Simulation of impacts of yards on flow conditions using a mesoscopic traffic assignment approach

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Abstract

This paper describes the activities carried out to check, in terms of transport analysis, impacts generated by the construction of the third lane on the A4 motorway, in the stretch between the gates of S. Donà di Piave ed Alvisopoli, in Italy. The purpose of this study is to choose the optimum configuration of yards, in terms of length and location, which reduces the effects of outflow. In particular, the application of a mesoscopic method for the simulation of outflow is dictated by the need to simulate a network broad enough to properly evaluate the influences between the disruption of the flow introduced by the yards that generate phenomena of queuing. The mesoscopic method allows us to analyze broad contexts congested with good reliability, but without the computational costs and efforts required for the calibration of microscopic models, suited to represent small networks.
Keywords: traffic impacts, mesoscopic, traffic assignment.

1 Introduction

Many studies (such as [1–3]) have highlighted the limits of static assignment models in analyzing phenomena connected to temporal variations in terms of both demand and supply, such as rising and scattering of queues due to temporary peaks of demand and/or capacity reductions of infrastructures. Thus, in order to comply with these phenomena, it is necessary to remove the intra-period stationarity hypothesis and choose within-day dynamic assignment models (Dynamic Traffic Assignment – DTA).

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In general, a classification of DTA models can be made according to the representation of traffic variables (continuous or discrete) and on the aspect of the variables representing network performances (aggregate or disaggregate). So-called macroscopic models, or flow-based analytical models [4–8], simulate network performances by means of aggregate variables (speed, density, flow) with explicit capacity, as in static models, and use a continuous representation of traffic; generally, in formulating macroscopic models, fluid-dynamic analogies of traffic are adopted. A second type of model, named mesoscopic [9–16], is similar to the previous one in the way it simulates network performances (aggregate variables with explicit capacity are used), but it differs in terms of traffic representation; the peculiarity of mesoscopic models consists of a discrete flow representation for groups of vehicles/users. A third type is made up by microscopic models, where individual trajectories of all vehicles are simulated by using disaggregate variables with implicit capacity, and a discrete traffic representation.

In this paper we present a specific methodology to estimate and predict the effects of presence of yards that generate critical conditions of outflow. In particular it is presented a method (model and procedure) to simulate the average speed and the length of queues. An aggregate approach (macroscopic) is proposed; the decision to use a mesoscopic model is dictated by the need to simulate a broad network to properly evaluate the influences between the disruption of the flow introduced by the yards that generate phenomena of queuing. The mesoscopic model allows to analyze broad areas congested with good reliability, but without the computational costs and efforts required for the calibration of microscopic models, suited to represent small networks.

The paper is structured as follows: in section 2, the assignment model adopted to evaluate flow conditions is described; section 3 describes the application of the proposed method and hypotheses adopted to carry out simulations in a real context. Section 4 presents an analysis of results obtained with the simulations and a comparison between these results and on site experimentation data. Brief conclusive remarks are reported in section 5.

2 Models

2.1 Supply model

Two elements are considered within the supply model:

- the topological representation of the network;
- the representation of outflow conditions by means of specific relationships.

The network is represented using fundamentals of graph theory. The classes of components making up the graphs are:

- centroids: these nodes represent the origin and/or destination of the trips of all users crossing the considered area. There is a centroid for each origin/destination gate;
- network nodes: these are located at each potential change of direction along a generic path or at significant variations in geometric and/or functional characteristics of a trunk (i.e. width variations);

- real links: these represent the connection between two network nodes; they coincide with sections of the road network;
- connector links: these represent the connection between a centroid and a network node.

The representation of outflow conditions requires that specific relationships among variables be defined. In this particular case functional dependence of speed with density was considered.

2.2 Demand model

The level of demand can be estimated separately for different vehicle categories. For this study we use the analytical information gained using the system of collection and provided by the motorway operator. We built the O/D matrix at intervals of 5 minutes, on 5 different vehicles categories, and flows at intervals of 5 minutes at entry and exit of each barrier.

Data on outflows to all barriers have been filtered to the detect the actual arrival time of collection, net of time spent in the queue, except for vehicles with automatic payment system (electronic toll collection).

