

Fire Station Management System Based on Digital Twin

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Abstract. To streamline travel, alleviate traffic congestion, and enhance overall traffic safety, the Internet of Vehicles (IoV) technology has emerged. This not only simplifies the lives of modern individuals but also integrates with other technologies, fostering advancements in various fields. Notably, the integration of digital twin technology with IoV is widespread, enabling the visualization of road conditions for informed route decisions and optimization. This paper focuses on applying this capability to a fire truck management system, empowering swift route selection, optimal vehicle deployment, and efficient execution of rescue activities in the shortest time and at the lowest cost.

Keywords: Internet of Vehicles, Digital Twin, Road Decision, Fire Station Management.

1. Introduction

Modern traffic challenges, encompassing issues like traffic congestion, driving safety, and environmental pollution, have gradually posed difficulties for individuals and society. Addressing these challenges has spurred innovation and improvements in information and communication technology, emerging as a focal point of interest. Intelligent Connected Vehicles (ICVs) have gained prominence, notably introduced in the "Made in China 2025" plan as a product resulting from the convergence of intelligent mobility and the Internet [1]. Defined in the "Energy-saving and New Energy Vehicle Technology Roadmap," ICVs are equipped with advanced on-board sensors, controllers, actuators, and other devices. They integrate modern communication and network technology to enable intelligent information exchange and sharing with entities denoted as X (including people, cars, roads, clouds, etc.). With capabilities such as complex environment perception, intelligent decision-making, and collaborative control, ICVs aim to achieve safe, energy-efficient, and comfortable driving, ultimately representing a new generation of vehicles capable of autonomous operation.

The technology facilitating information exchange among vehicles and other entities is referred to as the Internet of Vehicles (IoV). IoV is conceptually similar to the Internet of Things, with the key distinction being that moving cars are considered the primary perception objects. This is primarily achieved through the application of new information and communication technology to realize the aforementioned goals. The evolution of China's IoV market has progressed through stages such as basic IoV (support for remote calls), mobile Internet (integration of mobile phone applications with vehicles), in-vehicle infotainment (IVI), the 5G+V2X stage, and the current phase of integration with 5G technology. Vehicle networking comprises four layers: the perception layer, transmission layer, platform support layer, and application layer. Key components in IoV include radio-frequency technology and communication technology. Radio-frequency identification technology facilitates object identification and environmental sensing, while wireless sensor network technology incorporates various low-power, cost-effective, compact, and highly integrated sensing devices. Communication and network technologies establish connections between identification and sensing information, forming ad-hoc networks or interfacing with the Internet [2]. The limitations of sensors, the quality of data fusion, and the ability to understand the environment have yet to be solved in the vehicle perception system, which is one of the key directions of current research [3].

This paper primarily focuses on enhancing and refining the management system employed by fire stations. Currently, fire stations predominantly rely on human decision-making to allocate police resources and determine rescue routes. After the allocation, police officers choose routes based on existing navigation systems or their memory of familiar roads. However, during simultaneous

multiple disasters, efficiently formulating the most intelligent personnel allocation plan within a short timeframe becomes challenging. Ensuring the optimal allocation of police resources and prioritizing rescue activities becomes a complex task. Moreover, road conditions near disaster areas may be unpredictable for both navigation systems and drivers, including potential damage to road infrastructure caused by disasters. These factors hinder personnel from reaching the scene in the shortest time possible, resulting in inefficient rescue operations. Therefore, the intelligent cars are a way to help drivers and improve rescue efficiency. For example, Gipps model and MITSIM model can complete road change decisions according to road conditions [4]. Moreover, two attributes of "safety risk" and "time spent" need to be considered in the model to accomplish things that drivers cannot predict [5]. The integration of digital twin technology can offer a visual representation of the road situation. By employing optimization algorithms, the system can make informed decisions on the optimal routes, thereby constructing an intelligent fire station. This approach aims to achieve efficient rescue operations and minimize the impact of disasters.

