

Traffic congestion avoidance and evacuation system based on digital twin and IoV

Zhengan Song *

Harbin Institute of Technology, Harbin, China

* Corresponding Author Email: 15081402116@163.com

Abstract. This paper explores the current development of the Internet of vehicles (IoV) and its future potential when combined with digital twin technology. It proposes a traffic congestion evacuation and planning strategy based on digital twins to enhance urban traffic management and prevent congestion. The evacuation strategy is implemented by dynamically adjusting intersection signal light changes, while the traffic planning strategy optimizes vehicle navigation within the IoV system. By leveraging real-time data and simulation capabilities of digital twins, the proposed approach aims to improve traffic flow efficiency and reduce congestion risks. Finally, a case study is conducted to demonstrate the effectiveness and practicality of the proposed method.

Keywords: Digital Twin, IoV, Traffic Congestion Evacuation, Traffic Planning.

1. Introduction

The growth of intelligent emerging technologies and their capabilities (such as real-time, interactive services) has led to a significant increase in wireless data traffic, driving the development of the sixth generation (6G) to meet the high technical standards of new spectrum and energy-efficient transmission methods through 6G mobile networks with higher spectrum, and more. Users can expect higher speeds (data transfer rates are expected to be 100 to 1,000 times higher than what 5G offers), enhanced capacity, and lower latency, supporting new applications [1], including Internet of vehicles (IoV). The IoV is a concept rooted in IoT (Internet of Things) technology that aims to integrate vehicles, roads, drivers, and infrastructure into a unified network for communication and information exchange [2]. Using wireless communication, sensor technology, and data analysis, IoV enables vehicles to communicate with each other, interact with transportation infrastructure, and connect to drivers and cloud-based servers [3]. In the development process of IoV technology, V2X technology has emerged, that is, Vehicle to Everything communication technology [4]. By improving the coordination of vehicles, pedestrians, and transportation infrastructure, V2X has the potential to eliminate 80% of current road accidents and help facilitate smarter and safer ground transportation systems in the automotive and telecommunications industries [5].

In the development process of IoV, the combination of digital twin and IoV has a good development prospect. Digital twin (DT) is a technique for creating virtual models of entities in the real world and enabling real-time synchronization between virtual and real Spaces so that digital representations and physical entities can interact [6]. Advances in sensor technology have enriched the capabilities of DT. It continuously updates the virtual model based on real-time data collected from physical entities. These capabilities give DT unique advantages such as real-time responsiveness, interoperability, scalability, and autonomy [7]. At present, some researchers have proposed to apply digital twin technology to the safety test of autonomous vehicles [8], but digital twins clearly have a bigger role to play in IoV. Unacceptable communication delays can occur in large IoV transportation systems. To address this inevitable communication delay, dedicated short-range communication (DSRC) technology has been created. Scholars have studied the performance of DSRC and other communication technologies in urban IoV [9]. Applying digital twins into the IoV is another solution. A digital traffic system can be built according to the information of the traffic system in the real world. In the virtual traffic system, the prediction and unified planning of the traffic system in the real world can be realized, and the operation of the traffic system can be carried out through the planning of the traffic system in the virtual world, rather than relying on the real-time communication between the

elements of the system. This reduces the impact of communication delay. Some scholars have presented a digital twin (DT)-based collaborative autonomous driving (DTCAD) three-layer architecture in C-V2X to provide better resource management of autonomous vehicles [10].

Considering the advantages of digital twin technology in the application of IoV system, this paper designs a vehicle planning and congestion evacuation system based on digital twin technology. The system is divided into twin data building module, vehicle travel planning module and congestion evacuation module. The twin data building module is divided into road data building module and vehicle data building module. The former is to build the digital twin model of traffic facilities such as roads and traffic lights, while the latter is to build the digital twin model of all vehicles in the region. The vehicle travel planning module is responsible for the navigation of all vehicles while collecting the routes of all vehicles in a certain period of time and making route planning to prevent congestion. The congestion evacuation module is responsible for the evacuation of traffic congestion after the occurrence of vehicle congestion, including the congestion caused by too many vehicles and the vehicle congestion caused by traffic accidents. The application of digital twin technology can give full play to the advantages of vehicle interconnection and vehicle road interconnection, and effectively solve the traffic congestion problem.

The structure of this paper is as follows. First, the application scenario of this system and the application of digital twin in system design are introduced. Next, the vehicle planning based on digital twin and the design of traffic congestion evacuation system are introduced in detail, and the simulation cases under this system are given. Finally, the results of this paper are summarized.

