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Fusion Method of Urban Traffic Control and Route Guidance Based on Cyber-physical System Theory

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Abstract: A fusion framework for urban traffic control and route guidance (UTCGS) based on the Cyber-Physical System (CPS) was proposed. This framework involves computation, communication, control and physical components that facilitate the enhancement of the fusion degree of the Urban Traffic Flow Guidance System (UTFGS) and the Urban Traffic Control System (UTCS). The proposed framework focuses on the technical analysis of the feasibility of the depth fusion of both systems and provides a theoretical basis for the implementation of urban traffic control and route guidance fusion in intelligent traffic systems. The traffic system spatial-temporal congestion is mainly caused by three conditions, such as vehicle space distribution and vehicle time distribution are not consistent, vehicle space distribution is inconsistent and vehicle time distribution is inconsistent. The gap between vehicle space distribution and vehicle time distribution indicates that the different spatial-temporal distributions are divided into three categories. The formation mechanism of space factor congestion is similar to the formation mechanism of time factor congestion. For example, in vehicle space congestion, vehicle space distribution imbalance or space network structure imbalance will lead to congestion. Based on the congestion formation mechanism analysis, corresponding fusion method were proposed.

Key words: UTCGS, CPS, formation mechanism of congestion, fusion method

INTRODUCTION

UTCGS fusion is the key to solving the urban traffic problem. On the surface, the fusion of these two systems is difficult because of the contradiction between vehicle optimisation targets and intersection optimisation targets. In essence, fusion is difficult because of the contradiction between vehicle space distribution and vehicle time distribution.

Traffic flow is the ratio of vehicle time distribution to vehicle space distribution in a road network. Traffic flows with time and space (Wong and Hsieh, 2010). Traditional Traffic Guidance and Control (TGC) requires traffic flow prediction to show two spatial-temporal consistencies (Kamarianakis *et al*., 2012). Errors in traffic flow prediction results in actual traffic flow becoming the bottleneck of traffic control and traffic guidance. Inaccurate traffic flow prediction may increase the gap between space and time distributions which may lead to new congestion.

Early classical Traffic Guidance Algorithms (TGA) focuses on spatial factors. Recently, some TGA (Santos *et al*., 2007) has begun to consider the time factor. These algorithms do not have solutions in some cases, encounter computational difficulties, or arrive at multiple solutions. Considering the dynamic properties of a traffic system, the traffic network state is time varying. Scholars (Tavakkoli-Moghaddam *et al*., 2011) who stu--died guidance algorithms focused on the time factor.

Most Traffic Control Algorithm (TCA) are based on time factors (Oda, 2007). This approach can avoid the time lag between traffic measurement and signal control as well as the abrupt switching of control parameters that disrupt orderly traffic flow. The TCA achieves certain results, especially in non-congestion. Recently, some scholars have found that TCA focuses on time factor but does not eliminate congestion (Ukkusuri *et al*., 2010).

The current TGC algorithm cannot independently solve congestion problems. New developments in research must radically increase traffic control and guidance spatial-temporal consistency to benefit traffic system optimisation.

To further solve the spatial-temporal congestion problem, some researchers investigated the collaborated TGC (Yang *et al*., 2003; Zhao *et al*., 2010). These

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collaborative approaches to combine UTFGS and UTCS in the structure optimise the traffic system. TGA and TCA are not the same. They are not synchronised and are prone to error in space and time. The error needs to be eliminated by a coordinate TGC method.

In summary, the traditional method has weaknesses. The traditional method requires traffic flow prediction. TGA and TCA are not the same and are not synchronised. The synchronisation error and traffic flow prediction error may lead to traffic system spatial-temporal congestion and should be coordinated step by step.