Digital twin is a simulation process that employs intricate physical models and data acquired from sensors. By constructing a simulation model of complex driving scenarios through digital twins, a test environment featuring a plethora of diverse scenarios can be established for autonomous driving [6]. Since the digital twin exists as an information model in the virtual realm of a computer, possessing characteristics mirroring those of the corresponding physical entity, it can simulate and optimize the physical entity. Leveraging the advantages and characteristics of digital twins in conjunction with 3D modeling technology, traffic simulation technology, and GIS technology allows the creation of a traffic simulation scene with robust interaction and outstanding performance [6]. In order to ensure the accuracy of the position of the vehicle in the virtual space of the digital twin, it is necessary to couple the transformation of coordinates and rotation angle in the virtual space [7]. Consequently, digital twin technology is poised to play a pivotal role in the advancement of intelligent networked vehicles.

In this paper, we will devise a comprehensive, rapid, and systematic management system for fire stations leveraging digital twins. The objective is to ensure that upon receiving a disaster notification, emergency responders can swiftly reach the destination. Moreover, in scenarios involving multiple emergency tasks, personnel can be judiciously allocated. Furthermore, digital twin technology will be employed to chart the most optimized route for fire truck rescue operations. The final decision of the model is realized through two data analysis methods, decision tree [8] and artificial neural network [9] respectively.

2. IoV System and Digital Twin

The key technologies encompassed within the Internet of Vehicles (IoV) include radio-frequency identification technology, sensor network technology, satellite positioning technology, wireless communication technology, big data analysis technology, standards, and security systems. Leveraging the new generation of information and communication technology, IoV establishes an all-encompassing network connection among vehicles, cloud platforms, roads, and individuals. This realizes the concept of "triple play integration," involving the integration of Vehicle Intranet, Vehicle Internet, and Vehicle Mobile Internet [10]. Sensor technology plays a crucial role in perceiving the status information of vehicles. Importantly, the combination of wireless communication networks and advanced intelligent information processing technology facilitates intelligent traffic management, informed traffic decision-making, and efficient vehicle control. The diagram below illustrates the comprehensive connectivity of the Internet of Vehicles, where V2P denotes vehicle-to-personnel communication, V2N signifies vehicle-to-network platform, V2V represents vehicle-to-vehicle, and V2I stands for vehicle-to-infrastructure.

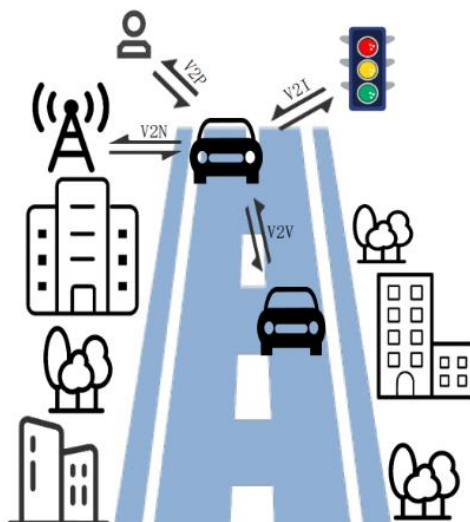


Figure 1. A typical IoV Scenario

The essence of the Internet of Vehicles (IoV) lies in leveraging vehicle-mounted equipment to efficiently utilize dynamic vehicle information within the information network platform through wireless communication technology (Fig. 1). This enables diverse functionalities during vehicle operation, including maintaining safe distances, reducing collision risks, aiding navigation, and enhancing overall traffic operation efficiency [11]. Globally, various countries are advancing intelligent transportation projects, aiming to establish seamless connectivity between vehicles and infrastructure using 5G communication technology. In the realm of vehicle perception, China is spearheading research on a "traffic accident multiple-spot warning system based on vehicle-road coordination," a critical initiative that integrates digital twin technology into the warning system's construction.

