crash cause as an event which can be changed or altered with one or several countermeasures. Hence, to make crash patterns from in-depth analysis more useful, it is necessary to filter out those events that cannot be altered or do not give an idea of countermeasures so that focus can only be made on those events that inform prevention measures. With this crash cause concept in mind, looking at the crash patterns in Fig. 2 above, it is evident that some causes (genotypes) are not useful causes (i.e., "non-relevant causes") since we cannot immediately think of the prevention measures to stop them.

For example, from Fig. 2, the crash chain F21 (violation of continuation expectancy) - F2 (expectancy of a certain behaviour) – C3 (incomplete judgement of situation) – Timing,[2] may not lead to any prevention measures due to its identified causes. Quoting Hauer [15], this crash chain is "barren for prevention". This is because drivers would always violate a certain type of expectancy or would always expect a certain behaviour contrary to what other road users think or expect, and these expectations cannot be changed or altered, nor the knowledge of them can provide information on how to stop future crashes. However, the study by Hauer [15] highlights that the inclusion of such crash causation factors (with no clues of prevention) generally does not lead to bias. We do not totally agree with Hauer [15]. While there might be no bias if such "barren" crash causes appear once (at the beginning) of a given crash chain, there might be a significant bias in the chain if a sequence of more than two causation factors is "barren" for prevention. The chain itself becomes "barren" for causation and cannot lead to prevention.

This type of bias may be a result of poor information collection. The presence of this bias will minimize efforts of linking the crash causation chains with prevention actions and limit opportunities for effective interventions to break off such chains in future crashes. This may become more problematic if the "barren cause" appears in the middle of the chain or closer to the phenotype. Hence, from this narrative, it follows that:

Crash causation studies must ensure that in any consecutive sequence of crash causation factors in a chain, one should easily think of prevention measures that can alter at least one of the crash factors in the sequence. Otherwise, there may be bias in providing prevention measures.

In addition to the problem of defining a crash cause in CCS, Hauer [15] identifies other biases common in CCS, which are the "but-for", "Not-Cause-if Absent" and "Not-Cause-if-Normal" biases. While these biases need to be corrected during the data collection phases, already conducted CCS may be able to limit these biases if prevention measures are developed in a systematic way, such that if one part of the system fails the others can protect. CCS may take advantage of the fact that a countermeasure may not necessarily be derived from the cause itself. For example, consider the crash chain in Fig. 2 in which insufficient skills (F6) – overestimation of skills (F5) is a sequence of genotypes which led to misjudgment of situation (C2) and hence rider applying too much or too little force (to throttle or brake) leading to loss of control and hence crash.[3] If initially, the absence of speed calming measures (such as speed bumps) was not identified as a crash cause within the chain ("Not-Cause-if Absent"), it does not stop to think of the prevention measures of providing speed calming measures as there is a natural link between speed calming measures and force phenotype. Hence, it follows that:

Crash causation studies should not limit countermeasures based on the identified "root causes or critical events" (which may suffer from bias) but should also consider other prevention measures which are naturally linked to causes even if they are not directly evident from the chain.

4.2. Crash prevention from crash causation patterns

Crash causation studies are typically conducted with the end objective of understanding the countermeasures that can be attributed to the identified causes. Although the linkages between the crash causes from CCS and countermeasures is often less discussed in the literature. Once a list of crash causes or patterns of causes are identified, prevention measures can be suggested to reduce or stop the

[2] Real life example: *"Vehicle 1, a motorcycle ridden by the trainee manager returning from work, was traveling along a dual carriageway with a 70 mph speed limit before transitioning to a single carriageway with a series of bends and a 50 mph speed limit. The rider negotiated a series of four bends, each with a consistent radius, until reaching a fifth bend which had a varying radius. On approach to this bend, vehicle 1 passed a car stopped in the gravel on the nearside, belonging to a friend of the rider, which disrupted their expectation of a clear path ahead. Due to an incomplete judgment of the situation, the rider failed to accurately assess the severity of the upcoming bend. Consequently, they lost control of the motorcycle, causing it to veer off course and skid. This mistimed evasive maneuver caused the motorcycle to cross into the opposing lane, where it collided with Vehicle 2, a car traveling on the correct side of the road".*

