A Survey of Traffic Control With Vehicular Communications

Li Li, *Senior Member, IEEE*, Ding Wen, *Senior Member, IEEE*, and Danya Yao, *Member, IEEE*

***Abstract*—During the last 60 years, incessant efforts have been made to improve the efficiency of traffic control systems to meet ever-increasing traffic demands. Some recent works attempt to enhance traffic efficiency via vehicle-to-vehicle communications. In this paper, we aim to give a survey of some research frontiers in this trend, identifying early-stage key technologies and discussing potential benefits that will be gained. Our survey focuses on the control side and aims to highlight that the design philosophy for traffic control systems is undergoing a transition from feedback character to feedforward character. Moreover, we discuss some contrasting preferences in the design of traffic control systems and their relations to vehicular communications. The first pair of contrasting preferences are model-based predictive control versus simulation-based predictive control. The second pair are global planning-based control versus local self-organization-based control. The third pair are control using rich information that may be highly redundant versus control using concise information that is necessary. Both the potentials and drawbacks of these control strategies are explained. We hope these comparisons can shed some interesting light on future traffic control studies.**

***Index Terms*—Traffic control, vehicular communication.**

I. Introduction

VEHICLE-TO-VEHICLE communications have attracted increasing concerns in recent intelligent transportation studies [1]–[7]. For drivers, real-time communications can provide valuable traffic information to support en-route choice decisions. For traffic operators, fast communications help monitoring traffic flow dynamics to apply appropriate control promptly [8]. Moreover, intervehicle communications also play as the backbone of any automated vehicle platoons [9]–[11].

In this paper, we will address the new control strategies in future research, as new vehicle communication technologies are becoming pervasive. The prominence is given to the isolated intersection control collaborated, since few existing literatures have studied the network-wide traffic control cases yet.

We attempt to make this paper appeal to diverse audiences. Readers who do not wish to learn the details of intervehicle communications can also understand the recent progress of traffic control studies. More precisely, our purposes are trifold here.

First, we would like to summarize various approaches proposed to improve traffic efficiency around intersections with the aid of vehicular communications, aiming to advance the state of art and also the state of practice in intelligent traffic control fields.

Second, we would like to highlight the underlying change of design philosophy for future traffic control systems, because the transition from pure response control to mixed anticipatory/response control emerges strikingly in many recent academic papers.

Third, we would like to compare several research directions of traffic control, such as 1) model-based predictive traffic control versus simulation-based predictive traffic control; 2) global planning-based traffic control versus local self-organization-based traffic control; 3) traffic control with rich information hidden in big data versus traffic control with concise information with small data. We believe these comparisons could shed some interesting light on future traffic control studies.

To give a detailed analysis, the rest of this paper is arranged as follows. Section II first reviews how to enhance the isolated intersection efficiency with the advanced vehicle-level traffic measurements. Then, the concept of "cooperative driving" is introduced and analyzed. Several scheduling models proposed to strengthen vehicle coordination are investigated. Section III further discusses the possible benefits of utilizing real-time vehicle information in designing network-wide traffic control systems. Section IV compares different design preferences and explains their merits/demerits. At last, Section V concludes the paper.

II. Isolated Intersection Control With Vehicular Communications

A. Intersection Control With Real-Time Vehicle Information

Let us consider a general traffic control problem, in which the state variable is denoted as $x(k)$ (e.g., queuing length) and the environment input (e.g., arriving vehicles) is denoted as $d(k)$.

Our objective is to minimize a certain performance index J over a finite time horizon $[0, K]$ by determining a sequence of control inputs $u(0), u(1), \ldots, u(K)$ (e.g., phase orders, green time allocations, etc.) subject to initial conditions, system dynamics, and other constraints.

Abstractly, we can formulate this optimization problem as

$$\min_{u(k)} J = f\left[x(K)\right] + \sum_{k=1}^{K} g\left[x(k), u(k), d(k)\right] \tag{1}$$

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L. Li and D. Yao are with Department of Automation, Tsinghua University, Beijing 100084, China (e-mail: li-li@mail.tsinghua.edu.cn; yaody@mail.tsinghua.edu.cn).

