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Using Perceptual Cycle Model and Text Mining to Investigate Ambulance Traffic Crashes

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Abstract
Ambulance crashes constitute a matter of utmost concern within public health, posing potential risks to both patients and emergency responders. Despite this critical importance, investigating the underlying causes of these collisions is difficult because of the scarcity of comprehensive and relevant datasets. To bridge this research gap and gain valuable insights, the present study embarked on a mission to shed light on the causative factors behind ambulance-related crashes. To achieve this objective, this study adopted a meticulous approach, collecting narrative descriptions from ten special investigation reports published by the National Highway Traffic Safety Administration. These reports were selected as they offered in-depth accounts of real-life ambulance crashes, rendering them an invaluable resource for analyzing the multifaceted aspects leading to such incidents. Central to this investigation was the utilization of the Perceptual Cycle Model (PCM), a well-established and comprehensive framework that facilitates a systematic examination of the various stages leading to a crash. The study examined the key influential factors associated with ambulance crashes by employing PCM and text mining. The results reveal diverse factors contributing to ambulance crashes, including varied causes, driver actions, and post-crash scenarios, providing a holistic understanding of road safety. The outcomes of this study will bolster the safety of ambulance operations, safeguard patients and personnel, and ensure the efficient delivery of life-saving emergency services to those in need.

Keywords
traffic safety, ambulance crashes, perceptual cycle model, text mining emergency response

Crashes involving emergency medical service (EMS) vehicles, including police vehicles, ambulances, and fire trucks, present a significant traffic safety risk, resulting in severe injuries and fatalities for both first responders and other road users. Despite the gravity of this issue, there is a paucity of research focused on understanding the contributing factors and their interactions in these incidents. The occurrence of ambulance crashes is a matter of utmost importance in public health, given the potential risks they pose to patients and EMS personnel (*1–3*). These crashes endanger the safety of individuals in need of urgent medical attention and raise serious concerns for the well-being of the dedicated EMS professionals responsible for their care (*4*). Data in the Fatality Analysis Reporting System revealed that ambulance-involved fatal crashes remained relatively rare from 2017 to 2021, with a national average of twenty-six fatal crashes and thirty fatalities per year (*5*, *6*). In the U.S., there are more than 400,000 police vehicles, 45,000 ambulances, and 150,000 fire trucks dedicated to responding to emergencies and rescuing individuals (*7*). First responders, such as police officers, EMS personnel, and firefighters, frequently operate in emergency mode to reach incident scenes swiftly. However, they must navigate through various hazardous road and traffic conditions, including reckless drivers, congested roads,

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and numerous distractions, while ensuring safe driving practices (*7*). Ambulance crash data research is crucial because of the alarming statistics indicating that ground ambulance crashes are the leading cause of death among EMS personnel. Previous studies (*1–4*, *8–15*) underscore the critical public health concern posed by ambulance crashes, highlighting risks to patients and EMS personnel, yet gaps persist in understanding their root causes on account of inadequate datasets.

To fill the research gap, this study aimed to uncover the reasons behind ambulance-related crashes. To achieve this objective, the researchers opted for a novel approach by analyzing narrative descriptions from special investigation reports published by the esteemed National Highway Traffic Safety Administration (NHTSA). These reports were selected for their comprehensive and detailed accounts of real-life ambulance crashes, providing invaluable insights into the complex dynamics of such incidents. Central to this study was the strategic implementation of the Perceptual Cycle Model (PCM) as the analytical framework (*16–20*). By employing the PCM to analyze narrative crash reports, the researchers aimed to shed light on the complex association between factors contributing to ambulance crashes. This approach is unique because it combines qualitative narrative analysis with a scientifically rigorous framework like the PCM. By examining the narrative descriptions, the study aims to identify key insights and context-specific details that may not be fully captured by quantitative datasets alone. Simultaneously, the systematic application of the PCM allows for a structured and standardized examination of the crashes, enhancing the reliability and comparability of the findings. Furthermore, the study employed text mining to identify patterns of keywords and their associations, enriching the analysis and enabling more robust investigation of policy implications.

The paper is organized as follows. The literature review section provides a critical overview of existing and relevant studies. The methodology section outlines the application of the PCM theory and the text network analysis, along with details on data collection and exploratory data analysis. The results section includes an in-depth analysis of the findings derived from the PCM framework's approach. Finally, the conclusion section comprehensively synthesizes the study's outcomes, summarizing the key findings and their implications for policy and practice.

Literature Review

Several studies have examined the factors implicated in ambulance-related crashes, including locations, times, and demographics. Ray and Kupas compared ambulance crashes in rural and urban areas, analyzing crash data from Pennsylvania (*1*). Rural crashes occurred more often on snowy roads and at nighttime without street lighting, whereas urban crashes involved angled collisions, intersections, and traffic signals. Operator error was the primary cause in both settings, but vehicle and environmental conditions affected rural drivers more often. Urban crashes involved more vehicles and people, whereas rural crashes frequently involved fixed objects. Sanddal et al. conducted a literature review on factors and issues related to rural ambulance crashes (*2*). Relevant papers were categorized into four groups: problem description, safety issues, lights and siren use, and legal and ethical risks. The study emphasized the importance of standardized driver training programs and the potential benefits of simulator training. Ambulance vehicle redesign was identified as a critical factor in improving crash avoidance and survival. Studnek and Fernandez examined the association between demographic and work-related characteristics of EMS professionals and their involvement in ambulance crashes (*3*). A national sample of EMS professionals was surveyed, and the data revealed that younger age and self-reported sleep problems were significantly associated with a higher likelihood of being involved in an ambulance crash within the past year. Onozuka et al. investigated the relationship between a full moon and the requirement for emergency ambulance transport following road traffic crashes in Japan (*8*). The results showed that on days with a full moon, there was a slightly increased risk of emergency transport owing to traffic crashes. Public health strategies should consider the impact of full moon nights to reduce emergency transport from traffic crashes.

Several studies have also looked at factors implicated with different injuries and crash severities along with crash rates. Brown et al. developed a multivariate analysis of factors predicting injury outcome in restrained child occupants based on medical records from a children's hospital (*9*). Crash severity was assessed by ambulance officers using a visual assessment of vehicle damage and reported impact speeds. The analysis showed a significant association between crash severity and injury severity, suggesting the potential value of this simple measure in estimating crash severity. Abebe et al. aimed to understand the clinical characteristics and outcomes of patients arriving at a trauma referral center following road traffic collisions (RTCs) in Ethiopia (*10*). The study found that over half of the patients arrived with high or moderate acuity, and ambulance arrival was observed in 59% of cases. Patients with high acuity were more likely to be referred but not necessarily to receive ambulance transport. The study suggested that despite ambulance expansion, ambulance use among RTC patients is concentrated among those with low acuity, with interfacility referral being a contributing factor. Watanabe et al. studied the crash rates of ambulances using lights and sirens versus those without lights and sirens during emergency responses (*4*). The results showed that the crash rate during the response phase was higher for ambulances using lights and sirens than those without. Similarly, the crash rate during the transport phase was significantly higher for ambulances with lights and sirens. The findings suggest that lights and siren use is associated with an increased risk of ambulance crashes, especially during the transport phase.

