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Cooperative control method strategy for autonomous roundabout

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Abstract: With the development of intelligent transportation system, the cooperative control of vehicles at intersections has become an important issue worthy of attention. However, existing research mainly focuses on conventional signalized intersections, autonomous roundabouts remain understudied and lack personalized right-of-way allocation solutions. Considering the above problems, this paper proposes a cooperative control method of autonomous vehicles at roundabout based on token ring, which maps virtual tokens to physical lanes and dynamically encodes spatio-temporal access rights, thus achieving conflict-free operation of vehicles at intersections and more equitable right-of-way allocation. The simulation results demonstrate that the proposed method can significantly improve the vehicle traffic efficiency under large traffic flow.

Keywords: Traffic engineering; Autonomous roundabout; Cooperative control; Token ring.

1 Introduction

Urban intersections, particularly non-signalized ones, are hotspots for traffic accidents. Currently, most non-signalized intersections are found in suburban areas or gated communities with low traffic volumes. This is largely due to the limited capacity of these intersections, where the right-of-way for vehicles is heavily reliant on the subjective judgment and decisions of drivers, and there is a lack of unified command and dispatching.

The advent of autonomous driving and V2X technology has paved the way for the establishment of a collaborative decision-making system, which is a crucial technical foundation for enhancing the capacity of non-signalized intersections. In recent years, numerous researchers have investigated vehicle passage control methods at intersections within intelligent transportation systems under vehicle-road collaboration or autonomous driving scenarios, demonstrating that autonomous intersections can enhance vehicle efficiency under certain conditions [1-3]. However, the majority of these studies have focused on traditional intersections and have not offered targeted solutions for roundabouts. Most studies on roundabouts have concentrated on improving capacity [4-5], efficiency [6], and safety [7] within a signal-controlled framework [8]. Some research has also explored the characteristics, applicability, and traffic efficiency of signalized roundabouts under specific conditions [8-14]. The theoretical nature of roundabouts makes them more suitable for a no-signal mode, as long as there are established rules for yielding. With such rules, vehicles can circulate in an orderly fashion without crossover conflicts. In conclusion, it is imperative to develop a collaborative control method for autonomous vehicles at roundabouts, leveraging autonomous driving and V2X technology, to improve the efficiency and safety of non-signalized intersections.Inspired by the operation mode of token-ring in network communication, this paper analyzes the characteristics of roundabouts, and proposes a cooperative control method of autonomous vehicles at roundabout based on token ring. The contributions of this paper are summarized as follows:

(1) An innovative method of mapping token ring to physical traffic flow at roundabout is proposed, which clarifies the connotation of individual vehicle right-of-way and accurately describes the process of vehicle passage at roundabout intersections through the construction of tokens and the corresponding rule formulation.

(2) A vehicle cooperative algorithm adapted to the characteristics of the roundabout intersection is constructed to realize the accurate matching of the constructed token attributes and vehicle information, which ensures the efficient operation of vehicles at the roundabout intersection.

(3) The proposed control method is suitable for roundabout with any number of entrances, and the modification of the token attributes can realize multi-objective and diversified management of vehicles as well as the vehicle platoon, such as ensuring priority access for emergency vehicles.

2 Methodology

2.1 Token-ring and vehicles at roundabout

The technique of Token-Ring, developed by IBM in the 1980s, is a LAN access method defined in the IEEE 802.5 standard [15]. In a Token-Ring network, all nodes share the same communication channel, and a digital token is passed through all nodes in the network in turn along a virtual logical ring network (Fig. 1). When the token arrives, a node has no requirement communication can release the token into the ring bus immediately, and only the node that obtained the token has the right to send information in the network. It ensures that only one node can be access to the channel at one time, so there will be no collisions occur. When all nodes on

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the ring are free, the token travels around the ring. Moreover, since tokens are passed sequentially on the ring, access is fair for all nodes in the network.

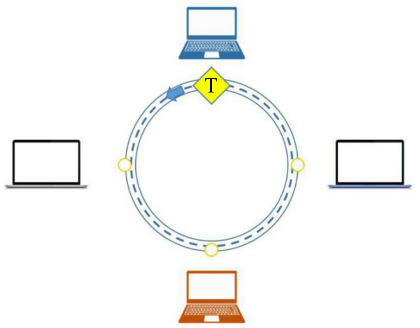

Fig. 1 Schematic diagram of token ring operation.

Though there are some similarities between the token in network technology and the operation of a vehicle at a roundabout, the differences are significant. The main difference can be summarized as tokens do not carry information and the network cannot be reused.

