USING PRE-EMPTION FOR DEPENDABLE URBAN VEHICLE TRAFFIC

Tiberiu Letia, Sergiu Barbu and Florin Dinga

Abstract:
A new approach for design and implementation of urban vehicle control system is proposed. The vehicle streams on lanes are considered similar with the streams of instructions in multitask programs. Real-time scheduling algorithms are used to allocate the green lights to phases. An adaptive component is used to calculate new vehicle flow parameters when a failure appears as a consequence of an accident. The real-time schedulers use the parameters to obtain new feasible resource allocations.

Keywords: *urban vehicle traffic control, real time scheduling, traffic congestion, real time control, dependability.*

1. Introduction

Urban vehicle traffic control is one of the most complex problems due to the large number of variables or parameters involved and their unexpected variations. There are controlled inputs (by the traffic lights) and uncontrolled inputs (vehicles that enter on the current lane from parking or from streets uncontrolled by traffic lights). The flow of the vehicle stream can be measured by appropriate detectors (or sensors). Vehicle presence can be detected and occupancy can be measured. The unmeasured inputs and outputs (from/to parking places) introduce non deterministic factors. The flow splits (in intersections) can be measured or estimated but cannot be controlled in an acceptable manner [8].

Better traffic control leads to improved safety for all road users, shorter travelling times through the controlled part of the traffic system and it also reduces negative environmental impact [11]. Therefore, vehicle traffic control systems have to face: variable inputs (part of them controllable) represented by the vehicle flows entering the systems, variable transfer splits of the flows on the intersections and accidents that significantly modify the parameters. These require the achieving of adaptive control systems that take into account the variable ratio of the rates with the aim to maintain a high throughput and to reduce travelling time. The control system gets information about traffic from the detectors and controls it using the traffic lights.

2. Approaches of Urban Vehicle Traffic Control

The cycle of an intersection is a sequence of all (traffic lights) signals that are applied to open sequentially all the lanes that enter the crossroad. The cycle duration is the time interval from application of a traffic light signal (starting of the cycle) of a phase until its next application.

A phase is a part of the intersection cycle allocated to any specific movement receiving the right-of-way or to any combination of traffic movements receiving the right-of-way simultaneously during one or more intervals. Usually, the intersection cycle duration is split into phases that open the input lanes such that the corresponding flows cross the intersection. The flow split refers to the ratio by which an input lane flow is divided into several output flows.

Urban vehicle traffic control can be actuated or non-actuated. Control can be non-coordinated (implemented for isolated intersections) or coordinated. The actuated urban vehicle traffic control can be implemented using the following approaches: controlling the flows (i.e. the volume control), density control, queue length control, singular event reaction, phase time extension until a minimum gap out, and phase time extension until timeout.

The solution for vehicle traffic control problem contains: the intersection cycle durations (if such cycles are chosen), the durations of phases (the split of the cycle) and their periods if there are no cycles, the order of phases (of each intersection) or their priorities, and the offsets (between intersections or phases).

Papageorgiou *et al.* present some methods for local, centralized or distributed control of vehicle urban traffic [14]. Bazan [3] presents a coordination method based on multi-agent system that uses game theory to get the crossing times and the synchronization of intersection signalling. The negotiation method can also be used [8]. Intelligent vehicle traffic management can be used, too [6]. Non artificial intelligent coordination methods are often based on optimization [15].

Kutil *et al.* use a model of a simple traffic intersection where the state variables represent the queue length and the average waiting times in the queues to obtain a fair traffic control [7]. They use the balancing waiting times to obtain a linear quadratic regulator and a nonlinear model predictive controller.

Liu and Tate propose an intelligent adaptation speed system that uses in-vehicle electronic devices to enable the speed of vehicle to be regulated automatically [12]. This offers a flexible method for speed management and control in urban area. Avella *et al.* present a method to solve the shortest path problem under resource constraints for vehicle fleet on a road net [1].

The majority of approaches (using deterministic or heuristic methods) consider the vehicle traffic system as working under probable (often previously measured and statistically expressed) conditions. But as a matter of fact, the demand (required green light) times and the granted durations (of neighbour intersections green lights) can vary considerably from instance to instance and are not known completely at the moment of the decision making. Even when these are known, the proposed methods are based on the estimated time demands of the traffic and on the probable values (splits) of the rates.

