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A BRIEF SURVEY ON ADVANCES OF CONTROL AND INTELLIGENT SYSTEMS METHODS FOR TRAFFIC-RESPONSIVE CONTROL OF URBAN NETWORKS

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Subject review
Traffic congestions in urban networks could contribute to adverse impact on the economy, environment and the quality of life. As a result, much research has been conducted to provide counter measures through traffic-responsive control strategies. These strategies aim to provide automated regulations of traffics through various control and intelligent systems methodologies. This paper provides an overview of control methods such as adaptive control, model-based and store-and-forward approaches for coordinated intersection control, freeway control as well as route-guidance and driver information systems. In addition, intelligent systems methods which include computational intelligence, agent-based and Petri nets are also reviewed with inclusion of some brief examples. The feasibility of these control and intelligent systems approaches is discussed with suggestions for future works.

Keywords: *adaptive control, intelligent systems, model-based control, store-and-forward, urban traffics*

Kratki pregled poboljšanja metoda upravljačkih i inteligentnih sustava za reguliranje gradskog prometa u neposrednoj ovisnosti od prometa

Pregledni članak
Zagušenje prometa na gradskim prometnicama moglo bi imati negativne posljedice na privredu, okoliš i kvalitetu života. Zbog toga su provedena mnoga istraživanja u cilju pronalaženja protumjera kroz strategije reguliranja prometa u skladu s postojećim stanjem u prometu. Te su strategije usmjerene osiguranju automatske regulacije prometa primjenom različitih metodologija inteligentnih sustava i upravljanja prometom. Ovaj rad daje pregled metoda regulacije prometa kao što su prilagodljivost zahtjevima regulacije prometa, pristup zasnovan na modelu te onaj kojim se registriraju i prosljeđuju informacije o stanju zbog koordiniranog reguliranja raskrsnica i ulaza na autoput. Daje se i sustav obavještavanja vozača o načinu usmjeravanja prometa po mreži. Uz to se daje i pregled metoda ineligentnih sustava koje uključuju računarske informacije, mreže koje povezuju više predstavnika i Petri mreže, sve popraćeno s nekoliko kratkih primjera. Raspravlja se o izvedivosti ovih upravljačkih i inteligentnih sustava uz sugestije za daljnje radove.

Ključne riječi: *gradski promet, inteligentni sustavi, prilagodljivost zahtjevima regulacije prometa, registriraj i proslijedi, upravljanje zasnovano na modelu*

1 Introduction

Urban traffic control strategies have been researched extensively in the past few decades to explore effective methods to curb traffic congestions. Traffic control strategies which fall mainly into fixed-time and traffic-responsive control have been innovated with various control and optimization methods with the aim to improve the traffic situations.

Fixed-time strategy is a type of pre-timed signal control scheme that is computed offline. With the aid of simulation tools such as MAXBAND [1] and TRANSYT [2]; signal offset, cycle time and optimal splits are calculated using historical traffic data before implementation in real-time. On the other hand, traffic-responsive strategies employ sensors that collect real-time traffic data and utilize control schemes that change the splits, cycle time and offset at individual intersections and evaluate the best signal timing plan for the traffic situation.

In this paper, we aim to review various control and intelligent systems methods in traffic-responsive strategies. Section 2 provides an overview of traffic-responsive control methods whereas Section 3 outlines the development of traffic control using intelligent systems methods such as computational intelligence, agent-based systems and Petri nets. The paper concludes with discussion and suggestions for future works.

2 Traffic-responsive control methods

Fixed-time control methods mostly apply to isolated intersections while traffic-responsive strategies aim to provide a coordinated control effort that involves a few intersections and even the whole urban network. The following sub-sections give an overview of various traffic-responsive coordinated control methods.

2.1 Adaptive control schemes

Adaptive control schemes such as SCOOT [3] and SCAT [4] have been applied mostly in cities in the United Kingdom and Australia, respectively. They run in a central computer networked with sensors that feed real-time traffic data. Based on real-time data both schemes optimize cycle length, offset and phase split at individual intersections. Comparative study of both SCOOT and SCAT is conducted in [5]. It is found that SCOOT performances deteriorate in saturated traffic conditions. Other similar methods include UTOPIA [6] and MITROP [7].