The token is actually a special format frame, which does not contain information itself and only controls the use of the channel. For example, if it is simply represented by a binary number, the token has only two assigned values: 0 or 1.

Within a very short time-slot, the use of the token and the so-called network bus is exclusive. That is, when a node in the network gets a token to use the network, no matter how much bandwidth the node uses, other nodes must wait until they finish using the network and give up the token before they have a chance to apply for the token and use the network, the network utilization efficiency is low. This is reasonable since the digital frame transferring in the network is very quick, and the delay will be no more than 1~10 milliseconds. Whereas in an actual ring intersection of road, vehicles cannot run too fast. Therefore, if the vehicles through the roundabout are dispatched in the mode like the network communication based on the token ring, it will inevitably lead to when one vehicle turns in the roundabout, the other vehicles have to wait, which resulting in idle resources at the roundabout, and may even further aggravate traffic congestion.

In order to construct a token ring that can be mapped to an actual ring intersection, a new token ring structure needs to be defined and constructed. The core principle is that a token has to contain two basic attributes which can be extended, as shown in the Fig. 2, one attribute is whether its state is occupied or not, and the other is the maximum available room capacity of the token.

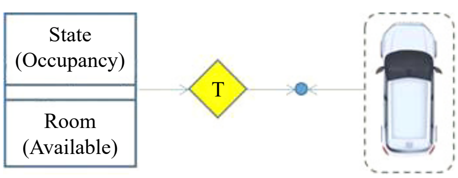

Fig. 2 Token’s attributes.

In addition, a ring is no longer limited to the simultaneous existence of only one token inside. Furthermore, there can be more than one sender in a node, as long as there are enough free tokens, a node can continuously serve the requests of multiple senders.

2.2 The model of token-vehicle mapping

2.2.1 The establishment of token room

According to the analysis above, as long as the space-time ownership of the token is assigned, then the autonomous driving vehicles will not interfere and conflict with each other , and there will be no accumulation of delays in the circular queue. Firstly, we consider the division of space, that is, we divide the ring-shaped vehicle driving area into appropriate multiple zones, which corresponds to the token room.

Fig. 3 is a schematic diagram of a roundabout, in which, the whole circle is divided into 8 regions, which are collectively referred to as token rooms in this study. In Fig. 3, the blue region in the room represents a certain length of vehicle or platoon, of course, for special vehicles such as buses, fire rescue vehicles, their length can be set to a variable or occupy two token rooms, but it does not affect the the calculation method of the model. If the rotation speed of vehicles in the ring is constant, the distance between vehicles can be reduced, so the token room can be set under this assumption.

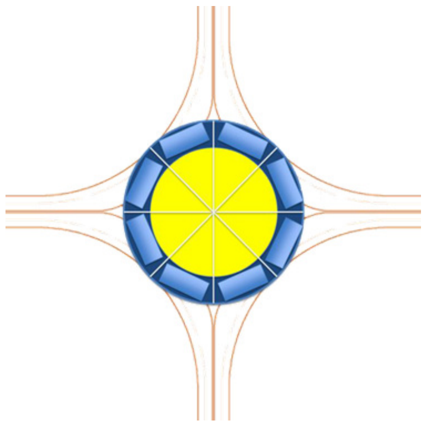

Fig. 3 Schematic diagram of a token division at a roundabout.

Here, we intercept two token interval vehicle area, assuming that the vehicle inside and the inner ring tangent point for the longitudinal center position, and the closest adjacent two interval vehicle form as shown in the Fig. 4. D indicates half of the length of the car, S indicates half of the length of the arc between the two tangent points, indicates the angle of the center of the circle, according to the circle radius , angle relationship and trigonometric functions can be introduced as:

$$S = \pi r \cdot \frac{\arctan(D/r)}{180}. \quad (1)$$

Therefore, the total number of tokens can be set to floor($2r / S$), where floor means rounding down. Further, it can be found that the length of D and S in the diagram is approximated under the current circular angle. For comparison, we can use the form of ratio, we divided D by S, the ratio is recorded as DPS. According to the equation transformation, derivative and monotonicity judgment, it can be proved that DPS is not significantly larger than 1, the schematic diagram is designed under experimental setting, while it is impossible for vehicles to be front and back contact, in a real case. Therefore, for the sake of computational simplicity, D can be used

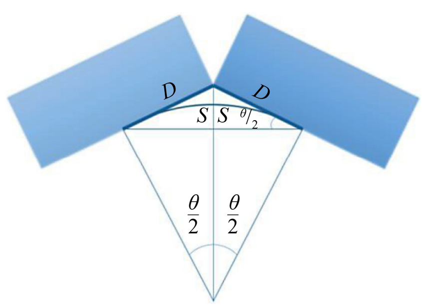

Fig. 4 Ideal geometric relationship between two adjacent vehicles.

to instead of S, so that the token room is safe for the vehicle.

