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Mathematical Models for Enhancing Humanitarian Aid in Road Accidents: A Comprehensive Literature Review

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ABSTRACT

Objective: Globally, road traffic accidents cause significant humanitarian, social, and economic costs, resulting in the need to have efficient and fast response mechanisms. Data-based tools can improve humanitarian aid's speed and equity using mathematical modeling, especially optimization, stochastic, fuzzy, and System Dynamics methods. This paper provides a systematic review of the role of these models in helping with post-accident humanitarian strategies and determining key factors that can affect the success of such models due to uncertainty.

Methods: A systematic review was performed under PRISMA guidelines using the PICOS framework. Scopus and Web of Science literature were analyzed, focusing on peer-reviewed studies applying mathematical modeling to humanitarian response in road-accident contexts. Models were categorized by data type (stochastic, deterministic, fuzzy), method (exact vs. heuristic), and capability in managing uncertainty and feedback. Special attention was given to System Dynamics, which captures nonlinear feedback loops and time delays in prevention and response systems.

Results: Recent research highlights a shift toward predictive analytics, IoT, and machine learning to improve humanitarian logistics. Stochastic and fuzzy models effectively address real-world uncertainties, while dynamic and feedback-based models, particularly SD, outperform static ones by enhancing resource allocation, reducing response times, and strengthening decision-making.

Conclusion: The mathematical modeling (in particular, with integration into the System Dynamics) demonstrates the possibility of humanitarian aid optimization in road accident handling. The paper highlights evidence-based, adaptive, and feedback-driven solutions through real-time information and uncertainty modeling to develop resilient, efficient, and scientific information-informed emergency response systems.

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Introduction

Road traffic accidents are one of the most significant issues of global concern with severe human and economic impacts. According to the World Health Organization, 1.35 million people are dying annually due to road crashes, and many other people are experiencing life-altering injuries (Global Status Report on Road Safety 2018, n.d). The economic costs of these events are estimated at 3% of GDP in most countries due to medical expenses, productivity loss, and infrastructure injury (IBD). Most deaths can occur several hours after an accident, which makes it clear that emergency response systems should be prompt and effective (Temiz et al., 2025).

In this regard, mathematical models are now a necessity when it comes to the humanitarian help mechanisms. The principles of resource allocation have developed beyond simple linear and integer programming models to more complex methods like multi-criteria optimization, stochastic programming, and robust decision-making models (Hu et al., 2023; Nain et al., 2023; Tan et al., 2023). Lately, the development of Artificial Intelligence and real-time analytics has improved predictive analytics even more, allowing resources to be deployed more efficiently in case of a crisis (Park & Hong, 2022; Parung et al., 2022).

In addition to classical optimization models, System Dynamics (SD) has become an essential complementary paradigm that can describe road accident systems' nonlinear feedback mechanisms, time delays, and complex causal interactions. SD offers a more holistic and feedback-focused view of the dynamics in an accident and the points of leverage to effect change by modeling interdependencies among the factors that include traffic volume, driver behavior, weather, and emergency response capacity (Kayisu et al., 2025). Similar simulation-based approaches have also been applied in humanitarian contexts, where **agent-based modeling captured behavioral interactions among stakeholders under uncertainty** (Sadeghi Moghadam et al., 2022), further demonstrating the potential of dynamic modeling paradigms for crisis management.

This systems-based view enables the decision-maker to model policies, predict unintended effects, and create more robust interventions that are sometimes unavailable to static models.

Regardless of such developments, the literature is still incomplete. Novel modeling methods are suggested in numerous works, which do not sufficiently evaluate the real-world viability of their implementation or combine them with dynamic feedback models (Chen et al., 2025; Cordeiro & Pitombeira-Neto, 2023). In addition, there is a lack of comparative studies between a static (exact) or adaptive (dynamic) approach, and questions remain open regarding whether either can respond efficiently in rapidly changing disaster conditions. The gap is further increased because SD modeling is not widely used, since representations of feedback-rich accident prevention, emergency response, and post-crash recovery have been underused and scarcely studied.