Available data for the simulations cover a period of seven days in different period of year (April, June, July, August, and October). To simplify the computational simulation period was divided into 2304 uniform intervals of 300 seconds, the first represents the range 00:00 to 00:05 of the first day in the period and the last the range 23:55 to 00:00 of the last day in the same period.

2.3 Demand–supply interaction model

Static models do not allow analysis of phenomena connected to temporal variations in terms of both demand and supply, such as rising and scattering of queues due to temporary peaks of demand and/or capacity reductions of infrastructures. The Dynamic Traffic Assignment (DTA) model considered here to simulate evacuation is mesoscopic and is based on that proposed by Cascetta and Cantarella [13] and subsequently developed [17–21], where users are assembled in packets that move on the network discretising demand for each origin-destination pair. The used approach refers to discrete time intervals, supposed of constant length (without any loss in terms of generality). Let δ be the length of the generic interval t and τ the current time within the interval, $\tau \in [0, \delta]$. Outflow characteristics are calculated at the beginning of each interval and are assumed homogeneous along a link; for sufficiently short lengths of the interval, they can be considered approximately constant for the entire duration of the interval, avoiding the need to allow for the inner fixed point problem that would arise. Once outflow characteristics on links for a generic interval are known, movement of users can be traced on the link, depending on the definitions of the link model and on the adopted movement rules described below.

2.3.1 Demand simulation

Demand is described in terms of vehicles that move on the network using a *modal facility*; modal facilities sharing the same characteristics are grouped into

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a *class*. In other words, a *modal facility* defines a type of vehicle, and differences among vehicles of the same type are expressed by the definition of a *class*. A set of modal facilities of the same class u departing at the same time η and following the same path k (and consequently related to the same origin/destination pair connected by path k) can be grouped together to form a *packet* $P \equiv \{\eta, k, u\}$ that represents a punctual entity moving on the network. Characteristics shared by each class of modal facility are expressed by means of parameters related to movement rules, occupancy, storage and grouping capability of the modal facility of the class; with reference to a class u of modal facilities, parameters used to define the class are:

- *speed parameter* ζ_u: this represents the speed at which modal facilities belonging to class u move on the running segment of the link. The speed parameter is expressed relative to the speed of a reference class, that is the class which adopted the speed-density function is referred to;
- *occupancy parameter* ξ_u: this indicates the occupancy rate of the modal facility that class u represents;
- *equivalence parameter* ε_u: this indicates the equivalence, in terms of utilized arc capacity, between the modal facility that class u represents and a reference class, which is that adopted as the unit in the definition or arc capacity;
- *filling parameter* φ_u: this indicates the maximum number of vehicles that can be accommodated by modal facilities belonging to class u. It is defined as an integer number;
- *grouping parameter* γ_u: this indicates the maximum number of modal facilities of the class that can be grouped together to form a packet. It is defined as an integer number.

2.3.2 Supply simulation

In order to define performances associated to link a of the graph whose length is L_a, two link segments are introduced, the *running segment* and *queuing segment*, whose difference consists of the adopted outflow rule; in particular, the running segment is crossed with a fixed speed while in queuing segments a deterministic queuing approach is considered and outflow depends on the capacity of the final section of the arc. The edge between the two segments is located at a section S whose abscissa, $x^S{}_a$, can assume values between 0 and L_a. Thus the *running segment* is the part of the arc with $x \in [0, x^S{}_a[$, while the *queuing segment* is the other part, with $x \in [x^S{}_a , L_a]$.

2.3.3 Loading model

Let, at time τ of interval t, packet P leaving at time η of interval h [with $h \leq t$; if $h = t$ then it is $\eta < \tau$] be represented on the graph by a point located at abscissa x of arc a belonging to path k. Let $v_a{}^t$ be the current speed on the running segment of this arc during interval t, Q_a the capacity of the final section of the arc expressed in terms of the selected unit (capacity that could also depend on t) such that $1/Q_a$ is the service time and $\rho^a{}_{max}$ the maximum density on the arc. Remembering the definition of δ as the time length of an interval, so that $\tau \in$