2.2.2 Sequence setting for tokens

Since the moments when vehicles carry tokens are likely to be different, then there should be a unique number for each token, otherwise it will increase the complexity of the calculation. Therefore, given the number of tokens composed in a ring be Cb , and the numbering of tokens in the initial state is set clockwise from B1 to BCb, for example, the sequence of eight tokens is shown in the Fig. 5.

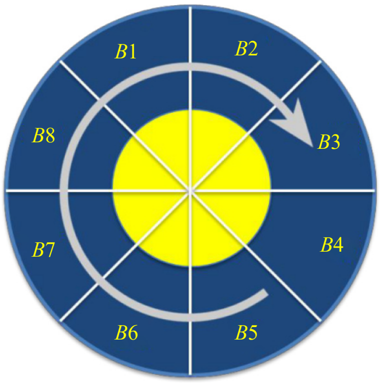

Fig. 5 Sequence of tokens.

However, for a certain roundabout, the occupation time of each token may be different, and if each token always keeps a constant number, the computation of these token positions will increase as time accumulated,. It is difficult to “photograph” an instantaneous intersection token occupation when all tokens are free. Therefore, a simple token numbering update model can be: sorting by vehicle, i.e., the correctness of the model is guaranteed by the correctness of the vehicle and token matching, as long as each update is still a vehicle corresponding to a token, without considering what the initial number of the token is, and only knowing at which time each token turns to the location of the circle. The advantage of the model is that, after each calculation of the time, when a vehicle is allowed to enter, the corresponding token’s arrival time is used as the next input, and the variable input order of the updated tokens is no longer considered by the initial sequence. Thus, the update of vehicles is from an entrance to an exit, while the update of tokens is accompanied by the entrance and exit of all vehicles in that token. After each round of computation, the model is able to give the moment of emptying for each token. Therefore, the computation can continue iteratively until there are no vehicles upstream of each inlet, and the vehicle information collected by the centralized control center can be processed continuously. In short, the accuracy and uniqueness of the token locations as well as their emptying and occupancy times need to be guaranteed.

2.2.3 The problem of tokens serving vehicles

The fundamental control process of the token is as follows: (1) The vehicle waits for a free token in the roundabout; (2) The vehicle is allowed to grab the free token and change the token into a busy one; (3) After the token service is completed, the free state is restored.

In a roundabout, as long as the token interval comes to the entrance of the roundabout at the moment when the vehicle is about to enter, then the vehicle can enter until that vehicle leaves, and the token complete its service to that vehicle.

$$\begin{aligned} \tau_{ti} &= \tau_{vj}, \\ P_{ti} &= P_{vj}. \end{aligned} \tag{2}$$

where, τ_{ti} is the time when token i arrives at a certain position; τ_{vj} is the time when vehicle j arrives at a certain position; P_{ti} represents the center position of the room corresponding to token i; P_{vj} is the front center position of the vehicle j and within the straight section of the entrance.

However, under the premise that the length of the token interval satisfies the length of the vehicle, the token and the vehicle should be in one-to-one correspondence; therefore, the above correspondence cannot be established for the remaining vehicle. For $\tau = \tau_{ti} = \tau_{vj}$, there is:

$$\forall k \neq i,\ P_{tk} < P_{vj} \text{ or } P_{tk} > P_{vj}. \tag{3}$$

To ensure the uniqueness of the service, 0-1 allocation variable S_i^j should be established for any token i and vehicle j. S_i^j means that token i does not allow vehicle j to use its corresponding room, while $S_i^j = 1$ means that the token allows the vehicle to use the room.

3 Results and discussion

The vehicle arrival data in this paper is randomly generated according to Poisson distribution. In the case of multiple lanes, each lane generates data independently, and adds the normal distribution random noise with the mean of 0. The experimental scenario is a roundabout with four entrances. The comparison of ordinary non-signalized and signal-controlled roundabouts is simulated in VISSIM, and the model calculation process is realized in MATLAB. Basic settings of the experiment include: the expected speed of all vehicles is 60 km/h, the unified vehicle type is ordinary car, and the vehicle can enter immediately after the conflict zone is cleared. Fig. 6 shows the decision path and conflict zone setting of an non-signalized roundabout.