A wealth of literature has been looking at different ways to mitigate injury and crash severity in ambulance-related crashes. Current et al. presented a test program to assess the effectiveness of mobile restraint systems in protecting occupants in ambulance patient compartments (*11*). The focus was on the vehicle chassis behavior and acceleration pulses observed during the tests. The program involved testing different types of ambulances with various impact scenarios, including side and frontal impacts. The results showed significant cab intrusion and forward rotation of the patient compartment in frontal crashes. Green et al. investigated the effects of restraint systems on worker safety through sled and crash tests (*12*). Results suggested that restraints providing mobility while allowing locking during impacts can enhance worker safety in various working conditions within the ambulance patient compartment. These findings highlighted the potential benefits of incorporating such restraint systems to improve EMS worker safety. Levick and Grzebieta compared the safety design and crashworthiness of concept safety ambulances in the USA with a standard Australian ambulance (*13*). It highlighted that U.S. ambulances lack certain crashworthiness features and do not meet established principles of occupant protection. The findings emphasized the need for the U.S. ambulance industry to prioritize crashworthiness and occupant protection principles to address existing safety failures. Erich evaluated the safety and fuel efficiency performance of a fleet of vehicles developed by a team of technical experts led by the EMS Safety Foundation (*14*). These vehicles were designed based on the safest aspects of ambulances and have been used for three years. The study provided an assessment of the performance of these vehicles, highlighting their safety features and fuel efficiency outcomes. Voitko et al. analyzed the efficiency of different shock absorber types in ambulance vehicles (*15*). The focus was on standard oil twin-tube shock absorbers, hydro-pneumatic shock absorbers, and air suspensions. The results indicated that single-tube hydro-pneumatic shock absorbers demonstrated the highest stability and smooth-running efficiency, which is crucial for operational safety. They were found to be a suitable replacement for standard shock absorbers without requiring design modifications.

These previous studies on ambulance-related crashes provide valuable insights into the complex nature of ambulance-related crashes and strategies to mitigate their occurrence and severity. The findings shed light on the factors involved in crash incidents, ranging from location-specific influences on operator demographics to work-related characteristics. Moreover, the studies highlighted the significance of standardized driver training programs, simulator training, and vehicle redesign to enhance crash avoidance and survival rates. Despite these important findings, however, further research on ambulance-related crashes using the PCM and text mining offers a comprehensive understanding of driving behavior, allows targeted interventions and training programs to improve driver performance, and enhances overall road safety for EMS professionals and patients.

Perceptual Cycle Model Studies

Socio-technical models like Accimaps, STAMP-CAST, and PCM are increasingly utilized because they offer a holistic understanding of complex systems by considering both social and technical aspects. Their benefits lie in their ability to provide multifaceted perspectives on safety issues, allowing for a deeper analysis of contributing factors and potential interventions. By integrating social, cognitive, and technical elements, these models enable researchers and practitioners to develop comprehensive safety recommendations that address the interconnected nature of human behavior, organizational factors, and technical system design. Neisser proposed in 1976 the idea that the human thought process and interactions with the external world are interlinked and mutually cyclically influence each other (*16*). Socio-technical approaches like PCM are gaining popularity in transportation safety research (*17–20*). Banks et al. examined the fatal Tesla crash in May 2016, proposing that design flaws in the Autopilot feature, rather than driver error, might have been the underlying cause, based on PCM analysis (*21*). Scott-Parker et al. investigated the crucial role of situation awareness skills (SAS) for young novice ambulance drivers in Queensland, Australia, recognizing the complex demands of emergency response situations (*22*). Using PCM, this study revealed that inadequate SAS pose significant risks for drivers, patients, and other road users. Understanding driver adaptation to the evolving relationship with semi-autonomous and highly autonomous cars is crucial for safety and consumer acceptance, as highlighted in Revell et al., employing the “think aloud” technique with UK drivers, using Neisser’s PCM to analyze interactions and proposing design considerations for a safer driver-vehicle interaction (*23*). Damman and Steen explored the processes shaping ports' zero-emission efforts using PCM (*24*). Debnath et al. explored pedestrian decision-making in a busy urban environment using PCM (*25*). This study identified factors influencing road-crossing behavior through verbal reports from forty-six participants in Dhaka city, revealing the impact of environmental conditions on pedestrian safety. Utilizing socio-technical transition theory, Wu et al. examined China's transition from traditional to new energy vehicles, revealing four distinct phases and emphasizing the pivotal role of government in shaping policy implications for electric power, technological innovation, and industrial coordination (*26*). Ceylan et al. applied a Systems Theoretic Accident Model and Process (STAMP) to analyze a ship allision accident, highlighting the dynamic and complex nature of maritime transportation systems and the limitations of traditional accident analysis methods (*27*). McKerral and Pammer investigated factors contributing to driver risk and expertise development by operationalizing situation awareness (SA) using a PCM-based scheme adapted to the driving context (*28*). Results suggest that although gaze metrics and verbalizations indicative of SA differentiate between expert and experienced drivers, they do not correlate with each other. Duarte et al. assessed various strategies implemented by municipalities to enhance citizen engagement by devising a methodology aimed at assisting local authorities in elevating public involvement and fostering stronger citizen commitment to the city (*29*). Das et al. utilized PCM to analyze narrative descriptions of twenty-four e-scooter collisions in Texas in 2021, offering policy insights and a novel approach applicable to broader road safety concerns (*30*). Recent research in ergonomics and safety emphasizes the integration of socio-technical methods, as demonstrated in Hamim et al. utilizing Accimaps, STAMP-CAST, and PCM to analyze a rail-level crossing incident in Bangladesh, revealing diverse perspectives and enabling comprehensive safety recommendations (*31*). The review indicates that socio-technical methods such as PCM are versatile tools used in various research domains, from analyzing vehicle crashes to understanding pedestrian decision-making in urban environments. Its application highlights the complex relationships between human behavior, environmental conditions, and technological advancements, providing crucial insights for safety measures and policy implications in diverse contexts worldwide.

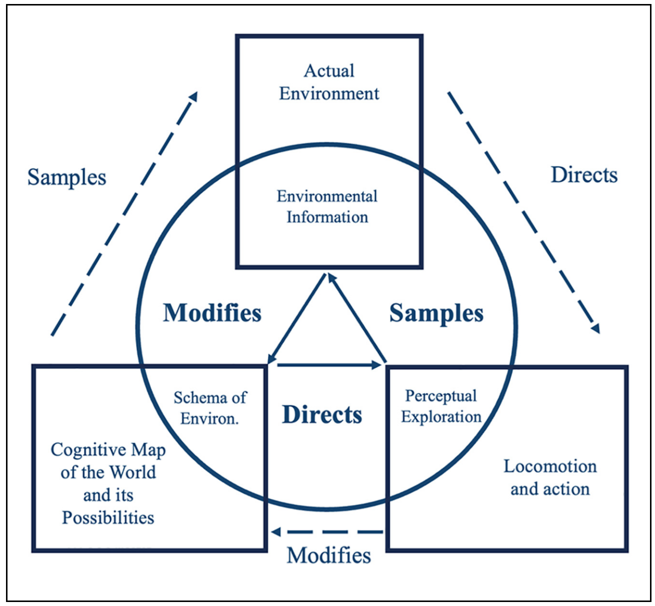

Figure 1. Schematics of the perceptual cycle model.