The concept of "twins" traces its origins back to NASA's Apollo program [6], where two identical space vehicles were created, with the one left on Earth referred to as the twin [12]. In 2003, Professor Michael Grieves from the University of Michigan introduced a digital conceptual model during product lifecycle management (PLM), defining it as a "virtual digital voice representation equivalent to physical products" [13]. From these early concepts, it becomes evident that both virtual space and physical space play crucial roles in the digital twin. A digital twin serves as an intelligent and evolving model, a virtual representation of a physical entity. Its purpose is to monitor, control, and optimize the functions of its physical counterpart. By acquiring analog and real-time data, the digital twin can develop autonomous learning capabilities and refine its digital model [14]. In the digital twin, data is stored as long as it is composed of a communication unit and a data transmission unit composed of V2X composed of LTE-V and UDP [15]. This autonomous learning ability enables it to achieve optimal solutions through calculations, predictions, and planning, minimizing reliance on human subjective judgment. As the advantages of the digital twin become more apparent, its integration with the Internet of Vehicles enables intelligent transportation. Currently, this integration can address collision warnings at intersections, left-turn assistance, blind spot warnings, emergency brake alerts, and reminders for emergency vehicles. Leveraging a self-developed twin visual system with a three-level structure comprising a platform, application, and portal, it offers a data-centric, online, and intelligent management service platform. This assists managers in real-time situational control, decision-making, and comprehensive analysis, management, and command. This paper aims to design an intelligent fire station management system based on digital twin technology.

3. IoV System Framework based on Digital Twins

The digital twin architecture comprises five layers: the physical layer, data layer, model layer, function layer, and application layer. This paper introduces a digital twin model specifically designed for simulating fire system tests. In the physical layer prototype of the model, key components include

the fire trucks involved in the test, on-board communication equipment, visual cameras, and radar-like ranging sensors. The data layer collects the digital form of the real physical entity. In addition, it still contains V2X communication units and data transmission units, and it should also include various parameters, such as the position and attitude of the test vehicle [15].

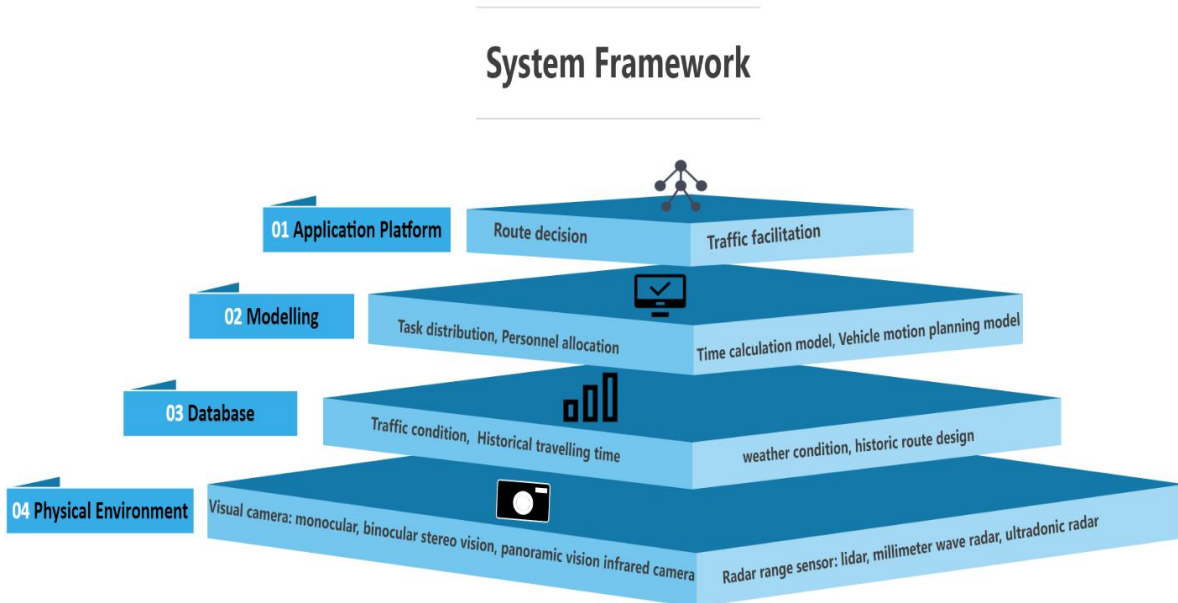


Figure 2. The framework of the proposed system

The model layer is divided into two primary aspects: the external planning model of the fire station and the internal vehicle and personnel allocation model. External planning encompasses the route model and information interaction model between vehicles and humans. Internally, when multiple tasks arise simultaneously, effective allocation is crucial for minimizing time consumption and manpower. Consequently, task allocation and personnel management models are essential. These models undergo continuous testing and updating, ultimately translating into real-world applications for emergency rescue plans, route decision-making, traffic facilitation, and other pertinent issues, thereby constituting the application layer of the digital twin architecture (Fig. 2).

