BLOCKAGE PREVENTION MECHANISM FOR TRAFFIC MANAGEMENT

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Abstract

Urban traffic networks play an important role in modern society. From a systemic perspective they are dynamic, nonlinear, large scale, complex systems. That is why modeling and controlling them are difficult aspects and a lot of research efforts are made towards solving these problems. This paper presents a study on urban networks and is proposing a general management architecture and, as part of this structure, a mechanism for junction blockages prevention. This fast dynamics control mechanism is used at the bottom level of the architecture and can have autonomy, if needed. In order to design this mechanism, the junctions and the incoming/outgoing road segments are modeled in a macroscopic manner. The model was created by making an analogy between compartmental networks' components (nodes and flows) and traffic networks fixed elements (crossroads, traffic lights and roads segments) and dynamic elements (cars flows). The blockages are avoided by use of a stabilizing nonlinear controller. The analogy, models and control solution, a case study and the manner in which the controller's command can be transferred to the traffic lights are presented. The open loop simulations can provide information on the cars flows values that lead to congestions or blockages, these observations can be used in order to reconfigure the traffic markings. A series of conclusions and possible improvements of this solution are discussed.

Keywords: urban traffic modeling, blockage prevention, compartmental networks

Presenting Author's biography

Andreea Udrea. She received the BSc and MSc degrees at Automatic Control and Computers Faculty, University "Politehnica" of Bucharest in 2006, respectively 2008. Since then she is a teaching assistant and PHD student and her research interests include numeric control and dynamical systems.

1 Introduction

Traffic networks play an important role in the modern society and have captured researchers' attention in terms of modeling, simulation, traffic management, optimization and control, as well as traffic forecasting.

Developing driving assistance systems for route optimization, prioritizing intervention vehicles, enhancing public transportation in urban areas, controlling the urban (metropolitan) traffic flow in order to eliminate congestions and to reduce the average waiting time of vehicles are the subjects of many research works.

Traffic can be seen as both a complex system (large scale, dynamic, nonlinear) and as an open system.

There are several traffic models ([1],[2]), but most of them are conceived for highways (including exiting and entering ramps).

Considering the level of detail, the models can be divided in :

- *microscopic models* - describe the space-time behavior of the involved entities - vehicles and drivers as well as their interactions at a high level of detail [3];

- *mesoscopic models* - do not distinguish between individual vehicles, the behavior of individuals is described in probabilistic terms; traffic is represented by groups of traffic entities, with interactions described at a low detail level ([3]);

- *macroscopic models* - describe traffic as a flow without distinguishing between entities; characteristics as flow-rate, density and velocity are used.

This paper describes in general terms a management architecture for the Bucharest traffic network and than proposes a macroscopic model roads and crossroads and a novel control algorithm that prevents junction blockages which generally lead to large traffic perturbations and are a great problem for the metropolitan transport. The mathematical theory of compartmental networks and a nonlinear controller for this type of systems is used.

2 General management architecture for traffic network

The management architecture is organized as a 3 levels structure due to the complexity of the system (as presented in Fig. 1).

At the bottom level stand the junction controllers with some specific autonomous tasks and that interface the physical level and the optimization and monitoring levels.

The supervisor level chooses from a range of offline predetermined control scenarios the most suitable one, function of each subregion dynamics and status.

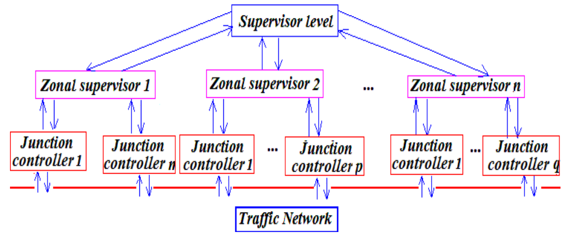


Fig. 1 Traffic management architecture

The scenarios are determined based on the degree of junctions load as follows:

- extremely rarefied traffic –generally night mode and suburbs mode: the cycle can be ignored and green can be accorded for a direction. If a car comes from the opposite direction, by driving over the inductive band placed at the junction entrance, makes its presence known, and with a certain delay, the light will turn green, it is a first arrived – first served strategy.

- medium density traffic – generally not leading to congestion – weekend/official holydays mode – optimal values predetermined at the second level.