To solve congestion problems, the fusion method of TGC was proposed based on CPS theory. Gong and Li, (2013) proposed a TGC fusion framework based on the CPS theory. The method based on CPS theory combined UTCS and UTFGS depth fusion in 3C (computing, communication and control) technology. Based on the proposed fusion framework and according to congestion formation mechanism, method was proposed in this paper. The method without traffic flow forecasting. TGA and TCA are the same and are synchronised. There are no synchronisation error and traffic flow prediction error. The Method fundamentally avoids traffic system congestion caused by vehicle distribution imbalance in time and space.

FUSION FRAMEWORK FOR UTCGS BASED ON CPS THEORY

Association between UTCGS and CPS are: System fusion of CPS provides a theoretical basis and technical support for the fusion framework of UTCS and UTFGS. The "fusion" of UTCS and UTFGS differs from their "collaboration," which indicates a mutual cooperation between the systems to achieve the overall goal while essentially maintaining their independence. Fusion considers the overall goal as a starting point and then creates mutual content as well as indistinct boundaries between UTCS and UTFGS. CPS embeds 3C technology into the physical world to achieve several technical indicators and service goals.

UTCGS is a large, complex system and CPS services such types of systems. UTCGS requires the unified control and real-time monitoring of a series of diverse sub-units, including vehicles, roads, traffic lights, communication equipment, computing platform and control equipment. Through 3C technology, CPS unifies the management and controls the different aspects of technology, equipment types and levels of system goals.

Reliability requirements and timeliness of UTCGS and CPS are consistent. Reliability requirements for UTCGS and CPS entail the real-time monitoring of service objects and themself. The dynamics of a traffic state determine the timeliness of UTCGS. The combination of CPS techniques and multiple equipment for projects is necessary for task completion. Each project requires time, thus necessitating the selection of timesaving methods.

The distributed and dynamic restructuring of CPS is similar to the basic principles of regional and dynamic restructuring. In CPS, area equipments are distribution controlled. When tasks dynamically change, a dynamic restructuring of equipment and technical resource is required. In a large-scale traffic network, dividing traffic areas based on dynamic traffic status and system technical requirements is necessary.

In UTCGS, the human factor is highly important.CPS possesses man-machine system characteristics. In UTCGS, traffic managers aim to achieve an optimal urban traffic system, whereas users aim to meet their own needs. Conflicts between these goals can be avoided by fully considering the human factors of UTCGS. CPS man-machine system characteristics are reflected in several aspects. Most service objects are man-machine systems. Through active regulation and control, people act as executors or maintenance staff for CPS. For service-object systems, users serve as 3C technology designers.

Applying CPS for UTCGS is theoretically feasible. Building a CPS fusion framework of UTCGS is a key step in realizing this theoretical method.

The traditional UTCGS framework can be divided into different modules according to function: integrated transport system state, user behavior, acquisition and selection of data, path planning and traffic control. Figure 1 shows the components of the fusion framework based on CPS, in which UTCGS is classified into different parts: computation, communication, control and the physical world. These parts interact with and provide input data to one another. In urban traffic systems, traffic information is dynamic and varies with time. By collecting and processing traffic information data as inputs for UTCGS and UTFGS, signal control strategies and path planning are derived.

Computation is divided into path planning and the control algorithm. Path planning involves single-vehicle path planning and system path planning. The control algorithm is similar in structure to path planning.

The communication process includes Internet of Things (IOT) and the GPS platform. IOT collects real-time phase traffic flow data on urban road intersections. Data are processed, then IOT provides corrected trigger signals to the path planning and control algorithm. Drivers provide travel plans to the GPS platform. GPS provides real-time vehicle location information, receives path planning information and then provides information to drivers in the control phase.

In UTCS, the control is the executive agency to control intersection traffic lights. In UTFGS, the drivers are the executive agency's counterparts in controlling vehicles.

In CPS, the physical world includes all vehicles, intersections and roads.

FORMATION MECHANISM OF CONGESTION

In a traffic system, vehicle space distribution and vehicle time distribution inconsistency has three types: road network has time allocation but has no space allocation for vehicles, has space allocation for vehicles but has no time allocation and has time and space allocation.

