NETWORKS OF QUEUES FOR THE SIMULATION OF URBAN FLOW SYSTEMS: AN INTERMODAL TRAFFIC SYSTEM

LEONARDO PASINI AND SANDRO FELIZIANI

Departments of Mathematics and Computer Science University of Camerino
62032 Camerino Italy
{sandro.feliziani, leonardo.pasini}@unicam.it

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1. Introduction

This investigation was carried out in the context of studies concerning the computer simulation of urban and metropolitan flow systems. The methodologies to simulate network-of-queues models are based on languages and procedures to evaluate the performances of computer systems elaborated in the United States from the 70s and later in France. In our context, we simulate systems of vehicular traffic [1] and systems of pedestrian flow [2].

The main aspect of these investigations is the possibility to represent a system of urban flow through an appropriate and detailed network of queues with controlled customers’ flows that reproduces, in its functioning, the evolution of the actual system under consideration. Queues are therefore used to represent this particular typology of flow systems.

The problem concerning methodologies to represent vehicular traffic systems was set in literature in [3]; there, some possible prospects are listed to solve this open problem, among which the hypothesis of networks of queues is quoted. To date, the only studies in literature on this matter concern analytic solutions relating to traffic systems that are subject to very specific conditions; therefore, they cannot be used to analyse systems which are commonly taken into account in an urban or metropolitan context, e.g. [4].

Actually, network-of-queues models used to represent urban flow systems proves to be complex, not analytically solvable and only simulate the transitory evolution of the specific system under consideration.
In this work a specific networks-of-queues model is defined that allows to simulate the evolution of a system of urban mobility characterized by the interaction of the following elements:

- a collective passengers transport system: train, subway, bus,
- a generic station, where public transport stops and a flow of outgoing passengers is generated,
- a moving staircases system for the mechanized transfer of pedestrians.

This model is therefore used to study issues that are frequently noticed in the planning of an intermodal urban traffic system. Intermodal traffic systems are one of the main elements of the rules to draw up and implement Plans of Urban Traffic [5].

The model allows to measure, through simulation, the exact impact of a project implying the use, in a given station, of n moving staircases for the mechanized transfer of pedestrians on customers flow. In the project, each moving staircase is characterised by specific width and speed, determined by an estimate of users’ flows based on incoming collective transport.

To implement the model and create the simulator, QNAP2 was used. QNAP2 is an object oriented programming language for the analysis of computer systems, developed in France by INRIA. Among the types of default data, QNAP2 includes queue object and a consumer object, and it implies two levels made up of a control language and an algorithmic language. In the present investigation this model is applied to the analysis of a system that is the main pedestrian approach to a city in Central Italy. The system is made up of a bus terminal connected to a moving staircase system linking to the upper town.

In this context, the analysis concerns the system’s functioning in peak time and allows to confirm direct observations.

2. The model

Let’s now define the network-of-queues model shown in Figure 1 and describe its components. This model is a multiple-class network of queues made up of the following devices.

A station – it is a source queue generating the incoming flow of public transport. This device is a single server queue with “infinite” customers belonging to the customer class that represents the public collective transport in the system under consideration, e.g.: train, subway, bus. When the service of a customer in A is finished, that customer is routed to the B queue and the following A queue customer starts its service. Therefore, service time in A represents the time between two incoming means of collective transport in the B station.

B station – it is a multiple server queue and represents the public transport arrival terminal. The M number of servers of this queue is the number of arrival platforms taken as crucial for the evaluation of the system under consideration. When executing the service algorithms of B queue servers, pedestrian flows are generated that are routed to the C station. Those pedestrian flows are marked according to customer classes. A passenger who steps off is routed to the C queue as customer of a specific class. Passengers assignment to their own customer class is made through a probability distribution the model is given as input datum. In this
context, a customer class represents the possible route a pedestrian follows to go from
the arrival platform to the entrance of the moving staircase he chooses to use. When
its service in the B queue is finished, each coach is routed to a way out.