2.2 Model-based methods

Model-based methods intend to model the behaviour of traffic and explicitly predict the change in traffic states in a future time horizon. Subsequently, control measures to optimize performance index are calculated. Schutter et al. [8] discussed these advance model-based methods and presented a model-predictive control (MPC) for integrated freeway and urban traffic networks. Their MPC includes a prediction model and control objectives with constraints. An on-line prediction model and optimization are used to determine the control actions that optimize a given performance criterion over a given time horizon subject to given constraints. Receding horizon strategy is applied using the first signal control sequence; next the optimization is started again with the prediction horizon shifted towards a future time horizon. The overall control objective is to reduce the total time spent by vehicles in the network.

A MPC structure in [8] is shown in Fig. 1. The controller contains a predictive model and an optimization module that runs repeatedly to find the optimal control signal at any given control time step. The signal is implemented in the traffic systems and traffic states are feedback into the controller to correct prediction errors.

Similar model-based approaches are found in control schemes such as OPAC [9], CRONOS [10], PRODYN [11], and RHODES [12]. These schemes contribute to dynamic optimization in a real-time traffic-responsive environment. Exponential-complexity algorithms are needed to perform global minimization in these schemes.

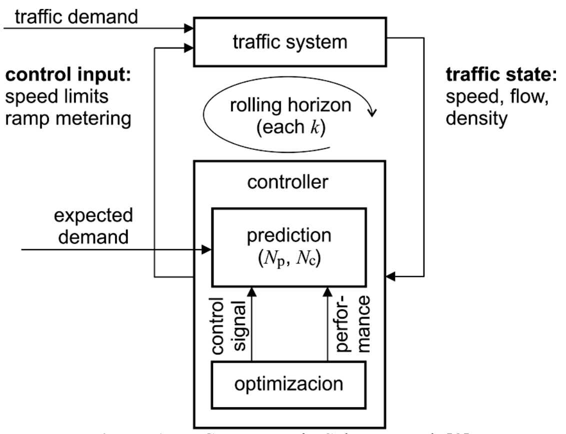

Figure 1 MPC structure in Schutter et al. [8]

2.3 Store-and-forward approach

Store-and-forward modelling was first proposed by Gasiz and Potts [13, 14]. It is then used extensively in various works in road traffic control. In store-and-forward models road traffic flow is described with mathematical description without the use of discrete variables. Papageorgiou et al. [15] discussed the benefits of this approach that open ways to a number of highly efficient optimization and control methods such as linear programming, quadratic programming, nonlinear programming and multivariable regulators. This allows for coordinated control of large networks especially in regulation of oversaturated traffic situations. These optimization and control methods are explained with an application example in [16]. An example of application of multivariable regulator approach is found in the signal control strategy TUC (Traffic responsive urban control) [17, 18]. As a matter of fact, TUC has been implemented successfully and is currently operational in part of Glasgow, UK [19] and Chania, Greece [20].

2.4 Traffic-responsive control of freeway

The methods mentioned previously primarily address responsive intersection signal control. However, the urban network does not only comprise of intersections but also includes freeways. Reactive ramp metering strategies have been implemented for responsive control of freeway traffics. One of these strategies such as the demand-capacity strategy is a type of feed forward control that regulates ramp flow based on inputs from upstream and downstream traffic measurements [21].

Another well-known ramp metering control scheme is ALINEA [22] which is a closed-loop strategy that regulates ramp flow based on feedback from downstream traffic (see Fig. 2). The controller reads,

$$r(k) = r(k-1) + K_{\mathrm{R}} \cdot \left[\hat{o} - o_{\mathrm{out}}(k)\right], \tag{1}$$

where $K_{\mathrm{R}} > 0$ is a regulator parameter and $\hat{o}$ is the desired set value of the downstream occupancy. The downstream flow is denoted as $o_{\mathrm{out}}(k)$. ALINEA is obviously an integral regulator where $\hat{o} = o_{\mathrm{out}}(k)$ during stationary state of upstream inflow i.e. q_{in} is constant. An improved and extended version of ALINEA is METALINE [23] which is based on multivariable regulator strategy. These strategies are explained comprehensively in [15].