3. Pre-emption Based Control of Urban Vehicle Traffic

Unlike the previous ones, another approach is based on the worst case behaviour of the system. That means the usage in design of the highest accepted demands and the highest requirements relative to the timelines instead of the corresponding probable values.

The usage of real-time scheduling methods to signal control of the traffic lights in urban vehicle traffic is introduced in [9]. Vehicle flows on the lanes associated to an intersection phase are considered similar with the stream of instructions (of a task) that has to be processed by a processor. Each vehicle stream has its own period (that can be different from the periods of other phases of the same intersection) and duration to cross the intersection. The proposed method is a feedback control. Its implementation fulfils real-time constraints. The resulted vehicle flows are expected to fulfil timing constraints too.

Figure 1 represents the vehicle streams of the traffic system.

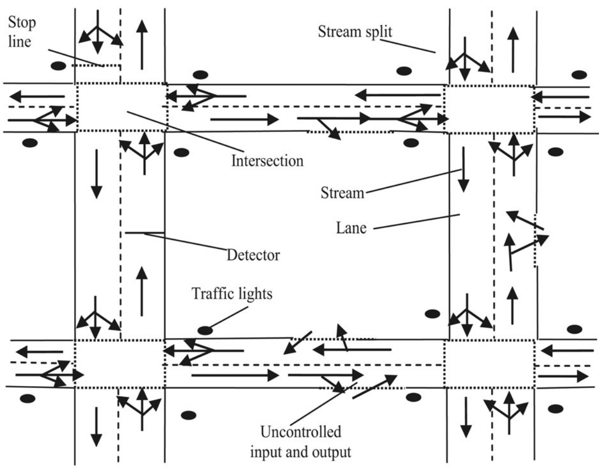

Fig. 1. Example of urban vehicle traffic net.

Lu *et al.* present a feedback control real-time scheduling framework for adaptive real-time systems [13]. They use feedback control theory to design algorithms that satisfy the transient and steady state performance of real-time systems.

One of the main problems of urban vehicle traffic control has to solve the scheduling of resources representing the places used by vehicles on lanes or intersections (most critical resources). The scheduling algorithms can be categorized as static or dynamic. In static scheduling algorithms have complete knowledge about stream set and its constraints (such as deadlines, crossing times, precedence constraints and future demand times). In dynamic scheduling the algorithms have no complete knowledge about stream set or its timing constraints. dynamic scheduling algorithms can be divided into algorithms that work in sufficient resource environment and those that work in insufficient resource environment. The traffic congestion is an example when the system reaches a state in which, at least for the moment, the available resources are insufficient.

Figure 2 shows the temporal relations between the demanded moments of time (dt) and green light durations of two consecutive intersections i-1 and i. Each of them should be opened within a specified period (T). The offset (O) between them also has to be implemented. The jitter (J) appears due to variation of vehicle speed or opening of the (linked) phase from the previous intersection. The opening of a phase before the demand moments of time (dt) is useless. If the end of the crossing time (C) is after the deadline (dd) this can lead to congestion. When a phase is opened at the dt (just when the vehicle stream arrives), because the vehicles have the desired speed (they are moving), the throughput is higher. This leads to a higher usage of the intersection (representing a critical resource). If the demanded durations are higher than the granted durations for some periods of time, this leads to congestions, also because lane capacities are exceeded.

Figure 3 describes the UML (Unified Modelling Language) state machine of a phase from an intersection. The switching of the phases is performed by the implementation of the real-time scheduler by updater (Figure 4) and dispatcher (Figure 5). They can implement different types of real-time schedulers used to control the urban vehicle traffic systems. The updater calculates the waiting times (w) and adds the phases (using add (phase) method) to the ready queue when they expire. It also calculates the number of requests (req) of each phase that are not honoured.