D. Wen is with the Center for Military Computational Experiments and Parallel Systems Technology, National University of Defense Technology, Changsha 410073, China (e-mail: wending2010@gmail.com).

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subject to

1) initial state condition

$$x(1) = x_0 \tag{2}$$

2) end state condition (e.g., dispatch all the vehicles in the queue, etc.)

$$x(k+1) = h\left[x(k), u(k), d(k)\right], \qquad \text{for } k = 1, \ldots, K \tag{3}$$

3) box bounds on control actions (e.g., maximum cycle length, maximum green ratio, etc.)

$$u_{\min} \leq u(k) \leq u_{\max}, \qquad \text{for } k = 1, \ldots, K \tag{4}$$

4) bounds on state (e.g., maximum queuing length, etc.)

$$\varphi\left[x(k), u(k), d(k)\right] \in \Omega, \qquad \text{for } k = 1, \ldots, K \tag{5}$$

where $f[.]$, $g[.]$, $h[.]$, and $\varphi[.]$ are certain functions, and Ω is a certain set of values.

Then, we categorize existing traffic control systems, according to the information that is used, into three kinds.

1) Fixed-time traffic signal control systems do not use any real-time information of vehicle arrivals [12]. Instead, the signal timing plans were determined off-line based on historical observations. That is, we set $u(k) = \text{const}$ and omit $d(k)$, for $k = 1, \ldots, K$, in the previous optimization Problem (1)–(5). Such control system cannot adaptively respond to fluctuations of vehicle arrivals and behave unsatisfactorily in many situations.
2) Actuated traffic signal control systems use limited real-time measurements provided by inductive loop detectors that are usually installed tens of meters upstream to the stop lines [13]. Each detected vehicle will generate a call to ask for an additional green time. However, actuated control systems only "know" the number of vehicles that have already passed the loop detectors. In other words, we have $u(k) = \theta[x(k), d(k)]$ in the previous optimization Problem (1)–(5), where $\theta[.]$ is a certain function. The number of vehicles that will arrive in the future is yet unknown, and hence, we can only solve Problem (1)–(5) when $K = 1$. This often makes the designed signal plan less effective.
3) Adaptive traffic signal control systems, such as SCATS [14], SCOOT [15], and RHODES [16], still use loop detectors to retrieve information, including when a vehicle passes the loop detector, how long it occupies the detector, and its instant speed. These control systems further employ prediction models to forecast the vehicle arrivals and estimate queue lengths at each intersection. That is, $u(k) = \varphi[x(k), d(k), \widetilde{d}(k+1)]$ in the previous optimization Problem (1)–(5), where $\varphi[.]$ is a certain function, and $\widetilde{d}(k+1)$ denotes the predicted traffic demands in the next time interval. Under such assumptions, we can solve Problem (1) with $K = 2$. The performance of timing plan thus depends on the prediction accuracy.

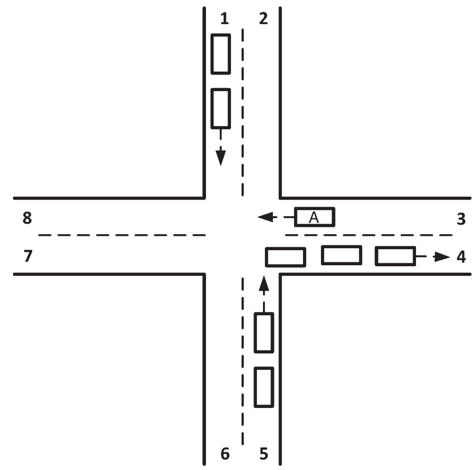

Fig. 1. Illustration of platoon-based control, where the lanes are clockwise labeled. The control system will block vehicle $\boldsymbol{A}$ and let vehicle platoons arriving from lane 1 and lane 5 to pass the intersection first, although vehicle $\boldsymbol{A}$ arrives earlier than other vehicles; thus, the total delay can be minimized.

