SIMULATION OF ROAD SYSTEMS AND QUEUING NETWORK MODELS

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Abstract: The purpose of this paper is to describe the versatility of queuing network systems for modelling vehicular traffic flows in road systems. These techniques are applicable in a simulation context because of the complexity of the resulting models, which can not be solved by mathematical analytical solvers. Moreover, these techniques can be used to model and simulate the behaviour of an automatic control system of vehicular flow in the same frame.

Keywords: queue systems, vehicular traffic systems, computer networks simulation

1. Introduction

In this paper we describe a technique used to model and monitor vehicular traffic systems in the general context of urban and metropolitan mobility problems [1].

Principally, these techniques concern the construction of queue-based simulators to study specific behavioural aspects of vehicular traffic systems. The problems we have studied concerned both the analysis of structural aspects of a road system in its planning phase and the analysis of alternative hypotheses of traffic management on existing systems. Moreover, we have developed studies where we have integrated this methodology with specifically defined control procedures based on non-parametric statistic techniques [2, 3]. Various types of procedures can be realised to conduct observations of real traffic systems and model simulations. In this context we are usually confronted with the following problems:

- Implementation of software procedures to execute real-time automatic processing of data flows obtained from devices monitoring vehicular traffic behaviour in a traffic system.
- Implementation of software procedures in a simulation with the corresponding data measured through observations of the real system under study. These techniques are aimed at evaluating the reliability of a simulator built as an expectation model for the simulated real system. We face this kind of problem

when we have to evaluate various hypotheses of vehicular traffic management on existing road systems.

- Implementation of software procedures to compare the data obtained in simulations concerning alternative management hypotheses of a considered traffic system. In these problems, the impact of alternative choices on the structure of a given traffic system is evaluated. They may concern both the system's structural aspect and management of the traffic flows. An instance of the latter is an evaluation of the impact of various hypotheses of a traffic light crossroads control system.

A central aspect of a study project concerning a vehicular traffic system is defining the queueing network architecture on which we base the implementation of our simulator. We have defined a number of queue service devices used as base elements together with the type of subject user to describe the functioning of a vehicular traffic system.

Starting from a map describing a given vehicular traffic system, we build a model queue-network system using the introduced types of service devices. The simulator system is then implemented in a specific programming context oriented at the classes where it is easy to define the queue variable and the user variable.

Generally, the following sub-components can be recognised in a vehicular traffic system, each of them determining a specific queue model:

- a road system with vehicular flows;
- a control system for automatic regulation of vehicular flows;
- a system to monitor and process the sampled traffic data.

These components are singularly modelled by queuing networks, through which customers flow. In the first case, customers represent vehicles, in the second case they represent signals in an automatic control system regulating vehicular flows, while in the third case they represent data flows from a monitoring system, suitably packed for processing.

2. Queueing network models

In this section we define queue service devices that will be used to define the architecture of the model of queues' network for the simulator of the system of vehicular traffic shown in Figure 1. This definition is a functional one; it specifies for each kind of device the functional meaning of its insertion in the architecture of the queues' network model, starting from the cartographic description of the system found in the Urban Traffic Plan.

A graphic icon and a functional description are associated with this kind of queue service. We attempt to automate defining the architecture of the model where the implementation of the system's simulator will be based. The model's architecture of the queue-network realises the first level of description of the illustrated model's dynamics. A complete description of the actual functioning of the system is obtained by defining the service algorithms of the various devices.