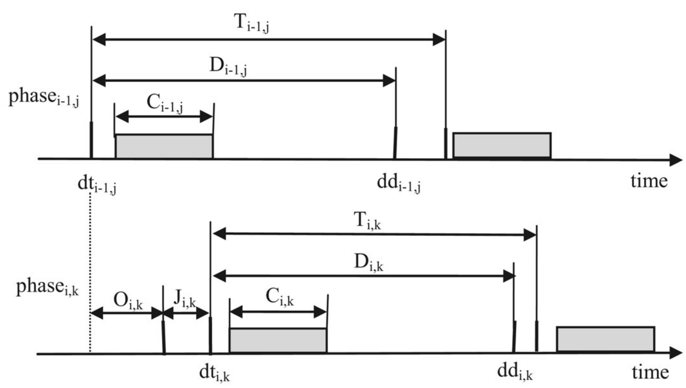

Fig. 2. Temporal relations between phases of two consecutive intersections.

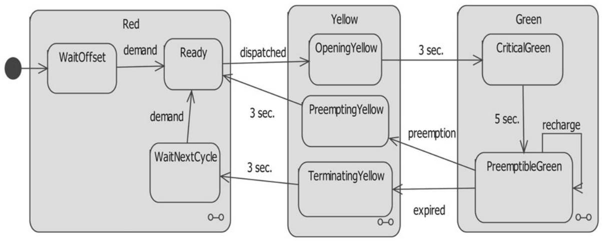

Fig. 3. UML state machine of an intersection phase.

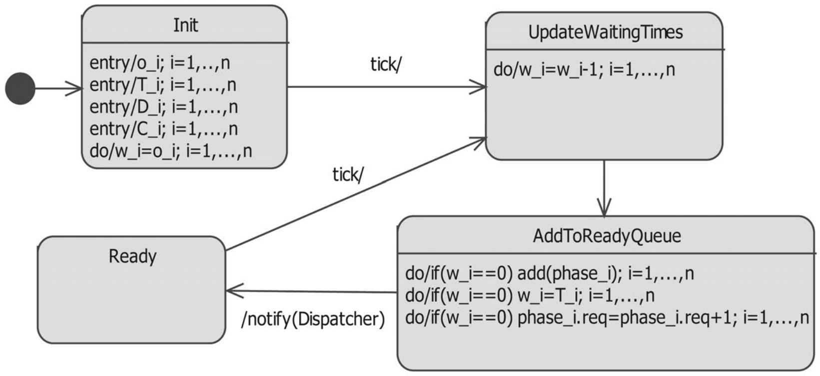

Fig. 4. UML state machine of Updater.

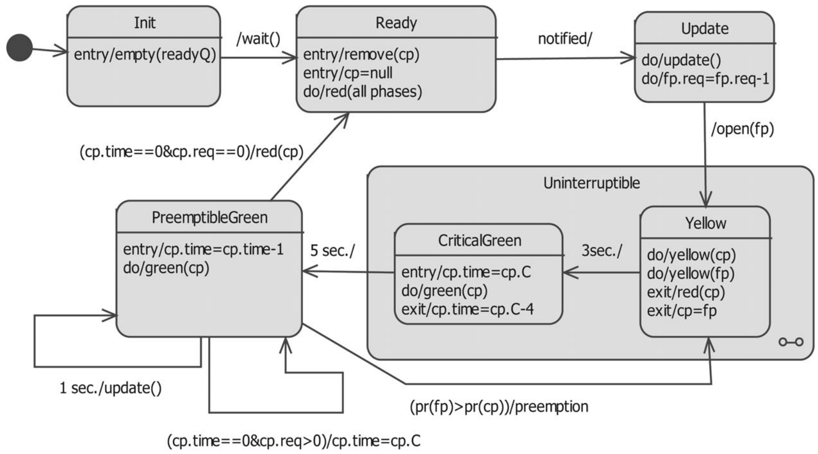

Fig. 5. Time driven dispatcher UML state machine.

The real-time schedulers use the following parameters:
- the crossing time (C) of a vehicle stream during a cycle (period) through an intersection,
- the period of a phase (T),
- the offset of the phase (O),
- the phase local priority and
- the global priority (when a distributed scheduling policy is implemented).

In Figure 5 are denoted by:
- cp the current phase,
- fp the first phase of the ready queue (readyQ),
- update() the recalculation of the ready queue according to the scheduling algorithm,
- remove(x) the removing of the phase x from the ready queue,
- red(x), yellow(x) and green(x) the application of the corresponding colour to the phase x.

For jitter implementation the diagram from the Figure 5 has to be extended with a new state and transitions to catch the demand events.