$[0, \delta]$, referring to the arc model described in point 2.1, if $x < x^S_a$, (point representing) packet P moves on the running segment at speed v_a^t and, within interval t, reaches at least abscissa x^S_a . Hence the distance that can be covered on the running segment is given by: $min\{ x^S_a - x, (\delta - \tau)\cdot v_a^t \}$. If it occurs that $x^S_a - x < (\delta - \tau) \cdot v_a^t$, packet P enters the running segment of arc a, at time $\tau' = \tau + [(x^S_a - x) / v_a^t]$. If $x \geq x^S_a$, packet P moves on the queuing segment; outflow on this segment is ruled by capacity of the final section of arc a. The queue length covered by packet P until the end of the interval is given by $\delta = [(\delta - \tau)\cdot Q_a] / \rho^a_{max}$. If $x + \delta > L_a$, then packet P exits arc a during interval t at time $\tau'' = \tau + [(L_a - x) \cdot \rho^a_{max}] / Q_a$.

3 Applicative context

The described model is applied in order to simulate impacts on traffic due to a set of yards for the extension of the motorway. In particular, after a verification and calibration of the supply model in a specific period with available traffic data, scenarios are defined by combining both planned phases of yard and different evolutionary scenarios of future supply and demand.

3.1 The site

At that stage a scenario, representative of the current situation in terms of supply and demand, has been simulated in order to verify the ability of the model to correctly reproduce network conditions in terms of arc flows. The highway system in study coincides with the "closed network" A4-A23 system the considered edges of which are East Venice, Trieste and Tarvisio Ugovizza barriers, as indicated in Figure 1.

The total length of the simulated network is approximately 200 km and the network has been schematized by a graph consisting of 151 nodes (17 centroids representing gates) and 223 links. The O/D matrix of vehicles was estimated through the analysis of data recorded by the toll collection system.

Figure 1: Considered highway system.

Given the particularities of the highway system it was possible to determine movements among exits through the analysis of data recorded by the toll collection system, obtaining O/D matrix characterized by date and time when gates (enter and exit) gates are crossed and class of vehicle.

Additional information was given by electromagnetic loops, positioned at the ramps of the node of Palmanova, as shown in Figure 2. The knowledge of the distribution of hourly traffic volume in such focal point of the network was considered in the model calibration phase.

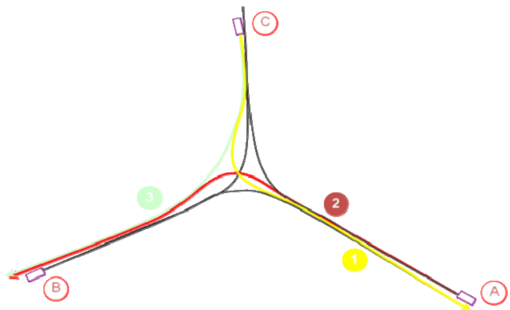


Figure 2: Scheme of flows obtained by electromagnetic loops.

Verification was conducted by comparing flows resulting from the assignment model considering O/D matrices of the month of June 2008 with flows counted by loops in the same period. Results, in terms of statistical indicators, refer to the comparisons made, for a whole day, considered significant in terms of working conditions and vehicular traffic composition; they are shown in Table 1.

Table 1: Values of statistical indicators relating to the comparisons between counted flows and simulated ones.

	MAE	MSE	RMSE	RRMSE
Coming from A	0.79	31097.08	176.34	0.118
Coming from B	0.50	13553.38	116.42	0.104
Direction 1	1.92	503.29	22:43	0.053
Direction 2	1.33	3130.75	55.95	0.084
Direction 3	0.13	2278.42	47.73	0.082

Values show the ability of the model to reproduce measured flows in current scenario. This result allowed to define the set of parameters used for simulations of future scenarios. For a visual comparison in Figure 3 graphs comparing flows obtained by the model and those recorded are reported.