2. IoV System and Digital Twin

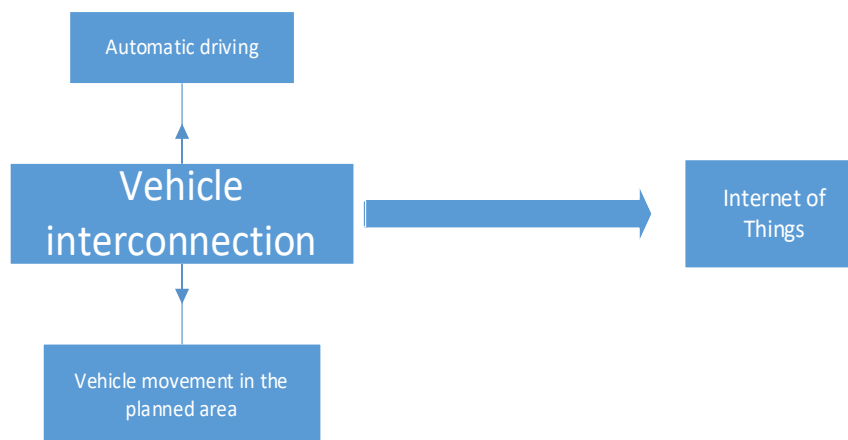


Figure 1. Function of the system

As shown in Figure 1, this system is mainly applied to urban traffic planning and evacuation of traffic congestion under the coverage of the IoV. By utilizing the characteristics of interconnection between vehicles and vehicles and between vehicles and traffic facilities in the IoV system, the overall traffic planning can be realized to reduce the occurrence of traffic congestion, and at the same time, vehicles can be evacuated in the event of traffic congestion. When vehicle driving planning or traffic congestion is carried out, if the instant communication of vehicles in the area is relied on for processing, the computing power of vehicles and the communication delay of the system have high requirements, and the existing technology is difficult to achieve this point. Therefore, it is a better choice to integrate all the information about roads and vehicles in the region and carry out unified planning. The digital twin technology can achieve the overall planning of vehicles in the area. With the application of digital twin technology, the information of roads and vehicles in the area can be integrated into a unified virtual model, which contains all the required information in the area, and can be used by relevant computing units (either vehicles in the area or dedicated equipment in the area) for unified planning of vehicles in the area.

3. Regional traffic planning and congestion evacuation system design based on digital twin

The system consists of three modules, twin data building module, vehicle travel planning module and congestion evacuation module. (System architecture diagram) The twin data building module can be composed of specialized equipment in the region. Since the twin data of traffic facilities (including roads, traffic lights, etc.) are generally fixed and can be obtained after the completion of the traffic facilities, the module is mainly responsible for collecting the position information and scale information (length and width) of all vehicles in the region. As well as the initial speed and acceleration when entering the area (it is assumed that the system can control the vehicle speed when planning vehicles in the area, so the vehicle movement information in the area is known), and the digital twin model of the overall situation of regional traffic is constructed according to this information and the traffic facility twin model. It is convenient for vehicle travel planning module and congestion evacuation module to realize their respective functions.

The main purpose of the vehicle travel planning module is to prevent traffic congestion and prevent traffic congestion from becoming more serious. First, assume that all unmanned vehicles in the IoV have accepted the navigation provided by the system, so that the current location and destination of each vehicle can be known, and the system can build a digital twin road model of the vehicle from the current location to the destination according to this information and the actual road information, and the model will show the vehicle congestion of each road section that the vehicle may pass through. There is usually more than one route to a place in the urban transportation network, so the system will plan the route of the vehicle based on the model and make decisions, so that the vehicle can avoid congestion to reach the destination.

The traffic congestion evacuation module relies on real-time adjustment of traffic lights to achieve congestion evacuation or minimize the total congestion time within the system. This real-time adjustment is carried out according to a regular function, which takes the congestion of each road adjacent to the intersection as a variable.

This paper focuses on the realization of traffic planning and congestion evacuation functions in the vehicle network system based on digital twins. Therefore, the modeling methods, intelligent analysis and system optimization of the traffic planning module and congestion evacuation module are respectively introduced below.

3.1. Modeling method

Firstly, the modeling method of the actual traffic system in the traffic planning module is introduced. In Figure 2, the line between the vehicle's current location and its destination can be abstracted as a grid. If the grid is m long and n wide, there are $(m+n)$ ways to reach the destination. The congested section can be identified by the system for subsequent route planning so that vehicles do not reach the destination through this section, as shown in the red part in Figure 2.