Fidge describes the most largely used real-time scheduling methods and their tests [4]. A review of real-time scheduling methods is given in [16]. Between them are: RMS (rate monotonic scheduling), EDF (earliest deadline first) and SPS (static priority scheduling). Using such scheduling methods for the network of intersections composing urban vehicle traffic system, a system that fulfils some specified timing constrains is obtained.

An output lane is fed by one or more input lanes. If there are more input lanes, one of them (usually the one with the highest vehicle rate) is chosen as main input lane. The opening moment of the main input lane of the current intersection should be correlated with the opening moment of the output lane (transformed in an input lane in the next intersection). When the vehicle platoons released (periodically) from the main input lane of the current intersection arrive at the waiting queue of the next intersection, it is desired to find the corresponding phase already open such that a *green wave* is obtained. If this requirement cannot be fulfilled, the corresponding phase of the next intersection should be opened not later than the deadline. This deadline is calculated such that the number of vehicles that entered on the lane that links these two intersections does not overflow (at any time) its capacity.

The real-time scheduling algorithm chooses between available (ready) phases the one which has to be currently opened according to the intersection policy using the phase (lane or flow) parameters.

4. Dependable Urban Vehicle Traffic System

Taking into account the article of Avizienis *et al.* [2], the dependability of an urban vehicle traffic system is given by the following attributes: availability (readiness for usage - i. e. the acceptance of vehicle entrance in the traffic), reliability (continuity of service - the moving of vehicles without unnecessary unbounded stops), safety (absence of catastrophic consequence on the user), confidentiality (absence of unauthorized disclosure of information, usually less important for vehicle traffic system in regular usage), integrity (absence of improper system alteration) and maintainability (ability to undergo repairs and evolutions). The failures of urban vehicle traffic system are:

- failures of the control system caused by bad control decisions, message transmissions or signalling of events or states;
- failures of traffic systems (distributed controlled process) caused by exceeding of specified demands or driver's faults that lead to accidents.

The vehicles that remain inside an intersection after their phase loses the right of crossing (green lights), because they cannot enter the output lanes, involve congestions [10]. Their number multiplied by a coefficient dependent on the structure of the intersection can be used as a measure of the current degree of congestion. The average values of the congestion degrees of all intersections of the traffic system provide information about current congestion degree of the entire system. The evolution of the average congestion degree can be used to evaluate the traffic system behaviour under the implemented control algorithms.

A fault of a driver can lead to a traffic failure (an accident) that blocks the vehicle streams of a street. Following this the remained vehicle streams are modified (some of them split) such that the traffic flows avoid the blocked lanes. As a consequence, new parameters should be provided to traffic lights controller (based on scheduling algorithms) to adapt to the modified environment and having the goal to avoid the congestion of the system. The congestion of an intersection can lead to the congestion of the entire traffic system if it is highly loaded with vehicles.

The on-line control uses the estimation of flows based on the measure of flow inputs and the flow splits. Using the real-time scheduling algorithms, the control system estimates if the necessary crossing times lead to a feasible solution (that fulfils the timing constraints). The local controllers receive the parameters (offset, period, green duration and priority) of each phase and implement the on-line schedulers that send the signals to the traffic lights.

The centralized adaptive algorithm activated at the detection of a failure is:

for *all intersections*
    Estimate or receive from local controllers the splits of the rates.

for *all intersections*
    for *all phases*
        Calculate the necessary crossing time.
    while *(feasibility if schedulling is not fulfilled)*
        Reduce the crossing time of each phase proportionally with its global priority, but not lower than a specified limit.
Communicate to local controllers the new scheduling parameters.
end