[3] Real life example: *"Vehicle 1, a motorcycle carrying a male and female, lost control while navigating a right-hand bend on Road A. The rider applied excessive brake force on the loose soil and foliage, causing the motorcycle to veer into the verge and fall onto its offside upon re-entry to the road. Confidence may have been lost while maneuvering the bends. Consequently, Vehicle 1 and its riders entered the opposing carriageway during the following nearside bend, colliding with the front offside of Vehicle 2, traveling in the opposite direction. Vehicle 2 braked heavily and steered left, coming to a stop on the nearside with its nearside wheels atop a damaged stone wall. The rider of Vehicle 1 was relatively inexperienced, having obtained their license around* 18 months *ago, and the motorcycle was only their second large bike. Two other motorcycles were present ahead of Vehicle 1, but no evidence suggests their connection to Vehicle 1 or awareness of the collision. It is plausible that the rider of Vehicle 1 may have been influenced to follow the more experienced riders ahead, potentially at an unfamiliar speed".*

reoccurrence of future crashes of that type. However, this is not simple and may be subject to bias if the causes were not initially well defined/identified or if the prevention measures are not well attributed/linked to the causes.

From the way crash patterns are being established in this study, i.e., a sequence of genotypes to phenotypes and then crashes, one can think of several approaches of attributing countermeasures to the chains or patterns to stop the reoccurrence of that particular crash chain or pattern in the future. However, it is important to understand the differences in the various approaches and the results derived from applying each approach in terms of crash prevention. This would lead to the identification of a robust approach. The different approaches may include:

(a) *Attributing countermeasures by looking at the critical events only (i.e., the phenotypes or the last cause* e.g.*, braking with a larger force, approaching curves with a larger speed).*

This approach focuses on identifying countermeasures that alter the immediate actions or behaviour (phenotype) that led to the crash. The key assumption using this approach is that "if the last cause that led to the crash were to be stopped through some countermeasures, then the crash could have been prevented". However, given that the last cause in the DREAM methodology (such as force, speed, timing and direction as depicted in Fig. 2) is often related to human errors, using this approach may lead to considering countermeasures that solely focus on reducing human errors. In addition, this approach may be subject to the "but-for" bias making it ineffective. Moreover, Hauer [15] defines the last cause used in prevention measures as a "quasi-finding which provides false respectability to a style of road safety management that makes the road user the primary target of prevention actions".

(b) *Attributing countermeasures looking backwards i.e., from the critical events (phenotypes-last causes) towards the first or root causes (genotypes).*

Generally, crash causation chains are built looking backwards, starting from the last cause (phenotypes) and moving backwards in steps (genotypes) to understand the factors that explain the occurrence of each step (genotypes), and when the first cause (genotype) is judged to have been established, the chain stops. For example, in Fig. 2, the crash chain "E41 (Alcohol) -E4 (under influence of substance) - Speed - Crash[4]" starts from the identification of speed as the main cause then moving backwards till when alcohol is identified as one root cause of the crash. The assumption underlying this approach is that "if a countermeasure is attributed to a critical event (phenotype) and also to the genotypes that explained the critical event, then it may be sufficient in stopping the occurrence of that crash type".

For example, let us consider the backward sequence crash – "phenotype: too high speed in curve (which led to loss of control)" – "genotype: driver misjudged the situation (e.g., did not travel at a speed appropriate to the conditions)" – "genotype: reduced friction, (e.g., road was wet)". Looking backwards, we may think of attributing countermeasures such as "speed calming measures at curve" – "intelligent speed advisory to remind drivers of their speeds"- "proper road maintenance". However, while this approach may be more effective as compared to approach (a) we may still term it a "quasi finding", especially if the crash chain had suffered from some initial biases of defining a crash cause. Besides this, since the goal of prevention is to stop the occurrence of future crashes and noting that future crash events or patterns may not be identical to those that gave rise to the established crash pattern, we may not be confident in reducing the likelihood of future crashes of a similar type if we apply countermeasures this way.

(c) Attributing countermeasures looking forward, i.e., from the first or root causes (genotypes) towards the critical events (phenotype).

Prevention measures may be attributed to crashes starting from the genotypes (which are the necessary conditions for other genotypes or phenotypes to occur) towards the critical events with the assumption that "if the first genotype were to be prevented through some countermeasures, then the next genotype or the phenotype (critical event) would not occur and hence the crash would be prevented".