- dense traffic – possibly leading to congestions.

- saturated traffic – a jammed junction begins to affect the neighboring junctions.

For the second and third scenarios green wave strategies (GWS) or genetic algorithms (GA) implemented at the second level (zonal supervisor) can be employed.

When sudden increase of the cars flows occurs, the use of GWS or GA fails to prevent saturated traffic. For this fourth case, decentralized control using the blockage prevention mechanism can be a solution.

The junction controller manages a single crossroad.

The entities at this level send to the above levels the car densities values on each input and output road segments, the percentage of cars that leave each entrance toward each allowed exit directions, the maximal allowed green light per phase in order to prevent the blockage of the junction that was calculated on line by junction controllers.

They also hold the last received cycle duration, phases order, green-red ratios, minimal and maximal green values durations, the probabilities that a percentage of cars on each entering segment that will take a specific exit. These are calculated at the second and third levels accordingly to the real time measurements they are provided.

Most importantly this level holds a mechanism for blockage prevention that we are proposing in this paper. This can work in parallel with the above levels and also as stand alone module in case of faulty communication with the supervisors.

In order to prove the necessity and importance of this module, a Bucharest congested junction is presented in Fig. 2. The blockage is appeared because of long waiting queues, unfavorable traffic condition and most of all inadequate green/red lights ratios.

Fig. 2 Blocked crossroad

3 The conservative networks based traffic model and blockage prevention module

In general, the ratio between green and red for each phase doesn't change accordingly to the fluctuations of traffic flow and is one factor that causes the appearance of blockages along with the fact that the cars density is larger than the density for which that part of the network was designed.

That is why the bottom layer must work in the timeframe of the real traffic environment and the blockage prevention mechanisms must be a fast response entity, based on methods that use only current measurements and already known data.

We further introduce a series of traffic network notions that we are going to use trough this paper. A simple phase refers to the flow rates and duration in which an input (source) road segment feeds the output (destination) road segments during green light of the traffic light cycle. A synchronous phase consists of two simple phases executed at the same time. The generalization of all the types of phases presented in figure 2.b. is a 2 inputs 6 outputs phase. For the simpler cases figure 2.a, the input output flows that are restricted can be considered 0. It is the same generalization that can be applied for T-junctions.

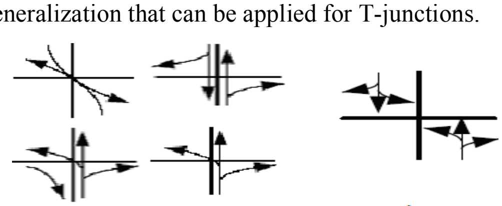


Fig. 3 Phase types and their generalization

Modeling the traffic networks elements as conservative networks is useful due to the congestion control mechanism that the later provides.

A conservative system ([4], [5]) is a compartmental system with a network-like structure presenting nodes (compartments, buffers) that can contain a certain amount of matter (mass, elements, energy); $x(t)=[x_1(t)\ x_2(t)\ ...\ x_n(t)]^T$ is the vector of the states of the system. The notation $f_{ij}(x(t))$ is used for the transfer rate (debit; flow), from buffer i to buffer j and $b_i(t)$ and $e_i(t)$ are flows into and out from the system. The flows balance is given by:

$$\dot{x}_i = \sum_{j \neq i} f_{ji}(x) - \sum_{k \neq i} f_{ki}(x) - e_i(x) + b_i, i = \overline{1,n} \quad (1)$$

where: $x_i(t) \in R_+, t > 0$; $f_{ij}, e_i : R_+ \to R_+$; $b_i(t) \in R_+$; and, if $x_i(t) = 0$ than $f_{ij}(t) = 0$ and $e_i(t) = 0$.

If these conditions are satisfied and if $f_{ij}(x)$ and $e_i(x)$ differentiable, then: $f_{ij}(x) = r_{ij}(x)x_i$ $\mathrm{e_i(x)=q_i(x)x_i}$, where the specific flows $r_{ij}(x)$ and $q_i(x)$ are continuous, differentiable and strictly positive, with positive function argument. So (1) becomes:

$$\dot{x}_i = \sum_{j \neq i} r_{ji}(x)x_i - \sum_{k \neq i} r_{ki}(x)x_i - q_i(x)x_i + b_i, i = \overline{1,n} \quad (2)$$

In order to model a junction, it is considered that the adjacent road segments represent network nodes - buffers that accumulate cars – and the directions of movement in the junction are the arcs that model the transfer of cars in the network.