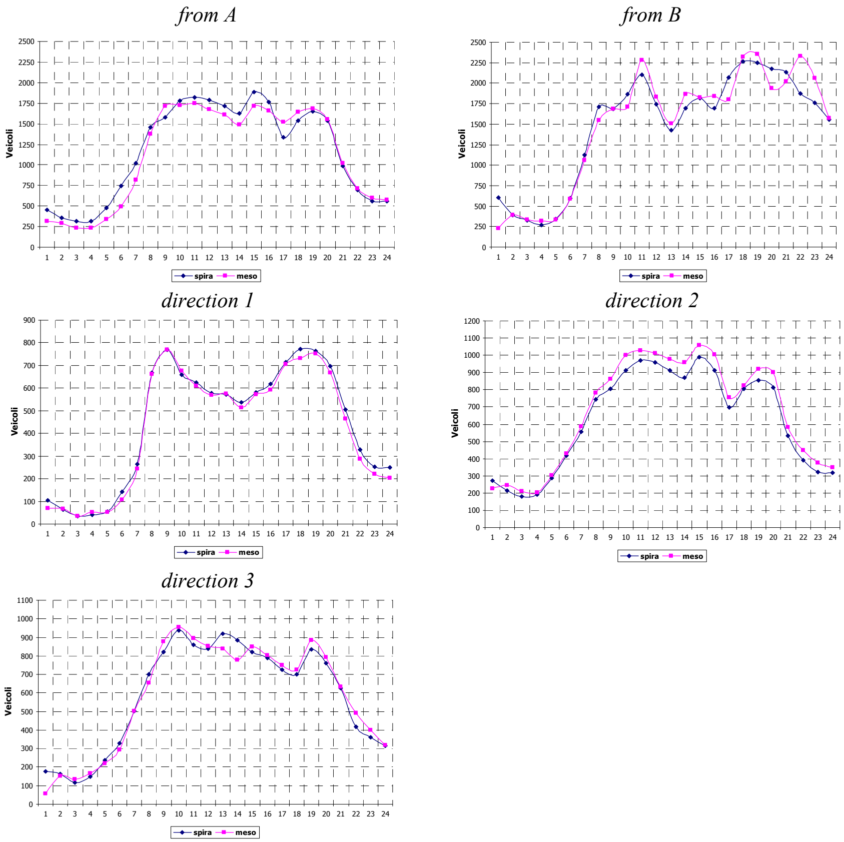


Figure 3: Comparison of measured flows (spira) and simulated (meso).

3.2 Evolutionary scenarios

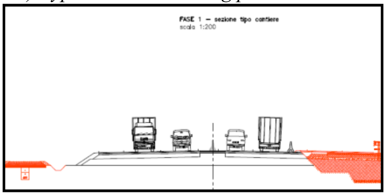
Considering the deadline of five years for the realization; to complete the work in that period, a contemporary start to work on more than one site is needed (Figure 4). The execution of works has been planned implementing the following steps:

1. enlargement in the southern part (carriageway east), for yards B, D (Figure 5a);
2. enlargement in the northern part (carriageway west) for yards B, D (Figure 5b);
3. implementation of the center seam for yards B, D (Figure 5c).
4. enlargement in the southern part (carriageway east), for yards A, C (Figure 5a);
5. enlargement in the northern part (carriageway west) for yards A, C (Figure 5b) and enlargement of the southern part (carriageway east) for the yard E (Figure 5a);

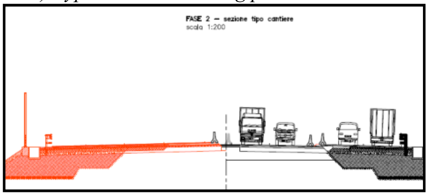
6. implementation of the center seam for yards A, C (Figure 5c) and enlargement of the northern part (carriageway west) for the yard E (Figure 5b);
7. implementation of the center seam for yard E (Figure 5c).

Figure 4: Location of the yards.

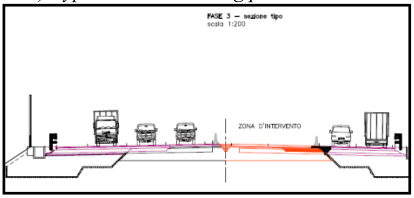
a) Typical section during phase 1



b) Typical section during phase 2



c) Typical section during phase 3



d) Typical section at the end of work

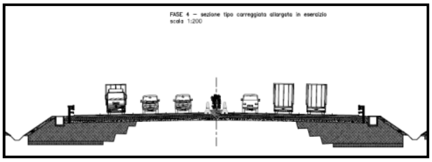


Figure 5: Diagrams of typical sections during construction.

From a preliminary analysis, considering the patterns of work site, their location and extension, to fully represent the worst conditions, it was considered sufficient to restrict simulations to the first two phases of processing.