For example, considering the reverse of the crash chain "too high speed in curve (lost control)" – "driver misjudged the situation (underestimated the speeds)" – "reduced friction, (road was wet)", one would say that had it been that the road designs were good, and the road properly maintained (the friction condition could have been better), then the rider would have been able to control their high speeds. In addition, if intelligent speed advisory and speed calming measures in that order were to be implemented, they could offer more layers of protection and that particular crash type would be fully eradicated since the chain becomes broken by the countermeasures. However, while this approach may be effective in preventing this specific crash chain, it may not be generalized to stop all future crashes for loss of control, and we may not be certain we would be reducing the likelihood of future crash events of that nature. Moreover, we may not always be sure that if a given genotype were to be prevented, it would fully prevent the next element in the chain. This is because genotypes are necessary but not sufficient conditions for explaining the occurrence of the next crash event Hopkins [26] in his paper argues that:

[4] Real life example: *"In favorable weather and light conditions, and with minimal traffic, the PTW rider was traveling from home to meet friends. Upon navigating the curve, the rider lost control of the motorcycle and fell to the ground alongside the PTW. Following the impact, both the PTW and the rider came to rest near the point of impact, with the motorcycle lying on top of the rider. Investigation revealed that the PTW rider tested positive for alcohol and drugs, indicating their impaired state at the time of the crash."*

"no future set of circumstances will ever be identical with those that gave rise to the accident that has been analyzed, and the more dissimilar the future circumstances the less certain we can be that changes based on a previous but-for analysis will have any preventive effect".

(d) Attributing countermeasures to the first cause (genotype) only.

The assumption here is that "if a countermeasure were to be attributed to the first genotype (which explains the occurrence of next events in the chain) then the chain becomes broken and the sequence of events in the chain that leads to the crash would no longer occur and the crash is prevented".

For example, this approach would mean that if the roads were to be maintained, then any crash related to friction in the road would not occur since the crash chain becomes broken due to the presence of adequate friction. The problem that may arise in this approach is that we are not certain that the genotype is fully responsible for explaining the occurrence of the next genotype or phenotype in the chain. Moreover, a given genotype (e.g., late observation in Fig. 2) may be explained by several other genotypes (such as reduced visibility, over-speeding, influence of drugs or alcohol), and we are not very sure of the relative strengths of their contributions to the crash, or if they are sufficient or just necessary in explaining the event "late observation". Hence, attributing countermeasures looking at only these genotypes may not even be very effective in preventing that particular crash type and especially not for future crash events which will not be identical to these.

The various approaches of attributing countermeasures to crash causation chains, (a) to (d), described above, show some lapses and suggests the need for a more robust or hybrid approach that takes into consideration these gaps. The solution to this is a broader systemic approach to crash prevention.

(e) Attributing countermeasures following a system approach.

This approach of attributing countermeasures considers not only the immediate countermeasures (applied to critical events or the first genotypes) but also extended countermeasures (other non-related factors which may be environment, road, vehicle, traffic or post-crash).

These measures should function in such a way that if one part of the system fails (e.g., a measure fails or is absent or insufficient), the others will protect to avoid the occurrence of that crash type or at least in reducing the severity. This approach is based on the theory that countermeasures may not necessarily be derived directly from the crash causes [16]. The system approach is important as it helps reduce potential biases such as the "but-for", "Not-Cause-if Absent" and "Not-Cause-if-Normal" biases that may have been introduced when defining/identifying the crash causes and forming the chains. Moreover, since a given countermeasure may be related to several causes (and the reverse is also true), using this approach considering both immediate and extended countermeasures may be cost-effective and has the advantage of eliminating future dissimilar crashes. This cost-effectiveness is especially true when prevention actions are targeted to several crash chains or a whole crash scenario rather than to individual crash chains (this is explained in detail in the subsequent paragraphs).