No-space allocation congestion is a road network that has time allocation but has no space allocation for vehicles. In a road network, roads or intersections enable vehicles to pass through in time but do not have the space to permit vehicles to enter. No-time allocation congestion is a road network that has space allocation but has no time allocation for vehicles. In a road network, roads or intersections do not allow vehicles to pass through in time but they have space to allow vehicles to enter. No-space and no-time allocation congestion is a road network that has no space and no time allocation for vehicles. In a road network, roads or intersections do not allow vehicles to pass through in time and has no space to allow vehicles to enter.

Space congestion is classified as congestion caused by vehicle space distribution imbalance and congestion caused by road network space structure imbalance.

Analysis from the perspective of space shows that traffic flow distribution in a road network is imbalanced when the system optimal target cannot be achieved. When traffic flow in roads or intersections is beyond their capacity, congestions occur in roads or intersections. vehicle space distribution imbalance is caused by vehicle origin-destination distribution imbalance and traffic guidance having too many vehicles on some roads or intersections.

The space of road network structure imbalance is categorised into two: the input and output capacities inconsistent in certain roads, intersections, or region and the insufficient space capacity caused by an intersection structure problem.

The first category belongs to the network design problem. It does not often occur in actual traffic environment. The main solution is to adjust the road network structure to make the input and output capacities consistent everywhere in the road network.

The second category case refers to all intersections shown as the roads overlapping in the intersecting space overlap. The intersection space is less than the total of all connected section spaces. When intersections do not exist, the road is disjointed in space. All vehicles running on the roads will cause not produce space congestion if the vehicles do not exceed the speed limit. Conversely, On the contrary, road network structure imbalance congestion may occur because of the existence of intersections.

The time congestion formation mechanism is similar to space congestion formation mechanism. Therefore, we will not discuss them any longer.

FUSION METHOD

The spatial-temporal inconsistency congestion occurs when error is found between space and time vehicle distribution. Avoiding error is more favourable than eliminating the error after it has occurred. The fusion method is provided to avoid congestion.

This study converts the traffic control time factor into a space factor combined with the traffic guidance spatial factors to make the TGC algorithm consistent and synchronised.

Traffic control is shown as time flow allocation. In traffic control, the time network (equivalent to a road network) is established. In the time network, length between intersections is expressed as the time required to pass through the road between intersections. In traffic control, time flow is equal to traffic flow in traffic guidance. Traffic and time flows should be synchronised.

The time flow allocation algorithm consists of two steps.

The first step is time flow distribution between any two intersections in the time network (i.e., intersection signal timing) called single time flow distribution. In traffic guidance, single-vehicle path planning distributes vehicles (i.e., travel route) between any two intersections in space (i.e., road network). Through conversion, single time flow distribution in traffic control is equivalent to single-vehicle path planning in traffic guidance.

Conflicts between single time flow distribution, unreasonable intersection signal timing and congestion are all possible. To avoid these problems and based on the traffic system optimisation goal, the second step of adjusting the overall of single time flow distribution, known as system time flow distribution, must be performed. In traffic guidance, system path planning takes traffic system optimisation as the goal. The overall single-vehicle path planning is adjusted to avoid conflicts between single-vehicle path planning. The conflict between single-vehicle path planning will lead to the excessive number of vehicles traveling to some sections, causing congestion in these sections. Through conversion, system time flow distribution in traffic control becomes equivalent to system path planning in traffic guidance.

TCA and TGA are the same through conversion. Table 1 shows the concept mapping for traffic control time factor and traffic guidance space factor.

Vehicle origin-destination distribution is decided by drivers' travel demand. Imbalanced vehicle origin-destination distribution is inevitable. Traditional traffic guidance is classified as single-vehicle guidance and multi-vehicle guidance. single-vehicle path planning may lead to an excessive number of vehicles on certain roads or intersections and the formation of space congestion.The system path planning usually achieves vehicle space distribution balance by sacrificing part of the single-vehicle path planning vehicle targets.