However, if all the vehicles had installed vehicular communication equipment, we could easily track the movements of all vehicles and precisely calculate the required information for signal timing.

Let us take the platoon-based control strategy as an example [17]–[19]. Generally, a platoon refers to a group of vehicles traveling together with short intervehicle headways. The interarrival between consecutive platoons can be quite large because of the influences of neighboring traffic lights. Hence, it is highly possible to set a timing plan that allows the platoons coming from different directions to pass the intersection without significant interruptions (see Fig. 1 for an illustration).

In the previous optimization model, this kind of control strategy can be recapitulated as finding a sequence of control inputs $u(k)$, each of which consists of a series of green time allocated for different phases, e.g., $u_k^1, \ldots, u_k^M$. The lengths and orders of u_k^j, $j = 1, \ldots, M$ are carefully set to give large platoons a higher priority to pass the intersection, given the accurate information of $d(k+1)$.

One difficulty of applying platoon-based control strategy is how to identify the coming platoons quickly, conveniently, and robustly [17]. Various clustering and grouping algorithms have been proposed and tested [17]–[19]. However, if every vehicle can send its movement information directly to the control systems, we do not need to worry about this problem any more [20], [21].

Now, we can solve the following optimization problem:

$$\min_{u(k)} J = f\left[x(K)\right] + \sum_{k=1}^{K} g\left[x(k), u(k), d(k)\right] \tag{6}$$

subject to previous constraints (2)–(5).

If foreseeing a longer time, we can solve Problem (1)–(6) with $K \gg 1$. This usually leads to global optimal control sequences that cannot be achieved by sequentially solving Problem (1) with $K = 1$ or $K = 2$.

However, it should also be pointed out that the platoon-based control becomes more complex and more difficult to solve, along with the increase in K. As shown in [22] and [23], each valid signal timing plan can be taken as a schedule that specifies the order in which all the platoons pass through the intersection one by one. In other words, the whole planning problem can be viewed as a single-machine total tardiness scheduling problem [24] with some additional constraints. The ordinary single-machine total tardiness scheduling problem is NP-hard [25]. Although the additional constraints can help reduce the solution space, we think the platoon-based control problem is still NP-hard.

B. Cooperative Driving With/Without Signal Control

In conventional studies, it was assumed that drivers would not change their driving plan but just notify the control systems about their positions and movements. However, in many recent studies, the moving plans of vehicles were also assumed to be changeable to further improve driving efficiency. One representative approach in this area is called "cooperative driving."

The concept of cooperative driving was first introduced in the early 1990s [9], [26], [27]. Initially, it only refers to flexible platooning of automated vehicles with a short intervehicle distance over a couple of lanes. In [28], the term "cooperative driving" further referred to implementing collision-free vehicle movement around unsignalized intersections aided by intervehicle communications.

Different from the platoon-based control strategy [17]–[19], a "cooperative driving" vehicle can either accelerate to joint in an already formed platoon or decelerate to depart from it [28]. Several vehicles can merge together to form a new platoon, too. In the previous optimization model, this assumption means that we can partly change $d(k)$ or even $d(k+1)$, when we are designing $u(k)$ at the kth time interval.

That is, we could rewrite the previous optimization problem as

$$\min_{u(k),\Delta(k)} J = f\left[x(K)\right] + \sum_{k=1}^{K} g\left[x(k), u(k), d(k), \Delta(k)\right] \quad (7)$$

subject to previous constraints (2)–(5)

$$\Delta(k) = \psi\left[d(k)\right], \qquad \text{for } k = 1, \ldots, K \quad (8)$$

where $\psi[.]$ is a certain function.

This certainly brings more flexibility of traffic controller and strengthens the traffic system efficiency.

Naturally, we shall use another kind of data structure instead of platoons to measure the traffic appropriately. In [28], each valid signal timing plan was taken as a schedule that specified the order in which all the vehicles passed through the intersection. Two or more vehicles are permitted to pass the intersections simultaneously, if no collision will occur. Thus, each driving schedule is an ordered sequence of vehicle pairs.