A list of service queue devices to be used as base elements to build the architecture of a queue-network model of the urban vehicular system shown in Figure 1 follows:

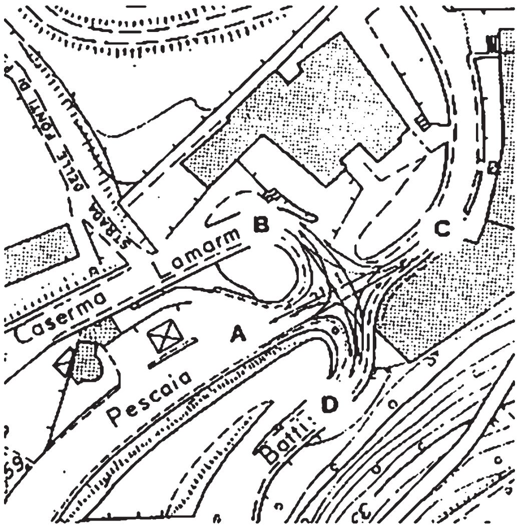
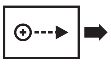
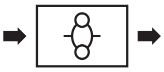
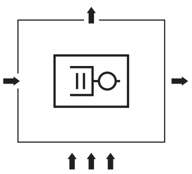


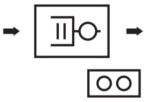
Figure 1. Road system from the UTP of a central Italian town

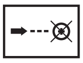

This device is a source flow to generate a vehicular flow. It is obtained by a single server station supplied by a queue that contains "infinite" customers, sent forward into the road system upon exit. The service time of a vehicle in a source station constitutes the inter-arrival time to the road system from the arrival of the previous vehicle. The modalities reproducing the arrival rate of vehicles relative to the vehicular flow are obtained by a suitable description of the service algorithm for the flow source station.

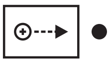

This device is an infinite server station. It is used to reproduce the traffic on road segments where it is possible to disregard the details of road utilisation conflicts between vehicles. In these cases, we need to reproduce the time of crossing the real system with the use of algorithms describing a vehicle's service time in the service station.

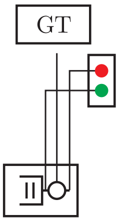

This device is a single server station used to represent road sections where utilisation conflicts among vehicles (*e.g.* of different flows) need to be reproduced. This section can be occupied by a single vehicle at any given every time. Access to the section is managed through a policy based on priority levels relative to vehicle class. A vehicle's class is unequivocally determined by its crossroads entrance and exit combination.


This device is a single server station, which decomposes a vehicular flow into several directions, paths or classes.

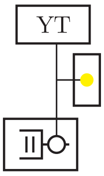

This device represents a single server station subjected to vacation periods controlled by a traffic light. It is used to model the points on the road where traffic flow accesses are controlled by traffic light systems. In this device, the server's state depends on the Flag state drawn next to it. The Flag has two possible states: open (green) and closed (red). When the Flag is closed the server becomes vacant or stuck and the vehicular flow is interrupted.


This device states a single server station used to represent the system's exit points. Users passing through this device leave the system. The modelling of a traffic light system, which manages the modality of access to crossroads for several vehicular flows is obtained by constructing a network of queuing service systems, parallel to the network simulating vehicular flows. The flow of customers in this control network models the activation signals of the different phases of the traffic light system. The architecture of a queuing network of this type can include the following types of service station elements.


This device is a source station generating a particular class of customers that represents phase changes in a traffic light system. In these stations, service time tends to have a deterministic value, corresponding to the time length of a traffic light cycle.

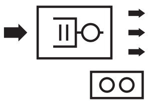


These types of service stations are usually placed in series. They are crossed by phase signals coming from the source station. They control, with their service algorithm, the opening and closing of a set of Flags starting and stopping vehicular flows. In fact, the service algorithm foresees, in sequence, the opening of flags controlled by the station, service time GT corresponding to the length of time of the green traffic light (Green Time), and the closing of the controlled flags.



This type of station is situated in line with the other queues of the traffic light system. It is usually placed between the two stations foreseen for flag control. Its service consists in time delay YT (Yellow Time), corresponding to the time since the closing of flags controlled by the previous station and the opening of flags controlled by the following station. Time YT represents the time interval characterised by the yellow traffic light controlled by the previous station.