3.1. System Modeling

In the process of modeling the digital twin system based on the fire station management system, the initial step involves replicating the authentic vehicle and road environment. Digital twins of both the vehicle and road environment are meticulously crafted within virtual space, ensuring synchronous mapping and bidirectional data transfer with their physical counterparts. To achieve position consistency between the real vehicle and its digital twin in virtual space, a coupling transformation is necessary, involving the coordination and rotation angle adjustments of the vehicle digital twin [15].

Digital twin technology facilitates the creation of a simulation environment tailored to simulate fire truck rescues. This environment requires the replication of real-world fire truck travel scenarios. Through digital twin technology, actual traffic scenes can be mapped in virtual space with ultra-high resolution, conveying road conditions, weather, and light intensity to the automatic driving algorithm controller via the communication module. Following analysis and processing, corresponding decision signals are relayed, enabling the interaction of digital twin scenes [15].

To construct an accurate simulated road environment, this paper suggests utilizing a UAV tilt camera and point cloud assistance (BIM) for precise mapping of the traffic environment. Once the vehicle and road environment are mapped in virtual space, the paper outlines a traffic diversion method to provide the shortest route for fire trucks. Upon receiving the task, the system promptly selects the route with the shortest time from various feasible options. Subsequently, the system issues instructions to vehicles on this route, prompting them to travel slightly later. These instructions notify other vehicles of the impending passage of the fire engine, fostering an interaction among the vehicles

and paving the way for a relatively unobstructed route for the fire engine to swiftly reach the disaster scene.

The trajectory of the fire vehicle often involves lane changes, making them a crucial aspect of the modeling process. During a lane change, the vehicle is influenced not only by its target trajectory but also constrained by the behavior of neighboring vehicles in the same or adjacent lanes, as well as road conditions. Lane change models can be categorized into several types, such as rule-based lane change models. Rule-based Lane change models, notably the Gipps model and MITSIM model, are employed to make lane change decisions. For example, rule-based lane change model mainly uses Gipps model and MITSIM model to complete lane change decision. By considering possibility and necessity, Gipps model can give the final decision. At the same time, the choice of lane change requires a condition that the required acceleration is less than the maximum acceptable acceleration, the lane change decision should be given when this condition is met [4]. The MITSIM lane change model, an extension of the Gipps model, considers vehicle spacing to determine whether and which lane to change. This model allows fire trucks to perform unrestricted lane changes in complex sections, ultimately reducing rescue time.

Furthermore, considering the time-sensitive nature of fire station rescue operations, the model must address the rationality of task allocation when faced with multiple urgent tasks simultaneously. The task assignment model should minimize both human effort and travel time. This paper introduces a two-layer coupling dynamic model, connecting the disaster site and the rescue station. The model is divided into two layers, which are used to select a fire station as the best emergency center, and assign tasks to the personnel in this fire station respectively. The lower model proposes the best task assignment scheme for the fire station management system, guided by the decisions made at the upper level.

3.2. Computation and Analysis

In the fire station management system based on digital twin, to formulate an optimal route decision scheme that aligns closely with real-world conditions, extensive data collection and intelligent data analysis are essential. This allows for route planning based on historical experiences and intelligent calculations. One of the data methods to be adopted in this system is decision tree, which builds a decision tree through a batch of known training data, and then it is used to analyze and predict the data [8]. The decision tree can offer an optimal route for various fire engines, taking into account the fire station's objectives when faced with multiple feasible routes in the decision-making process. The decision tree's data analysis method facilitates the visualization of data rules, enhancing comprehensibility and efficiency. However, it may encounter challenges when applied to complex data analyses.

To address challenges in complex data analysis, this paper incorporates artificial neural networks as an additional data analysis method. The Artificial neural network is a parallel data information processing model, which is mainly realized by imitating the animal nervous system. Its main characteristics are high adaptability, mapping ability and considerable fault tolerance [9]. This data analysis method contributes to the simplification of complex data, thereby enhancing the efficiency of real-world applications. The integration of this data analysis method effectively enhances the practicality of the fire station management system model.