However, to effectively apply this systemic approach in a crash chain, with the idea of stopping future crashes of similar or dissimilar nature, it is necessary to consider the following guidelines (referred herein as steps):

i. Analyze the crash chain and the situations that cause the crash; identify all the causes that can be altered or changed and filter out "barren" causes. Generally, the most important events to emphasize are the first cause-genotype (e.g., reduced friction) and the last cause/critical events-phenotype (e.g., too high speed). Nevertheless, all other elements which are identified as causes within the chain must be highlighted.
ii. Make a list of effective countermeasures that have a direct influence on preventing the first genotype and the phenotype while also incorporating countermeasures for other identified causes in the chain. It is crucial that the selected countermeasures are supported by scientific evidence from reliable research that demonstrates their effectiveness. For instance, see Refs. [30,31] for scientifically proven interventions in the context of PTWs. These interventions may cover road user, vehicle, road, or traffic countermeasures. It should be noted that the selected countermeasures may not necessarily be derived directly from the identified causes themselves but can be chosen from extended countermeasures that indirectly address the underlying causes of crashes.
iii. For each cause, make a list of extended countermeasures (including human, vehicle, road, traffic or post-crash factors), different from the direct influencing measures, that may protect the road users in case the direct countermeasures fail. For example, if human causes and corresponding prevention actions were identified in the previous step (ii), then at this step (iii), a list of vehicular, road or traffic related countermeasures must be proposed.
iv. Consider external factors (policy implications) such as cost, benefits, and politics and select the most feasible countermeasures while ensuring a balanced distribution of the measures between vehicle, road users, infrastructure, and post-crash factors. At this stage, the responsibilities of government, manufacturers and planners should be incorporated.
v. If the goal is to eliminate a specific crash chain, the evaluation process concludes at step (iv). However, if the objective is to eliminate an entire crash scenario, such as LoCC involving multiple chains as depicted in Fig. 2, steps (i) to (iv) must be

evaluated for each individual crash chain within the scenario. However, this evaluation requires further considerations to enhance the overall effectiveness of crash prevention.

Given the fact that a specific countermeasure may be linked to several causes (with the reverse also true) and considering that extended countermeasures (which may be similar between chains) need to be identified for each crash chain, it is likely that when steps (i) to (iv) are applied to different crash chains within a scenario, repetitive countermeasures may arise or overlap across chains. It becomes crucial to consider these countermeasures just ones (redundancy) but also giving it more weights. This ensures cost-effectiveness and efficiency. Furthermore, it is essential to consider the synergies and interactions between countermeasures to optimize their combined effectiveness. Redundancy is also made possible as common or overlapping causes may be identified between different crash chains. Therefore, it is necessary to evaluate both overlapping causes and countermeasures.

For example, an integrated road safety education and rehabilitation program, traffic calming and speed enforcement, automated stability control for PTWs, and routine road maintenance may be overlapping countermeasures that addresses the crash chains "Reduced Friction - Driver Misjudged the Situation - Too High Speed in Curve – Crash", "Inadequate Road Designs - Insufficient Guidance - Misjudgment of Situation - Too High Speed – Crash" and "Inadequate Training - Insufficient Skills or Knowledge - Misjudgment of Situation - High Force – Crash". These countermeasures contribute to preventing multiple crash chains by addressing common causes, and in this way, it is more efficient to design road safety interventions considering several chains or a whole crash scenario rather than just one or few crash chains.

As an example, Fig. 3 shows how this systemic approach (steps i to iv) may be applied to the crash chain: "reduced friction, (road was wet)" – "driver misjudged the situation (underestimated the speeds)" – "too high speed in curve (loss of control)" – crash (PTW vs opponent vehicle).

Overall, the proposed approaches and framework for attributing countermeasures to crash causation chains can be applied transversally across different crash scenarios or types. By following the systematic approach outlined above, researchers and policymakers can analyze the chain of causation for any given crash scenario and identify the various causes and contributing factors, based on the correct definition of a cause and a prevention action. They can then develop a comprehensive list of countermeasures that address each cause and factor, considering both immediate and extended prevention measures. At the same time, identifying overlapping causes and countermeasures, enabling the design of interventions that address multiple crash chains or a whole crash scenario.