When we translate a scheme describing a vehicular traffic system in the architecture of a model of queues for the construction of its simulator, we can define symbols that individuate devices whose functionality is a sum of functionalities of various basic types as illustrated in the following example.


This device indicates a single user station that performs a division into different classes of the entering vehicular flow and is subjected to vacant periods controlled through a traffic light.

3. Model of the crossroads

In this section we define the architecture of queue networks' model for the simulator's implementation, starting from a functioning scheme of the road system illustrated in Figure 1.

The crossroads shown in Figure 1 are a delicate point in the vehicular traffic network of a middle-sized town in central Italy, the junction of roads A, B, C, and D as shown in the figure. Its global daily throughput is about 25 000 vehicles (vpd) and it is regulated by traffic lights, which permit vehicular flows in two phases.

The possible vehicle paths at the crossroads, subdivided by the phases of the traffic light control system, are shown in Figures 2 and 3. In the first phase, the traffic

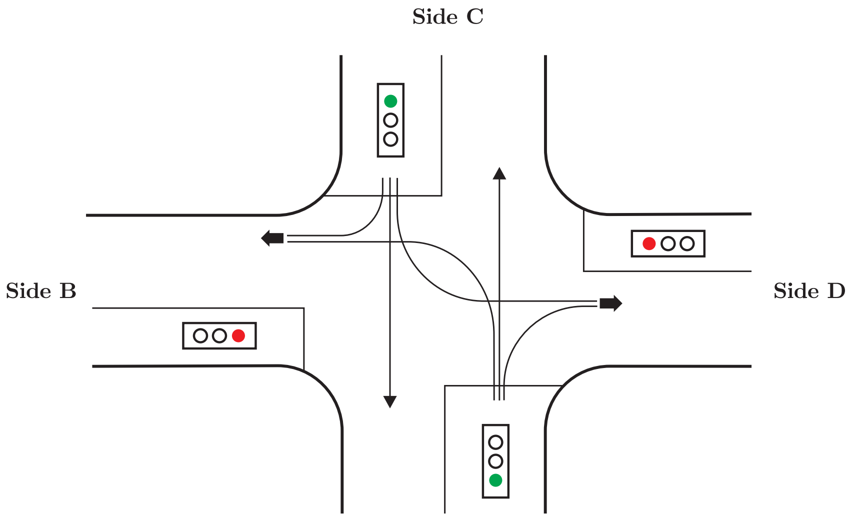


Figure 2. Scheme of vehicular paths of the traffic lights' phase one

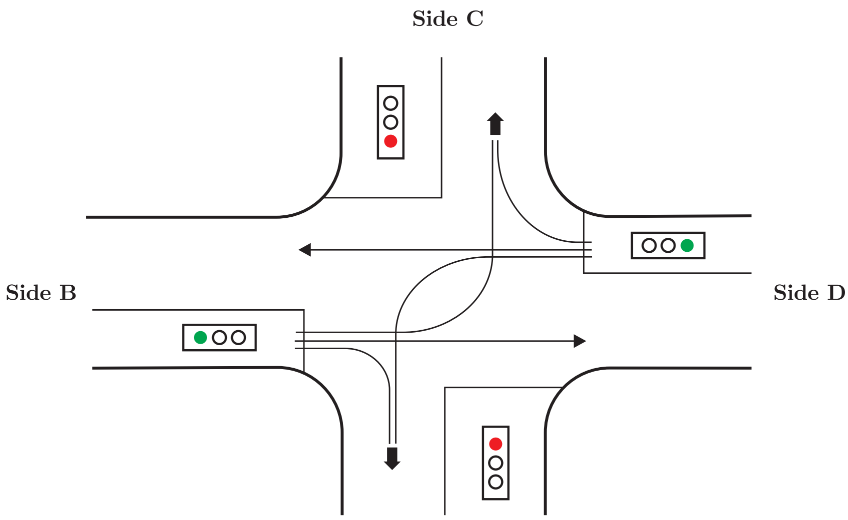


Figure 3. Scheme of vehicular paths of the traffic lights' phase two

lights are green for vehicular flows incoming from sides A and C and red for flows incoming from sides B and D, as shown in Figure 2. In the second phase, the lights are green for sides B and D and red otherwise, as shown in Figure 3.