Methodology

Perceptual Cycle Model

The PCM offers a structured and comprehensive approach to examining the various stages leading to a crash, encompassing crucial aspects such as hazard perception, decision-making processes, and the execution of actions. PCM is an appropriate approach for ambulance-related special investigation studies as it offers a comprehensive understanding of human cognition and behavior within the context of complex systems. PCM, rooted in Neisser's concept of the cyclical relationship between human thought processes and interactions with the external world, allows for a complex analysis of ambulance drivers' SAS and their interactions with the dynamic environment during emergency response situations. Studies like Scott-Parker et al. (*22*), Das et al. (*30*), and Banks et al. (*21*) have demonstrated the relevance of PCM in recognizing the complex demands placed on road users and the potential risks associated with inadequate SA. By applying PCM, this study can identify factors influencing ambulance driver decision-making and behavior, ultimately informing safety interventions and strategies to mitigate risks for drivers, patients, and other road users in emergency scenarios.

Figure 1 shows the PCM as a connection between world, schema, and actions. Neisser (*16*) stated that top-down (TD) and bottom-up (BU) processing is necessary to link the relationships between the world, schema, and actions. With the activation of a schema, TD processing occurs as specific information kinds are then anticipated. BU processing typically follows, in which actions are intended to find specific information and are interpreted within the constraints of the current schema. In the PCM framework, perception is a dynamic interplay between TD and BU processing. TD processing relies on pre-existing knowledge and expectations to interpret incoming sensory information, allowing us to make sense of ambiguous stimuli based on prior experiences. On the other hand, BU processing is driven by the raw sensory input, analyzing individual elements to form a complete understanding without heavy reliance on prior knowledge. When observations conflict with expectations from an existing schema, the schema must be changed, or an alternative schema must be chosen.

The PCM is an approach that examines both technical and social aspects of intricate systems, including transportation systems (*16*). This makes it well-suited for examining the complexities of ambulance-involved collisions. This study aims to present a fresh perspective on ambulance-related crashes and provide valuable insights for enhancing safety interventions. By contrasting the findings derived from the PCM, this study seeks a comprehensive understanding of the underlying factors and dynamics contributing to ambulance-related crashes. To effectively address the complexity of ambulance collisions and formulate a comprehensive strategy for improving safety, a dual-method approach utilizing both PCM and text mining is imperative. These two methods complement each other, with PCM offering a cognitive perspective and text mining providing valuable insights from textual data. This dual-method approach incorporates both perceptual and data-driven aspects, enhancing the ability to devise effective measures for ambulance safety.

Text Network Analysis

Text network analysis (TNA) is a versatile natural language processing tool that has found widespread applications, including in analyzing ambulance-related crash reports. It has recently been widely used in transportation safety studies (*32–37*). TNA leverages nodes and edges to establish connections between keywords within a given corpus. Its real strength is its ability to represent keywords and uncover their relationships visually. In TNA, the node size corresponds to the frequency of each keyword in the corpus, whereas the edges represent the co-occurrence of keywords in the network. This visual representation allows researchers to gain valuable insights into the patterns and associations in the text data, facilitating a comprehensive understanding of the underlying relationships and themes.

For ambulance-related crash report analysis, TNA can be applied to extract critical information from a large corpus of crash reports. By identifying and visualizing the key keywords, TNA helps to reveal the common themes, contributing factors, and patterns in these reports. For instance, the node size may represent the prevalence of specific crash-related terms, such as "roll-over," "intersection," "ambulance driver," or "patient injuries," providing an overview of the most frequently occurring elements in the reports. The edges between nodes demonstrate the co-occurrence of these keywords, unveiling their interconnectedness and shedding light on how certain factors or events are related.

Data Collection and Analysis

Table 1 shows key information for ten special investigation reports on ambulance crashes, collected from NHTSA. The crashes occurred in various locations and times, including interstate highways, intersections, and rural roadways, during different lighting conditions (e.g., dark, dusk, daylight, and night). The maximum posted speed limit (PSL) ranged from 35 to 75 mph. These crashes involved a varying number of vehicles, from single-vehicle incidents to crashes involving two vehicles. The occupants also varied, including drivers and passengers of different ages and genders. The severity of the crashes varied, with some resulting in fatalities and others causing incapacitating injuries. The table provides age and gender information about the drivers and occupants involved in the crashes. The crashes occurred in different states and at various times, ranging from 2016 to 2020.

Results and Discussions

Results from PCM

Table 2 describes PCM mechanisms for ten special investigation reports on ambulance crashes. Different elements, including world, schema, and action, are described for each crash. Figures 2 and 3 show visual depictions of the PCM mechanisms for the different crashes.

World: The third column of Table 2 describes the world of the PCM framework. There was great diversity in the road conditions and their potential impacts on road safety.

Multiple crashes occurred on roadways with different lane configurations, including two-lane and four-lane roads and undivided and divided roadways. Additionally, some crashes occurred at urban intersections, whereas others happened in rural areas. This highlights the diversity of road environments in which these incidents occur. The weather conditions vary significantly across the incidents. For instance, crashes occurred from snowy with near white-out conditions to clear skies with calm winds. Temperature fluctuations are also evident, with temperatures ranging from −27°F to 86°F in different incidents. Another distinguishing factor is the presence of specific roadway features in each crash. Some incidents mention fog lines, rumble strips, asphalt shoulders, and edge lines, whereas others describe elements like guardrail systems, metal guardrails, and concrete roadways. These

Table 1. Key Information for Ten Special Investigation Reports on Ambulance Crashes

Id	Date, State	Crash location/time	#Veh	Max. PSL	Driver(s)	Occupants	Max. severity
1	Apr 2016; Colorado	Two-lane divided interstate highway/dark	1	75 mph	23 years/female	53 years/female; 57 years/female	Fatal
2	Sep 2016; Ohio	Intersection of a two-lane state highway and a two-lane rural roadway/ dusk	2	55 mph	45 years/female; 48 years/male	42 years/male; 45 years/female	Fatal
3	Jul 2016; New Mexico	Four-leg intersection in an urban environment controlled by three-phase traffic signs in all directions/daylight	2	35 mph	24 years/female; 35 years/female	21 years/female; 32 years/female; 6 weeks; female; 21 years/male; 60 years/male; 63 years/female	Fatal
4	Aug 2017; Oklahoma	Interchange and a four-lane, divided interstate highway/night	1	60 mph	33 years/male	28 years/female; 66 years/female	Fatal
5	Jun 2017; Georgia	Four-lane roadway/night	1	NA	21 years/female;	29 years/male; 55 years/male	Fatal
6	Oct 2018; Ohio	Rural two-lane, State-maintained roadway/ evening	2	NA	28 years/male; 22 years/male	43 years/female;	Fatal
7	Mar 2018; Ohio	Five-lane, undivided U.S. highway	1	50 mph	26 years/male	49 years/female; 76 years/male	Fatal
8	Feb 2018; Virginia	Four-lane divided roadway in a rural setting/morning	2	55 mph	29 years/male; male	26 years/male; 47 years/female	Fatal
9	Jan 2019; Michigan	Intersection of two undivided roadways/ afternoon	2	50 mph	44 years/male; 73 years/female	45 years/male; 25 years/female; 79 years/female	Fatal
10	July 2020; Missouri	Interchange of a four-lane interstate highway/ afternoon	2	70 mph	61 years/male; 60 years/female	27 years/male; 48 years/male	Incapacitating

