Investigating the capacity of a Metro line by means of a simulation model

A Ballis*, **K Liberis** and **T Moschovou**
Department of Transportation Planning and Engineering, National Technical University of Athens, Greece

Abstract: The expansion of the urban railway in the city of Athens with two new Metro lines required the upgrading of the existing infrastructure in order to comply with the new modern lines in terms of capacity and quality of service. This paper presents a simulation-based modelling tool that was developed and used for the purposes of the relevant capacity analysis. The model offers a graphical and interactive environment that facilitates the calculations, provides the necessary information and allows for sensitivity analysis under user-defined scenarios that enable the investigation of the behaviour of the system when longer than anticipated delays or abnormal situations occur. It also allows for the investigation of the synchronization of the trains that enter the system after the turn back procedures in the intermediate stations.

Keywords: urban railway line, capacity, simulation

NOTATION

A	train front surface
A_{mid}	dwell time of train m at station i in direction d
b	acceleration
$b_{\alpha\pi}$	deceleration due to grade resistance (rise gradient)
C_0	coefficient for the axles of the trailer
C_1	coefficient for the axles of moving cars
C_2	coefficient of air resistance for the car
C_3	coefficient of air resistance for the following cars
d	direction of train movement
g	acceleration due to gravity
$G_{\Pi EP}$	total weight of rotary acceleration of wheels and axles
G_Σ	total weight of the train
G_1	trailer weight
G_2	moving car weight
L	Metro railway line capacity
L_Σ	train capacity
n	number of stations
N	number of cars
R_{id}	waiting time of the trains in station i in direction d
s	longitudinal slope
t	headway between trains
T	duration of one round trip
T_{int}	length of time at the turn-out track of the turn back stations
T_{mid}	running time that train m spends in order to go from station i to the next station, in direction d
v_{m}	average velocity
v_1, V_1	starting velocity
v_2, V_2	ending velocity
w_{g}	specific track resistance
w_{R}	specific curve resistance
w_{S}	specific grade resistance
w_0	specific train resistance
W	train resistance
z_{b}	specific acceleration resistance
$\varDelta$	number of passing trains from a certain section
Δt	time period
ρ	allowance for rotary acceleration of wheels and axles
Σ	number of trains in operation

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* *Corresponding author: Department of Transportation Planning and Engineering, National Technical University of Athens, 5 Iroon Politechniou str., Zografou Campus, Athens 157 73, Greece.*

1 INTRODUCTION

Athens was declared the capital of Greece in 1834. At that time, the city had a population of 12 000 people.

Nowadays, Athens, including its suburbs, accommodates more than 3 million inhabitants, one-third of the country's population. Overcrowding in a city that has not been designed to support such numbers of people has led to tremendous traffic problems.

The demand for transport was mainly covered by a bus network, which, because of the city's heavy traffic congestion, could not operate efficiently, as well as one urban railway line (the so-called ISAP line), which connects the southern seaport of Athens (Piraeus port) with the city centre and its northern suburbs. The continuous expansion of the above areas led to their integration and converted the ISAP line to a Metropolitan Railway.

Because of economic, technical (poor ground conditions) and procedural problems (e.g. owing to the existence of archaeological findings during excavations), the creation of additional lines of the Metropolitan Railway (which for purposes of differentiation in the following will be referred to as the Metro) [**1**], began only during the last decade (the term Metro stands for an urban railway system with electrical traction that uses its own lines, and in the centre of the city is mostly underground).

During the initial planning of the new line, it was decided that the existing urban railway (ISAP) should form part of the future integrated network. The Metro management team required an increased level of service [**2**] on the ISAP line to mirror the capacity and quality of the proposed new line [**3**]. Thus, a study was initiated to determine the upgrade requirements.

The required upgrade concerns rolling stock upgrade (train configuration having six cars instead of the existing five), modifications to station infrastructure (platform lengthening, turn-out track lengthening and stairway widening), railway line improvements (in order to increase the maximum speed to 80 km/h), improved signalling systems, new power substations, etc.

2 EXISTING INFRASTRUCTURE AND ROLLING STOCK

The existing ISAP line consists of 27.5 km of double track (3.2 km of which is underground) linking 23 stations. The railway uses a ballasted trackform with timber sleepers. Forty per cent of the line is composed of horizontal curves of between 160 and 1000 m radius.