The entrance flow from side A of the crossroads with its decomposition into three crossing paths is shown in Figure 2. We use this component of the system as an example to illustrate the definition of a model of network of queue service devices starting from the system's function scheme.

An entrance lane is noticeable in this component and so a source of vehicular flow that generates the traffic entering the crossroads on side A. The generated traffic is sent to a decomposition station in users' classes for division into the three crossing fluxes represented in the scheme. The functioning scheme shows that the entering vehicular flow is divided into the three crossing paths at the entering point in the crossroads' inner area. The presence of a traffic light controlling the opening and closing of the vehicles' access to the crossroad's inner area is also noticeable.

Figure 4 illustrates the queue-network model of the component consisting of the crossroads' entrance flow from side A. This model was generated by starting from the scheme of Figure 2, using the devices described in Section 2.

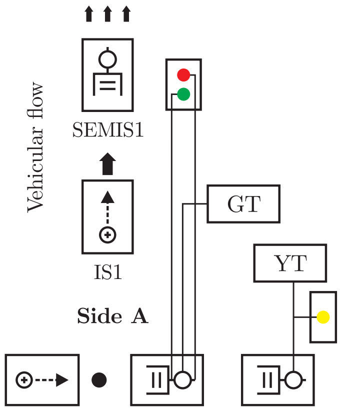


Figure 4. One side entrance flow queueing model

The component of the model of queues relative to the vehicular flow is shown in Figure 4. This component consists of the flow's source entering the crossroads through the entrance lane on side A and of the SEMIS1 single server device that manages the following functionalities:

- division of the vehicular flow into user classes according to their crossing paths;
- control of the state of the traffic light with the SEM1 flag in the case when the flag is closed and the service is interrupted;
- performance of the service time necessary for a vehicle to cross the entrance line in the crossroads' inner zone.

Another component of the model, the functioning of the traffic light system controlling the traffic is also shown in Figure 4. This component consists of the following devices:

- a source generating the signals of phase for individual traffic lights;
- a station managing the opening and closing of one or more control flags, connected to the SEM1 flag and guaranteeing access to vehicles entering during green time of any traffic light phase;
- a delay station that blocks the phase signal for yellow time, reproducing the effect of the yellow signal on traffic lights managed by the previous station.

The individual vehicular flows generated by the station separating the main flow upon entering the crossroad's traffic light system from side A are routed as shown

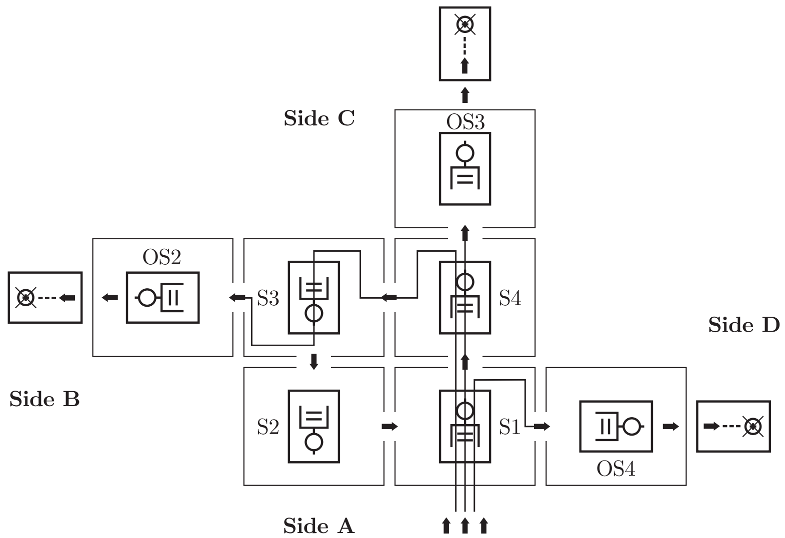


Figure 5. Crossing paths for vehicles entering from side A

in Figure 5. This figure illustrates the model of queue networks concerning the inner part of the crossroads and its exit lanes. The model of the inner part of the crossroads is composed of four sections that are devices present in the set of devices introduced previously.