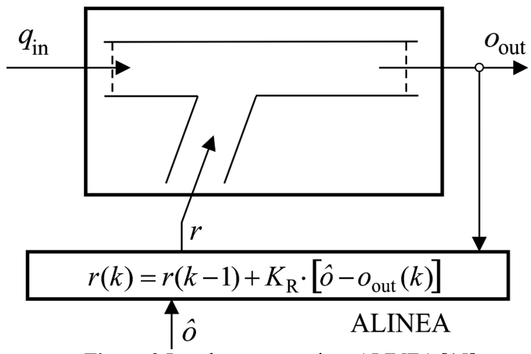

Figure 2 Local ramp metering: ALINEA [15]

The methods mentioned above are usually designed and implemented independently; as a result synergistic work is carried out to coordinate these independent control actions to maximize the effect of freeway flow. An example of such coordinated approach is found in AMOC [24] which is an integrated freeway network control tool that executes simultaneously ramp metering and route guidance.

2.5 Route guidance and driver information system

Route guidance and driver information system (RGDIS) is an approach to provide road users with real-time information regarding the traffic conditions via communication devices that indirectly or directly affect their route choice decisions. Commonly used en-route communication devices such as radio-broadcasting and variable message signs (VMS) provide a basis for route choice decision for over decades. The recommendations obtained from these sources cause traffic diversion to alternatives route to reduce congestions and improve network efficiency. Route guidance can be viewed as a control system that aims to achieve user-equilibrium in the traffic network which was first introduced by Wardrop [25]. Route guidance strategies such as reactive, predictive, one-shot and iterative strategies are discussed comprehensively in [15]. They are used to predict future traffic flow via computations and simulations by using current traffic measurements and recommend alternative route to road users. As a result, the route choice of the driver has an impact on the traffic flow in the network. Hence, system optimum or user-optimal conditions may be attained.

3 Intelligent systems

In this Section, three areas of intelligent systems are surveyed. Section 3.1 outlines the contributions of computational intelligence; Sections 3.2 and 3.3 briefly provide the development of agent-based methods and Petri nets respectively.

3.1 Computational intelligence

Computational intelligence (CI) methods are cost effective control methods in dealing with the complexity and dynamics of today's traffic situation. CI methods such as fuzzy systems, artificial neural networks (ANN), evolutionary computing (EC) and swarm intelligence (SI) are excellent control methods for the urban networks. On the other hand, multi-agent system consists of multiple intelligent agents interacting with each other to solve problems that are too difficult for a monolithic system to solve.

Fuzzy-based control systems evaluate the traffic situation based on some set of rules (membership functions) and approximate an optimal signal control strategy. Lin et al. [26] proposed a dynamic model that feeds traffic predictions into a fuzzy controller that approximates optimal timing plan in real-time. A fuzzy controller is implemented in [27] to control the time length of each light phase. Kononen and Nittymaki [28] proposed two types of fuzzy method namely Mamdani and Maximal Fuzzy Similarity to control a traffic junction by adjusting optimal timing plan. The performances of both methods are compared. Lee et al. [29] extended a two-stage fuzzy controller with a more complicated fuzzy control method to adjust phase sequence and splits to regulate traffic at intersections. A fuzzy rule based system proposed in [30] is to regulate traffic at oversaturated intersections. Based on traffic data, the rules decide whether to extend the current green signal or terminate it.

The ANN processes data with the concept which is similar to the brain. It memorizes training data through updating the weights of the neurons. Hence, it is capable as a self-learning method that can memorize and recognize features and patterns. Various types of ANNs have been applied for the urban traffics where they were found to be useful forecasting models. A pattern recognition method using feedforward ANN is developed to estimate traffic patterns using input from detectors [31]. The method is also able to select suitable timing plans in anticipation of abnormal traffic patterns. Xiaojian et al. [32] forecasted crossroad traffic flows using back propagation (BP) ANN. The work is capable of forecasting short term traffic flow at crossroads. BP ANN is also applied in [33] for traffic flow estimation. In [34], it is applied for accident detection at intersections. Hence, a control scheme for intersection recovery from accident is implemented. Besides feedforward ANN and BP ANN, other types of ANN such as probabilistic NN [35] and recurrent NN [36] have been used for incident forecast and modelling traffic flow respectively.

As urban traffic control aims to possess both predictive and decision making abilities, it is a novel practice to integrate both fuzzy system and ANN to achieve more efficient traffic control. A fuzzy neural network (FNN) is developed in [37] for traffic signal control. As the NN learns the traffic flow patterns it performs tuning on the fuzzy rules and optimizes system parameters. This resulted in a variable fuzzy rules set that can adapt to variable traffic conditions. Similar work on using NN to adjust membership function of a fuzzy controller to adapt to unpredictable traffic situations is found in [38]. This neuro-fuzzy controller performed better than fixed-timed controller. However, the neuro-fuzzy controller needs to be trained with various input data. The method is simulated for signal control at two 4-ways traffic junctions [39] to minimize delay experienced by driver through the adjustment of green light time by the fuzzy control system.