To evaluate demand several assumptions, sometimes discordant one another, have been compared. On the one hand, hypotheses on growth of highway traffic (source AISCAT) put on view a sharp increase, in the last 20 years, both for cars, and – double in size – for heavy traffic. On the other hand estimates suggest a reduced growth of traffic flows due to a different modal split of freight which yields to a contraction respect to AISCAT data. The values of growth rates used are 8.31% and 7.56% respectively for light and heavy vehicles.

The analysis of traffic data showed a peak during weekend between June and August. To properly assess the effects induced by the phases of construction it was decided to simulate the most extreme conditions of both summer and winter.

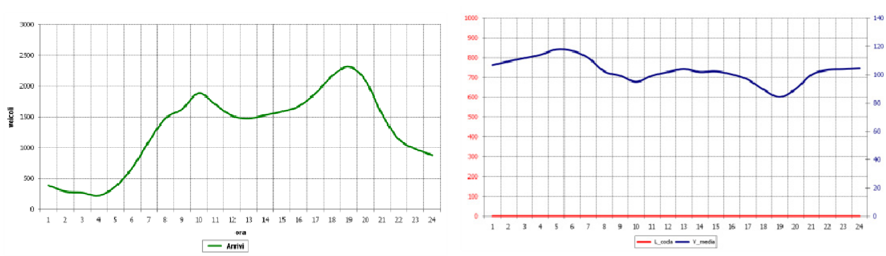
Supply configuration of phase 3 is identical to phase 1, therefore redundant. The same observation has been used for phase 4 and 6. These considerations have led to simulate only four scenarios (phase 1, 2, 4 and 5) for each periods of the year, yielding to a total of 8 scenarios. Scenarios have been simulated by modifying geometric characteristics (width) and flow parameters (speed and capacity) of the links in accordance with phases of yard.

4 Analysis of results

Among different parameters obtained from the simulation, average speed and length of queues for links upstream of the site were considered as indicators for the evaluation of the effects of yards. Simulations were carried out with reference to two different time period and traffic conditions: average winter weekday and peak summer days, to represent both normal working conditions occurring most of the year and conditions occurring during particular periods.

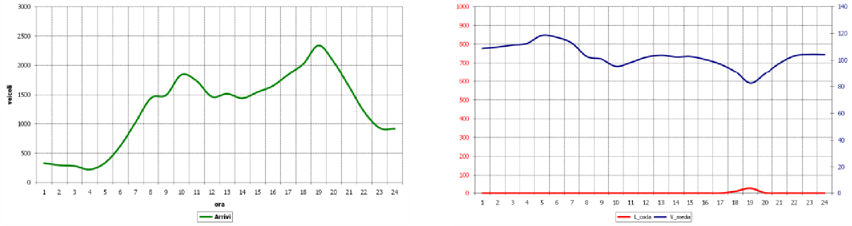
In the following figures, only for sections that are critical (A, C, E yards), are respectively plotted the distribution of arrivals per hour at the start of construction, average speed and average queue length within the upstream site.

Winter scenario – Considering direction A (Figures 6 to 8) it is possible to observe a traffic volume greater than the other on the opposite lane and the related presence of delays and queues in the early evening hours at temporary peaks in demand ahead yards C3 (Figure 7) and C5 (Figure 8). The estimated queue length is always below 100 meters.



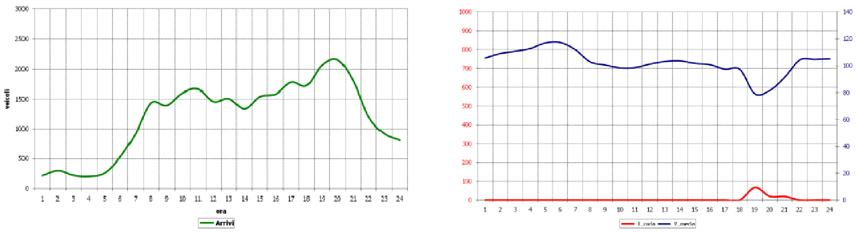
arrivals at the yards *average speed and length of the queue upstream the yard*

Figure 6: Arrivals, average speeds and queues on the yard C1 (direction A).



arrivals at the yard *average speed and length of the queue upstream the yard*

Figure 7: Arrivals, average speeds and queues on the yard C3 (direction A).