The signalling is based on the automatic block system, which consists of main signals and overlap sections, between the main signals and the insulating joint. The maximum length of the overlap sections is about 175 m, equal to the braking distance at a speed of 70 km/h. The distant signals [**4**] inform the train driver of the indication of the next main signal. Owing to the relatively long headways between trains (usually more than 3 min) and the relatively slow speed of the trains, the majority of block sections are defined by the starting signal of the previous station and the home signal of the next station. Intermediate sections exist whenever the distance between stations exceeds 2 km. Main signals are also used to control movements at turn-outs. The traffic is controlled from the Traffic Control Centre, which is located at a central station (Omonia station), as well as from other intermediate points. The train circulation pattern includes:

(a) the traffic between the two end terminals,
(b) additional traffic between two intermediate stations.

This configuration allows for an increased frequency of trains in the shared infrastructure. The term 'common block' is used hereinafter to refer to this part of the line. Figure 1 presents the common block (from Station Tavros to Station Patisia) for the ISAP line.

The connections between the existing ISAP line and the proposed new lines occur at Omonia and Attiki stations. Turn-out tracks and sidings (for the accommodation of trains when they are not circulated in the line) are located at various stations.

The ISAP fleet consists of trains of different eras (1958–2000) and consequently of miscellaneous technologies. A 750 V d.c. third rail traction power supply system is provided. The maximum train speed is 70 km/h.

3 INVESTIGATION OF RAILWAY LINE CAPACITY

Investigation of the various aspects of the single-line track capacity is an ongoing process [**5–9**]. The context of the current research study was the determination of the upgrade necessary for the ISAP line to be integrated with the proposed new lines of the network. Within this framework, the following two main issues were examined:

(a) design of the optimum length of block section,
(b) provision of supplementary rolling stock and determination of the train composition.

Three different scenarios of passenger flows were investigated: 16 000, 20 000 and 24 000 pphpd (peak passengers per hour per direction). The 16 000 pphpd scenario corresponded to the existing operating conditions. The scenario of 20 000 pphpd assumes a 3 min headway (with the train fully occupied), while the scenario of 24 000 pphpd assumes a headway of 2.5 min. Both the headway of 3 min and the headway of 2.5 min can be achieved after the upgrading of the signalling system. It must be mentioned that the above values concern the maximum capacity of the system which, in order to be achieved, requires additional input

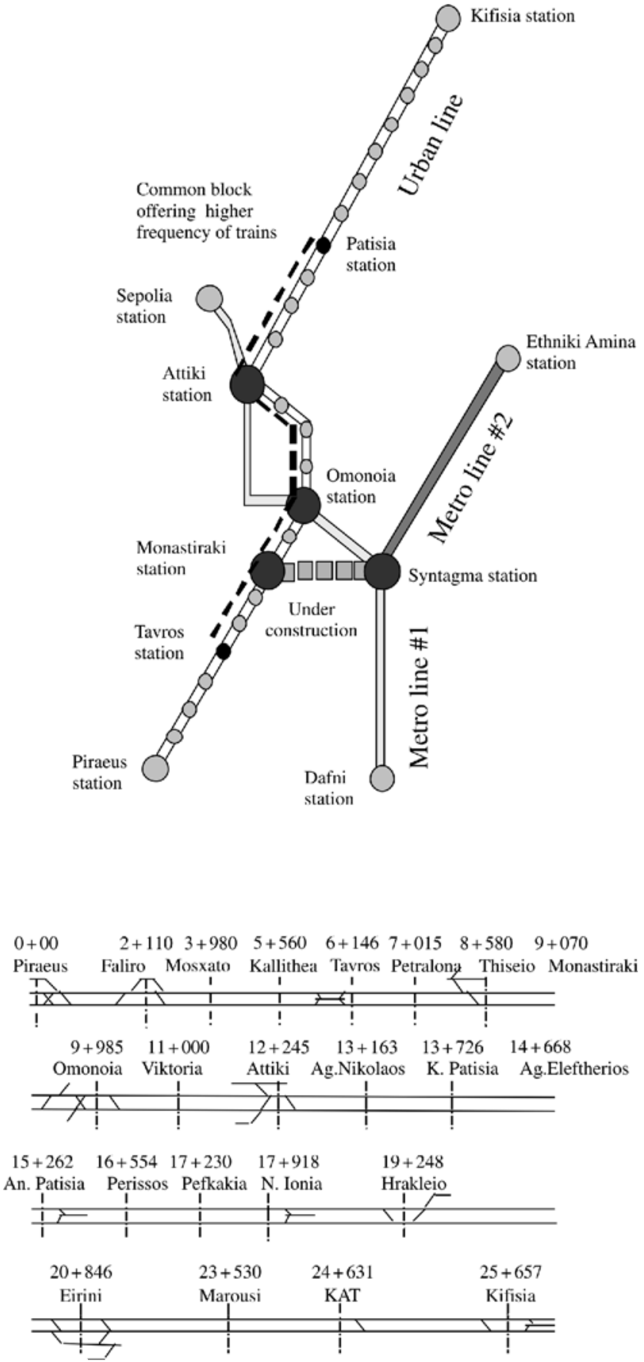


Fig. 1 Athens urban and Metro railway lines (upper part) and track layout of the urban railway line (lower part)