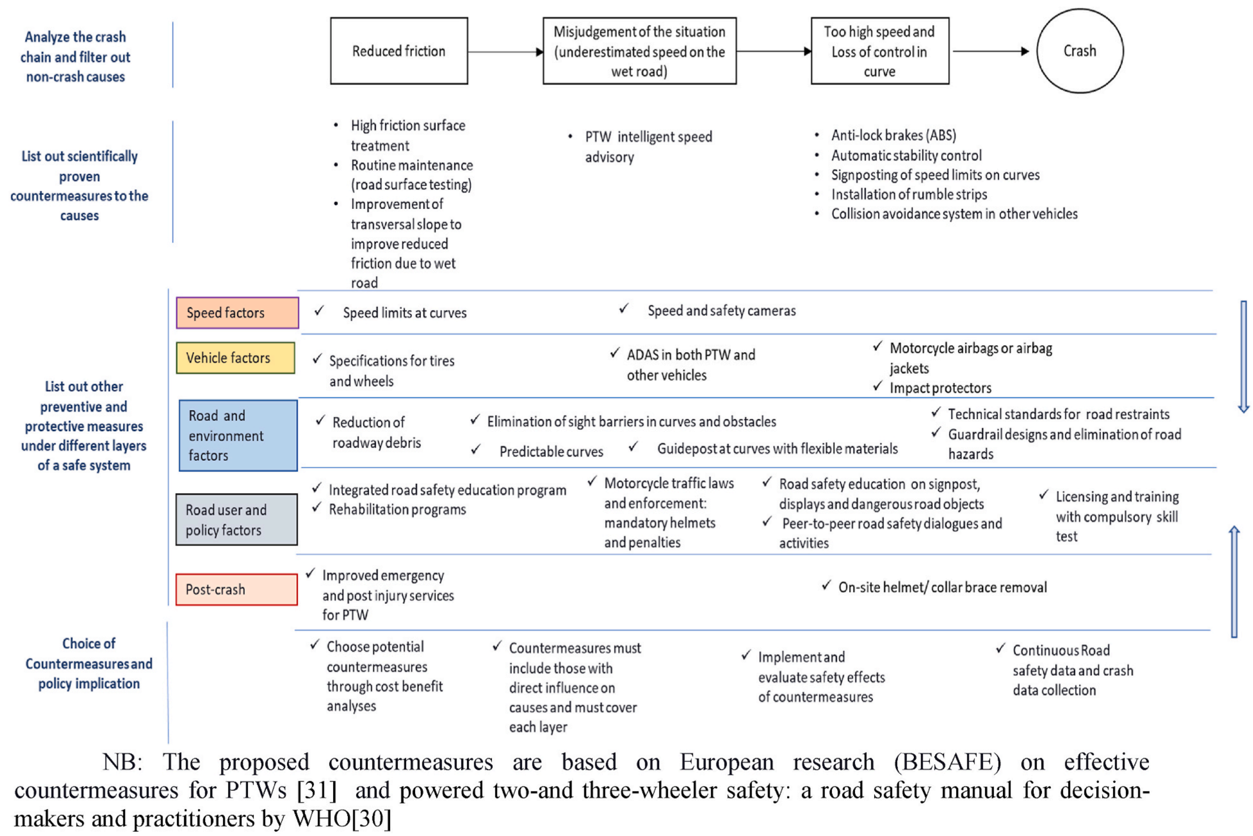

Fig. 3. Example of a systemic approach to countermeasure selection for a PTW crash chain.
NB: The proposed countermeasures are based on European research (BESAFE) on effective countermeasures for PTWs [31] and powered two-and three-wheeler safety: a road safety manual for decision-makers and practitioners by WHO [30].

This application ensures that prevention strategies are not limited to individual causes but encompass the entire system, leading to more effective and efficient crash prevention.

It is, however, important to note that implementing interventions across multiple causal factors or chains can be challenging due to potential limitations such as resource constraints. As highlighted by ELvik [32].

> "… It will not always be the case that all these measures can be implemented, but those who have the power to decide on their use should at least be required to justify why a certain measure was not used. Such a requirement would clarify the responsibility of system designers for the safety of the road system as defined according to the Safe System approach to road safety".

Developing and implementing effective countermeasures requires significant financial resources, expertise, and infrastructure. For example, in addressing human factors in crashes it entails a broad spectrum of interventions including training, education, infrastructure changes, enforcement, vehicle adaptation or even post-crash care measures. However, the scarcity of funding, but also capacity, can restrict the scope or implementations of these interventions, often resulting in a concentration on select causal factors.

Another potential limitation is stakeholder involvement in the implementation of interventions. Preventing crashes requires collaboration and coordination among various stakeholders, including government agencies, law enforcement, transportation departments, vehicle manufacturers, and community organizations. Each stakeholder may have different priorities, resources, and perspectives, which can make it challenging to develop and implement comprehensive interventions. Additionally, stakeholder engagement is crucial for ensuring the acceptance and effectiveness of interventions.