The three exit lanes represented in the queue model shown in Figure 5 start from side A and go anti-clockwise towards the exit lanes of sides B, C and D of the crossroads. Each of them consists of a section and an exit queue. The three crossing paths of vehicles entering the crossroads from side A are described with a continuous line and characterised by the sequence of sections the vehicles have to cross to go from the entrance queue at the crossroads SEMIS1, shown in Figure 4, to one of the exit queues from the system. We can similarly describe the crossing paths of vehicles entering the crossroads from sides B, C and D.

The queuing network model of vehicular flows of the crossroads shown in Figure 1 is presented in Figure 6. This model was obtained using the symbols of devices introduced in Section 2, developing, for each entrance, the same kind of analysis that lead to the construction of the components shown in Figures 4 and 5.

The vehicular flows of the crossroads shown in Figure 1 are subjected to traffic light control, regulating the access of vehicles from the entrance lanes to the crossroads' inner area. This is realised in the queuing model of the system by modifying the state of the SEM1, SEM2, SEM3 and SEM4 flags.

The SEM1, SEM2, SEM3 and SEM4 flags regulate the opening and closing of the periods of access for vehicles in the entrance lanes. Figure 7 shows the inner component to the queuing network model describing the functioning of the traffic light system. This synchronised component manages the flags' state controlling the vehicular flows access to the crossroads.

The following service devices are shown in Figure 7:

- Css is the source generating the phase signals of the traffic light system. Its service time is constant and coincides with the length of a traffic light cycle.