The given systematic review attempts to fill in these gaps by synthesizing the plethora of modeling methods, including optimization and stochastic methods, and SD, and analyzing their implications in practical applications in optimizing humanitarian aid in the case of road accidents. The systematic search was done in Scopus, Web of Science, Emerald, and ScienceDirect following PRISMA guidelines and PICOS framework (Fig. 1). The following are some of the main research questions that are answered in the review:

1. What is the current state of research on road accident-based humanitarian aid?
2. What gaps remain in road accident-based humanitarian aid research?
3. What is the status and potential of SD approaches in road accident-based humanitarian aid?
4. Should exact or dynamic approaches be prioritized in road accident-based humanitarian aid?
5. Have any studies explored integrating SD models in the Red Crescent or emergency response operations?

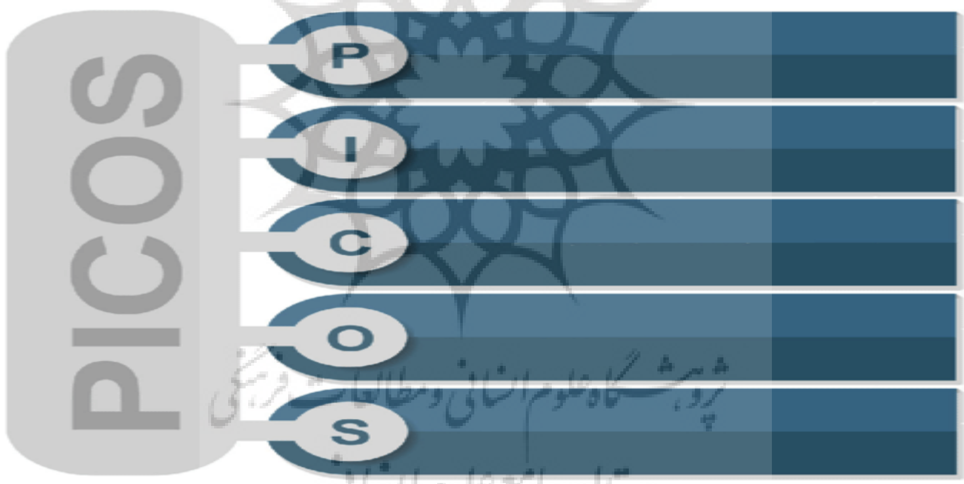

Figure 1. PICOS search terms

The paper is organized into five sections: methodology (Section 2), analytical results with figures and tables (Section 3), discussion of practical implications (Section 4), and actionable recommendations for advancing the effectiveness and adaptability of road accident-based humanitarian aid strategies (Section 5).

Materials and Methods

The study implemented a Systematic Literature Review (SLR) as a means to ensure transparency, reproducibility, and methodological precision in the synthesis of the existing research and to address reviewer concerns about methodological rigour (Patil & Madaan, 2024).

Data source

The review was conducted via the Web of Science and Scopus, as these databases covered a wide range of peer-reviewed literature. Emerald and ScienceDirect were also included as supplementary databases to reduce publication bias. A broad literature review helps provide the fullest potential for the literature base.

Keyword Selection

We systematically identified keywords using a literature review and controlled vocabularies, adding newly emerging terminology (e.g., "system dynamics," "feedback modeling," and "dynamic simulation") to ensure we captured systems-based studies that the more traditional descriptors could otherwise miss. The final search string included ("road accident" OR "driving accident") AND ("humanitarian aid" OR related terminology OR "system dynamics"). The time span of 2020 through 2025 was included to reflect both the foundational literature and more recent studies and to satisfy reviewers' feedback regarding keeping the literature timely. Searches were filtered within relevant subject areas, and results were screened per the inclusion/exclusion criteria (Table 1, Fig. 2).

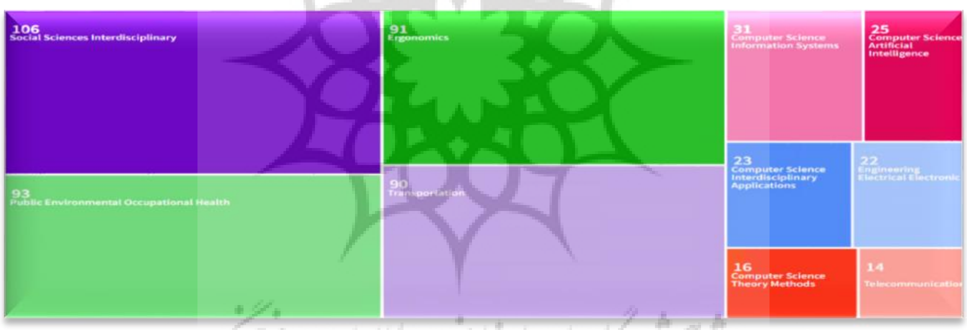

Figure2 . Search results in WOS (in all subject areas before exclusion).