If the storage capacity of a destination node is exceeded, the extra cars are going to accumulate in the junction causing blockage. To prevent this, when the capacity limit of a destination node is going to be overcome, the green traffic light must change into red. The algorithm for this will be presented next.

The car flows (number of cars per unit of time) between these buffers are similar to transfer ratios (flows) between the nodes of a compartmental network.

The compartmental systems have a series of important mathematical properties: are positive systems (if $r_{ij}(x)$ and $q_i(x)$ are differentiable the system is time invariant); they assure mass conservation $M(x) = \sum_{i=1}^{n} x_i$ and if (2) is written as:

$$\dot{x}_i = A(x)x + b \quad (3)$$

- $A(x)$ - the compartmental matrix - is Metzler: all elements except the ones on the principal diagonal are nonnegative ($a_{ij}(x) = r_{ji}(x) \geq 0$); the principal diagonal contains only non positive elements ($a_{ii}(x) = -q_i(x) - \sum_{j \neq i} r_{ij}(x) \leq 0$); and is a diagonal dominant matrix ($|a_{ii}(x)| \geq \sum_{j \neq i} a_{ij}(x)$).

$A(x)$ is nonsingular and stable, $\forall x \in R_+^n$ if and only if the compartmental network is fully connected to the output flow ([4]). The system's (3) Jacobian is:

$$J(x) = \frac{\partial[A(x)x]}{\partial x}$$

When $J(x)$ has a compartmental structure and is invertible, the system has a unique equilibrium point which is global asymptotical stable (GAS) for a system with input and output flows. If $J(x)$ is singular; the unicity of the equilibrium GAS point is still preserved for al closed systems that are strongly connected.

The blockages can appear for input flow demands larger than the network capacity. This can be avoided by use of a nonlinear controller with a structure like the one of the compartmental system.

The control problem states that, given a totally input and output connected compartmental network with limited flows and buffers capacities and with a certain demand for the input flows - d_i; the congestion prevention can be done by controlling the input flows $b_i(t)$ - injected in the system – by making them less than the demand $d_i(t)$:

$$b_i(t) = u_i(t) d_i(t), 0 \le u_i(t) \le 1,$$

where: $u_i(t)$ is a fraction of the $d_i(t)$. It is considered that the output flows are the measurable output measures of the system.

Let v_j be the cars outflow from the destination nodes and f_{ij} cars flows between source and destination nodes. The flows of cars can be decomposed like the flows of the compartmental network: $f_{ij} = \beta_{ij} v_i(x_i)$ where $\sum \beta_{ij} = 1$ are the percentages of the total cars flow leaving the source node i which is distributed to the destination nodes j.

The inflow to a source node is a time variable rate of cars that depends on the features of the section. The outflows depend on the state of node - the occupancy level of the node - and the state of the section which is connected with the node. These flows are defined as follows:

$$v_i(x_i) = \mu_i \frac{x_i}{x_i + 1}$$

where: μ_i is the flow of cars on the section i and the function $g(x_i) = \frac{x_i}{x_i + 1}$ models the behavior of cars leaving the node. The outflow will increase monotonously to the value dictated by the section.

The control problem solution is a dynamic nonlinear controller:

$$\dot{z}_i = y_i - \Phi(z_i) \sum_{k \in Q_i} \alpha_{ki} d_k \, (i \in I_e)$$

$$u_j = \sum_{k \in P_i} \alpha_{jk} \Phi(z_k) (j \in I_i)$$

with: - $\alpha_{jk}; (j,k) \in R$ - the characteristic parameters of the network; they satisfy the following property:

$$0 \le \alpha_{jk} \le 1 \text{ and } \sum_{k \in P_j} \alpha_{jk} = 1;$$

- $\Phi : R \to R_+$ is a monotonically increasing, continuous and derivable function, such that $\Phi(0) = 0$ and $\Phi(\infty) = 1$.