**C station** – it is an infinite servers queue for the pedestrian type customers.
All customers are served in C according to their belonging class. Service time of
a customer in this station represents the time a pedestrian needs to move from the
arrival platform to the entrance of the moving staircase he is going to use. Therefore,
customer’s service time in C is a random variable subject to a probability distribution
that is specific for each customer class and is given to the model as input datum.

**Area stations** – they are single server queues. This type of device represents
the area before the access to a mobile staircase. This is the area where a queue
of customers waiting to get on the mobile staircase can form. Actually, the model
can detect if pedestrian flow towards some of the N mechanized facilities exceeds
the maximum flow the relevant mobile staircase’s access area is able to absorb. The
Area stations act then as access queues for the staircase sectors of entrance to the
staircase. We will see that these sectors are single server devices with no waiting space,
equipped with a status indicator for the Area station just behind. A customer’s service
algorithm in the Area queue server monitors the status of the entrance sectors. Being
the entrance free, the pedestrian is transferred to the first step of the staircase in no
time, otherwise he is kept in the server, holding up the following customers.

**Scala stations** – they represent the mobile staircase mechanized facilities for
the pedestrian transfer. The model of these devices, as shown in the figure, consists
of two queues set in a line. The staircase queue is the pedestrian access point to the
mobile staircase. This component can be a bottleneck in the pedestrian flow system.
It is made up of a server with no waiting space. A customer’s mean service time
(t) in staircase is the mean time a customer takes to climb and slide on the access
step of the escalator. It follows that \( \frac{1}{t} \) is the mean frequency for pedestrians to
climb on the mobile staircase. This parameter depends on the staircase’s width \( (L_s) \)
and slide speed ($V_s$). Increasing $L_s$ or $V_s$ we increase the mean access frequency to the staircase ($F$). Given $L_s$ and $V_s$, our model is implemented to work with two possible mean values of $F$: under normal conditions and under congestion conditions. Therefore, given the structural physical staircase characteristics $L_s$ and $V_s$, $F_{\text{max}}$ represents the mean access frequency that occurs under congestion conditions when pedestrians climb “crowding” on the staircase occupying the whole available access section.

Leaving the staircase station the pedestrians enter the staircase station. This is an infinite servers queue. A pedestrian service time ($t_s$) in this device is the transfer time from the access position to the exit position of the mobile staircase. In this model, $t_s$ is a constant value that depends on the $L_s$ length of the staircase and its $V_s$ slide speed. The $n_s(t_0)$ number of customers that, at a given $t_0$ instant, stand in this service device represents the number of pedestrians that simultaneously stand at $t_0$ on the mobile staircase, properly positioned along the staircase according to their access instant.

3. An exemplary application

In this paragraph we describe the application of the previously defined networks-of-queues model to the investigation of a specific intermodal urban transport system through simulation. The system under consideration is made up of the following components:

- a bus public transport system,
- a bus terminal station, for the arrival of incoming passengers,
- an up escalator for pedestrians transfer from the bus terminal to the upper town.

This system is one of the main points of access to the city of Chieti, a medium-size city of Central Italy (see Figure 2). In the subsequent subsections we describe the details of the model as applied to our example (3.1) and then we present exemplary results (3.2).

3.1. System specification

In Figure 3, the configuration of the model to simulate the considered exemplary system is shown. In the Figure components are so described:

- A is the source of buses arrival flow,
- B is the bus terminal, endowed with 20 arrival platforms,
- C is the queue that simulates the pedestrian routes from the arrival platforms to the mobile staircase,
- D is the pedestrian area just before the mobile staircase to go to the upper town,
- E is an up escalator for pedestrians with the following characteristics:
  - the time to climb the staircase is 2.44267 minutes,
  - the time to move from step to step is 0.012 minutes,
  - the staircase width is 100 centimetres.