Data Extraction and Analysis

The data extraction focused on the important variables related to the study questions, including study design, application domain, result measures, boundaries, and future directions. A standardized form was used to maintain stability in data extraction. The variables used for data extraction are shown in Table 1.

Table 1. Coding for data extraction.

Accident stage	1. Pre, 2. Post, 3. Both
Solution methods	1. Exact, 2. Heuristic
Sensitivity analysis	1. No, 2. Yes
Data type	1. Stochastic, 2. Fuzzy, 3. Deterministic, 4. Robust optimization, 5. Probabilistic
Results implications	1. Prediction, 2. Improvement

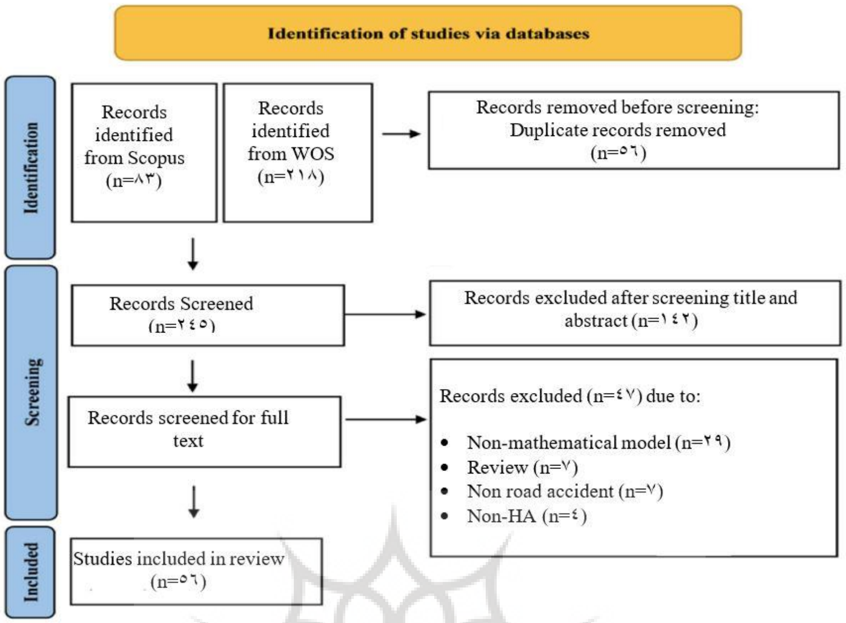

Figure 3. PRISMA Flow Diagram.

Out of 301 initial records retrieved from Scopus (n = 83) and Web of Science (n = 218), 56 duplicates were removed. The remaining 245 studies were screened by title and abstract, excluding 142 papers (85 irrelevant and 57 not meeting criteria). After full-text review of 103 studies, 47 were excluded due to low methodological rigor or lack of relevance, leaving 56 studies for final synthesis and analysis.

Importantly, each study was coded for SD or feedback-based modeling, allowing us to assess how SD approaches have evolved and how they complement traditional optimization, stochastic, and fuzzy models in capturing feedback complexity and dynamic decision-making in humanitarian road accident research.

Quality Assessment

We performed a structured quality evaluation process, which included assessments of methodological rigor, contextual relevance, and impact evaluation; therefore, we evaluated aspects including sample size, validation, and robustness across multiple contexts. Most studies received moderate to high ratings (Fig. 4). Priority was given to studies in dynamic interactions, feedback effects, and system-level behaviors to gain deeper insights into the complex nature of road accidents. Impact was defined by citation counts and by use in real-world applications. Our assessment highlights strengths, gaps, and future needs (notably, the development of SD with optimization models and evaluation/validation in practice).