Note: NA= not available, Max. = maximum; #Veh = vehicle number; PSL = posted speed limit.

differences highlight the diverse characteristics of the road infrastructure where the crashes occur. Additionally, the geometry of the roadways, such as curves or intersections, could play a role in some crashes.

Schema: The fourth column of Table 2 describes the schema of the PCM framework. It lists different incidents on the roadway involving different vehicles and their drivers. The causes of the crashes vary significantly, all leading to potentially dangerous consequences. Factors such as weather conditions, driver behavior (including alcohol consumption and medical conditions like hypoglycemia), and misperception of signals contribute to different incidents. The specific actions taken by the drivers also differ, such as losing control on wet roads, colliding with a tree after drifting off the road, or attempting evasive maneuvers to avoid crashes. Additionally, some ambulances were transporting emergency patients, whereas others were transporting non-emergency patients. These differences highlight the complex and unpredictable nature of crashes on the road, emphasizing the need for drivers to adapt to various circumstances and exercise caution. It also underscores the importance of adhering to traffic rules and avoiding impaired driving.

Action: The fifth column of Table 2 describes the action of the PCM framework. Some of these crashes share the outcome of rollovers, but they exhibit significant differences across various factors. Firstly, in some incidents, the ambulances rolled over multiple times before coming to rest on their right side. Secondly, specific factors led to unique scenarios, such as one crash causing the patient's cot to detach because of a fractured attachment arm. Thirdly, another rollover occurred when an ambulance collided with another vehicle, leading to the ejection of the ambulance driver. Additionally, there were cases where the ambulance collided with an impact attenuator, resulting in an eight-quarter-turn right-side-leading rollover, and both the patient and personnel were ejected from the patient compartment. These findings have similarities with other studies (*1*, *2*, *38*). Moving to other occurrences, certain crashes involved front-to-side impacts and subsequent rollovers, with the

Table 2. PCM Mechanism for Ten Special Investigation Reports on Ambulance Crashes

ID	Crash	World	Schema	Action
1	2016 CO	Crash occurred on a two-lane interstate highway bordered by white fog line, rumble strip, and asphalt shoulder. Speed limit was 75 mph. It was dark with no streetlights, snowy with near white-out conditions with slush-covered road. Weather at nearest reporting station: 21°F, 98% humidity, 1.5 miles visibility.	Vehicle traveling with emergency lights flashing at 56.3 mph. It was transporting a patient with cardiac issues. The belted 23-year-old female driver was driving in winter weather. Driver objected about strong wind, and lost traction and control on the wet roads.	Ambulance rolled over in the median multiple times, covering 39.8 ft before stopping on its right side. Crash caused patient cot to detach because of fractured attachment arm.
2	2016 OH	This crash occurred at dusk in the intersection of a two-lane, rural lane rural roadway and state highway. Both lanes were about 10 ft wide with solid white edge lines and 55 mph of PSL. The weather was clear with 10 miles visibility, a temperature of 75°F, a dew point of 66°F, according to local weather reports.	Ambulance transporting non-emergency patient approached rural intersection. The driver consumed alcohol, increased speed, and initiated left steering and braking before crash.	Ambulance collided with second vehicle, causing rollover. Ambulance rolled over and traveled 66 ft, while vehicle 2 came to rest in cornfield after traveling 154 ft. Ambulance driver ejected from vehicle.
3	2016 NM	The crash occurred in a four-leg urban intersection, with an IH frontage road and a two-way roadway. PSL for the roadway was 35 mph, with two lanes in each direction separated by a double yellow painted stripe and delineated by solid and dashed white painted stripes.	Ambulance with emergency lights and siren transported 6-week-old patient. It entered intersection with misperception of green signal and collided with Vehicle 2 despite braking.	Crash involved front-to-side impact and subsequent rollover. Vehicle 2 rotated 90 degrees, tire de-beaded, and deflated, leading to rollover. Vehicle 2 ended up resting on its right side in intersection.
4	2017 OK	The crash occurred on an interchange of a four-lane divided interstate highway. The travel lanes had a left curve with 984.2 ft of radius and + 2.5% grade. The PSL was 60 mph. Weather was cloudy with clear visibility, 8.4 mph winds, and a temperature of 73°F with a dew point of 71°F.	Ambulance departed roadway in left curve at high speed. Driver attempted to steer back, yawed with 10 degrees before impact.	Ambulance collided with impact attenuator, resulting in right-side-leading rollover. It completed eight quarter turns, covering 105.0 ft, before coming to rest. Patient and paramedic were ejected from patient compartment.
5	2017 GA	The crash occurred on a four-lane roadway, with the impact on a tree located 34.4 ft from the edge line of the roadway and 92.5 ft from an intersection. The impact caused the tree to fracture and uproot. Environmental was reported with clear skies, a temperature of 71°F, 100% relative humidity, and calm winds.	Ambulance on rural highway drifted off road during left curve, collided with a tree without input from the sleeping driver.	The ambulance collided with a tree, resulting in a 30-degree rotation and left side leading rollover. It rolled three-quarter turns, covering approximately 61.0 ft, before coming to rest on its right side.
6	2018 OH (1)	The crash occurred in the evening on a rural two-lane roadway with a single travel lane in each direction, divided by a double solid yellow centerline and delineated by single-solid white fog lines. Each lane was 13.1 ft wide, and there were no shoulders. The PSL was 55 mph. The weather was cloudy, with moderate rain, a temperature of 50°F, and 100% relative humidity.	Ambulance driver noticed oncoming vehicle but couldn't react in time. Second vehicle negotiated curve, traveling at 51 mph. Non-contact vehicle detected ambulance and safely stopped on right road edge.	Ambulance collided with vehicle 2, causing rotation. Vehicle 2 hit fence before stopping. Ambulance rested in roadway with tire positions. Post-crash fire occurred in ambulance engine area.