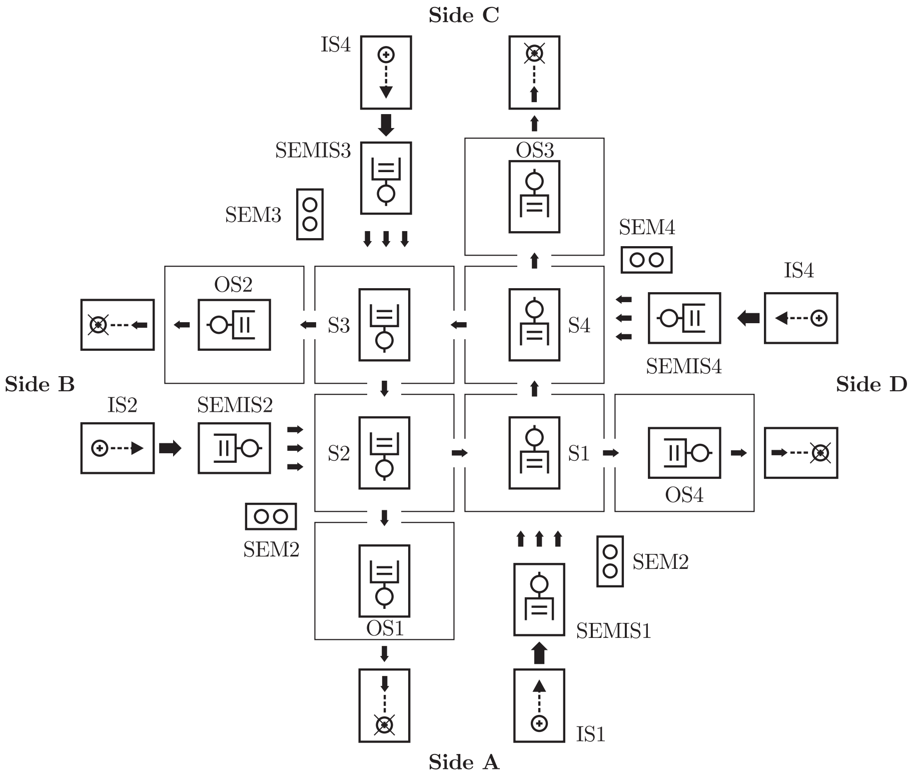


Figure 6. The queue model of the crossroads' vehicular flows

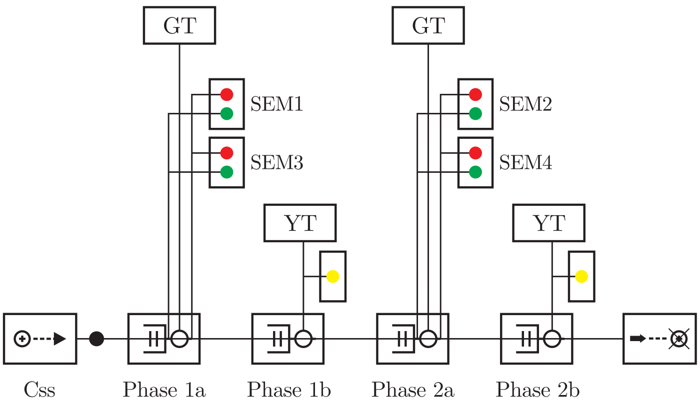


Figure 7. The queue model of to the traffic light control flows

This interval is the cumulative time that the signal needs to go from the source to the queue in the final exit, passing through the four phase stations. When a control signal leaves the system, a new signal is emitted from the source. The functional cycle of the crossroads' traffic light control is reproduced;

- Phase 1a is the station controlling the opening and closing of SEM1 and SEM3. When the system is initiated, all the control flags are in their closed state, corresponding to the red light of the traffic light for each entrance lane. The functioning of Phase 1a reproduces the traffic light phase shown in Figure 2;

- Phase 1b is the delay station for the control signal separating the execution of phase 1 from that of phase 2. During this interval of time, YT, all the control flags are in their closed state. Actually, this time would correspond to the duration of the signal of yellow light, following the green one, for the entrance lanes from sides A and C of the crossroads. During this time interval no vehicle can enter the inner zone of the crossroads' from the entrance lanes; only the vehicles already at the crossroads complete their crossing paths;
- Phase 2a is the station controlling the opening and closing of the SEM2 and SEM4 flags. The functioning of this station reproduces the traffic light phase shown in Figure 3;
- Phase 2b is the delay station separating the execution of phase 2 of the current traffic light cycle from the execution of phase 1 of the following cycle. This delay represents the duration of the signal of yellow light following green for the entrance lanes from sides B and D of the crossroads. When the control signal terminates its service in this station, it leaves the system through the last queue of the model. This event does not imply any execution time and it occurs at the same moment when the Css source generates a new control signal, thus starting a new cycle in the functioning of the traffic light system.

We have built a program simulating queue network service devices whose components are shown in Figures 6 and 7. The program was realised in the context of the QNAP2.V9 language [4], with a number of pre-defined variables including the queue type and the customer type. The algorithm language of this programming context enables definitions of new types of complex objects like those introduced in the previous paragraph.

The simulation concerned an interval of 20 minutes of real time. The sources of vehicular flows entering the crossroads generated vehicles with varying average arrival frequencies. The average frequencies varied continuously, linearly or according to the simulation time. When corresponding to the starting moment of the simulation, they had a value equal to 1/10 (1 vehicle every 10 seconds). We assumed that, at the moment when the simulation began, the system was empty. The average frequencies of vehicles' arrival assumed the following intermediate values: 1/4.5 (1 vehicle every 4.5 seconds) at the 250 moment, 1/10 (1 vehicle every 10 seconds) at the 500 moment and 1/20 at the 1000 moment. These data correspond to those actually supplied by Urban Traffic Plan [5] Its data for vehicles' arrival frequencies describe the changes in vehicular flows at the beginning of a peak period followed by a period of progressively decreasing intensity of traffic.