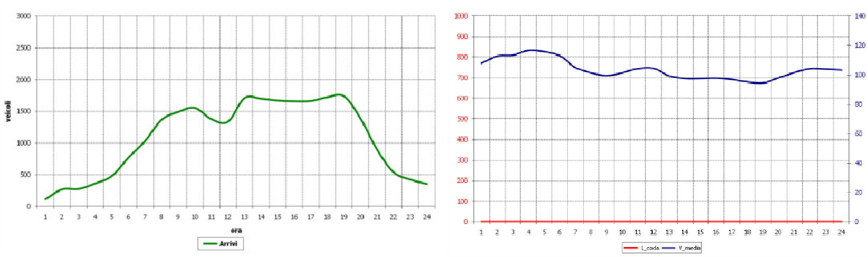
arrivals at the yard *average speed and length of the queue upstream the yard*

Figure 8: Arrivals, average speeds and queues on the yard C5 (direction A).

Considering direction B (Figures 9 and 10) critical phenomena are not observed, the average speeds hovering around 100 km/h in the two trunks of roadway subject to lane change.

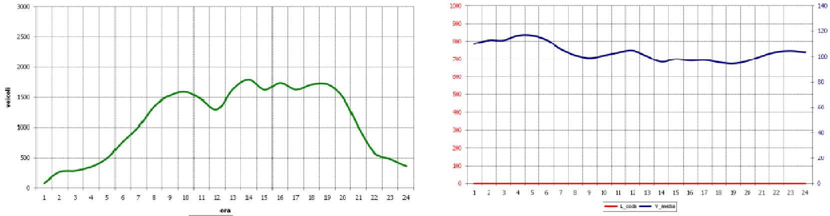
Summer Scenario – Phase 1 – The simulation of phase 1 of yards C2 and C4 shows a fairly regular flow during most of the day with volumes of less than 2500 veh/h. During peak period of the morning (10 am) and of the evening (6–11 pm), with volumes close to capacity, slowing and queuing phenomena may occur which are exhausted by the end of the day. Figure 11 shows trend on the C4 site.

Summer Scenario – Phase 2 – Along direction A traffic volume is significantly reduced compared to the opposite lane, however, the disturbance introduced by the lane change generates phenomena of slowing down exceeding the threshold of 2000 veh/h.



arrivals at the yard *average speed and length of the queue upstream the yard*

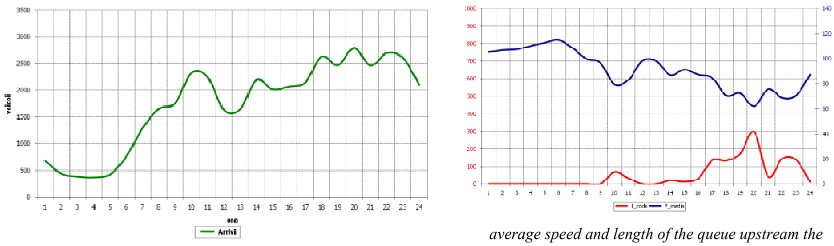
Figure 9: Arrivals, average speeds and queues on the site C3 (direction B).



arrivals at the yard

average speed and length of the queue upstream the yard

Figure 10: Arrivals, average speeds and queues on the site C1 (direction B).

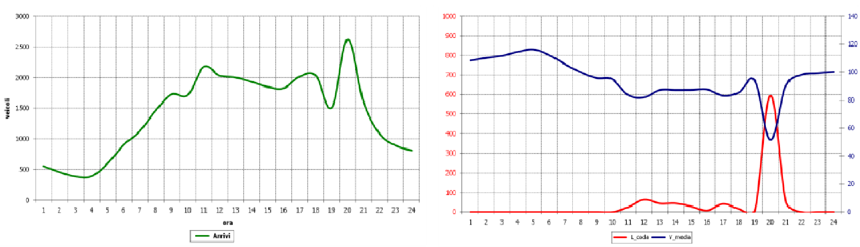


arrivals at the yard

average speed and length of the queue upstream the yard

Figure 11: Arrivals, average speeds and queues on the yard C4 (direction A).