from other transport means. It is expected that during the Olympic Games, which will be held in Athens in 2004, this ultimate capacity will be utilized to satisfy the generated demand [**10**].

3.1 Railway line capacity calculation

The railway line capacity is defined by the number of transferred passengers per direction for a specific period (1 h is usually considered for urban railways) [**11**]. The formulae used for the calculation of the urban railway line capacity (expressed in peak passengers per hour per direction) is as follows:

$$L = \frac{L_\Sigma \Sigma}{T} \qquad \text{(pphpd)} \tag{1}$$

where

$L_\Sigma =$ train capacity (passengers per train); it is determined by the composition of the train (number of cars per train) as well as by the number of standing passengers per square metre plus the seated passengers per square metre per train

$\Sigma =$ number of trains in operation

$T =$ duration of one round trip

It should be noted that in equation (1) the units of L (pphpd) do not comply with the synthesis of the units of its components. This is due to the fact that train capacity is by default defined by the number of passengers transported in *one direction*, assuming that an equal number of passengers are transported in the other direction. Since the trip durations (go and return) can be uneven, the duration of a round trip, T, is taken into account in the calculation.

Instead of the variable Σ, either the headway between trains, t, or the number of passing trains from a certain section, Δ, can be used. These variables are related by the following formulae:

$$t = \frac{3600}{\Delta} \qquad \text{(s/passing train)} \tag{2}$$

$$\Sigma = \frac{T}{t} \qquad \text{(number of trains)} \tag{3}$$

The duration of a round trip, T, consists of the running time of the train from Piraeus to Kifisia station, T_1, and the running time from Kifisia to Piraeus station, T_2. Each of the above elements is calculated as follows:

$$T_\chi = \sum_{i=1}^{n-1} (T_{mid} + A_{mid}) + R_{id}, \qquad \{x = 1, 2\} \tag{4}$$

where

$n =$ number of stations

$T_{mid} =$ running time that train m spends in order to go from station i to the next station, in direction d; this time is defined by the technical specifications of the train (traction capacity, braking system), the track resistance (due to grades and curves) and the signalling system (in relation to the block sections); it also depends on other parameters such as the maximum allowable speed, the track and rolling stock conditions and driver behaviour

A_{mid} = dwell time of train m (since the number of car doors affects passenger boarding/alighting time) at station i in direction d

R_{id} = waiting time of the trains in station i in direction d; this time also includes the time for the turn-out procedures

D = direction of train movement

Based on the above formulae, the detailed analytical calculation of the cycle time can be performed manually. Nevertheless, the manual approach requires significant effort and time (mainly because of T_{mid} calculation) and therefore is not appropriate to the investigation of alternative designs as well as for the investigation of the behaviour of the system under user-defined scenarios.

For this reason, a simulation model was developed and used in the investigation of the railway line capacity when various design parameters alter [number and dynamic characteristics of the trains, timetable, number of stabling siding tracks, dwell time (for the boarding/alighting of passengers)], as well as for the analysis of the stochastic behaviour of the system.

3.2 Modelling approach

The above-mentioned simulation model is part of a design methodology consisting of four phases. The *first phase* includes the development of different scenarios concerning the configuration and the characteristics of the trains that will use the line. Within this phase, trains of five or six cars with maximum speed limits of 70 and 80 km/h and an accepted number of standees of 4 and 5 passenger/m^2 are considered.

The *second phase* includes the description of the stations as well as of the railway line. The stations are described by their position (starting and ending points of the platform), the number of siding tracks and the time required for the movement of trains from the siding tracks to the platform.

The railway line is described by its block sections, which are defined by the position of the insulating joints, the position of the stations as well as the position of the signals and the distant signals [**4**]. Each of the above positions is defined by its distance from a common reference point (the starting point of the platform of the first terminal in the line).

The *third phase* accommodates the calculation of the driving diagrams for each train type. The relevant calculations are performed by using a complementary program, and the results are automatically saved and then used again automatically by the simulation model. In this way, the replication of the time-consuming calculations is avoided, whereas the simulation procedures are executed faster.