To overcome these limitations, it is important to prioritize and allocate resources effectively, considering the potential impact of interventions on multiple causal factors or a given crash scenario. Stakeholder engagement should be fostered through partnerships, communication, and shared decision-making processes. Collaborative efforts can help leverage resources, expertise, and knowledge to develop sustainable interventions. Additionally, continuous evaluation and monitoring of interventions are essential to assess their effectiveness.

5. Conclusion

In-depth crash causation studies are often carried out to understand the contributory factors to crashes of a given road user group and to determine the pattern and linkages between these factors and how they affect crashes. The end objective of these studies is often to provide guidance on countermeasures which should be applied to stop future crashes. However, linking the crash causation factors and countermeasures is not simple and must be carefully considered. One of the difficulties may be due to the bias in defining/identifying a crash cause during the investigation. Another difficulty is how countermeasures can be attributed to the chains of crash causes to ensure future crashes of similar or dissimilar nature are stopped.

This study uses an in-depth evaluation of motorcycle crashes occurring in six European countries to evaluate the above issues. A case study of Loss of Control on Curve (LoCC) for rural areas is used to evaluate and apply some of the theories of crash causation and prevention, highlighting areas of improvement in crash causation studies. Different approaches for linking countermeasures and crashes are discussed, and a more robust approach is proposed. Key highlights from the study include:

- Crash causation studies must ensure that in any consecutive sequence of crash causation factors in a chain, one should easily think of prevention measures that can alter at least one of the crash factors in the sequence. Otherwise, there may be bias in providing prevention measures.
- Crash causation studies should not limit countermeasures based on the identified "root causes or critical events" (which may suffer from bias) but should also consider other prevention measures which are naturally linked to causes even if they are not directly evident from the chain.
- Several approaches of linking causes to countermeasures can be derived from a crash scenario in CSS. These approaches lead to diverse results in terms of crash prevention, suggesting the need for a more efficient approach to optimize the crash prevention benefits.
- A more nuanced approach for attributing countermeasures to crash causation chains is by utilizing the safe system approach through a series of steps which includes: Analyze the crash chain and filter out non-crash causes; List out scientifically proven countermeasures to the causes identified; List out other preventive and protective measures under different layers of a safe system; and consider external factors (policy implications) such as cost, benefits, and politics.
- Given that a countermeasure may be linked to several causes, it is more efficient and effective for prevention strategies using the safe system approach to be applied to a whole crash scenario or to several crash causation chains rather than to single crash chains.

The differences between the various approaches ((a) to (e)) discussed in this study matter in terms of crash prevention. These approaches provide different insights on crash prevention, and can have a great influence on the effectiveness and efficiency of preventive measures aimed at stopping the occurrence of future similar or dissimilar crashes. Among the various approaches discussed, it is evident that adopting a systemic approach is most advantageous if the goal is to prevent future crashes from occurring. This approach is very useful in defining prevention actions from crash causation chains as it ensures that interventions are not limited to individual causes but address the entire system.

While this research was limited on the PTW rider perspective only, the proposed countermeasure approach can be similarly applied considering the perspective of the other road users involved in a crash with a PTW, in other crash scenarios.

The findings and theories presented in this study are of great significance to engineers, researchers, and policymakers for understanding the connections between crash causation, as identified through in-depth studies, and the corresponding prevention measures. In terms of road safety practice, the study highlights the necessity for policymakers to adopt a more comprehensive and systematic approach to crash prevention. It stresses the importance of linking countermeasures to the myriad interconnected causes of crashes, rather than isolating them to individual causes or events. By adopting a systemic approach and considering the entire causation chain, policymakers can devise more effective and efficient prevention strategies. This approach ensures that interventions are comprehensive, addressing the entire system and thereby leading to enhanced road safety outcomes. Future studies need to apply, monitor and evaluate the effectiveness of this systemic approach.

Overall, this study represents a significant contribution in road safety for Powered Two-Wheelers (PTW) by systematically linking crash causation factors to countermeasures through the development of a novel set guidelines that adhere to the safe system approach. By employing theories and concepts related to crash causes and countermeasures, the study focuses on LoCC for PTWs, which are critical for PTW safety. This case study approach offers insights into different approaches for linking causes and countermeasures, highlighting potential variations in outcomes and identifying the most effective prevention strategies. This addresses a notable gap in the current state-of-the-art concerning the connection between crash causation factors (particularly those related to human factors) and prevention measures — a link largely overlooked in prior in-depth crash studies — thus marking a substantial leap forward in conceptualizing and applying prevention actions to enhance PTW crash prevention strategies.