EC and SI are both optimization algorithms inspired by nature. EC imitates natural evolution theory under the principle of survival of the fittest while SI derives the collective behaviour of biological species such as birds, ants, bees, etc. [40]. Both EC and SI simplify nonlinear programming problems through heuristic search of near-optimal or optimal solutions.

Ant colony optimization (ACO) which is a type of SI is applied to find the optimal signal timing plan for a signal intersection [41]. The inputs to the ACO controller are vehicle queues and predicted vehicle waiting time. The prediction of vehicle waiting time is provided by a rolling horizon approach. Based on these inputs the ACO generates optimal signal switching time after performing a heuristic search. Two different types of ACO namely Ant System and Elite Ant System considered in this work show better results compared to actuated signal control.

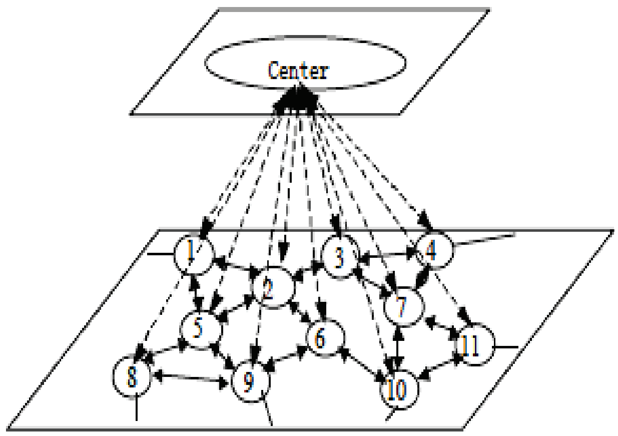

Figure 3 Self-organizing traffic control [42]

EC mainly comprises of genetic algorithms (GA), genetic programming, evolutionary programming, differential evolution, cultural evolution and so on. Wang et al. [42] proposed the application of genetic algorithm (GA) in a self-organization control of urban traffic networks. Fig. 3 shows the structure of the control system with a Traffic Control Centre (TCC) and the respective single junctions at the bottom of the structure. A bottom-up self-organization control at the respective single junctions uses the self-organization model to share the traffic information with the surrounding junctions, sends its control rules and environmental news to the TCC. GA is applied to find the optimal rules and update the rules according to environmental information received. The new rules are sent to bottom controller in definite or indefinite time. Hence, TCC is able to send self-adaptive top-down optimal rules to the junctions.

Most EC and SI methods are good optimization algorithms for traffic controllers. Hence they are combined with other intelligent methods to optimize traffic control. A hybrid GA and cellular automaton simulation to calculate travel time and optimize signal setting plan is developed in [43]. GA is also used to find optimal membership functions for fuzzy rules in fuzzy-based traffic control system based on real-time traffic data [27, 44, 45]. Hence, the fuzzy rule sets are adaptable to the ever changing conditions of traffic. Optimal membership functions in fuzzy system can be obtained using particle swarm optimization (PSO) which is a type of SI. Yun et al. [46] applied PSO to improve rule-sets in a fuzzy controller so that the control system has a self-learning ability. The simulation results are better compared to traditional fuzzy controller without optimization.

One of the trade-off of EC and SI is the amount of computation time involved when generating an optimized solution. They may be more suitable when used for offline calculations. However, online control of traffic signal requires fast computations in real-time. Emerging new computational techniques such as reinforcement learning (RL) and adaptive dynamic programming (ADP) offers faster searches of optimal solutions. Examples of such works to control signalled intersections are found in [47] and [48] which use dynamic programming. Similar to EC and SI, ADP has also been applied to optimize a fuzzy controller [49]. RL method such as Q-Learning was applied to discover optimal control policy in intersections [50, 51]. It is found to be effective in finding optimal solutions in time-varying and stochastic traffic flows.