3.3 Train driving diagrams

The calculation of the driving diagrams is based on the 'coasting' technique [**12**]. According to this technique, the train accelerates until the velocity reaches a specific value for which the acceleration resistance of the train, z_b, is minimized, and then continues under coasting, moving by kinetic energy. The calculation of the driving diagrams (see Fig. 2) was implemented by iterative calculations where the speed of the train was increased by a constant step. This step was selected to be equal to 0.0005 km/h so that the maximum train movement between successive steps was about 1 m. The formulae used [**13**] are as follows:

$$\Delta l = k\,\frac{v_2^2 - v_1^2}{z_b} \qquad \text{(m)} \tag{5}$$

$$\Delta t = \frac{\Delta l}{v_m} = \frac{7.2\ \Delta l}{V_1 + V_2} \qquad \text{(s)} \tag{6}$$

where

$$v_m = \frac{v_1 + v_2}{2}, \qquad v_2 = v_1 + bt$$

$$b = \frac{9.81}{1000\rho} z_b \qquad \text{and} \qquad k = \frac{1000\rho}{9.81 \times 26} \tag{7}$$

$$\rho = \frac{G_\Sigma + G_{\Pi EP}}{G_\Sigma} \tag{8}$$

where

v_1 = starting velocity (m/s)

v_2 = ending velocity (m/s)

V_1 = starting velocity (km/h)

V_2 = ending velocity (km/h)

Δt = time period (s)

v_m = average velocity (m/s)

b = acceleration (m/s^2)

z_b = specific acceleration resistance (‰)

ρ = allowance for rotary acceleration of wheels and axles

G_Σ = total weight of the train (t)

$G_{\Pi EP}$ = total weight of rotary acceleration of wheels and axles (t)

The specific acceleration resistance is calculated according to Fiedler [**14**], where the special resistances from the horizontal railway curves are calculated from Röckl