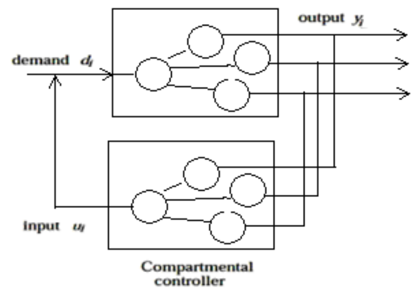


Fig. 4 The feedback structure of the compartmental system

The closed loop equations lead to the expression:

$$\begin{pmatrix} \dot{x} \\ \dot{y} \end{pmatrix} = \begin{pmatrix} A(x) & B(d)K(z) \\ C(x) & G(d)F(z) \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \stackrel{def}{=} L(x,y) \begin{pmatrix} x \\ y \end{pmatrix}. \qquad (4)$$

$L(x,z)$ is a compartmental matrix so the system is positive; is closed and the state variables are limited:

$$0 \le x_i(t) \le \sigma; i = \overline{1,n}$$

$$z_j(t) \le \sigma; j = \overline{1,p}$$

The first objective of blockage prevention mechanism is obtained by using the controller in the proposed form: σ is less than the free capacity of the road segments x_i^{max}, such that the saturation avoidance is assured. Moreover, it can be observed that σ depends on the initial conditions $(x(0),z(0))$. Many applications impose that the real system begins from null initial conditions $(x(0)=0)$, σ can be chosen exclusively by using the initial conditions of the controller $z_j(0)$ and equals: $\sigma = \sum_{j=1}^{p} z_j(0)$.

The command measures $u_j(z)$ take values between 0 and 1, so, with the restriction $0 \le \Phi(z_i) \le 1$, it results:

$$0 \le uj(z) = \sum_{k \in Pj} \alpha_{jk} \Phi(z_j) \le \sum_{k \in Pj} \alpha_{jk} = 1.$$

Since the controlled network is input and output fully connected and due to the controller's structure, (4) is a strongly connected compartmental closed system. If the controlled system's Jacobian is a compartmental matrix, then the Jacobian of the closed loop system is a compartmental matrix and for a certain demand flow, there is only one equilibrium point and it is GAS ($\mathbb{R}^n_+$).

A good choice of Φ in order to satisfy the conditions is $\Phi(z_i) = \frac{z_j}{z_j + \varepsilon}$, where - ε is a small positive constant.

4 Case study

4.1 X-crossroad with 4 phases modeling and control

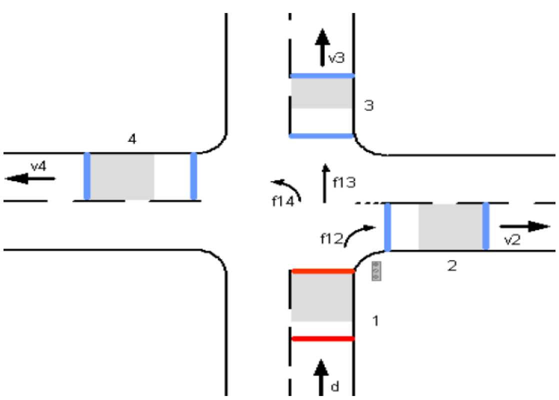
The first example on blockage prevention is demonstrated on a X-crossroad with four phases per traffic lights cycle. During each phase, the cars flow entering the crossroad can go towards any of the three exits – Fig. 5. a. A control algorithm must prevent congestion in the following circumstances: large inflow, small outflows, and destination buffers almost saturated (dense traffic on following road segments).

The model for the simple phases of a X-crossroad is presented in Fig.5.b. and has the following expression:

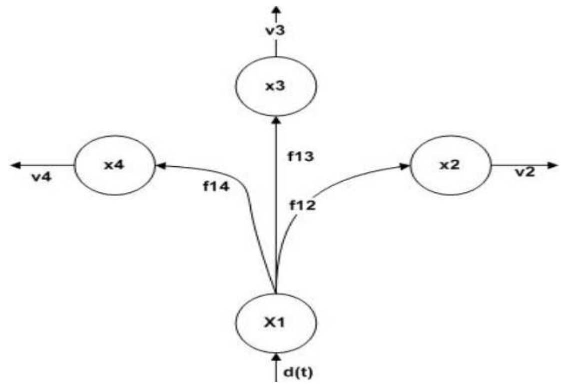
$$\begin{cases} \dot{x}_1 = du - v_1(x_1) \\ \dot{x}_2 = \beta_{12} v_1(x_1) - v_2(x_2) \\ \dot{x}_3 = \beta_{13} v_1(x_1) - v_3(x_3) \\ \dot{x}_4 = \beta_{14} v_1(x_1) - v_4(x_4) \end{cases}$$