The diagram shown in Figure 8 describes the change in the length of vehicle queues measured at the crossroads during the simulation's execution. The length of vehicle queues was measured during the simulation's execution using the procedures supplied by the QNAP2.V9 context to manage the tracing of possible events.

We connected the "Reset" events relative to individual traffic lights with the procedures calculating the number of vehicles queuing at the crossroads entrance points. These procedures calculated, for each entrance during the simulation, the number of vehicles queuing at the moment when the traffic light turned green. These data were recorded in files and created, for each entrance, a sequence of the number

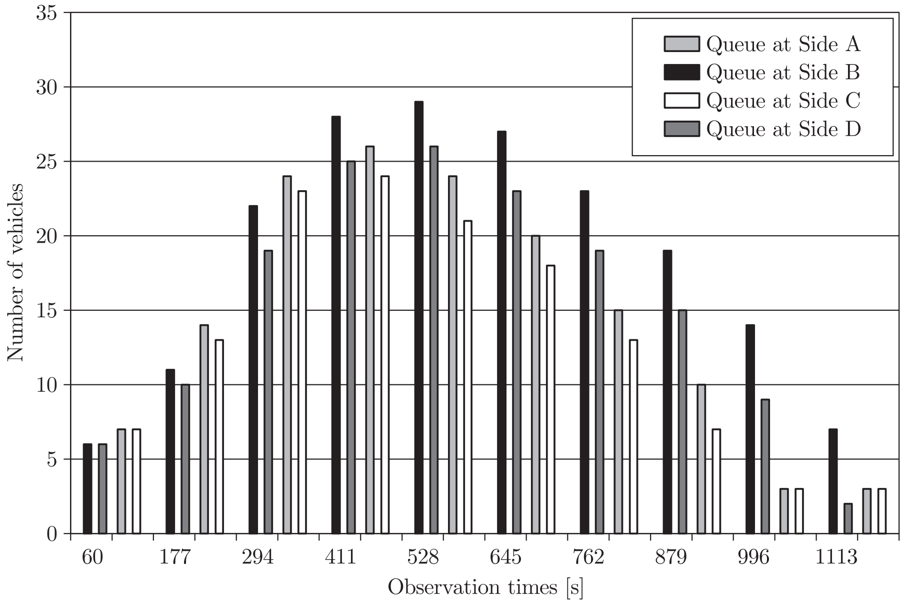


Figure 8. Vehicles' queues at traffic lights

of vehicles in a queue at the close of the red periods. These data were subsequently imported through an MS-VBA macro in a MS-Excel file and processed to produce a graphic illustration of the queues' behaviour as shown for example in Figure 8.

This diagram shows the performance of vehicle queues, calculated at the entrances a moment before the green signal, depending on the simulation time. The calculated changes are due to changes in frequency of vehicles' arrivals upon entering the crossroads. In this case, the crossroads system works in an acceptable way. In fact, the maximum value calculated for an entrance queue is 29 vehicles, at the 528 moment of simulation time, corresponding to the maximum traffic peak. This value tends to be greatly reduced in the following ten minutes of the system's functioning due to decreasing entering traffic.

The simulation was carried out on a Personal Computer with an Intel® Pentium IV CPU of 1.8GHz with 511MB of RAM memory and the MS Windows XP Professional operating system and required a few seconds of CPU.

4. Statistic control of vehicular traffic processes

In the context of simulating vehicular traffic systems, statistics presents itself as a tool with three aspects of interest:

- a tool for collecting data;
- a tool for process control;
- a tool for data verification.

Here, the term "control" is very general in meaning and it often expresses real-time contact with the observed process to manage the requests to a limited resource.

