Research and Design of Traffic Mitigation and Rescue Assistance Products for Highway Accident Sections

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Abstract. To address congestion, delayed rescue, and safety hazards from highway accidents, a traffic mitigation and rescue product integrating intelligent transportation, real-time data analytics, vehicle-road coordination, and holographic projection early-warning is designed. It enables precise accident-info push, personalized traffic guidance, high-risk vehicle interception, and multi-department collaborative dispatch, significantly improving emergency response efficiency.

Keywords: Intelligent Transportation System, Emergency Management, Big Data Analysis, Collaborative Scheduling, Vehicle-Road Cooperative System.

1 Introduction

1.1 Design Background

China's highway network has grown dramatically from a mere 147 km in 1988 to 161,000 km by 2021, ranking second globally, yet this rapid expansion has brought increasing safety challenges in mountainous regions. However, frequent collapse accidents—especially in mountainous areas—pose serious safety threats, exposing critical shortcomings in early warning and traffic management. The July 2024 Zhaoshui Bridge collapse, caused by flash floods, killed 38 people, as monitoring systems failed to detect hidden structural dangers in advance[1], and emergency channels were blocked during golden rescue time. As shown in Fig. 1 and Fig. 2.

Fig. 1. The collapse site of Zhashui Bridge

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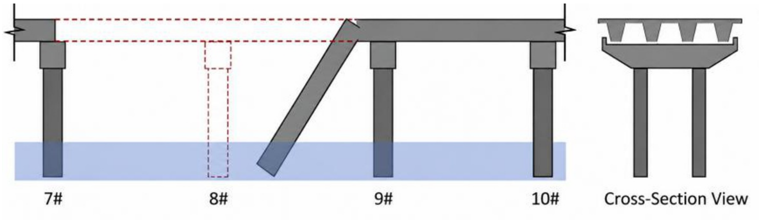

Fig. 2. Diagram after the bridge collapsed

The May 2024 Meida Expressway landslide saw slope monitors fail due to multipath false alarms, with 23 vehicles blindly entering the collapse zone. Rainfall triggers 96.6% of slope failures, yet existing systems lack reliability. Zhaoshui floods destroyed base stations, causing communication outages, while rescue relied on single-point satellite phones. Unreliable early warning, manual diversion, and inadequate rescue equipment remain key unsolved bottlenecks[2].

1.2 Research Subjects

This designs a traffic mitigation and rescue system for highway collapse sections, addressing incomplete info acquisition, static diversion, inefficient resource allocation, and weak user protection via an intelligent multi-tech platform.

1.3 Research Objectives and Significance

The research aims to design integrated mitigation and rescue products for mountainous highways that combine real-time monitoring, dynamic traffic diversion, and specialized rescue equipment for immediate incident response. Aligned with smart highway needs, this approach integrates infrared monitoring, holographic warnings, and vehicle-road collaboration to address early warning blind spots and diversion chaos exposed by the Zhaoshui Bridge collapse and Meida landslide cases, ultimately shortening response times, reducing secondary risks, and optimizing rescue resource allocation. For the first time, MEC+SAR+holographic projection have been integrated into the highway rescue scenario.

1.4 Research Methodology and Workflow

This design follows a systematic design process: (1) analyzing core issues of traffic diversion and rescue in accident-prone sections via literature and cases (e.g., Zhaoshui Bridge); (2) user research via questionnaires and interviews; (3) ideation, sketching, digital modeling, CMF design and rendering; (4) testing and iteration. The full cycle from problem analysis to prototyping ensures practical rescue products.

2 Pre-Design Research

2.1 Market Status Investigation

2.1.1. Highway Construction in Mountainous Areas and Characteristics.

China's mountainous roads account for 40% of national mileage, featuring complex geology, extreme weather, and high bridge/tunnel ratios. Rainfall-induced infiltration destabilizes slopes[3]. The 2024 Meida & Zhaoshui accidents exposed monitor flaws like multipath false alarms and delayed warnings.

2.1.2. The Current Situation of Intelligent Highways.

China's smart highways follow a "1+3+N" framework (one cloud platform, three perception systems, N applications)[4], yet emergency rescue remains weak. Traditional slope monitoring relies on manual on-site collection—slow, imprecise, and weather-vulnerable—causing delayed deformation response[5]. Emergency coordination across departments is poor, and heavy rescue equipment like mechanized bridges has long deployment times, missing golden rescue windows.

2.2 Analysis of Market-Related Products

(1) SAR enables long-range, all-weather, decimeter-resolution detection, but multipath-induced ghosting degrades image quality[6][7].

(2) Vehicle-mounted bridges deploy within minutes, yet high costs limit their long-term deployment.

(3) V2X Intelligent Transportation achieves data transmission latency under 60ms with 5G compared to 300ms on 4G[8], yet OBU-RSU communication requirements of over 50Mbps and under 50ms still challenge autonomous driving[9], while future 5G+UWB integration promises higher precision for vehicle-road coordination.