Flow conditions do not appear critical even in the presence of light queues ensuring a flow speed of more than 85 km/h. The evening peak demand (8 pm) produces a queue that dissipates rapidly due to the reduction of the number of arriving vehicles. Figure 12 shows the trend on the C2 site.

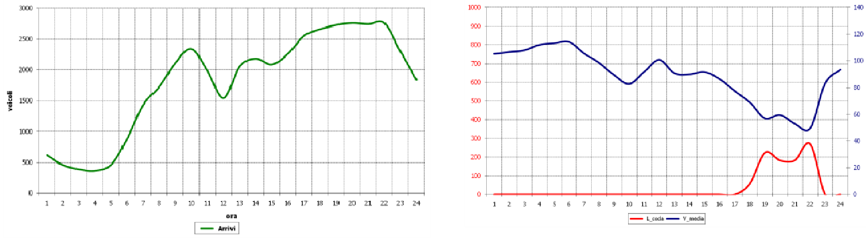


arrivals at the yard

average speed and length of the queue upstream the yard

Figure 12: Arrivals, average speeds and queues on the site C2 (direction B).

Summer Scenario – Phase 5 – Site C1 (Figure 13) is affected by queue phenomena only during the hours of late afternoon, when demand gets to levels close to the capacity. The effects consist of queuing phenomena from early afternoon accompanied by reduction of speed; in the late afternoon, queues reach



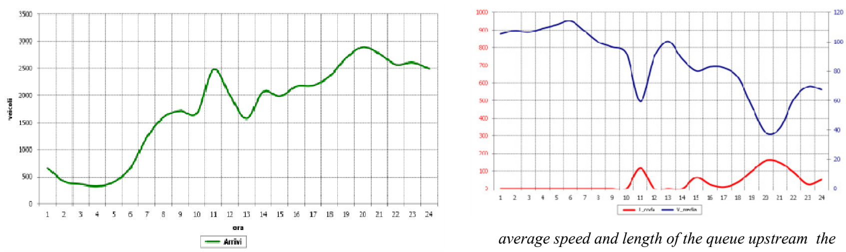
arrivals at the yard

average speed and length of the queue upstream the yard

Figure 13: Arrivals, average speeds and queues on the yard C1 (direction A).

the values of maximum length (300 m) between 7 and 10 pm. In the early hours of the morning, demand reduction restores the normal flow conditions.

Summer Scenario – Phase 6 – In Site C5 (Figure 14), effects of access ramps of the Palmanova node have been also considered. Queues occur in the morning in both scenarios peaking between 8 and 9 pm. Spillback does not seem to affect access ramps and flow conditions are less critical than the upstream yards. Along carriageway west, traffic queuing phenomena occur for a greater capacity restriction due to lane change in the westward current.(direction A).



average speed and length of the queue upstream the yard

arrivals at the yard

Figure 14: Arrivals, average speeds and queues on the site C5 (direction B).

Analyzing simulation results it is clear that, during peak hours in the average working day, speeds slow down with only rare occurrences of queuing. On the other hand, considering heavy traffic days (summer exodus, holidays, etc.), there are queue phenomena concentrated in peak hours with spillback of queues in upstream links. These phenomena are related both to a limited capacity, due to restrictions on cross section, and to demand peaks that cause a temporary over-saturation of the network.

The length of yards does not seem to influence flow conditions, while a large number of interruptions or restrictions of the roadway and discontinuities of the road section cause a deterioration of flow conditions. Therefore the approach minimizing the number of interruptions enlarging the extension of yards can be considered correct, subject to ensure a fast access to emergency vehicles.

It is always important to ensure during working two traffic lanes on both carriageways, as a possible reduction of the cross section to one lane would cause a decrease in the flow capacity to about 1500 vehicles/hour with consequences easily conceivable because of the volume of traffic simulated that exceeds this limit during several hours of the day.

5 Conclusions and perspectives

The main result of this paper concerns both the application of a mesoscopic dynamic network assignment model in a multimodal context and the specification and calibration of some cost functions adopted in this model. A comparison between experimental data and simulation results shows how the usage of appropriate simulation models can realistically reproduce user behavior. It was shown that these models can be used as support for both the design of yards (length and location) and to check the effectiveness of existing yards.

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