3.3. Closed-loop Optimization

In the practical application of automotive sensing systems, several challenges persist, encompassing sensor limitations, data fusion quality, and environmental understanding. These challenges represent key research directions [3]. Sensor limitations, such as the susceptibility of millimeter-wave radar to weather and light, pose difficulties in handling complex environments. Moreover, data fusion problems arise from the diverse formats of each sensor, necessitating improvements in data fusion algorithms. To enhance decision-making, this paper proposes optimization solutions for system validation. One approach involves conducting extensive simulation

tests and real road tests, allowing immediate improvements by comparing actual performance against expected results. Additionally, adopting an evaluation method for datasets, generated by collecting real-world performance data from numerous vehicles, enhances the authenticity and reliability of the proposed fire station management system based on digital twins.

4. A Typical Example of the Proposed Fire Station Management System

This paper predominantly addresses the route selection of fire station vehicles when responding to tasks, primarily directed toward disaster sites. Diverging from conventional route planning, roads near disaster sites are prone to varying degrees of damage, such as fire spread, building collapses, crowd congestion, and other impediments hindering the passage of fire trucks. These factors significantly contribute to increased time consumption for rescue vehicles reaching the disaster scene. Consequently, the paper proposes an emergency rescue line planning algorithm to mitigate this issue, ensuring the swift arrival of fire trucks at the rescue scene for efficient rescue operations. The algorithm aims to minimize losses incurred by sudden disasters to both personnel and the surrounding residents and environment.

Emergency rescue route planning falls within the realm of network optimization, characterized by the following attributes: the post-disaster road network is treated as edges in the network model, while the disaster site is considered nodes. Since road damage caused by disasters will affect normal road decisions, two attributes of "safety risk" and "time spent" should be considered in the final part of the model [5]. The magnitude and severity of disasters can variably impact the condition of surrounding roads. Consequently, when multiple disasters unfold simultaneously, it becomes imperative to prioritize the order of rescue tasks for different workers.

Refining the model based on the aforementioned security risk and time spent factors involves making several assumptions:

- 1) In the fire-affected area, the fire engine must reach the disaster site as quickly as possible for rescue operations and subsequently proceed to the supply point to obtain necessary provisions.
- 2) Each location that the fire truck must reach is designated as a node in the network model, necessitating the design of multiple route connections between any two points to establish the connectivity graph.
- 3) Every site affected by a disaster must be accessible to a fire engine.
- 4) Ensuring the availability of a secondary alternative route is crucial to circumvent potential road damage from secondary disasters and alleviate impediments to vehicle traffic.

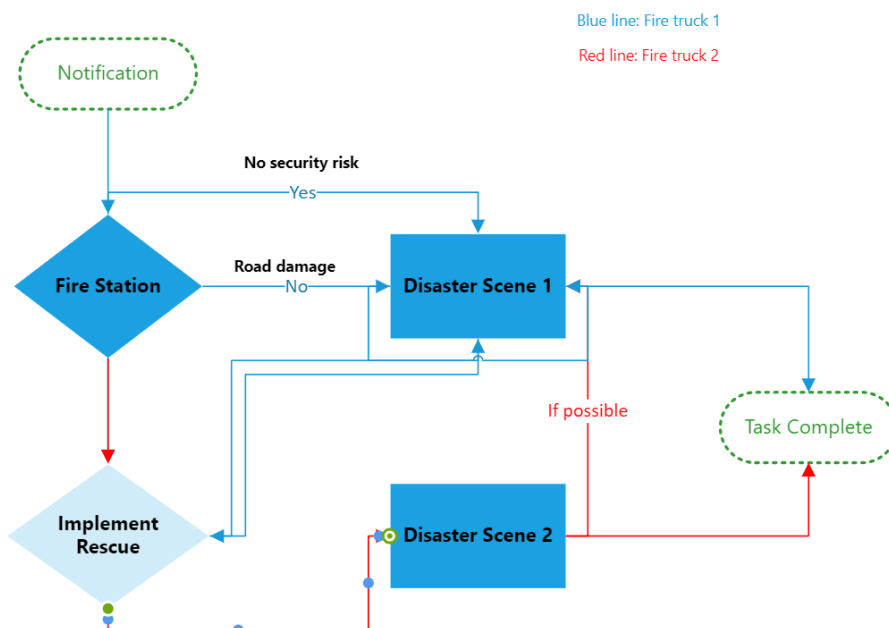


Figure 3. The process of the proposed emergency rescue line planning algorithm

The process of selecting specific routes involves an initial assessment of the extent of damage at the disaster site, considering the potential for secondary disasters on alternative routes in the vicinity. Following the evaluation of the system model, the shortest route is chosen from among the feasible options without safety risks. Additionally, the co-communication system is utilized to transmit messages to vehicles currently on the road and those intending to travel on the same route. These messages inform drivers about the passage of a fire truck, ensuring they can create a relatively clear path for the emergency vehicle (Fig. 3).