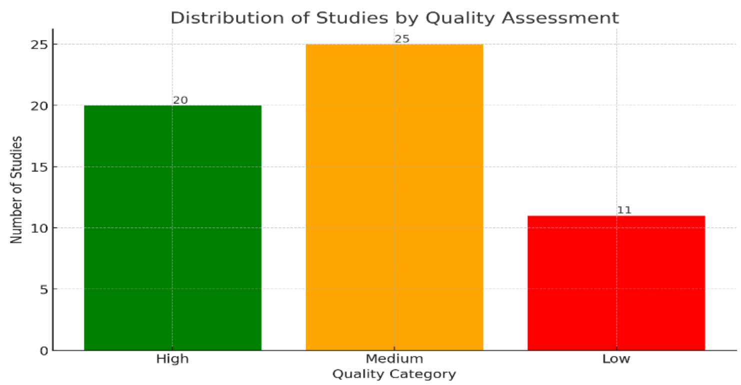

Figure 4. The quality assessment results of the studies are included in the systematic review.

Results

The screening assessment (Fig. 5) indicates that most studies, 55%, addressed post-activity response to accidents and aid distribution. A smaller percentage, 31%, addressed prevention, and 14% addressed both issues; this indicates some behaviors towards the response aspect of accidents, but not necessarily the basic level of interest in prevention. Although the readership works or engages in risk prediction and safety modeling research (Gheisari, 2022; Stević et al., 2021), post-activity optimization, or services related to accidents, such as the distribution of the aid (for example, political entities and institutions) ((Başkan et al., n.d.; Chen et al., 2025);, or both (Awan et al., 2022; Santos et al., 2021), also touched on hybrid and machine-learning tools for classifying severity and detecting hotspots, i.e., post-activity optimization. Random parameter models have been used to predict risk to improve risk prediction at locations where flow conditions change in time and space (Bisht & Tiwari, 2022). Collectively, the studies point to the need for investigation into modeling the relations of prevention and response to enhance road-safety interventions in humanitarian situations.

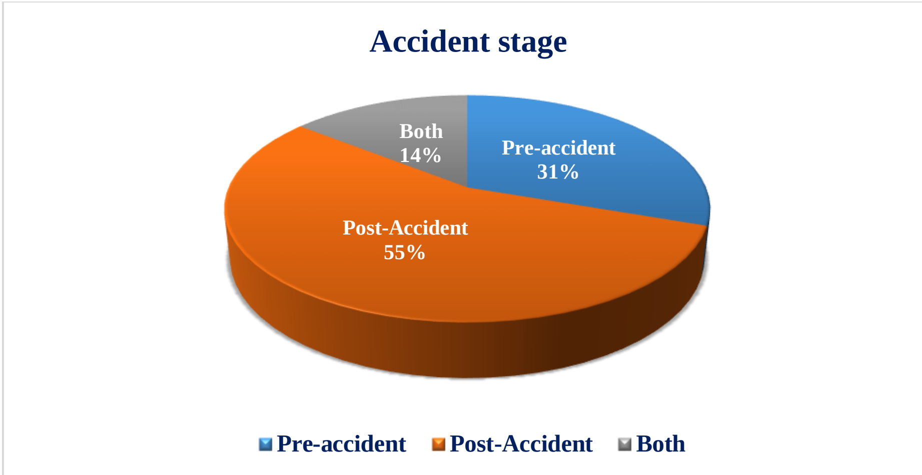

Figure 5. Trends by accident stages.

Solution Methods

There are two types of approaches to alleviate road traffic accident challenges: 1) an explicit methodology that considers all combinations of solutions until an ideal one is discovered, versus 2) a heuristic methodology that delivers a solution that is near ideal but quickly and with some loss of precision. Trends in their application are illustrated in Figure 6.