The nonlinear controller structure for this network is:

$$\begin{cases} \dot{z}_2 = v_2(x_2) - \Phi_2(z_2)\alpha_{12} d \\ \dot{z}_3 = v_3(x_3) - \Phi_3(z_3)\alpha_{13} d \\ \dot{z}_2 = v_4(x_4) - \Phi_4(z_4)\alpha_{14} d \end{cases}$$



a.



b.

Fig. 5 a. X-crossroad; simple phase; b. compartmental network model of simple phase

The expression of the command is:

$$u = \alpha_{12}\Phi_2(z_2) + \alpha_{13}\Phi_3(z_3) + \alpha_{14}\Phi_4(z_4),$$

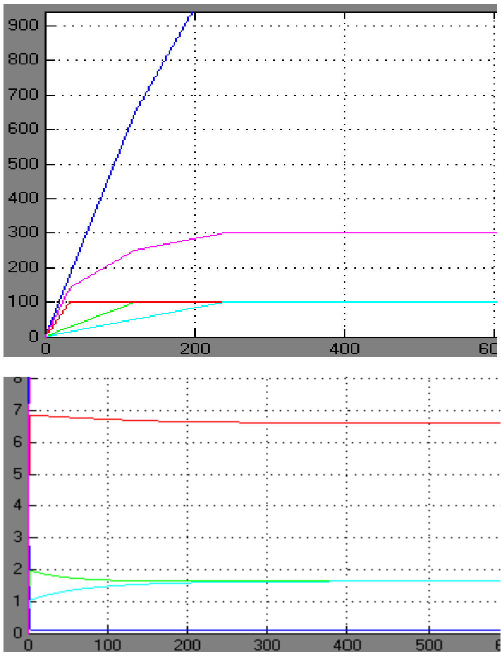
where: $v_i(x_i) = \mu_i \frac{x_i}{x_i + 1}, i = \overline{1,4}$ are the total evacuation flows; $\Phi_i(z_i) = \frac{z_i}{z_i + 1}, i = \overline{1,4}, \varepsilon = 0.1$ are the virtual evacuation flows from the nonlinear controllers nodes; μ_i is the maximal allowed flow that can exit from compartment i; α_{ij}, β_{ij} are stand for the proportion of the flow that exits from i node.

The simulations were done in Matlab- Simulink. The used values were determined from real data measured on a typical congested crossroad; the maximal evacuation flows - μ_i – were also measured such they reflect the real traffic situation. The proportions of cars taking a certain exit are the mean value measured over time for this phase:

$$\mu_1 = 300/60, \mu_2 = 10/60, \mu_3 = 25/60, \mu_4 = 5/60;$$
$$\alpha_{12} = \beta_{12} = 0.2, \alpha_{13} = \beta_{13} = 0.7, \alpha_{14} = \beta_{14} = 0.1$$

The comportment in open loop and in closed loop- using the controller is presented for the case when the input flow varies – the data (cars/s) were measured by means of inductive band placed at all the entrances in the crossroad.

The Fig.6.a. the congestion appears – the cars are accumulating in the crossroad because the buffers limit capacities are exceeded. In Fig.6.b. it can be observed that congestion is avoided. The inflow is limited at a value that the intersection can process without overload the following buffers.



a.