3.2 Agent-based methods

Another emerging intelligent system method is multi-agent system (MAS). It consists of multiple intelligent agents interacting with each other to solve problems that are too difficult for a monolithic system to solve. MAS is a decomposition of a system into multiple agents that interact with each other to achieve a desired global goal. In agent-based system, the traffic system is comprised of distributed subsystems collaborating with each other to execute traffic control and management based on real-time traffic measurements. In [52], a MAS traffic responsive control comprises agents which are traffic controllers for an intersection in a traffic network. Each agent employs a multistage online learning process to update its database and decision-making procedures. Each agent also shares an optimization FNN. Another example of MAS is developed by Guo et al. [53]. In this work, each agent employs Group Decision-making Support System (GDSS). By integrating GDSS of both central and intersection agents, intelligent and self-decision in real-time control of traffic is implemented.

While CI has shown novel methodologies in optimized control of traffics, MAS can be seen as a design and application architecture which can contain any technology under its architecture. For a more comprehensive review of CI and MAS, the reader can refer to [54] and [55] respectively.

3.3 Petri net methods

Petri net (PN) which originated from C. A. Petri dissertation in 1962 has found its application in communication protocols, distributed-software and database systems, flexible manufacturing control systems, discrete-event systems, programmable logic and VLSI arrays, etc. [56]. PN can suitably describe the urban traffics and transportation system that possesses system states that are distributed, parallel, deterministic, stochastic, discrete and continuous. To date, the applications of Petri net in urban traffics can be categorized into modelling and simulations, evaluating the safeness and reliability of traffic signal control and optimizing traffic performance via signal control.

PN traffic models aim to describe and emulate an actual traffic system. Hence, traffic conditions such as traffic flow, average speed, density and queues can be estimated via simulations of these models. Subsequently, these predictions are used to facilitate the type of control and optimization strategies for the traffic operator or the traffic controller. Modelling and simulations could take on a microscopic [57, 58], macroscopic [59, 60] and even a mesoscopic [61] approach.

Analysis of the good properties of PN such as liveness, safety, reachability and reversibility gives an evaluation of the system performance. This is of great importance with regard to traffic-responsive signal control as these good properties can assess whether the control signal could reach all desirable states, is able to recover from error, provides a deadlock-free regulation of vehicles at intersection and ensures infrastructure usage is within capacity. List and Cetin [62] developed using PN, a signal-control model that describes an eight phase traffic light. The model is capable to facilitate phase transitioning when interfaced with an "optimization layer" for adaptive traffic control system. P-invariants analysis conducted confirms the control logic implemented in PN meets up to safety rules. In addition, the PN is confirmed deadlock-free using coverability tree method. Soares and Vrancken [63] modelled traffic signal control with ordinary PN. In order to ensure all signal cycle could be reached and non-occurrence of unsafe state, sequent calculus of Linear Logic is applied to analyse reachability and reinitiability of the net to evaluate a set of possible markings from a given marking. This approach which has been conducted by Girault et al. [64] has advantage over the classic coverability tree method which has the problem of state-space explosion due to the high number of states that could be reached in the model.

In traffic-responsive control, adjustment of offset, split and cycle time are common practice to response to varying traffic data received from sensors. These adjustments are also applied in PN-based models for traffic-responsive control. A traffic-responsive model is developed by Soares and Vrancken [65] using p-timed Petri net to model the dynamic behaviour of a group of traffic signals controlling a network of intersections comprised of a main road and arterial roads. Time is associated with places which are given a minimum and maximum duration for enabling transitions. Green time duration at places can be extended from a minimum to maximum to give priority movement to vehicles on the main road depending on demand on the non-priority road or arterials where demands from non-priority roads are detected by sensors.