(continued)

Table 2. (continued)

ID	Crash	World	Schema	Action
7	2018 OH (2)	The crash happened in the afternoon on a five-lane, undivided U.S. highway with a guardrail system. The roadway was straight and traversed in both directions. The PSL was 50 mph. Weather was cloudy with 20 mph winds, with temperature of 35°F, and dew point of 22°F.	Ambulance driver with Type 1 diabetes, conducting non-emergency transport, experienced hypoglycemia and lost control. Ambulance veered off shoulder at 53 mph, collided with guardrail end terminal.	Ambulance collided with guardrail end terminal, traveling down grade. Hit marker post, fractured trees at bottom of embankment. Fell-over rollover wedges cab and patient compartment into ditch bank. Vehicle rotated 180 degrees, coming to rest on wheels.
8	2018 VA	The crash occurred in a rural setting on a four-lane divided roadway during daylight. The roadway had two lanes in each direction separated by a 30.8 ft wide grass median. The PSL was 55 mph. The sky was clear, with a temperature of −27°F, 100% relative humidity, and calm winds.	Ambulance traveling at 64 mph approached intersection. Volvo tractor and another vehicle stopped at intersection. Ambulance driver made hard left turn to avoid crash, leaving rotating tire mark.	Ambulance collided with tanker's back plane owing to abrupt steering, deforming patient compartment and causing rotation, and entered grass median. Ambulance separated from tanker and struck vehicle 2's rear. Vehicle 2 and tanker came to rest near right shoulder.
9	2019 MI	The crash occurred at an intersection of an undivided roadway. The straight and level concrete roadway had tall willow bushes at the corner, obstructing visibility. The PSL for both roadways were 50 mph. The weather was fair, with a temperature of 53°F and 74% humidity.	Ambulance responded to the stroke patient with lights and siren. Driver slowed down in second lane at intersection. Vehicle 2, driven by 73-year-old female, changed lanes but stopped truck obstructed view.	Both vehicles enter intersection. Vehicle 2 braked before crashing. Ambulance impacted by front of vehicle 2, resulting in 90 degrees rotation and left side leading rollover. Ambulance rested on left side, while vehicle 2 rested after rotation.
10	2020 MS	The lane was 13.1 ft wide with bituminous shoulders, rumble strips, and metal guardrails. The PSL was 70 mph, with dry roadway surface. Weather was partly cloudy with a temperature of 86°F.	Ambulance transporting patient without emergency lights or siren, in the right lane at speeds ranging from 60 mph to 65 mph. Vehicle 2 in the left lane nearly collided with witnesses, driver suspected to be impaired.	Vehicle 2 crossed into right lane, colliding with ambulance back bumper. Ambulance rotated, veered off roadside hitting guardrail, then cable barrier, resulting in rollover. Vehicle 2 collided with guardrail, coming to rest on roadway edge.

Note: PSL = posted speed limit.

vehicle resting on its right side in an intersection after rotating 90 degrees. Furthermore, a collision with a tree resulted in a 30-degree rotation and left side leading rollover, with the ambulance rolling three-quarter turns before coming to rest on its right side. Additionally, another crash saw the ambulance colliding with another vehicle, leading to rotation, while the second vehicle hit a fence before stopping. The ambulance rested in the roadway, and a post-crash fire occurred in the engine area. In addition, there was an incident where the ambulance collided with a guardrail end terminal, traveled down a grade, and hit marker posts and fractured trees at the bottom of an embankment. This resulted in a rollover, with the cab and patient compartment wedged into a ditch bank, and the vehicle came to rest on its wheels. In another crash, the ambulance collided with a guardrail end terminal after the other vehicle crossed into the right lane and collided with the ambulance's back bumper. This caused the ambulance to rotate and veer off the roadway into the guardrail. Lastly, abrupt steering in a different crash led to the ambulance colliding with the backplane of a tanker, deforming the patient compartment, and causing rotation. Other studies also showed similar evidence (*39*). Subsequently, the ambulance separated from the tanker and struck the other vehicle's rear. Both vehicles came to rest near the right shoulder.

Table 3 describes the post-crash occurrences and the driver kinematics for special investigation reports on ambulance crashes. The post-crash scenario columns list various incidents and responses, highlighting the challenges drivers, emergency responders, and law enforcement personnel face.

Among the post-crash descriptions of ambulance crashes in the table, several commonalities and variations

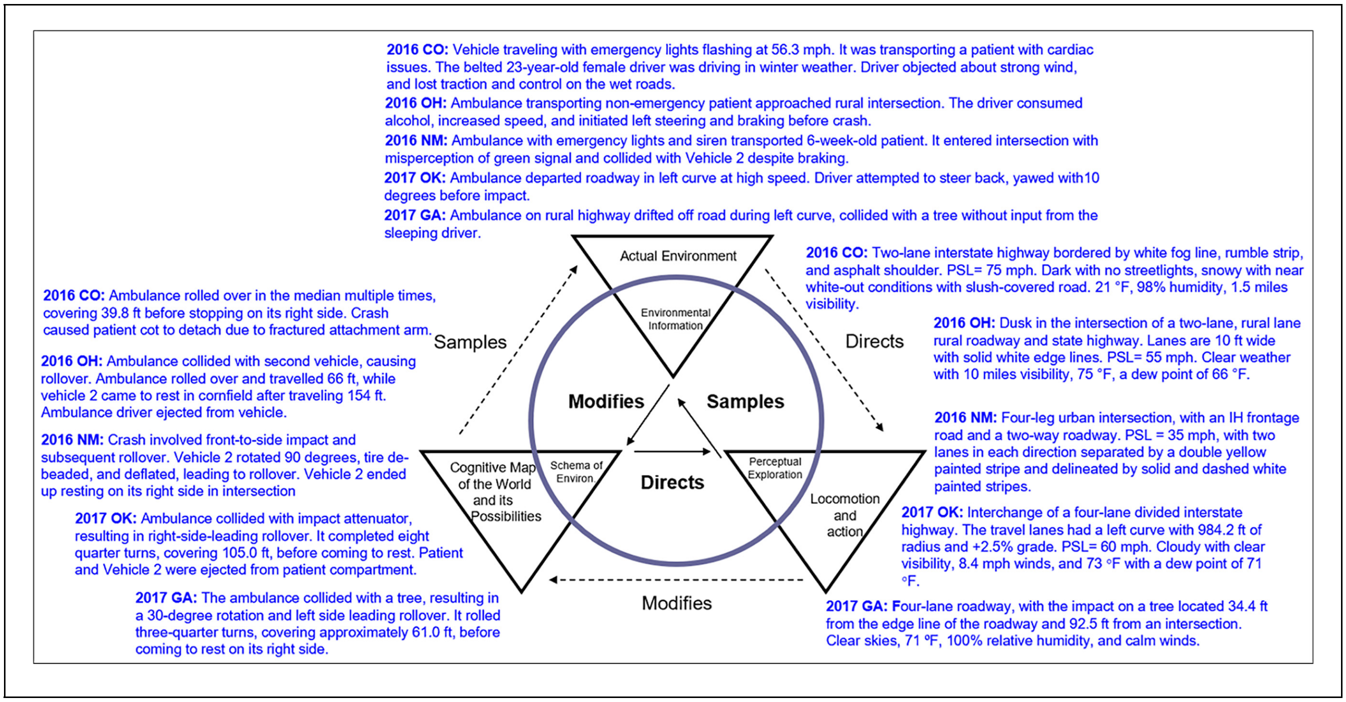

Figure 2. Perceptual cycle model for special investigation reports on ambulance crashes (ID 1–5).