The solution space can be then represented as a tree. Suppose a total of N vehicles are considered. The root node has a number of children nodes, which represent all the possible permutation orders of the vehicle sequence without any groups. Then, for each node in the nth level of the tree, we generate $N+1-n$ children node by inserting only one separator into the sequence that is represented by this node. Here, $1 \leq n \leq N$. Finally, we can get the solution space as a tree.

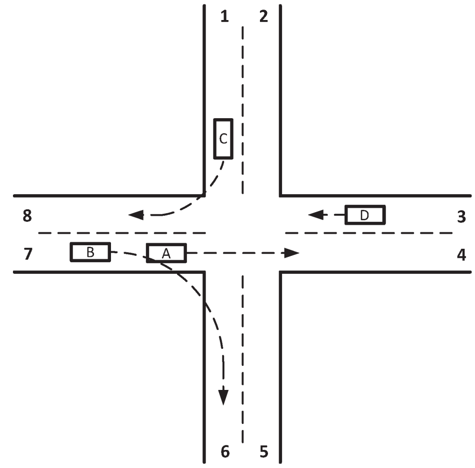

Fig. 2. Driving scenario at a two-lane intersection, where the lanes are clockwise labeled. Vehicle $\boldsymbol{A}$ intends to move from lane 7 to lane 4, vehicle $\boldsymbol{B}$ from lane 7 to lane 6, vehicle $\boldsymbol{C}$ from lane 1 to lane 8, and vehicle $\boldsymbol{D}$ from lane 3 to lane 8.

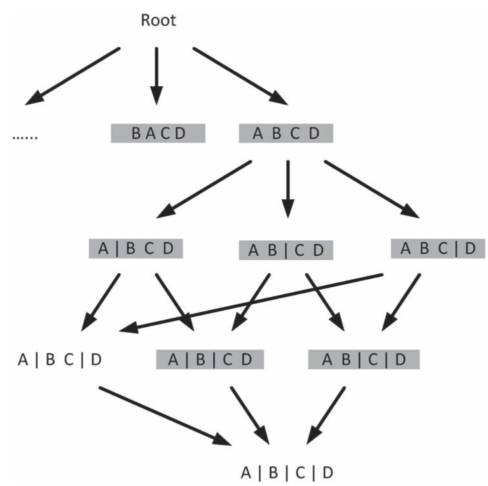

Fig. 3. Schedule tree stemmed from the driving scenario shown in Fig. 2. Some nodes are children of more than one parent node. The shadow nodes represent invalid driving schedule.

Let us use the four-vehicle driving scenario shown in Fig. 2 as an example. Fig. 3 shows the corresponding schedule tree. Here, "|" is a separator symbol that divides the sequence into several subsets. In particular, vehicles $\boldsymbol{B}$ and $\boldsymbol{C}$ are in one subset, indicating that they will pass the intersection at the same time.

Clearly, a great number of nodes in this tree can directly be discarded since they represent invalid driving schedules. For example, the $\boldsymbol{B\ A\ C\ D}$ node shown in Fig. 3 is invalid, since vehicle $\boldsymbol{A}$ must pass the intersection before vehicle $\boldsymbol{B}$. This kind of knowledge will help reduce the solution space and thus decrease scheduling time cost.

A more important difference between platoon-based control and cooperative driving is that we cannot use the total delay to evaluate the intersection performance. Indeed, it is hard to define the delay for cooperative driving, since we may allow a part of or even all vehicles to pass the intersection with slow speeds but without any fully stop.[1] Hence, the throughput of intersection or some other measures should be considered instead.

Equivalently, our objective is to find a collision-free and feasible schedule that makes the studied vehicles pass the intersection in the shortest time. The feasibility of schedule is often difficult to test, since we need to consider whether the empirical ac/deceleration capability of vehicles can produce the desired vehicle trajectories. Some detailed discussions can be found in [28] and [32]–[34]. It should also be pointed out that some other reports neglected such constraints and therefore drew unsatisfactory conclusions.