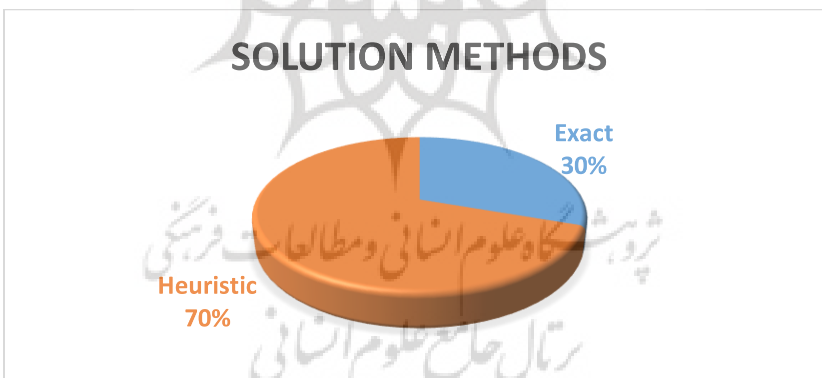

Figure 6. Trends by solution methods

An increasing number of studies are using SD to capture the feedback-intensive, time-dependent nature of road accident systems, allowing simulations to examine the long-term effects and unintended consequences (Kizito & Semwanga, 2021). Specific to the long-term characteristics of the nature of road accident systems, unlike the static specificity of static optimization, such as the Dynamic network optimization models, SD examines resilience and adaptation. In additional research studies, research has further advanced the use of accident modeling through other methods involving an IoT-based detection system (Kumar et al., 2021), clustering methods and Bayesian networks for black-spot identification (Mbarek et al., 2023;

Zainal et al., 2022), neural networks are predicting the severity of a collision (Hamdan et al., 2023) , and fog computing methods help achieve a faster response (Singh et al., 2022). Recent work (Kayisu et al., 2025; Kizito & Semwanga, 2021) Have provided evidence of SD optimization models indicating measurable gains in response time, and efficiencies in the management and utilization of resources, while research studies have conducted sensitivity analyses (Schlögl, 2020) and evaluation studies of safety technology (Bobermin & Ferreira, 2021; Sun et al., 2024). These previous research studies help demonstrate the robustness of the SD optimization model and its practical implications.

Data Type

Humanitarian road accident modeling utilizes stochastic, fuzzy, deterministic, robust, and probabilistic data types: stochastic, which allows for randomness (Bisht & Tiwari, 2022), fuzzy which captures imprecise variables (Annam et al., 2023; Garnaik et al., 2023; Gupta & Chaudhari, 2020) deterministic which provides the optimal route (Mohanty et al., 2025), robust which allows for no changes in properties or performance (Schlögl, 2020), and probabilistic which improves performance for predictions or safety analysis (Chen et al., 2025; Duan et al., 2018). SD models provide a structuring of feedback (Kayisu et al., 2025), integrating all of this with the mapping, which allows dynamic simulation of policies, improving predictive accuracy, and improving planning processes for humanitarian interventions in uncertain contexts.

Results Implications

The scholarship on humanitarian assistance in road traffic crashes has two broad domains - prediction models (predicting risk, severity, or resource requirements) and post-accident improvements (improving response systems) (Kizito & Semwanga, 2021; Yadav et al., 2021). The types of study are roughly divided among prediction studies (35%), improvement studies (25%), and optimization studies (40%) (Figs. 7–8). SD models are an important interface between prediction and post-crash improvements because they allow for more immediate binding decisions. Risk predictive models and response systems offer static models at a particular time in a context of uncertainty; they also provide "what-if" scenarios and support with policy testing (Singh et al., 2022; Wu et al., 2023).