The new method to vehicle space distribution imbalance which is to meets the single-vehicle path planning target and considers the vehicle space distribution balance target, is achieved. The method avoid the excessive number of vehicles on certain roads or intersections. system path planning takes vehicle space distribution balance as the goal. The single-vehicle path planning target is considered to prevent the decrease in traffic guidance acceptance rate and make guidance effective.

The above method can resolve the congestion of intersections structures congestion. Intersection delay caused by the proposed method is less than the intersection delay caused by the traditional method. The proposed method has a certain feature of 'effective delay'.

'Effective delay' should meet the following conditions:

- Single-vehicle path planning meets drivers' travel demand
- Multi-vehicle path planning achieves traffic system optimisation target (i.e., traffic flow balances the target)

Table 1: Traffic control time factor and traffic guidance space factor concept mapping

Traffic control algorithm	Traffic guidance algorithm
Time network	Road network
Time difference between intersections (through section time)	Distance between intersections (section length)
Time flow	Traffic flow
Single time flow distribution	Single-vehicle path planning
System time flow distribution	System path planning

- Delayed vehicles are not excessive, time is not too long and the delay will not lead to more serious congestion

Effective delay has three methods:

- Adjust traffic guidance. By adjusting the vehicle route, the vehicle avoids 'effective delay'. Changing vehicle travel routes will not conducive to traffic system optimisation. Changing the vehicle travel route may detour the travel route or extend travel time which may cause or aggravate congestion
- Adjust vehicle speed. By adjusting vehicle speed, vehicles do not reach intersections at same time, avoiding 'effective delay'. Vehicles decelerate is not easy to be control. Vehicle acceleration may lead to vehicles exceeding the speed limit

Control the traffic light of an intersection (called, 'give way principle'). To reduce delay at intersections, the 'give way principle' should be consistent with the three conditions of 'effective delay'. Consider the first condition, many vehicles in one direction giving way to fewer vehicles in another direction is better than the other way around. Consider the second condition, fewer vehicles in one direction can cause many vehicles to converge in another direction and vice versa. Consider the third condition, fewer vehicles in one direction should give way to many vehicles in another direction to allow these vehicles to leave the intersections as soon as possible. At the same time, the 'give way principle' should maintain spatial-temporal consistency.

Comparing the three conditions, the third method is preferred.

The method of time congestion is similar to method of space congestion. Therefore, we will not discuss them any longer.

CONCLUSION

A fusion framework for UTCGS based on CPS theory was proposed. From a technical perspective, UTCGS is divided into four following: computation, communication, control and the physical world. The proposed framework enhances the degree of UTCGS fusion, providing a theoretical basis for implementation in ITS.

Analysis of the formation mechanism of traffic system congestion from the spatial-temporal view, Fusion method were proposed based on the congestion problem. The concept of 'effective delay' was proposed based on space road network structure imbalance. 'Effective delay' refers to the delay that achieves the system path planning and traffic system optimisation targets and does not lead to ‘congestion’. Solving ‘effective delay’ can reduce traffic system delay and benefit system optimisation.

The fusion method can unify and solve TGC contradiction in the spatial-temporal problem. The fusion method also synchronises and integrates TGC in real time and solves TGC contradiction at the technical level. In this study, TGC method was proposed to explore TGA and TCA complementary advantages and to support TGA and TCA in time and space. The fusion method also enables the traffic system to meet the spatial-temporal requirements and prevent traffic congestion.

In future, with in-depth study, to verify the proposed method need simulation. And ‘effective delay’ still has three issues that will require investigation in the future: (1) judgment on whether ‘effective delay’ meets the three conditions, (2) judgment on whether ‘effective delay’ meets DTD and (3) judgment on how to further reduce ‘effective delay’.

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