Data availability

Data will be made available on request.

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Ethics declarations

Review and/or approval by an ethics committee was not needed for this study because it is a secondary data analysis, and the analysis does not involve contact with human subjects.

CRediT authorship contribution statement

Stephen Kome Fondzenyuy: Writing – original draft, Methodology. **Davide Shingo Usami:** Methodology, Conceptualization. **Brayan González-Hernández:** Writing – review & editing. **Laurie Brown:** Writing – review & editing. **Andrew Morris:** Writing – review & editing. **Luca Persia:** Supervision.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly in order to check grammar related issues. After using this tool/ service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Declaration of competing interest

None.

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Appendix A. PTW – Rural – LoCC

Critical event

Multiple cases where motorcyclists drove at high speeds, causing them to lose control of their vehicles and crash. In some cases, they approached bends or intersections too quickly, while in others they used excessive force when braking. In one incident, the road was also affected by ongoing construction.

B2 (4)

<p>The car and PTW driver turned too late and the motorcyclist noticed the bend and did not brake before the impact.</p>

C2 (15)

<p>The motorcycle rider underestimated their speed, misjudged cues for anticipation, and did not adapt their driving style to the road environment. They took the risk of driving without the necessary skills, lost confidence, and misjudged their approach to a bend, resulting in attempting to brake at the last minute and losing control. They also did not focus on driving the motorcycle and did not fully understand the specific road conditions. The PTW driver was driving too fast for the circumstances, causing them to brake too hard and slip on a muddy road due to construction on the nearby cycle path.</p>

C3 (2)

<p>The car suddenly moved into the rider's lane, which was unexpected and quick. Despite riding at high speed, the motorcyclist anticipated making a sharp left turn.</p>

D (1)

The rider went on the journey to accompany his friends for fun, and was thrill seeking and not prioritizing his own safety or that of others.

E (17)

<p>The rider is driving under the influence of drugs and alcohol. The rider lacks experience in motorcycle driving and is distracted by other factors, such as an altercation with a car driver, insufficient skills, and not getting enough sleep the night before. The rider also has a history of enjoying driving and riding fast. Tramadol, a prescribed medication, was found in a sample at a level considered toxic. The article suggests that the combination of these factors led to the accident.</p>

F (23)

<p>The PTW driver is not familiar with the area and lacks practical driving skills. The driver may also have insufficient knowledge and experience about the local area and roads. The driver is also too confident, despite not having a license to drive the powerful motorcycle. The rider is relatively inexperienced and unfamiliar with the area. When entering a bend, speed, acceleration, and position are important factors to consider for stability and safety. The rider had an inexperienced riding style and insufficient knowledge of the local area to adjust their riding style appropriately. The motorcyclist did not have a license, and friends describe them as a thrill-seeker who often rides at high speeds. The rider was following friends in a car and did not know the severity of the bends in the area. Overall, the rider did not adjust their driving style to the terrain and was not familiar with the area.</p>

J1 (2)

It was dark when the accident happened.

L (6)

<p>There is an upcoming danger of an oil spill that can make the road slippery and cause loss of control, which happened to a biker in this case. The geometry of the intersection is poorly designed, with a slope that encourages high speed and a sharp turn into the roundabout. The warning sign for the bend was also misleading. Furthermore, the cycling path was filled with sand and gravel due to ongoing roadworks.</p>

N4 (2)

<p>There may not be enough training to learn the necessary skills and knowledge for a certain task. The vehicle may become

unpredictable under certain circumstances, such as encountering an animal. Additionally, driving training may not provide the skills needed to drive this particular type of vehicle (PTW).</p>

O (2)

<p>The national road management officers did not remove an oil puddle, and the maintenance of a nearby cycle path was affected by roadworks.</p>

P (1)

The characteristics of the vehicle become unpredictable under certain circumstances. Or an external phenomenon an animal for example.

Q (2)

<p>The approach to the intersection is poorly designed with a wall right after the slope leading to the roundabout. The confusing road sign may have played a role in the accident, leading to its replacement as per police recommendations.</p>

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