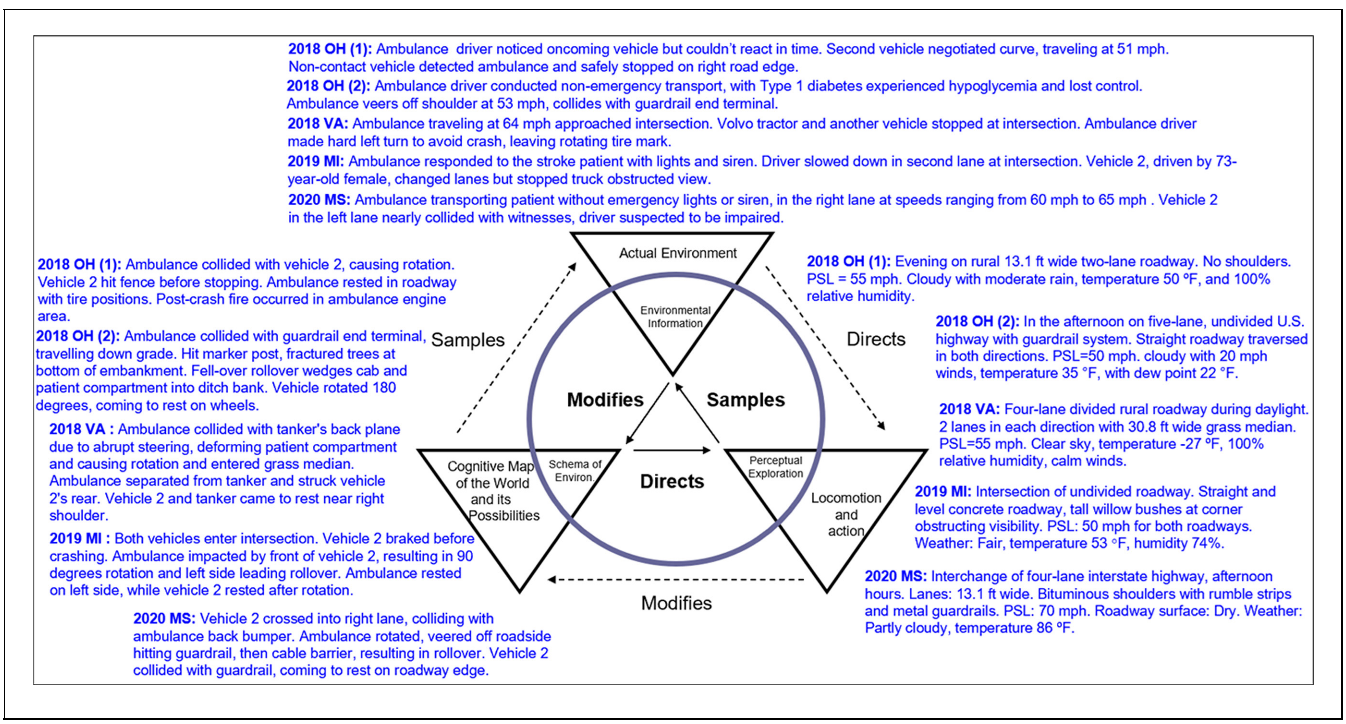

Figure 3. Perceptual cycle model for special investigation reports on ambulance crashes (ID 6–10).

exist. In many instances, there is a clear focus on providing medical assistance to the occupants involved in the crashes, either by witnesses or trained Emergency Medical Technician (EMT) responders. Witnesses and passersby assisted the victims in one crash, breaking windshields, clearing glass, and turning off oxygen flow and the engine. In another case, a nurse found a child in the patient compartment and provided emergency care.

Table 3. Post-Crash and Driver Kinematics for Ten Special Investigation Reports on Ambulance Crashes

ID	Crash	Post-crash	Driver kinematics
1	2016 CO	Two witnesses assisted crash victims, breaking windshield and clearing glass. Ambulance driver moved to patient compartment, found patient displaced from cot. Third passerby turned off oxygen flow and engine. Driver sustained non-incapacitating injuries.	The 23-year-old female ambulance driver experienced counterclockwise vehicle rotation. She was displaced to the right during deceleration and alternately to the right, top, and left during the rollover. Her left thigh contacted the steering wheel, causing a contusion. Although her torso remained secured by the seat belt, hyper-extension of her head and neck resulted in a muscle strain in her cervical spine. She self-extricated and was subsequently transported by ambulance to a local hospital for treatment.
2	2016 OH	Vehicle 2's patient sustained incapacitating injuries. Ambulance driver passed away after crash. Patient remained restrained on cot and transported with incapacitating injuries. Vehicle 2 driver has non-incapacitating injuries and had been drinking. Both vehicles towed as a result of damage.	The driver, with a medical history of cholecystectomy, thyroidectomy, and partial bowel resection with stoma, experienced multiple injuries. The frontal airbag was deployed, displacing the driver left and forward and resulting in rib fractures, pulmonary contusions, laceration of the left lung, and spleen injuries. Additionally, the driver was further displaced when Vehicle 2 struck the ambulance's left side. During the subsequent rollover, she was ejected through the disintegrated left front glazing, sustaining a forehead laceration from contact with Vehicle 2's left front window.
3	2016 NM	Nurse found child in patient compartment and provided emergency care. Vehicle rested on right side. Another ambulance arrived, assisted occupants, and transported to local hospitals.	The belted 24-year-old female driver was seated upright and actively steering the vehicle. Approaching the intersection, she manually sounded the air horn, slowed down, and checked for other vehicles. On impact with Vehicle 2, the driver was displaced to the left. The vehicle initiated a rotation and a right-side-leading one quarter-turn rollover, displacing the driver to the right. Despite this, she remained held in place by her seat belt. After the vehicle came to rest, the driver exited with assistance.
4	2017 OK	Driver and paramedic injured, taken to hospital. Driver treated and released; paramedic remained hospitalized for 12 days before transfer to nursing facility. Patient deceased at crash scene. Ambulance towed because of damage	During the crash, the driver, who was seated in a rear-most position with a reclined seat back, experienced the deployment of the frontal airbag and seat belt pretensioner. The impact caused the driver to be redirected in multiple directions during the rollover, resulting in head contact with the roof and a scalp abrasion. The driver was taken to a local hospital by another ambulance and later treated and released.
5	2017 GA	Driver exited overturned vehicle through window. Unresponsive patient was found pinned under cot, pronounced deceased. Driver and EMT were transported to hospital. Coroner removed deceased body, and ambulance was towed to agency's facility.	The five-week-pregnant driver, who had a pre-existing medical condition called LQTS, experienced morning sickness and headaches before the crash. Admitting to falling asleep while driving the ambulance, she failed to navigate the left curve of the roadway, resulting in a straight trajectory. Despite the vehicle's undulations, she couldn't react in time to avoid the crash.
6	2018 OH (1)	Emergency services responded to the crash site. A fire in the ambulance engine compartment was put out. The driver suffered incapacitating injuries and was taken to the hospital. Sadly, the front-row right occupant passed away at the hospital. The ambulance was towed away from the crash scene.	The driver's specific posture was unknown. On impact with vehicle 2, the driver moved forward, and the seat belt system was loaded, causing potential soft tissue and internal injuries. The driver remained in the driver's seat until emergency responders cut the seat belt system to remove him from the vehicle because of perceived serious injuries.