When traffic flow is sparse, we can enumerate the whole solution space to find the best schedule [35]–[39]. However, when facing heavy traffic, the problem becomes intractable.

One kind of solution is using mathematical programming or heuristic algorithms to find some near-optimal solutions. The reported algorithms include genetic algorithm, ant-colony algorithm, etc. [40]–[42].

Another kind of solution is letting the vehicles that almost arrive at the intersection formulate short-term driving plans via bilateral negotiations [39] ,[43]–[48]. Different from planning-based approaches, only a few vehicles nearby the intersection are considered to make decisions within a selected time interval. As a result, the solution space is much smaller, and the search cost is limited. Such approaches can be viewed as a one-step-ahead greedy search. The performance of negotiation-based control is sometimes lower than that of planning-based control, but negotiation-based control consumes less computation costs and generates agile reactions under any unexpected changes.

Although some of these solutions still adopted traffic lights to guide vehicles, most researchers in this new direction clearly expressed intents of a transition from modern-day signalized traffic control systems to future unsignalized traffic control systems. However, we are still not sure when this goal can be reached.

III. Network-Wide Traffic Control With Vehicular Communications

A. *Network-Wide Traffic Control With Real-Time Vehicle Information*

Similar to isolated intersection control, highway ramping control and urban road network control also require accurate vehicle position information.

For example, different algorithms were proposed in the last few years to estimate the vehicle queue lengths at metered on-ramps [49], [50] and the queue lengths and the travel times for congested signalized arterials [51]–[55] and for a road network [56], [57]. All these studies used certain *a priori* knowledge of traffic flow dynamics to infer/predict the required traffic flow parameters (flow rate, occupancy, speed, etc.) at the locations with no measurements.

However, if the position and movement information of all vehicles can be achieved via vehicular communications, such difficulties will be solved neatly. Such changes indeed reflect a transition of design philosophies for traffic control systems.

As pointed out in many literatures [58]–[60], most existing traffic control systems conform to the concept of feedback control, because they specify the control rules in response to the current values of state variables.

In many recent approaches, researchers have began to integrate both feedback and feedforward characters to build traffic control systems. When traffic demands can be measured or effectively predicted before they enter the current system, we can take a preemptive action to optimize the traffic efficiency. In such systems, we can formulate a new optimization problem (6), with control $u(k)$ determined upon future states $x(k+i)$ and demands $d(k+i)$, where i may equal to 1, 2, ... Although the dimensions of variables are much larger than those that had been considered for isolated intersections, their instinct nature is the same.

Different preferences on choosing control $u(k)$ will be discussed in Section IV.

B. *Network-Wide Cooperative Driving*

Researchers have also considered cooperative driving at adjacent intersections [61], [62].

Suppose we divide the studied road network into several nonoverlapped segments (nodes) and define a graph to model the connection properties of these segments. Further assume that each vehicle has a specified route from its origin to its destination and will pass a few segments sequentially, the desired trajectory for any vehicle can be then roughly sketched as a series of time slices when the vehicle enters the selected segment. The control design problem becomes finding a set of trajectories that allow vehicles reach their destination nodes in the shortest time.

It is apparent that such a discrete-time graph-scheduling problem is much more complex than the simple tree scheduling problem formulated for isolated intersections. Even if we omit the detailed driving plans of any vehicle in the segments, the solution space will expand quickly with the increasing number of intersections. Currently, knowledge on the feasibility and benefit of the network-wide cooperative driving is very meager. To the authors' knowledge, only [63] had proposed a greedy search strategy.

IV. Different Preferences

A. *Model-Based Versus Simulation-Based Predictive Controls*

How to utilize the rich information collected via vehicular communications is a key problem in future traffic control system designs.

One representative approach in this direction is based on the model predictive control (MPC) theory [64]–[67]. In such approaches, the dynamics of traffic flows at different locations (nodes) are abstractly described by a set of difference equations, such as (3) previously. When the current states of the nodes

[1] It is now widely believed that if the number of stop-and-go events can be reduced, fuel efficiency will increase while emissions will be reduced. Please see [29]–[31] for detailed discussions. Therefore, we prefer to make all vehicles pass the intersection without any fully stops.