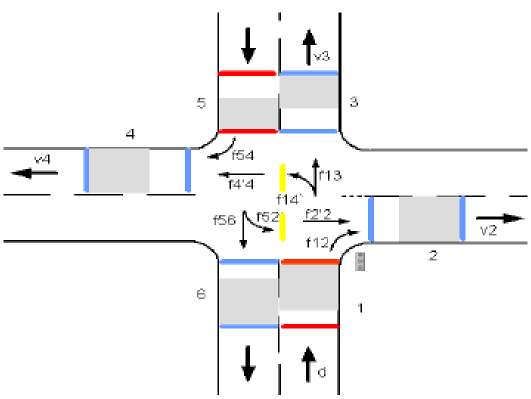
b

Fig. 6. a. Open loop evolution of the 4 outflows of the analyzed phase; b. closed loop evolution of the 4 outflows

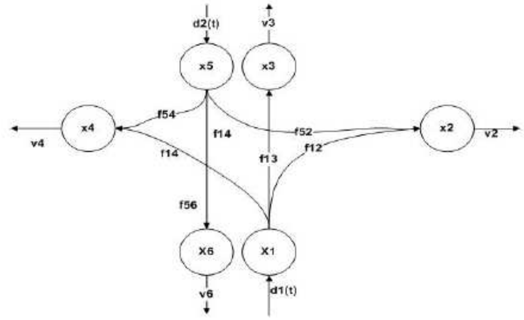
The initial conditions for the process are chosen as follows: for the source buffer the value is the sum of the capacities of the destination nodes and for the rest of the nodes is zero. The initial values for the controllers nodes are equal to their capacities.

4.2 X-crossroad with 2 double phases modeling and control

We consider a X-crossroad with two double phases per traffic lights cycle (phase generalization) as a second example for modeling and blockage prevention. During each double phase, the cars can enter the crossroad from opposite direction and can go towards any of the three possible exits – Fig.7. a.



a.



b.

Fig. 7 a. X-crossroad with double phases; b. double phase model

The model for this type of phase (Fig. 4 b) is:

$$\begin{cases} \dot{x}_1 = d_1 u_1 - v_1(x_1) \\ \dot{x}_2 = \beta_{12} v_1(x_1) + \beta_{52} v_5(x_5) - v_2(x_2) \\ \dot{x}_3 = \beta_{13} v_1(x_1) - v_3(x_3) \\ \dot{x}_4 = \beta_{14} v_1(x_1) + \beta_{54} v_5(x_5) - v_4(x_4) \\ \dot{x}_5 = d_2 u_2 - v_5(x_5) \\ \dot{x}_6 = \beta_{56} v_5(x_5) - v_6(x_6) \end{cases}$$

and the controller is:

$$\begin{cases} \dot{z}_2 = v_2(x_2) - \Phi_2(z_2)(\alpha_{12} d_1 + \alpha_{52} d_2) \\ \dot{z}_3 = v_3(x_3) - \Phi_3(z_3)\alpha_{13} d_1 \\ \dot{z}_4 = v_4(x_4) - \Phi_4(z_4)(\alpha_{14} d_1 + \alpha_{54} d_2) \\ \dot{z}_5 = v_6(x_6) - \Phi_6(z_6)\alpha_{56} d_2 \end{cases}$$

Two commands u_1 and u_2 are:

$$\begin{cases} u_1 = \alpha_{12}\Phi_2(z_2) + \alpha_{13}\Phi_3(z_3) + \alpha_{14}\Phi_4(z_4) \\ u_2 = \alpha_{52}\Phi_2(z_2) + \alpha_{56}\Phi_6(z_6) + \alpha_{54}\Phi_4(z_4) \end{cases}$$

where: $v_i(x_i) = \mu_i \dfrac{x_i}{x_i + 1}, i = \overline{1,6}$ are the total evacuation flows; $\Phi_i(z_i) = \dfrac{z_i}{z_i + 1}, i = \overline{1,6}, \varepsilon = 0.1$ are the virtual evacuation flows from the nonlinear controllers nodes; μ_i is the maximal allowed flow that can exit from compartment i; α_{ij}, β_{ij} are stand for the proportion of the flow that exits from i node:

$$\mu_1 = \mu_5 = 300/60, \mu_2 = \mu_4 = 10/60, \mu_3 = \mu_6 = 30/60;$$
$$\alpha_{12} = \beta_{12} = 0.25, \alpha_{13} = \beta_{13} = 0.65, \alpha_{14} = \beta_{14} = 0.1,$$
$$\alpha_{52} = \beta_{52} = 0.25, \alpha_{54} = \beta_{54} = 0.65, \alpha_{56} = \beta_{56} = 0.1$$

The open loop and closed loop results are showed in the Fig.8. In open loop mode, the congestion appears because the cars accumulate in the crossroad because the following buffers' capacity is exceeded.