(4) MEC Technology shifts computing to the network edge, enabling real-time slope detection by cutting transmission delays and boosting processing efficiency, overcoming traditional monitoring latency for timely early warning[10].

2.3 User Research

Focusing on drivers, rescue personnel, and traffic managers in highway accidents, this section analyzes typical cases and conducts interviews to identify behavior patterns, pain points, and functional needs, guiding user-oriented product design.

(1) Drivers lack disaster warnings in navigation and manual alerts fail in low visibility, with survivors on Meida Expressway reporting that navigation only showed congestion without collapse warnings, highlighting the absence of real-time risk assessment and post-accident rescue information access.

(2) Rescue Personnel face slowed grid searches from rainfall, blocked underwater inspections, equipment incompatibility, and communication failures delaying multi-department coordination.

(3) Traffic managers suffer from delayed alerts, ineffective guidance, and unreliable manual monitoring, as demonstrated by Meida's dynamic diversion which lacked real-time data-based intelligent algorithms.

Summary: A multi-technology emergency product is needed to serve all three user groups, boosting response speed and decision accuracy.

The Design Process and Results

2.4 Function Positioning

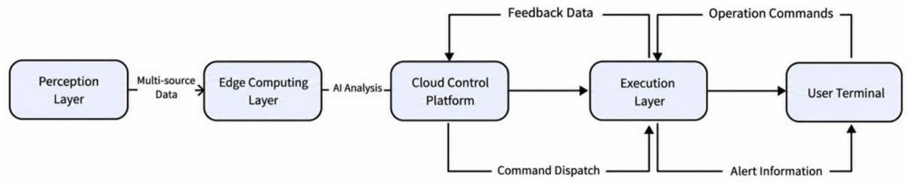

Fig. 3. System architecture design

Fig. 3 shows the system comprises three integrated modules. (1) Full-Scenario Monitoring & Early Warning: 3D deformation monitoring via SAR, infrared, GNSS, and Beidou+5G triggers three-level alerts where green (<1 mm/day) sends maintenance notifications, orange (>3 mm/day) activates traffic control with holographic warnings, and red (>5 mm/day) initiates vehicle escort with dynamic 3D "road collapse" signs. (2) Intelligent Traffic Management: V2X-based dynamic routing with AR HUD guidance and three-level holographic-to-forced-interception warnings prevent chain accidents. (3) Fast Interception Assistance: A modular device with an aluminum honeycomb airbag absorbs impact energy, and an electromagnetic switch inflates the bag 5× upon rear-end collision for effective energy absorption.

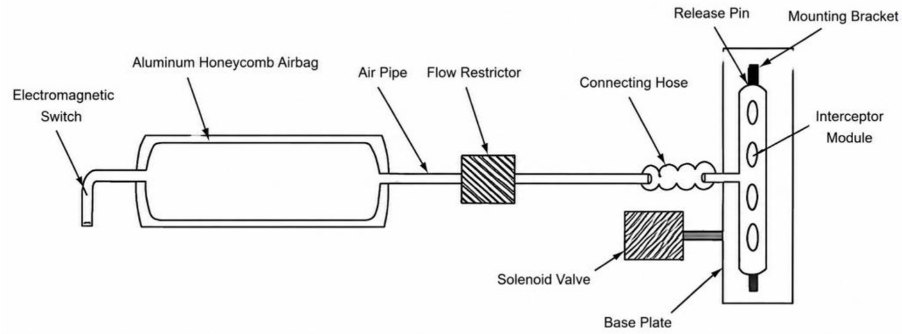

Fig. 4. Internal Switch Structure of the Anti-Collision Airbag

Electromagnetic switch triggers gas cylinder inflation on rear-end impact, expanding airbag 5× for energy absorption. The structure is shown in Fig. 4.

2.5 Design Concept and Development

Guided by the principle of integrating intelligent monitoring, vehicle-road guidance, and holographic warnings, the design followed a systematic flow: Initial Intention & Sketching analyzed rescue workflows (early warning→guidance→rescue) to generate concept sketches Fig. 5, iterated dimensions for portability-function balance, and used traffic-light logic to inform the warning system. Modeling & Feasibility Exploration utilized KT/cardboard/foam mock-ups Fig. 6 and Fig. 7 with iterative adjustments to verify feasibility, complemented by digital modeling refinement.

Detail Optimization incorporated stabilization technology and functional modules (warning lights, holograms, sensing) to enhance adaptability, ensuring efficiency, stability, and safety under highway conditions Fig. 8.