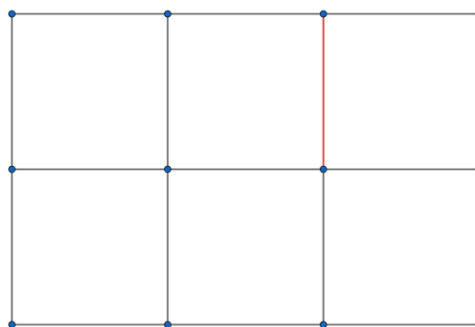


Figure 2. Modeling of traffic routes

The following introduces the modeling method of traffic congestion evacuation system. In general, each junction is connected to four roads, each of which has two passages in opposite directions (i.e., each junction is connected to eight passages). In order to use the method proposed in this paper to

evacuate traffic congestion, it is necessary to mark four channels entering the intersection as "entry channels" and four channels leading to other intersections as "exit channels". Therefore, the modeling of each intersection is shown in the Figure 3.

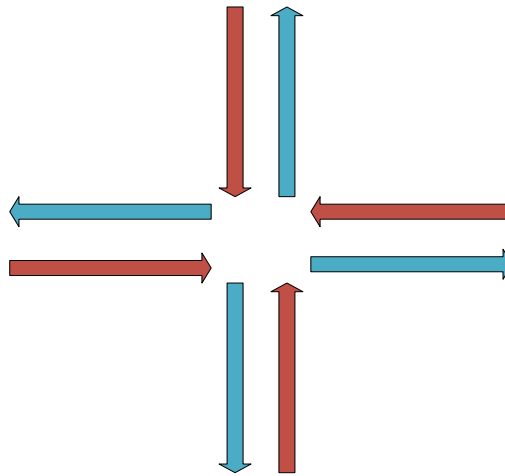


Figure 3. A diagram of the intersection (red for the entry channel, blue for the exit channel)

3.2. Intelligent analysis

It can be seen from 3.1 that the line between the current position of the vehicle and the destination can be abstracted into a grid line diagram with length m and width n , then there are $(m+n)$ ways to reach the destination, and the vehicle needs to pass through $(m+n)$ sections to reach the destination. Before introducing the vehicle route planning method, the congestion coefficient of A section is first defined, where $A = \frac{\text{the traffic flow of the section}}{\text{the traffic flow when the section is congested}}$. When the value of A is greater than or equal to 1, the section is marked as the congestion state. Note that any definition of congestion here is independent of the definition of congestion as described in the congestion evacuation module in this section. The method of route planning is very simple, traversing $(m+n)$ kinds of paths to the destination, excluding the path through the congested section, and adding the A value of the remaining paths through the section, the A value and the smallest path is the road of the vehicle. If $(m+n)$ paths all need to pass through congested sections, then the original grid with length m and width n is changed into a grid with length $(m+k)$ and width $(n+k)$, where k is a positive integer, and the above calculation is repeated. The idea is to explore the possibility of vehicles bypassing congested sections of road. Obviously, the value of k cannot be infinite in practical applications, and the vehicle may need to make a trade-off between getting stuck in a jam and detouring further. In the system, the maximum k_m of k is adjustable. If k reaches k_m and the system still does not find a passable path, the system will navigate the vehicle to the nearest and non-congested road section from the destination.

The following introduces the analysis of the function realization of the traffic congestion evacuation module. The traffic congestion evacuation module relies on real-time adjustment of traffic lights to achieve congestion evacuation or minimize the total congestion time within the system. This real-time adjustment is carried out according to a regular function, which takes the congestion of each road adjacent to the intersection as a variable. The traffic light rules are as follows: When the red light is red, the vehicle can only go right, and when the green light is green, the vehicle can go forward, left, and right. During congestion evacuation, the passable direction of each signal light will change according to the congestion situation of the exit channel at the junction. For example, when congestion is detected on an exit channel, the vehicle will be prohibited to travel in that direction regardless of the status of the signal light. Therefore, there may be a situation where the light is green but the vehicle can only go to the right, or a situation where the vehicle cannot go in either direction when the light is red. When there is no congestion in the eight channels associated with the intersection, the traffic lights at the intersection change according to the normal cycle. At the same time, the congestion situation of the four exit channels at the intersection is detected every other cycle.

The same intersection should have different criteria for judging whether the exit channel and the entry channel are congested. For its exit channel, its passable direction is restricted by the traffic light at the next intersection. At this time, if the vehicle on the channel can only drive to the right or is prohibited to drive in any direction, and the queue length of the vehicle exceeds $aL(0 < a < 1)$, it is determined that the exit channel is in a congested state, and vehicles are prohibited from driving in the channel under any circumstances.