The implementation of a simulator based on the networks-of-queues model shown in Figure 2 was realized using the QNAP2 programming language developed by
Networks of queues for the simulation of urban flow systems

Figure 2. Photos of the principal elements of the considered communication system

Figure 3. Schematic representation of the studied communication track

INRIA in France. This is an object oriented language whose types can be determined by the user. The language has, among its base types, a ‘queue’ object and a ‘customer’ object and a Flag type for synchronizations. QNAP2 implements an algorithmic language that is similar to Pascal and a command based language that separates the source program’s compilation and execution phases in different sections. The
following are a few sections of the QNAP2 program that implements the networks-of-queues model described in Figure 3.

The `/DECLARE` command introduces a section that defines variables whose type has been previously described.

```
/DECLARE/
  QUEUE A, B, C, D, INSCALA, SCALA;
  FLAG FERMO;
  REF CUSTOMER RC;
  INTEGER N;
```

The `/STATION/` command introduces a section that defines a service station based on a queue type variable.

```
/STATION/
  NAME=A;
  TYPE=SOURCE;
  SERVICE=IF (TIME>=T1) AND (TIME<T2)
    THEN EXP(0.32)
    ELSE EXP(2.037);
  TRANSIT=B;

/STATION/
  NAME=B;
  TYPE=SERVER, MULTIPLE(20);
  SERVICE=BEGIN
    FOR N:=1 STEP 1 UNTIL 50
      DO BEGIN
        RC:=NEW(CUSTOMER); EXP(0.1);
        TRANSIT(RC,C);
      END;
  END;
  TRANSIT=OUT;
```

```
/STATION/
  NAME=D;
  TYPE=SERVER, SINGLE;
  SERVICE=IF INSCALA.VALUE <= 1 THEN
    BEGIN
      UNSET(FERMO);
      TRANSIT(INSCALA);
    END
  ELSE
    BEGIN
      WAIT(FERMO);
      TRANSIT(INSCALA);
    END;

/STATION/
  NAME=INSCALA;
  TYPE=SERVER, SINGLE;
  SERVICE=BEGIN
    UNSET(FERMO);
    IF (D.NB)>=50
      THEN CST(0.0084444444)
      ELSE CST(0.0120666666);
    SET(FERMO);
  END;
  TRANSIT=SCALA;
```

```
The service algorithm of the B station, representing the bus terminal, includes the execution of a for loop containing the RC:=NEW(CUSTOMER) statement. Customer is a QNAP2 variable base type and represents a network user. In the same loop, the TRANSIT(RC,C) statement sends the customer pointed by RC to the C station. In this way, we have pedestrian flows of passengers getting down from the buses and going towards the mobile staircases.

The SET() and UNSET() procedures are used to assign the “open” or “closed” value to the FLAG variable, while the WAIT() procedure forces the present customer to wait the FLAG opening, stopping its service in the device.

The InScala station has a service time that depends on the overcrowding in the D queue, representing the access to the mobile staircase. Checking the number of customers in the D station during the simulation, we can distinguish two different service times for a pedestrian’s passage from the access position to the position on the staircase. These are service times that account either for congested conditions (maximum load time) or for normal conditions (standard load time). Maximum load time is defined as the ratio between the time to move from the first to the second step and the maximum step load (in our case \(0.012/1.5=0.00844\)). The standard load time is defined as the ratio between the time to move from the first to the second step and the standard load step (in our case \(0.012/1.0=0.012\)).

The staircase station is an infinite server and represents the residual component of the mobile staircase. Note that the access to this device takes place in a serial way from the first step. This device is used to evaluate the number of presences on the mobile staircase over time. Service time is invariable for all customers and corresponds to the necessary time to move from the exit from the first step up to the exit from the staircase.

### 3.2. Exemplary simulation results

The system analysis presented herein concerns the conditions of maximum congestion.

We have fixed one minute as the unit of simulation time, and 60 minutes as the simulation duration. The A queue is the source of flow of buses arriving to the terminal. In its service algorithm two different generation frequencies are distinguished, as the buses’ inflow in the 7.55–8.00 time interval is higher. If the variable called “time”, (the current time of simulation) assumes values between instant 15 and instant 20, the mean time between the arrival of two buses is 0.32 minutes, otherwise it is 2.037 minutes.