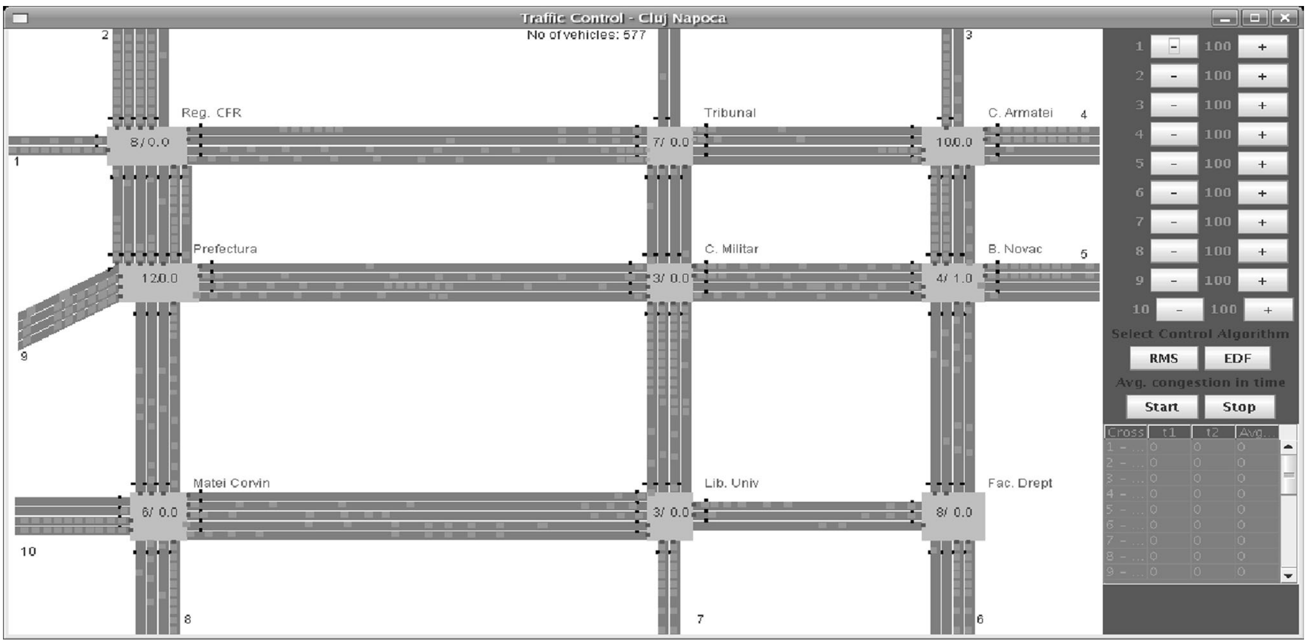

Fig. 6. Traffic simulator window.

5. Testing and evaluation

The performance evaluation of urban vehicle traffic system can be developed from the concepts of real-time systems given by [5]. The evaluation can be based on: qualitative binary criteria, qualitative gradual criteria and quantitative criteria.

1. Qualitative binary criteria are: timelines (the ability to meet some specified deadlines), no unbounded delay nor arbitrarily long crossing (or travelling) times, functional correctness, permanent readiness, all applicable physical constraints and congestion prevented.
2. Qualitative gradual criteria are: safety, reliability, availability, congestion, simplicity, and fault tolerance, graceful degradation on the occurring of undesired events, portability (of the control system), flexibility (to change of the vehicle traffic structure) and extensibility (of the control system with the development of the traffic net).
3. Quantitative criteria are: worst case travelling times on a specified path, worst case crossing times of an intersection, worst case duration to detect the failures and to correct the consequences (speed of adaptation), capacity (throughput) reserves and transfer capacities (throughput) of road net system or intersections.

To evaluate the proposed control method a special urban vehicle traffic simulator was built as can be seen in Figure 6. It uses the microscopic method for simulation of vehicles on lanes and a macroscopic method to evaluate the number of vehicles inside intersections. The simulator is able the calculate the congestion degree of each intersection taking into account the number of vehicles that remain inside the intersection after the traffic lights of the lanes they leave change to the red light, and the intersection structure. The values of the current number of vehicles (inside intersection) and the intersection congestion degree are displayed on the intersection rectangle. The current number of vehicles contained into the entire system is printed on the upper side of the window. The simulator has buttons to modify the input flows of the traffic system and to choose different schedulling algorithms.

The average intersection congestion degrees are used to evaluate the entire vehicle traffic system congestion degree. This degree as well as the total number of vehicles that remain inside the traffic system after the transitory regime can be used to evaluate the control performances of the different control algorithms.

Figure 7 presents the variations of the total numbers of vehicles (steady state) with the input flows, using the algorithms EGT (classical extended green time), RMS and EDF respectively. The lowest value of the number of vehicles characterises a traffic system with higher vehicle throughput.