When the congestion detection is performed on the exit channel at the intersection, if the detection result is that 3 or 4 exit channels are all in a congested state, there is no need to detect the congestion state of the entry channel, and the traffic lights do not need to change alternately. When the four exit channels are congested, all vehicles on the entry channels are prohibited from passing in any direction, waiting for other intersections to clear the traffic. When the three exit channels are congested, any vehicle entering the channel can travel to the uncongested exit channel.

When the number of exiting channels in the congestion state is 0,1,2, the congestion state in the entry channel is detected, and the traffic lights at the intersection must be changed alternately. The congestion state detection standard for the entry channel: the intersection is red and the queue length exceeds $bL(0 < b < 1)$, then it is determined that the channel is a congested channel. Because the traffic lights change alternately at this time, a maximum of two entry channel on an intersection can be judged to be congested at the same time, and they must be the two lanes traveling in opposite directions. When the entry channel with congestion is detected at the intersection, the traffic light pre-transformation state is entered, and the two entry channels perpendicular to the congestion channel are detected. It is assumed that after the traffic light transformation, the queue length $L1$ of the vehicles line in the two entry channels exceeds $cL(0 < c < b)$, the transformation is not carried out, and the length of $L1$ is detected every certain period; Otherwise, immediately change the traffic lights and give priority to the traffic of vehicles in the congested section.

There are only two exceptions, as shown in Figure 4. If there are two vertical exit channels congested, there will be two special entry channels at the intersection, one of which can only go left regardless of the traffic light, and the other can only go right regardless of the traffic light. The optimal treatment is to mark the two entry channels as non-congested in all cases and wait for the adjacent intersection to relieve traffic congestion.

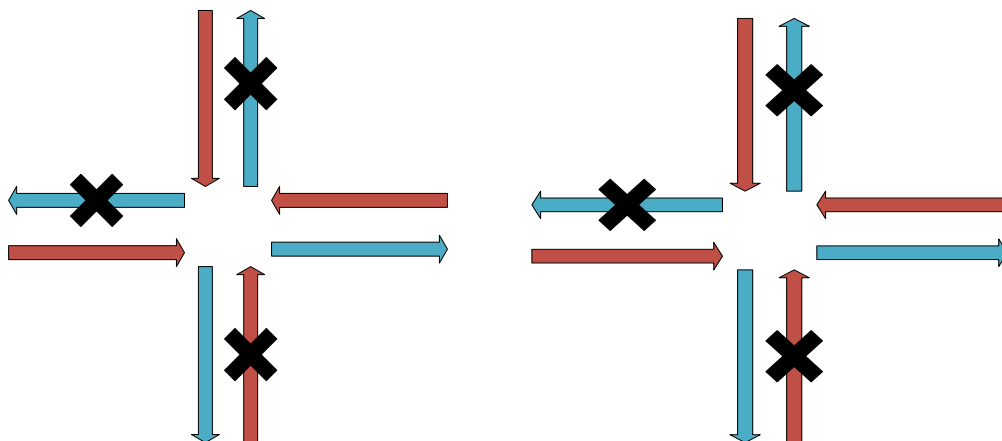


Figure 4. Two exceptions

The flow of alleviating traffic congestion by changing traffic lights is shown in Figure 5.