In scenarios where multiple tasks arise simultaneously, the emergency rescue time is calculated based on the severity of the disaster at each site. For instance, if one location (P1) is significantly affected and requires m personnel, and another site (P2) needs n personnel but has a less severe disaster, the allocation strategy involves assigning $M-N$ personnel to P1 to contain the disaster's spread. Simultaneously, after completing rescue activities at P2 in a short time, the n personnel can promptly return to P1 for subsequent rescue operations, effectively minimizing manpower costs.

5. Conclusions and Future Work

The benefits of the Internet of Vehicles are gradually being realized and applied across various domains. This paper proposes the application of the Internet of Vehicles and Digital Twins in a fire station management system to enhance the execution of rescue tasks. While ensuring the lowest labor cost, this system seeks to efficiently organize police dispatch tasks and make optimal driving route decisions through the utilization of the system model. The primary objective is to ensure that rescue workers can safely and swiftly reach disaster scenes.

However, the system model based on digital twins, as presented in this paper, encounters certain challenges such as sensor perception and data fusion. Addressing these issues requires continuous refinement of data processing methods and extensive simulation tests in real-world scenarios. This approach aims to enhance the reliability of the system model, providing convenience for both firefighters and injured individuals, rather than unnecessary complications.

References

- [1] Gao Huimin, Introduction to V2X communication technology and application of vehicle networking, DOI: 10.13825/j.cnki. motorchina. 2020. 03. 017.
- [2] CHENG xiang, ZHANG Haotian, YANG Zongwei, HUANG Ziwei, LI, Sijinag, YU, Anlan, Integrated sensing and communication for Internet of vehicles: current status and development trend, 2002, 08, Vol. 43 No. 8.
- [3] Li Shengbo, Guan Yang, HOU Lian, et al. Key Technologies of Deep Neural Networks and Their Applications in the field of Autonomous Driving [J]. Journal of Automotive Safety and Energy Efficiency, 2019 (2): 119 - 145.
- [4] LIU Bingqing, Research and Application of Conditional Autonomous Vehicle Behavior Modeling, 2023, 05.
- [5] GAO Penghui, Models and Algorithms for Post Disaster Rescue Route Optimization, 2019 03.
- [6] R. Rosen, G VonWichert, G. Lo, et al. About the importance of autonomy and digital twins for the future of manufacturing [J].
- [7] LIANG Enyun, Research and Implement of Digital Twin Scene Interaction for Automatic Driving Simulation Test, 2022, 05.
- [8] Yang Shulin. Development status and application of intelligent analysis technology [J]. China Public Security. 2015, 08 (14) 207 - 209.
- [9] SUN Tonghui, Research on the Wisdom Tourism Route of Zhoushan, 2019, 05, 12.
- [10] Deng Yukang, Zhang Lei, Li Jing. Car network privacy protection and research review [J/OL]. Computer application: 1 - 18 [2022-06-27]. DOI: 10.19734 / j.i SSN. 1001 - 3695. 2022. 02. 0091.

- [11] kram Amuti. Analysis on the development and Application prospects of Vehicle Networking Technology [J]. Automotive & Parts, 2018, (32): 50 - 51.
- [12] ZHUANG Cunbo, LIU Jianhua, XIONG Hui, et al. Connotation, architecture and trends of product digital twin [J]. Computer Integrated Manufacturing Systems, 2017, 23 (04): 753 - 768.
- [13] M. Grieves. Digital twin: manufacturing excellence through virtual factory replication [Z]. 2015.
- [14] LIANG Enyun, Research and Implement of Digital Twin Scene Interaction for Automatic Driving Simulation Test, 2022, 05.
- [15] LIANG Enyun, Research and Implement of Digital Twin Scene Interaction for Automatic Driving Simulation Test, 2022, 05.