The congestion is avoided – the cars do not accumulate; the inflow is limited to a value that the crossroad can process.

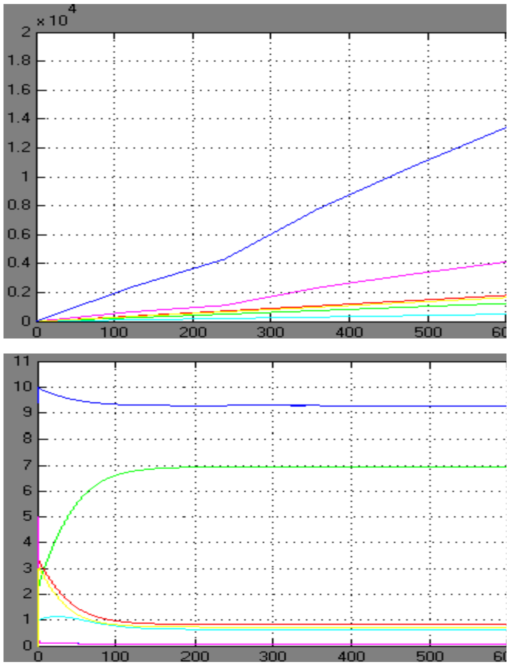


Fig.8 a. open loop evolution of the 4 outflows of the analyzed phase; b. closed loop evolution of the 4 outflows;

It can be observed that the nonlinear controller can avoid the congestion. It generates a command that limits the large inflow – letting just a portion of the flow to pass in order not to block the crossroad. The command values are always between 0 and 1. When obtaining an extremely small inflow – it is preferred not to activate that phase, because the green time will be extremely small and the cars passing trough the crossroad would probably block it.

4.3 The command transfer

The command transfer (command values in green light duration) to the traffic light controller, which is the actuator of the crossroad system, can be done using this formula:

$$d \cdot t_v = d_c \cdot t_{v\max}$$

where: d – is the free flow between the input node and the destination node; d_c – inflow calculated by the controller:

$$d_c = d \cdot u_{\mathrm{m}}$$

- u_m – mean command value
- $t_{v\max}$ –the maximal green time allowed for a phase;
- t_v – the green light duration – calculated by the controller:

$$t_v = \frac{d_c \cdot t_{v\max}}{d} = \frac{d \cdot u_m \cdot t_{v\max}}{d} = u_m \cdot t_{v\max}$$

This duration is a percent - u_m - of the maximal green light. If u_m is too small, that phase should not begin. This mechanism can be used along with the optimal values transmitted from the second level in order to prevent any eventual blockage situation and, also, alone, in case of connection failure.

5 Conclusions

Modeling urban traffic with compartmental networks offers three advantages. First, from open loop simulations, important information: the flows values that lead to a congestion in a certain crossroad and the specific crossroads that are predisposed to congestion can be identify. These observations can be used in order to introduce supplementary road signs or transform a two ways street in a one way street in order to fluidize the traffic Second, this kind of model that allows the decomposition of a large scale problem in sub problems that can be solved separately. Third, the congestion can be prevented by using a stabilizing nonlinear controller that calculates the green/red ratios for each traffic light in the crossroad

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7 References

[1] M. Papageorgiou. Some remarks on macroscopic traffic flow modeling. *Transport. Res*. A 32 (5), 1997

[2] C. Daganzo, N. Geroliminis. An analytical approximation for the macroscopic fundamental diagram of urban traffic. *Transportation Research Part B* 42:771–781, 2008

[3] S.P. Hoogendoorn, P.H.L. Bovy, State-of-the-art of Vehicular Traffic Flow Modelling, *Proceedings of the IMECHE, Part I, Journal of Systems & Control Engineering*, Vol. 215, 4:283-303, 2001

[4] G. Bastin, V. Guffens. Congestion control in compartmental network systems, *Systems and Control Letters*, Vol. 55, 8 :689 – 696, 2006

[5] L. Imsland, A. Foss. Positive Systems - chapter State Feedback Set Stabilization for a Class of Nonlinear Systems. *ed. Springer Berlin / Heidelberg*, pages. 337-344, 2004