In this framework, it is interesting to see statistics as a tool for automatic process checking. In real congestion systems, real-time process checking may enable one to detect an incoming congestion state, thus allowing decisions to pilot the system.

Vehicular traffic flows can be described by a discrete, random, variable number of arrivals in a defined interval of time or by a continuous, random, variable inter-arrival time between two consecutive customers. Depending on the type of variable used, different statistic tests can be applied.

According to our experience, inter-arrival time is preferable when monitoring an arrival process. In fact, observation of this variable yields the same information that is obtained when counting the number of arrivals during an interval of a given length. Moreover, monitoring systems based on this variable are more general and turn out to be more realistic. For example, if we consider a traffic system characterised by the presence of vehicular flows subjected to entrance variations and choose an interval that is too long to count the number of arrivals, it may happen that when we are ready to make a decision the system is already blocked.

Non-parametric statistics produce tests unbounded in distribution on the observed random variable. It follows that without assumptions on the observed random variable's distribution, we know the distribution of the random test variable.

There are many tests easily applicable as basis to define control software procedures which can be run on common processing systems and provide ready answers to changes, as required in dynamic control systems. In fact, we use some statistic tests to see when the changes in the observed process are so evident as to constitute a variation in act of the phenomenon.

For example, in [6] we implemented a procedure that enabled us to compare some data sequences obtained in a real traffic system to the corresponding data sequences obtained during a simulation of a queue-network model. In this specific case, the system was crossroads similar to that described in this paper. The data sequences were yielded by the length of queues in the crossroads' entrance lanes measured a moment before the traffic light turned green. There was a series of data observed for each entrance lane in the real system and during simulation in the model. The data series referred to 45-minutes' time intervals.

The data series from the simulated model were exactly the same as those illustrated in the previous paragraph of this paper. In this specific case, we have verified the correspondence between the real system and the simulated one according to the runs' theory. This enabled us to establish the validity of the following proposition for every entrance lane:

The hypothesis $H_0: F_1(x) = F_2(X)$ *is acceptable at a confidence level of 99%.*

In this formula $F_1(x)$ is the distribution of the variable length of an entrance queue observed in the real system, while $F_2(x)$ is the distribution of probability of the same variable observed in the simulated system. In this case, the non-parametric statistics of the runs has served as a basis for a software procedure to evaluate the reliability of the simulator in the relevant time: from 1:00 pm to 1:45 pm.

In other cases, we have adapted a statistical test to the real systems, implementing it in the simulation model to value the impact on control management.

In phenomena like vehicular traffic flows, some changes in an arrival process are not singled out imposing predetermined, stiff limits. In fact, the number of arrivals in an interval is a random variable, which swings around an average value or median (increases or reductions would mean changes in the statistical characterisation of the process). Thus, the statistical test has the task of singling out when the changes in the arriving process are so important as to indicate a change in the arrival process to the server. In this case, automatic control modifies the service time to avoid a congestion state or, on the contrary, a prolonged empty state.

Applications of these concepts have had various forms. For example, we have built an algorithm for a vehicular flow monitoring system, which automatically detects the time division in homogeneous intervals for stochastic characterisation of the process of vehicular passages at a point along a road, thus automatically following the daily traffic flow evolution [2]. In another case, we have built an algorithm for a vehicular-flow monitoring system, which detects changes in vehicular flows arriving at crossroads and manages the green and red time of automatically controlled traffic lights [3].

It is evident that these concepts, unchanged in their basic idea, may find applications in numerous situations.

5. Conclusion

We have described how we use queuing networks to model vehicular traffic systems with automatic control. This approach permits us to perform impact valuation of the use of specific control algorithms derived from non-parametric statistics on traffic system performance. This context seems to be an interesting framework to develop and test tools and ideas for automatic control of vehicular traffic flows. Particularly, we have studied a local problem in a urban traffic network individuated by a cross-road system. In a more general view, as introduced in [4], we can extend the use of these techniques to simulate the behaviour of wider components in a urban traffic network.

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