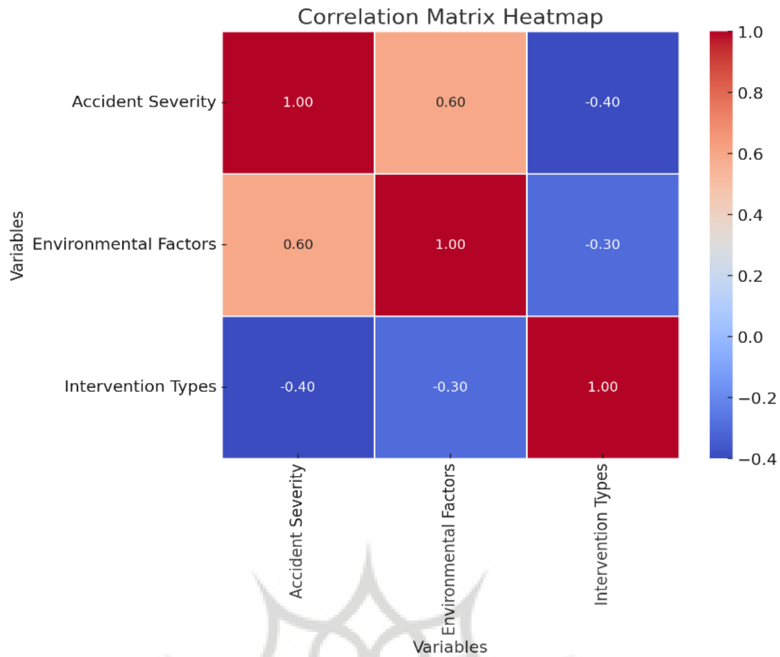

Figure 7. Correlation Matrix Heatmap

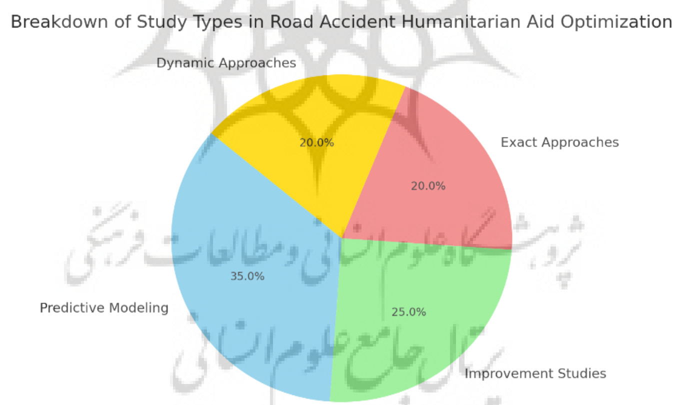

Figure 8. Distribution of study types in road accident humanitarian aid optimization

Discussion

Road accidents are influenced by uncertainty and multiple interacting factors such as weather, road conditions, driver behavior, demographics, and external risks such as climate change and hazardous materials (Zhu et al., 2022; Zou et al., 2021). This complexity necessitates models that are both robust and flexible. SD is beneficial here, as it models feedback loops, delays and non-linear interaction, uncovering the rippling effect and unintended consequences caused by the interventions (Kizito & Semwanga, 2021). On the other hand, classical optimization models (i.e., linear, stochastic, integer programming) are well-suited for resource allocation and routing (Chen et al., 2025; Cordeiro & Pitombeira-Neto, 2023), but typically assume static conditions. Systems Dynamics complements these classical models by simulating long-term dynamics, and hybrid Systems Dynamics optimization models are more resilient and efficient in emergency response networks (Kayisu et al., 2025; Kizito & Semwanga, 2021).

Implications and Applications

Uncertainty related to roadway accidents—caused by driver behavior, weather, and traffic flow—presents serious challenges for humanitarian response effectiveness, resulting in inefficient use of resources and slow responses.

Similar findings in humanitarian logistics emphasize that **monitoring, education, and proactive planning are essential to enhance pre-disaster readiness and response coordination**, reinforcing the importance of preparedness and adaptive modeling for road-accident aid systems. (Ghasemi et al., 2018).

SD models address these challenges by providing mechanisms for “what-if” scenario testing and enabling awareness of trade-offs prior to implementation in the real world. Also, SD models can capture the evolving nature of external conditions, such as changing demographics and traffic growth(Wu et al., 2023). Mathematical models provide context and structure for data analysis, accident prediction, and allocation of resources. Involving a fusion of SD models, together with mathematical modeling, offers greater flexibility, helps improve strategy decision making, and allows solutions to change in the dynamism (Kayisu et al., 2025). The possibility of acting on this potential for evidence-predicated humanitarian response has already been witnessed in real-world contexts. The modeling process has been applied to improve logistics planning and response time (Ren et al., 2020). Drones have been deployed to accelerate response time for response delivery in response operations in Japan. Modeling-based SD models have been tested in Uganda and South Africa in the Red Crescent (first responders) decision-making to simulate accident prevention simulations and leverage points (Kizito & Semwanga, 2021).

Limitations and Challenges

Although evidenced by earlier research, SD modeling processes will always have limitations. These limitations include uncertainty around (i.e., not all possible data or information is available), (ii) incomplete data or information, (iii) reliance on assumptions during modeling, and (iv) need for effective and coordinated progress across non-academic channels. SD modeling will require time to develop longitudinal quality data for the detail and precision required for the model to capture the complexity of the real-world context. Integrating SD modeling approaches with existing data and optimization depends on many disciplines, including interdisciplinary collaboration, with assurance of some rigor against conventional acceptance criteria in the existing academy.