(continued)

Table 3. (continued)

ID	Crash	Post-crash	Driver kinematics
7	2018 OH (2)	Driver with possible injuries taken to hospital. Paramedic found in patient compartment stairwell, airlifted to hospital for treatment. Patient deceased at crash scene, transported to coroner. Tow truck called to remove ambulance.	The driver, seated with the seat track adjusted forward, experienced a forward trajectory on impact, loading the seat belt webbing as the retractor locked. The seat belt prevented contact with frontal components. As the vehicle translated down the embankment and hit trees and the ditch bank, the driver was displaced forward and right but remained secured by the seat belt. During the end-over-end rollover, the seat belt kept the driver in place, preventing interior contact and potential injury.
8	2018 VA	Fire department, law enforcement, and EMS responded to crash scene. Patient was freed from ambulance cot and transported to hospital and succumbed to injuries 8 days later. Ambulance driver and front passenger transported to hospitals. Drivers of truck tractor and vehicle 2 uninjured. Ambulance taken for investigation, other vehicles released to owners.	The driver's seat belt usage was determined based on its post-crash condition. Utilizing the vehicle's cruise control, driver maintained speed while approaching a controlled intersection. Sudden left steering and abrupt braking indicated possible distraction near the stationary semi-trailer. On impact, the driver moved forward and slightly to the right, extending his arms and potentially sustaining injuries to his finger and elbow. No other injuries were found to support the driver's motion during the crash.
9	2019 MI	Law enforcement and ambulance driver provided medical assistance to rear occupants. Female EMT hospitalized. Ambulance driver reassessed and treated at hospital. Patient deceased. Male EMT treated and released. Both vehicles towed.	At impact with Vehicle 2, the driver was displaced toward the front and right. During the rollover, he was further displaced to the left, contacting the left side window. He assisted in treating other passengers with his back and head pain. The driver was evaluated at the crash site and then transported to a hospital for treatment. He reported visible injuries and a minor headache. He was discharged from the hospital after three hours.
10	2020 MS	Paramedic found on rear door, rescued by EMS. All occupants taken to hospitals with incapacitating injuries. Vehicle 2 driver transported with non-incapacitating injuries. Both vehicles towed, ambulance to salvage yard, vehicle 2 to recovery service's yard.	The driver of the ambulance experienced a rear impact with vehicle 2 (Event 1) and was displaced to the right as the ambulance rotated and struck the end terminal of the W-beam guardrail and the cable guardrail systems (Events 2 and 3). This caused the ambulance to roll in a right-side leading event (Event 4). The driver sustained injuries to the scalp, face, and soft tissues. He was transported by ambulance to a hospital, where he was admitted for treatment.

Note: EMS = emergency medical services; EMT = emergency medical technician.

Ambulance drivers, paramedics, and patients or passengers typically sustained injuries and were taken to hospitals for treatment, with some being released whereas others remained hospitalized for extended periods. Tragically, there are cases where patients and EMTs involved in the crashes succumbed to their injuries at the scene or in the hospital. Additionally, the vehicles' status differed across crashes, with some being towed because of damage, taken for investigation, or sent to salvage yards. Overall, the post-crash descriptions of ambulance crashes highlight the critical role of first responders, the varying degrees of injuries suffered by occupants, and the unfortunate loss of life in some instances.

The driver kinematics described in the table provides insights into the various movements and injuries experienced by ambulance drivers during crashes. Similarities can be observed in some incidents, such as drivers being displaced to the right on impact or during rollovers. Deploying frontal airbags in certain crashes also resulted in drivers being displaced left, right, or forward. Seat belts were crucial in securing drivers, preventing them from being fully ejected and minimizing the risk of interior contact and potential injury. However, specific injuries varied among the drivers, ranging from contusions, rib fractures, and lung injuries to lacerations and soft tissue injuries. Additionally, pre-existing medical conditions, distractions, and driver fatigue contributed to some crashes.

The PCM provides a broad understanding of the stages involved in road crashes. The "World" column highlights the diversity of road conditions and their potential impact on safety. Crashes occurred in various settings, including different lane configurations, urban intersections, and rural areas, with various weather conditions and temperatures. Specific roadway features and geometry, such as curves and intersections, also played a role. The "Schema" column describes the varying causes of crashes, including weather conditions, driver behavior, and misperception of signals. The actions taken by drivers differed significantly, resulting in distinct crash outcomes and circumstances, with most crashes resulting in rollovers. The "Action" column depicts the crashes' outcomes, which exhibited similarities and differences. Rollovers were common, but the specific details, such as collisions with other vehicles or objects and final resting positions, varied greatly. Similarly, insights into post-crash information and driver kinematics were obtained and analyzed. Common themes include providing medical assistance to occupants, injuries sustained by ambulance drivers, paramedics, and patients, and the unfortunate loss of life in some cases. Witnesses and trained responders are critical in aiding victims during these incidents. The kinematics of ambulance drivers during crashes reveals displacements and injuries experienced, emphasizing the importance of seat belts in preventing ejections and minimizing interior contact. The presence of pre-existing medical conditions, distractions, and driver fatigue also contribute to such crashes.

Results from TNA

Figure 4 presents the TNA of reports on ambulance crashes, categorized into four groups: world, schema, action, and post-crash. The world network contains significant keywords, such as roadway, intersection, lane, direction, conditions, traffic, and travel. Noteworthy connections within this network include travel and roadway, intersection and roadway, lane and roadway, traffic and intersection, and traffic and occurred. These findings suggest that collisions predominantly occurred while ambulances were traveling on roadways, especially at intersections, and the crashes involved traffic and various lane configurations. Moving to the schema network, prominent keywords include patient, speed, emergency, ambulances, impact, and right. The top connections within this network are speed and prior, speed and patient, impact and patient, intersection and patient, emergency and right, and intersection and right. This suggests that the schema of these crashes involves factors such as previous speed, emergencies, speed during patient transportation, and intersections, potentially involving right turns or right lanes. In the action network, significant keywords include impact, clockwise, rollover, right, front, and struck. The primary connections observed in this network are impact and patient, event, and patient, and front and impact. These connections indicate that several crashes had patients involved during the impact, and the crashes potentially involved the front of the ambulance. Lastly, the post-crash network highlights keywords such as transported, emergency, patient, local, towed, hospital, and injury. Noteworthy connections within this network include local and emergency, compartment and removed, patient and removed, local and fire, local and towed, injuries and transported, and hospital and transport. These connections imply various post-crash scenarios, such as local emergency responses, transportation of injured patients to hospitals, towing of vehicles, and potential post-crash fires. Overall, this TNA provides a comprehensive understanding of various aspects of ambulance crashes, such as location patterns, contributing factors, and post-incident scenarios.