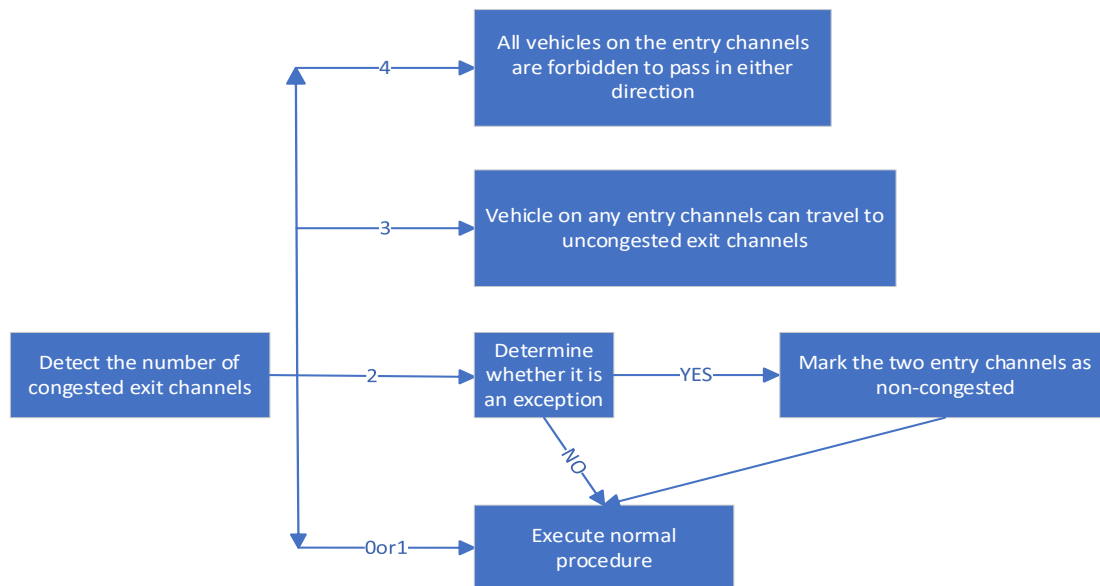


Figure 5. Flow of alleviating traffic congestion by changing traffic lights

3.3. System optimization

The mathematical models we built for the traffic planning module and the congestion evacuation module do not perfectly describe the operation of the actual traffic system. This error is inevitable: the traffic planning module, the error comes from the actual traffic system roads are not always orthogonal, intersections are not all cross-shaped, but these can be solved by the algorithm of permutation combination. One of the sources of error between the congestion evacuation module and the real system is also due to the fact that intersections are not always cross-shaped in reality, but this can also be solved by classifying more situations. Another source of error between the digital system of the congestion evacuation module and the actual system is the value of a and b, that is, the question of when the road should be defined as congested versus when it is defined as free from congestion. Obviously, the initial values of a and b can be artificially reasonable estimates and set an initial offset. The system can continuously adjust the feedback according to this offset, so as to minimize the average congestion time of the system in a day. In addition, it should be noted that according to the actual situation, the a and b values of each channel should be unrelated.

4. Simulation Results

In this section, the traffic congestion evacuation module proposed in this paper will be analyzed to verify the effectiveness of this module to evacuate traffic congestion. According to 3.1, in order to use the method proposed in this paper to evacuate traffic congestion, it is necessary to mark four channels entering the intersection as "entry channels" and four channels leading to other intersections as "exit channels". In the analysis, the total congestion time (the sum of the congestion time of all "entry channels") under the traditional traffic signal rule and the traffic signal rule proposed in this paper is compared. In order to show the effect of the method proposed in this paper, the sum of the waiting time of the same amount of traffic at the current intersection and the next intersection is compared here. Let the additional congestion time of the traffic flow due to the congestion of the "exit channel" be c (the effect of the congestion of the next intersection on the congestion of the current intersection). Since the traffic flow on each channel is the same under both rules, the time from the signal light to the red light to the congestion of the channel is a fixed value t. Set the initial traffic light duration to T. Due to the small amount of data involved, the total congestion time in each case is obtained by deducing method. Table 1 shows the total congestion time caused by the two traffic light rules under different conditions. The special case mentioned above is not taken into account here.

Table 1. Total congestion time caused by the two traffic light rules under different conditions

Number of congested exit channels	Number of congested entry channels	Congestion time under traditional rule	Congestion time under new rule
4	¥	¥	¥
3	2	$2(T-t) + 2c$	$2c$
	1	$T-t+c$	c
	0	c	c
2	2	$2(T-t) + 2c$	$2c$
	1	$T-t+c$	c
	0	c	c
1	2	$2(T-t) + 2c$	$2c$
	1	$T-t+c$	c
	0	c	c
0	2	$2(T-t)$	0
	1	$T-t$	0
	0	0	0

It can be seen that the method proposed in this paper can effectively alleviate traffic congestion.

5. Conclusions and Future Work

This paper first introduced the current development status of the Internet of Vehicles (IoV) and explores the promising prospects of integrating IoV with digital twin technology. It then proposed a traffic congestion evacuation and traffic planning strategy for IoV based on digital twin technology, aimed at effectively preventing and mitigating traffic congestion. To validate the proposed approach, a case study was conducted, demonstrating its effectiveness. While the techniques proposed in this paper focus on the macro-level planning of vehicle movement, practical applications of IoV must also consider specific route planning. This includes handling obstacles, coordinating with other vehicles, and navigating complex intersections. Existing research has already addressed some of these challenges, highlighting the need for a comprehensive approach. In the future, our work will focus on integrating macro-level traffic planning with detailed route optimization to ensure a seamless and efficient transportation network. Both levels of planning will be essential as IoV technology becomes more widely adopted.

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