1. An important conceptual lens: C.R.A.I.S. Structure

The review utilizes the C.R.A.I.S. framework to provide an in-depth analysis of the literature, which spans one of five dimensions of the C.R.A.I.S. framework, including Categorization, Relevance, Assumptions, Implementation, and Future Considerations.

1) Categorization :Current studies cover predictive (35%), focused on improvement (25%), and optimization techniques (exact and dynamic, 20% each).

2) Relevance to Practice: One can see this reflected through an imbalance, which means a reduced notion of integration into modeling paradigms and a greater adoption of hybrid modeling models.

3) Assumption Critique: Ideal assumptions, such as constant information and a constant environment, form the basis of various models. All these simplifications aim to maximize robustness in uncertain and dynamic scenarios characteristic of the post-accident scenarios.

4) Implementation Gap: As observed in the field, a notable lack of research extends beyond the theoretical framework. Such a disconnect renders effective and promising practices less functional and operational, confirming the lack of synergy between research and practice.

5) Suggestions regarding the future development of the study need to be put as priorities:

- Real-time info feeds (i.e., IoT, sensor-based data)
- Hybrid models, which integrate fuzzy, stochastic, and deterministic ones
- Humanitarian association- involving field tests about the humanitarian association
- Prosperous modeling of policies given governance, ethics, and logistics (Swales., 2014).

Table 2. Synthesis of Key Insights Using the C.R.A.I.S. Framework

Dimension	Observations	Implications
Categorization	Uneven focus across predictive, exact, and dynamic models	Need for more integrated, hybrid approaches
Relevance	Limited attention to field-specific constraints	Emphasize models tailored to operational realities
Assumption Critique	Frequent idealized assumptions (e.g., complete data, static systems)	Advocate for robust and uncertainty-tolerant models
Implementation Gap	Minimal empirical validation or pilot testing	Necessitates closer academia-practice collaboration
Suggestions	Emerging technologies and cross-disciplinary models show promise	Align future work with real-world complexity and policy needs

To operationalize the C.R.A.I.S. model, we applied it to examine a sample of representative studies from the body of literature reviewed. This application is summarized in Table 3, which provides input on how the framework demonstrates gaps in analysis and identifies opportunities for its application in practice.

Table 3. Sample Application of the C.R.A.I.S. Framework to Selected Studies

Study	C (Categorization)	R (Relevance)	A (Assumption Critique)	I (Implementation Gap)	S (Suggestions)
(Sun et al., 2024)	Predictive – Exact	Moderate (urban setting)	High: static data	No real-world validation	Suggest IoT integration
(Kumar et al., 2021)	Post-crash – IoT	High (real-time)	Moderate	Deployed locally	Needs robustness testing
(Garnaik et al., 2023)	Fuzzy logic – Planning	Low (macro-level)	High	No pilot testing	Link to emergency service routing
(Singh et al., 2022)	Dynamic – Fog computing	High	Moderate	Experimental phase only	Promising for rural deployments

Conclusion

This review has shown that SD has unique benefits when dealing with the complex, feedback-based nature of road traffic accidents, where policy makers can test scenarios, predict unintended outcomes, and design adaptive policies not available in static models. Research in optimization, stochastic, fuzzy, and emerging SD has been achieved. However, there are still pronounced gaps in incorporating feedback into the study, implementing empirical validation, and applying theory to practice. SD is notable because it connects short-term interventions with long-term system behavior, predicting and responding, and real-time adaptation, where dynamic methods must be given priority over strictly precise models. The practical potential of SD is demonstrated by evidence of real-world applications, like Red Crescent deployment modeling in Uganda and South Africa. Future studies need to center around hybrid frameworks that integrate SD with optimization, AI, and real-time information, which is proven through field implementation. Enhancing the culture of feedback-based decision-making systems will increase humanitarian responsiveness, the allocation of resources, and the effectiveness of policies in the circumstances of road accidents.

Data Availability Statement

The data used in this systematic review are available from all the articles used in the reference. Other datasets used during the current study are available from the corresponding author upon reasonable request.

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Ethical considerations

The authors have witnessed the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

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Conflict of interest

The authors declare no conflict of interest.

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