The B queue – representing the bus terminal with 20 arrival and departure platforms – is a multiple server and, according to our recordings, it requires a mean service time of about 5 minutes per one arrival (the customers outgo and the bus departure). The congestion probability in this station turns out to be negligible. Actually, the probability for all the servers to be busy approximates to a value of
Table 1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Service</th>
<th>Busy pct</th>
<th>Cust nb</th>
<th>Response</th>
<th>Serv nb</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.283</td>
<td>1.000</td>
<td>1.000</td>
<td>1.283</td>
<td>43</td>
</tr>
<tr>
<td>B</td>
<td>0.1775</td>
<td>0.6360\cdot10^{-2}</td>
<td>0.1272</td>
<td>0.1775</td>
<td>43</td>
</tr>
<tr>
<td>D</td>
<td>0.987\cdot10^{-2}</td>
<td>0.3538</td>
<td>40.15</td>
<td>1.120</td>
<td>2150</td>
</tr>
<tr>
<td>InScala</td>
<td>0.1005\cdot10^{-1}</td>
<td>0.3602</td>
<td>0.7173</td>
<td>0.2002\cdot10^{-1}</td>
<td>2150</td>
</tr>
<tr>
<td>Scala</td>
<td>1.796</td>
<td>0.3202</td>
<td>67.90</td>
<td>1.895</td>
<td>2150</td>
</tr>
</tbody>
</table>

1,3894929e-9. In order to obtain the latter value we can refer to a single bus station component, and (making some exemplifying hypotheses) consider the well-known M/M/20/20 finite memory system. Knowing that 43 buses arrive in the period of maximum congestion we can develop, taking into account one hour of real time, the following calculations: \( \lambda = 43/60 \) buses per minute, \( \mu = 1/5 \) buses per minute, \( P_k = P_0(\lambda/\mu)^k/k! \), so that \( P_{20} = 1.3894929 \cdot 10^{-9} \). Such an evaluation is possible because, in this model, the B station is the access entry of customers in the network and the functioning of this component is independent – as very rarely happens when dealing with urban flow – of other components of the system.

Table 1 illustrates some results of the simulation. Times are given in minutes and some of the system queues are shown with relevant data concerning mean service time, busy percentage of the station, average number of customers, system’s response time and number of served users (buses, persons).

Figures 4–6 illustrate, respectively, the time evolution of the following variables: the number of customers produced by station A, the length of the access queue to the mobile staircase, and the customers’ number on the mobile staircase. We can therefore remark what follows. In the peak time, around minutes 15–20, we have the heavier inflow to the system; this heavy inflow can determine a temporary congestion we are able to measure. It is to be observed that the A–B subsystem, that is the bus terminal, does not reveal any congestion problems, in agreement with analytical calculation above. We can be more precise and point out that we get the heaviest inflow of

![Figure 4](http://www.bop.com.pl)
4. Conclusions

In the present investigation we have analysed the customers’ flow in a node of a specific intermodal urban transport system, applying the simulation with networks-of-queues models. The concerned node is a bus terminal that acts as junction to a moving staircase system in the city of Chieti.

The technologies used in this work are developed by some research centres of the French INRIA we work with. They are procedures to simulate discrete flow systems
using synchronization and service centres’ networks. To better understand how the customers’ flow works in the system under consideration, we usually integrate such methodologies with spatial interaction models.

The analysis concerns the system in the maximum congestion timeframe; in the simulation, the functioning of the mobile staircase is reproduced also. The analysis points out the parking area of the bus terminal is over-dimensioned. On the other hand, the pedestrian access area to the mobile staircase is adequate to the incoming customers who, when the peak inflow takes place, while waiting to climb the mobile staircase fill a surface that rounds a maximum of 100 square metres.

References

[1] Pasini L 1994 Traffico Veicolare – Analisi dell’incrocio di Colonna San Marco a Siena Studio per il Comune di Siena