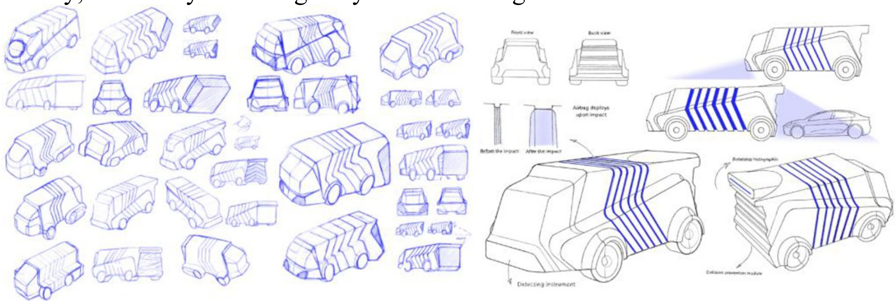

Fig. 5. Sketch

Fig. 6. Mold Simulation

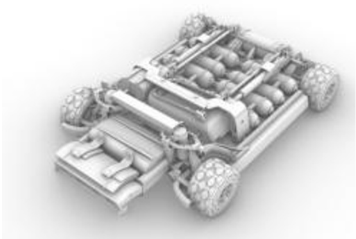

Fig. 7. Component Detail Illustration

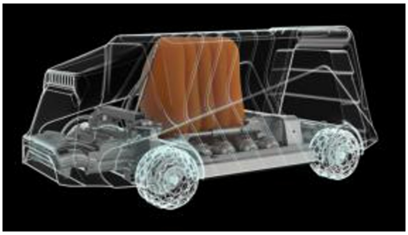

Fig. 8. Internal Detail Illustration

2.6 Expression of Design Outcomes

The product measures 5500 mm × 2200 mm × 3200 mm, constructed from steel/cast iron and energy-absorbing modules of aluminum honeycomb and polyurethane. Fig. 9 shows the silver-orange CMF scheme conveys technological sophistication (silver) and dual visual-psychological warning (orange), achieving functional-emotional integration like Fig. 10. Fig. 11 display the logo "Smart Flow" represents vehicle-road intelligence and traffic guidance control.

Fig. 9. CMF (Color, Material, Finish)

Fig. 10. Rendering Image

smartFLOW

Fig. 11. Logo Design

2.7 Technical Validation

Fig. 12 display the interception vehicle’s design follows a "modular energy absorption + rigid safety cage" logic: 5 independent energy-absorbing modules (0.3 m × 2.5 m × 0.16 m each) are horizontally arranged to cover the full lane width, paired with a 3.0 m × 2.5 m × 2.0 m cockpit (including roll cage, counterweight, and control system) to ensure driver safety. Total mass ≥ 3 tons to prevent rollover.

Functional Module	Key Metric	This Design	Existing Solution Comparison
Early Warning Response Time	From Detection to Alert	<5 seconds (MEC Edge Computing)	Traditional Solution >30 seconds
All-Around Warning Triggering Distance	Effective Visual Distance	≥200 m	Traditional Signage <50 m
Airbag Deployment Time	Millisecond Level	<50 ms (Electromagnetic Trigger)	Mechanical Type >200 ms
Rescue Equipment Deployment Time	Minute Level	<3 minutes (Modular Design)	Traditional Mechanical Bridge >15 minutes

Fig. 12. Component Function

Component	size(length*width*height)	functional description
Single energy absorption module	0.3m * 2.5m * 0.16m	Horizontally arranged, covering the width of the lane
Total occupancy of energy absorption zone	2.0m * 2.5m * 0.16m	including module gaps and support structures
Cockpit and rear	3.0m * 2.5m * 2.0m	including roll cage counterweight and control system
Intercept the vehicce as a whole	5.0m * 2.5m * 2.0m	total mass ⩾ 3 tons, to prevent rolling

Fig. 13. Design a quantitative comparison table

Fig. 14. LS-DYNA simulation deformation diagram

Collision safety is verified via LS-DYNA numerical simulation as the Fig. 13 shows: Under a 60 km/h (16.67 m/s) impact, the system absorbs 208 kJ of kinetic energy, reducing driver acceleration to ~9.4 g (<15 g safety threshold). Fig. 14 reveal the simulation confirms the design effectively mitigates collision risks while maintaining structural integrity.

3 Conclusion

An integrated system combining intelligent monitoring, holographic warning, and vehicle-road guidance improves highway collapse response and reduces secondary accidents. Four gaps remain:

(1) Extreme environment adaptability is limited as monitor stability degrades under heavy rain, high dust, and seismic activity.

(2) Cost constraints exist because modular interception devices involve high manufacturing costs without mature mass-production support.

(3) System compatibility is hindered as V2X and MEC integration faces significant technical barriers, limiting cross-platform interoperability.

(4) UI interaction is suboptimal as the user terminal interface lacks intuitive design and efficient information delivery.

In future work., work will target extreme-environment reliability via new materials, low-cost modular design for scalable deployment, deeper V2X–MEC–platform fusion, and refined UI/UX to complete the "monitoring–warning–diversion–rescue" chain for smarter highways.

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