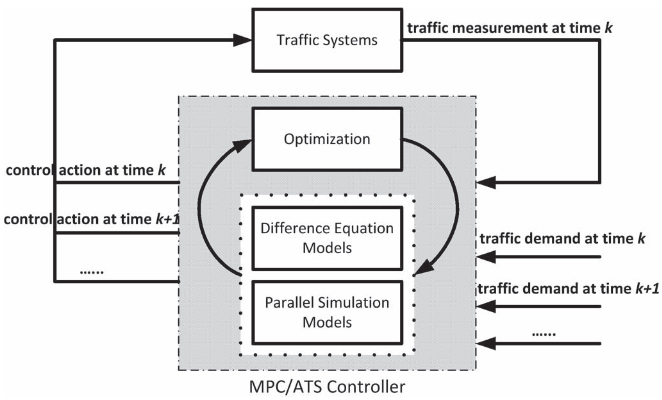

Fig. 4. Schematic view of MPC and ATS control.

(e.g., traffic flow rates and densities) are known or at least partly known, we can foretell the future states of traffic flows by recursively solving this set of difference equations with desired control actions. Searching the solution space for control actions, we finally adopt the control actions that will lead to the best future states of traffic flows.

Notice that the difference equations may not be able to accurately characterize the time-varying stochastic traffic flow dynamics; researchers now show increasing interests in the parallel simulation of traffic systems. In such approaches, the so-called artificial transportation systems (ATSs) [68]–[72] were built to model and analyze traffic flow dynamics. Through the parallel interactions of an actual transportation system and its corresponding ATS, we can evaluate the effectiveness of different traffic strategies under various conditions.

Both MPC and ATS control use online optimization to design control actions. Their difference is that MPC uses an explicit prediction model, whereas ATS control uses an implicit prediction model. Usually, both MPC and ATS control simultaneously schedule the control inputs $u(0), u(1), \ldots, u(K)$ for a relatively long time horizon to find a global optimal solution for J. In addition, both of them allow modifying inappropriately scheduled control inputs in the following time intervals.

Compared with difference-equation-based MPC, parallel-simulation-based ATS control provides a more flexible and living ontology to represent and organize knowledge of transportation systems (see Fig. 4). This enables us to choose even better control strategies by using ATSs. However, the computation costs of ATS methods are much higher, too [70].

Obviously, intervehicle communication can serve as a key component in all these new traffic control systems, since we can capture the variation of traffic demands in advance. However, the best way to fuse the predicted/simulated traffic states conveniently and promptly with the sampled states still need further discussions. We are expecting the shift of research interests into this promising area in the near future.

B. Planning-Based Versus Self-Organization-Based Controls

Whether to apply global planning-based control or local self-organization-based control is another interesting and important problem. Generally, global planning-based approaches refer to control city-wide road networks that may contain tens of intersections or on-/off-ramps via long-term scheduled control actions [73], [74], whereas local self-organization approaches refer to build short-term changeable control actions [75], [76].

Intuitively, global approaches seem better, because more information will be used to obtain an even better nongreedy solution. However, the temporal–spatial size of an independent traffic control system is restricted by many factors in practice.

The first constraint lies in the performance limit of vehicular communications. The packet drop rates, end-to-end packet delays, and network throughputs all influence the amount of information that can be correctly delivered in time and thus limit the temporal–spatial size of traffic control systems [3]–[7].

The second constraint comes from the possible vulnerability of control systems. It was argued in [75], and [76] that many man-made systems become unstable and create uncontrollable consequences, as the complexity and interaction strengths in a networked subsystem increase, even when decisions are well planned. Noticing that all the measurements may be distorted or inaccurate due to various reasons (e.g., transmission errors in wireless communications), applying local self-organization-based control is believed by many researchers as a better choice.

We are interested in receiving more opinions on this topic.