Figure 8 shows the steady state relationships relating the input flows' changes to system congestion degree using the same algorithms. The lowest congestion degree corresponds to the best control algorithm.

Relative to the considered (practical measured) regular values of the traffic rates (corresponding to around 50% of vehicle generator frequency), the input flows were increased and decreased by the vehicles generator of the simulator. Each time, the number of vehicles that remain inside the simulated traffic system after the transitory regime is stored and so is the system congestion degree. They are represented in Figure 7 and Figure 8. Similar graphics were analysed for the system dependability.

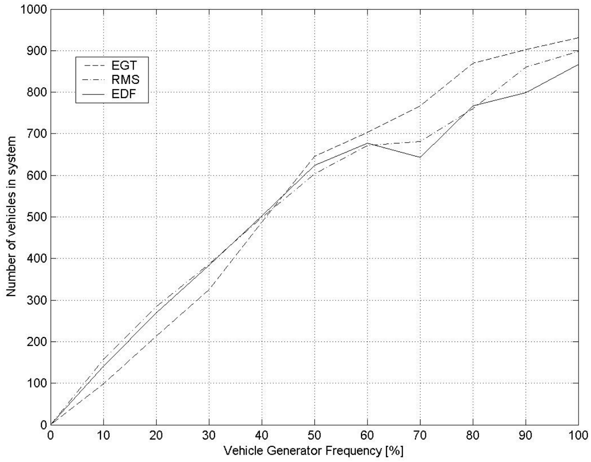

Fig. 7. Variations of steady total vehicle numbers with input flows.

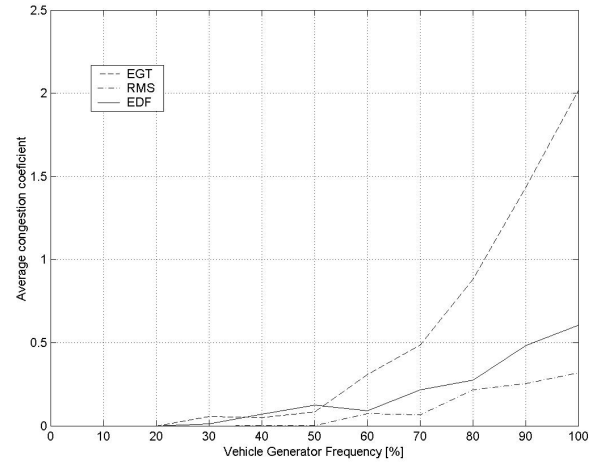

Fig. 8. Variations of the system congestion degrees with input flows.

Figure 7 shows that EDF algorithm leads to a lower number of vehicles moving into the system, so the traffic system throughput is higher. Figure 8 shows that RMS and EDF algorithms have lower congestion degrees (close to each other) compared to classical EGT algorithm. When the traffic rates have low values the differences between these three algorithms are not significantly different from the point of view of throughput and congestion. The real-time schedulling algorithms (EDF and RMS) work better in the range of 50-80%. The system congestion degree is lower at the upper input flow values due to the fact that the vehicles that exceed the system throughput capacity are stopped to enter into the traffic controlled area.

6. Conclusions

The urban vehicle traffic dependability can be improved by specification, design of the control system and synthesis of the control algorithms. Observations of the urban vehicle traffic behaviour when failures appear are useful to obtain better specification of description and requirements.

Models that describe more closely the behaviour of drivers when failures appear should be used to improve the requirements of the control system. The proposed method uses different periods for the phases of the same intersection. Usually, the periods of phases linked in a path should be correlated. Further studies should be developed to find the need (the effect) of modification of phase periods at the failure appearance.

The local priorities are used to schedule or analyse the feasibility of critical resources scheduling. The global priorities are used to determine the global behaviour of the traffic system. They serve to maintain the main features of the system when failures appear. The relations between global priorities and quantitative criteria (for traffic performance evaluation) are to be studied with the aim to improve dependability.

The performance evaluation results (from simulations) demonstrate that the proposed algorithms provide better transient and steady state performance when traffic volumes are at low values when traffic failures appeared. At high volumes, the controlled traffic system has better performances with real-time scheduling algorithm, but without a throughput reserve the control system is not able to correct completely the effect of failures. The necessary reserve is depends on the place of the expected failure and the current volumes of neighbour flows.

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