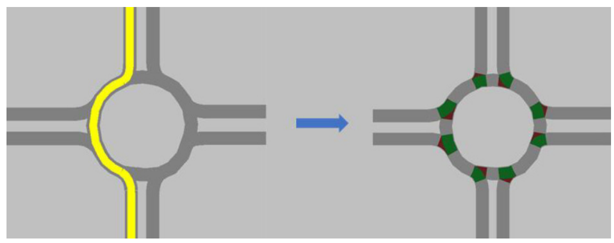

Fig. 6 Simulation setting of roundabout.

Through repeated tests, under the low flow of 600 veh/h, the average delay of vehicles at signal-less intersections is not high, no matter how the random seeds are set, and after the flow exceeds this range, the large-scale queuing of vehicles is obvious, while the traffic at signalized intersections is smooth as usual. The average delay of each vehicle at non-signalized roundabouts even exceeds 100 s. Under 1 200 veh/h, there is no obvious queuing of vehicles at signalized intersections. In the roundabout, the delay of using the token-vehicle mapping model is far lower than that of the non-signalized and signalized ones. In no-signal case, when the traffic flow in a single lane is larger than 600 veh/h, the delay has begun to accumulate, while the average delay of the token ring model in this study has always maintained at a low level, in a relatively large range of traffic flow until the traffic flow condition reaches about 2 200 veh/h.

When the flow does not reach about 2 200 veh/h, the model calculation results maintain a delay distribution similar to the flow of 2 000 veh/h in Fig. 7. The average delay is stable at 1−2 s, with only a small fluctuation. The possible reason is that the density of emptying in the ring is greater than the density of vehicles entering, that is, the token can meet the requirements of vehicles arriving with small delay. However, when there is too much traffic, due to the limitation of its own capacity in the ring, the empty density of the token cannot meet the densely approaching vehicles, thus resulting in continuous delay.

In addition, according to the calculation, the change of the parameter quantity of the optimization function in the model is shown

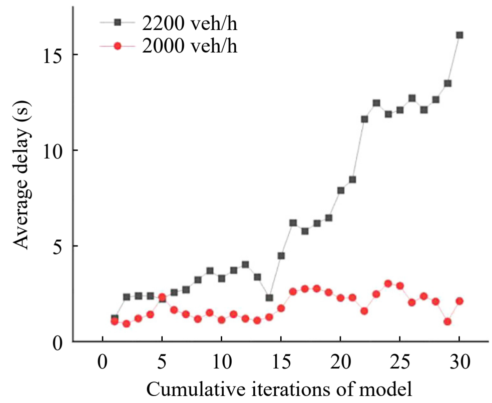

Fig. 7 Average delay of vehicles using token-vehicle mapping model.

in Fig. 8. With the increasing number of tokens in the calculation, the parameter quantity rising faster, which leads to the continuous increase of the calculation time. Although the problem is not critical when the upstream section is long, the calculation can be carried out in stages. The number of tokens calculated each time can be reduced, and the next round of update can be carried out after the unified summary, which can effectively improve the overall calculation speed.

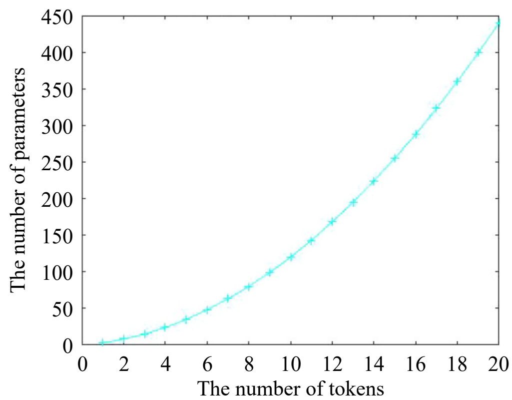

Fig. 8 The relationship between tokens and parameters.

4 Conclusion

Considering the distinct detour characteristics of roundabouts, this study has abstracted the spatial layout into multiple detour token rooms to optimize traffic flow. Through information interaction, the intersection acquires vehicle data, matches available tokens with incoming vehicles in a sequential manner, and facilitates immediate entry for waiting vehicles upon the departure of others from the roundabout. This approach has been shown to significantly enhance the space utilization efficiency of roundabouts and to mitigate vehicle conflicts within the intersection area.The control method proposed in this paper delineates the detailed setting of individual tokens, establishes a token-vehicle mapping model, and specifies the configuration of relevant variables and constraints.

Looking forward, we plan to refine the algorithm further by incorporating the dynamics of vehicle platoons to minimize the effects of weaving. Additionally, we will consider the safety of pedestrian crossings by introducing measures such as allocating a designated all-red period. These enhancements aim to improve the robustness and safety of the control system for autonomous vehicles at roundabouts.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Data Availability Statement

Some data and models supporting this study are available from the corresponding author upon reasonable request.

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