C. Big-Data-Based Versus Concise-Data-Based Controls

Similar to studies in many other fields, there are two diversions in employing the amount of traffic information to design traffic control systems. One is to use the rich information, as what had been discussed earlier [77]. The other is to use concise information that is necessary.

A representative example of the second kind of approach is the traffic control system based on urban-scale macroscopic fundamental diagrams (MFDs) [78]–[81]. Since modeling the traffic flow dynamics of each link and intersection in a large urban network is a complex task, such approaches aim to capture the primary characteristics between network-wide vehicle densities and network-wide space-mean flow rates. That is, we consider the collective behaviors of a lot of vehicles rather than the movements of individual vehicles. Then, parsimonious control rules can be designed for the whole road network, based on the measurements collected at sparsely located sensors.

A typical example of MFD-based control is perimeter control for a city-wide network with complicated structures. Here, perimeter control means the access metering to maintain the mobility of cars at a stabilized level. The detailed traffic dynamics in the studied region are not studied. Instead, we describe the average degree of congestion for the region by means of average vehicle densities and space-mean flow rates estimated by a few fixed detectors and floating vehicle probes. To prevent overcrowding, traffic flow toward a congested region is restricted, whereas traffic flow toward an underutilized area is facilitated. Although we do not know the evolution details of traffic flow at every part of a region, the overall traffic is under control.

Differently, the aforementioned vehicle-coordination-based approach will track every vehicle in this region, analyze their traveling plans, and set up the signal timing plan for each intersection within this region to make the overall traffic smoother.

MFD-based approaches have many merits, such as a simpler design algorithm that is relatively robust to traffic demand disturbances and much lower implementation costs. However, the drawbacks of MFD-based approaches, including inaccurate estimation of performance indexes (e.g., queue length at every intersection), are apparent, too.

It is now impossible to assert which of these two extreme research directions is better. We are looking forward to more testing results on this interesting question.

V. Conclusion

Due to the ever-increasing need for more efficient transport, vehicle-to-vehicle communications are introduced into traffic control systems to better coordinate vehicles and traffic signals nowadays. This change promotes new research frontiers to be further explored. Constrained by the length limit, we just focus on a few questions on the advance of control systems in this paper.

It should be pointed out that few studies have addressed the following two problems in this field.

First, the performance limits of vehicle coordination are left untouched in this survey. It was estimated in [82] that the benefit-to-cost ratio of retiming conventional traffic signal systems was typically 40 : 1. We believe the potential benefit of the intelligent vehicle coordination might be even higher. However, this technology cannot dramatically eliminate traffic congestion when all the roads are crowded. The estimation of performance limits needs further investigations.

Second, the achievements of any intelligent traffic control system previously mentioned are rooted in a successful integration of lots of sensors, controllers, operations software, and hardware [83], [84]. The failure of any component in this integrated system will result in performance degradation [85], [86] or even severe traffic accidents. How to identify failure (maybe at individual vehicle level) in time and tolerate faults of some components (maybe at regional control system level) also needs to be carefully studied.

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Li Li (S'05–M'06–SM'10) is an Associate Professor with the Department of Automation, Tsinghua University, Beijing, China, working in the fields of complex and networked systems, intelligent control and sensing, intelligent transportation systems, and intelligent vehicles. He has published over 30 international journal papers indexed by the Science Citation Index and over 40 international conference papers as a first/corresponding author.

Dr. Li is an Associate Editor for IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS.

Ding Wen (M'95–SM'99) is a Professor with the Center for Military Computational Experiments and Parallel Systems Technology, National University of Defense Technology, Changsha, China, where he is also a Senior Advisor. His research interests include behavioral operation management, human resource management, management information systems, and intelligent systems. He has published extensively and received numerous awards for his work in these areas.

Danya Yao (M'04) received the B.S., M.S., and Ph.D. degrees from Tsinghua University, Beijing, China, in 1988, 1990, and 1994, respectively.

He is a Full Professor with the Department of Automation, Tsinghua University. His research interests include intelligent detection technology, system engineering, mixed traffic flow theory, and intelligent transportation systems.