Conclusions

The PCM has proved to be a powerful tool in providing a comprehensive understanding of the stages involved in road crashes. The "World" column analysis reveals the diverse range of road conditions and environments that can affect safety. The "Schema" column sheds light on the varied causes of crashes, including weather conditions, driver behavior, and misperception of signals. The actions taken by drivers differed considerably, resulting in distinct crash outcomes and circumstances, with rollovers being a common occurrence. The "Action" column depicts the crashes' outcomes, which exhibited similarities and differences. Although rollovers were frequent, the specific details, such as collisions with other vehicles or objects and final resting positions, varied greatly. Moreover, post-crash information and driver kinematics were analyzed, revealing common themes like providing medical assistance to occupants, injuries sustained by ambulance drivers, paramedics, and patients, and unfortunate loss of life in some cases. Witnesses and trained responders were critical in aiding victims during these incidents. The key findings from the application of the PCM include the diverse range of factors contributing to road crashes, the varied causes of crashes, and the significant impact of driver actions on the crash outcomes. The model provides a holistic understanding of the interconnected factors influencing road safety by examining

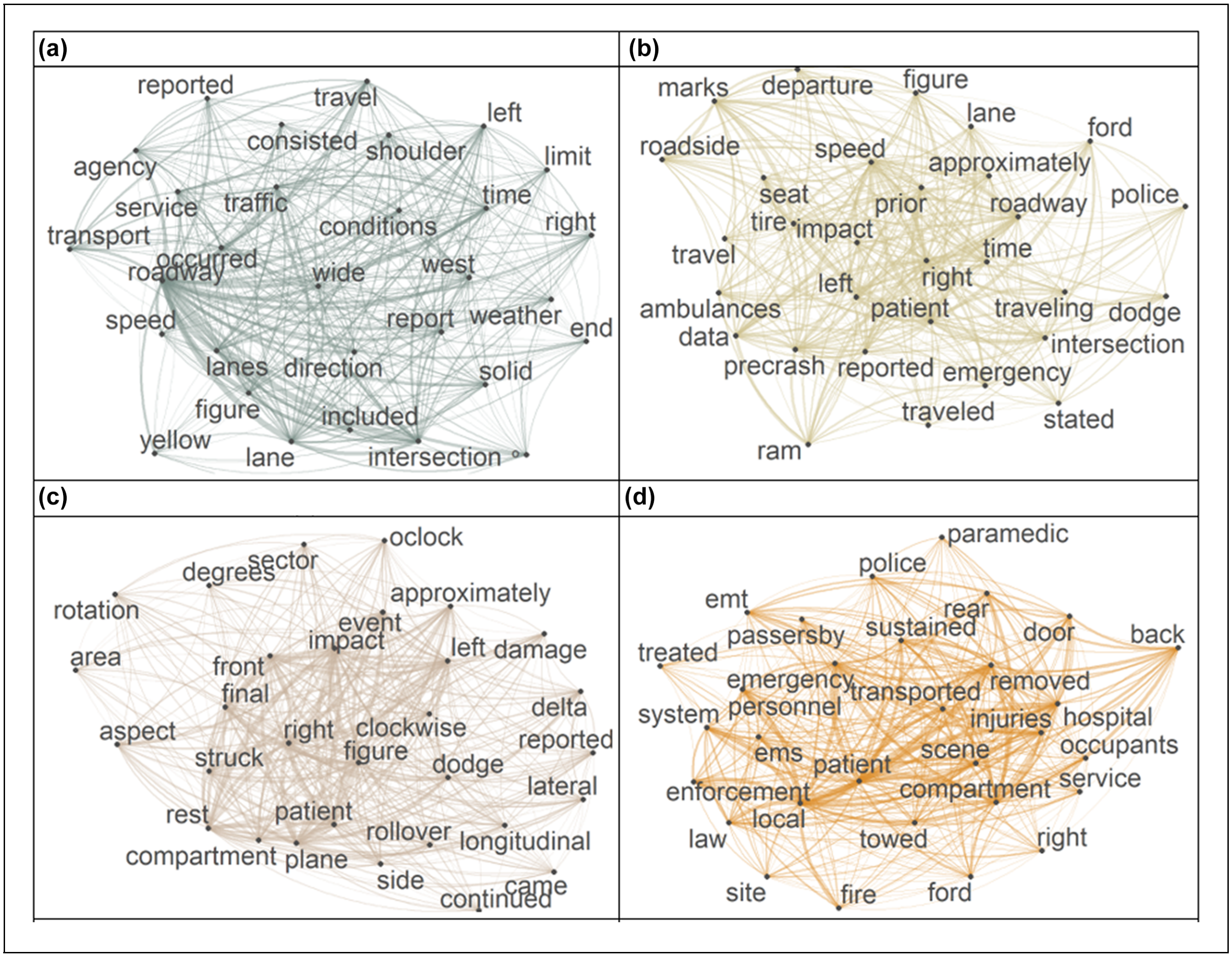

Figure 4. Text network analysis: (*a*) world, (*b*) schema, (*c*) action, and (*d*) post-crash.

these three components. Moreover, the TNA visualization offers valuable insights into crash reports' underlying themes and connections. This analysis suggested that ambulance crashes frequently occur on roadways, especially at intersections, with traffic being a prevalent factor. The crashes involve patients being affected and potentially injured, leading to post-crash scenarios involving local emergency responses, transportation to hospitals, and vehicle towing.

The findings of this study, based on the analysis of a limited dataset comprising ten in-depth special crash investigation reports, necessitate a cautious interpretation. The small sample size underscores the preliminary nature of the identified patterns and trends, urging restraint in making broad generalizations. The observed occurrences, particularly concerning rollovers and specific crash details, should be considered indicative rather than conclusive. The study's outcomes provide initial insights but warrant further investigation with larger and more diverse datasets to validate and enhance the robustness of the results. This study has constraints for the lack of detailed information on seat-belt usage for individual occupants, especially if such data are inconsistently documented in NHTSA special case reports. This limitation restricts the depth of the analysis about the influence of restraint device utilization on injury outcomes in ambulance crashes. Future research should prioritize improving data collection methods to ensure comprehensive documentation of seat-belt usage for all occupants involved in ambulance crashes. Additionally, it is essential to acknowledge the limitations of the PCM and TNA employed in this study. The effectiveness of the PCM relies on data quality and completeness, suggesting a need for more comprehensive datasets in future research. External factors not considered by the PCM, such as infrastructure changes, may affect road safety dynamics.

Similarly, TNA's accuracy depends on meticulous data pre-processing and the size and diversity of the crash report corpus, emphasizing the importance of using representative datasets for improved generalizability.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Subasish Das; data collection: Subasish Das; analysis and interpretation of results: Subasish Das, Rohit Chakraborty; draft manuscript preparation: Subasish Das, Rohit Chakraborty, Abbas Sheykhfard, Boniphace Kutela, and Xinyue Ye. All authors reviewed the results and approved the final version of the manuscript.

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