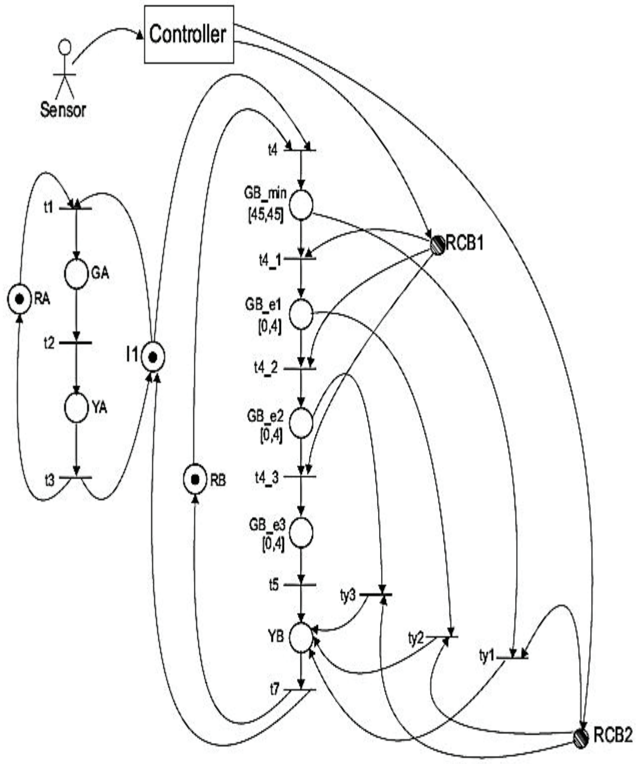

Figure 4 A Petri net model for green time extension [65]

Fig. 4 shows an example of the PN model in [65]. The demand of non-priority road which is detected by a sensor determines the activation of place RCB1 and RCB2. The activation of these places in turn determines whether the green phase should be extended for the main road via places GB-e1, GB-e2 and GB-e3 respectively. Each of these p-timed places contains an extension time duration. Besides green time extension, a real time correction of green time phases applied based on measurements of physical queue sizes at intersections is found in [66].

Adding to the modelling and analysis advantages PN models describing traffic signal control sequence can be translated into sequential function chart (SFC) for implementation into programmable logic controllers (PLC) [67, 68]. Other works on translating PN models of traffic signal control include translating into executable C-code for microprocessor-based controllers [69, 70].

4 Discussion

This section aims to discuss briefly the feasibility of the control and detection methods reported in this paper. Each control method comes with advantage and disadvantage points. For instance, SCOOT and SCAT provide very marginal improvements [67] and do not perform well under oversaturated traffic conditions [15]. Though model-based methods have contributed to significant improvements in reducing total time spent by vehicles in the network, the discrete variables in these models require exponential complexity algorithm for global minimization. Hence, the control strategy is not real-time feasible for more than one intersection and a decentralized scheme is needed to address this problem [15, 67]. The store-and-forward approach simplifies programming effort as the traffic flow process is modelled with simpler mathematical model without discrete variables. The benefit of this method is the underlying optimization methods that can be applied with it [16]. It is reported that TUC (a type of store-and-forward control) leads to a 15 to 25 % improvement in average network speed compared with pre-existing time-of-day plan [68]. However, regulation of traffic only allows for split optimization, while cycle time and offset must be delivered by additional algorithms [16]. RGDIS type of control is a novel approach that uses information system to influence driver route-choice behaviour but the impact of such approach is difficult to be quantified systematically and real implementations of iterative strategies are still in-progress due to the code complexity of the algorithm [15].

The development of intelligent systems particularly PNs have contributed mostly to modelling and simulations of traffic situations to facilitate better control of traffics. Though PNs provide both an analysis and a code generation platform, few works based on Petri nets have been implemented on real-time controllers for traffic signal control. Hence, PN based methods are simulative and generally function as a predictive tool. Consideration should be given to enhance the modelling powers of PN such as estimating vehicle route-choice behaviour, optimizing signal control using evolutionary algorithms and origin-destination matrix estimation. This can be achieved by extending or integrating PN with other artificial intelligence methods such as fuzzy logic and neural networks.

In the areas of CI, the conventional fuzzy logic and ANN have been integrated and combine with SI and EC optimizing algorithms. In view of the trade-off in optimization approaches that requires high computational time and complex algorithm there is much room for improvement in developing optimizing algorithms that require lesser computational times and possess greater processing powers such as adaptive dynamic programming, linear programming and nonlinear programming. Besides developing less computational costly algorithm future research work should focus on developing driver and information communication technologies for RGDIS. Examples of such technologies are inter-vehicle communication [69] and Roncaili [70] which provide position-dependent real-time information to drivers.

5 Conclusion

To this end, this paper has presented a comprehensive overview of developments in the area of traffic-responsive control of urban traffic. Though the coverage is wide, the fundamentals concepts and current developments in the areas of traffic-responsive control such as adaptive control, model-based, store-and-forward approaches, freeway control, RGDIS, computational intelligence, agent-based and Petri nets have been summarized. The survey also discussed and highlighted the contributions of these methods. On the other hand, the discussion also pointed out some limitations with current technologies which mostly lie in real-time feasibility of such systems due to code complexity and costly computational time. The paper recommended improvement works that include system integration and development of better optimizing algorithms that are real-time feasible.

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