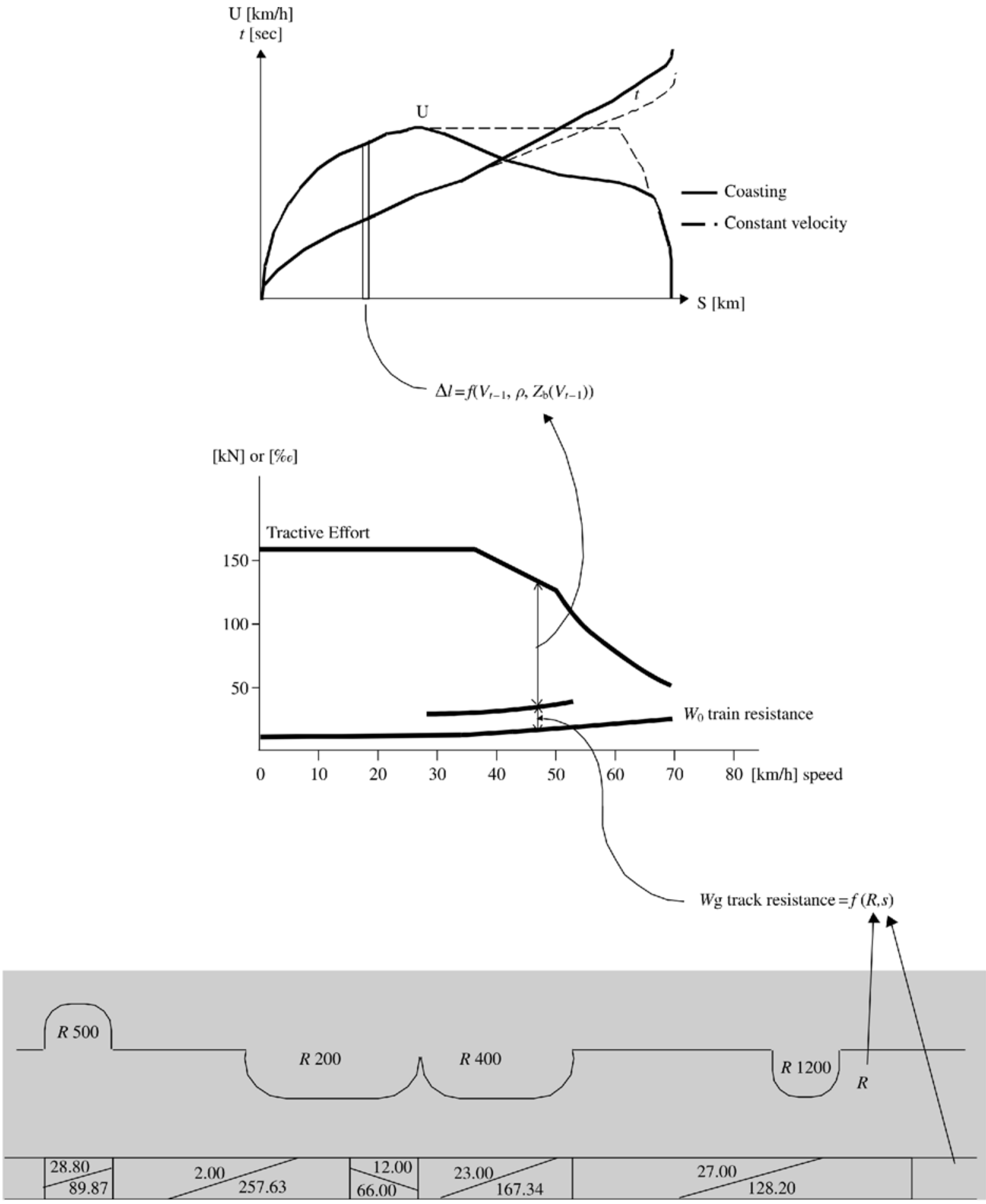


Fig. 2 Driving diagram calculation

types as

$$w_R = \frac{650}{R - 55} \qquad (\%) \tag{9}$$

where radius $R \geqslant 300$ m and

$$w_R = \frac{500}{R - 30} \qquad (\%) \tag{10}$$

where radius $R < 300$ m. Therefore, the specific track resistance, w_g, is equal to

$$w_g = w_R \pm w_S \ (\%) \tag{11}$$

where

w_R = specific curve resistance (%)
w_S = specific grade resistance (%)

(+ in the case of a rising gradient, − in the case of a falling gradient).

The deceleration values, $b_{\alpha\pi}$, of the train while moving under 'coasting' are approximately calculated by the following formula:

$$b_{\alpha\pi} = -\frac{g}{\rho}\frac{(w_0 + s)}{1000} \qquad (\mathrm{m/s^2}) \tag{12}$$

where

$b_{\alpha\pi}$ = deceleration due to grade resistance (rising gradient)

g = acceleration due to gravity (9.81 m/s^2)

s = longitudinal slope

The calculation of the specific train resistance, w_0, is performed by the following formula

$$w_0 = \left(\frac{W}{G_\Sigma}\right) \times 1000 \qquad (\%) \tag{13}$$

where W is the train resistance (kN), which is calculated from the following formula:

$$W = \left[C_0 G_1 + (C_0 + C_1)G_2 + (C_2 + C_3 N) \times 0.5\frac{A(V+15)^2}{100}\right] \times 9.81 \times 1000 \tag{14}$$

where

G_1 = trailer weight

G_2 = moving car weight

N = number of cars

A = train front surface

and C_0, C_1, C_2 and C_3 are coefficients for the axles of the trailer and moving cars and coefficients of air resistance for the car and for the following cars respectively. The values of the above coefficients are given by the manufacturers of the relevant rolling stock [**3**].

Finally, taking into account the slopes of the railway line under investigation, two deceleration values were estimated in the calculation of the associated braking distances: 1.1 m/s^2 for the rise gradients and 1.0 m/s^2 for the fall gradients. Braking is required while the train is entering the stations as well as for speed reduction to comply with a restrictive signal aspect.

3.4 Simulation of train operations—timetable formulation

The *fourth phase* of the methodology concerns simulation of the train operations. A simulation model, called MetSim, was developed purposefully taking into account the procedures of a double line with a common block, operating under a fixed timetable. The model simulates the train circulation in the line by accelerating, coasting with momentum and decelerating to enter into the stations (following the above-mentioned train driving diagrams) or decelerating to comply with the red signal indications [**3**].

The model enables graphical representation of simulated system operations on the computer screen (on-screen animation graphics, see Fig. 3), in combination with an arithmetic output. In addition, the model offers an interactive environment that enables the user to intervene in the simulation run. This interactive environment provides an understanding of the behaviour of the simulated system by allowing the user to intervene in the following actions/commands:

1. Immobilization and reactivation of specific trains. The selected train is immobilized and remains on the railway line, obstructing the operation of the residual trains. This action can be used to simulate train breakdowns, abnormally long delays at the stations, etc. It can also be used for the introduction of purposefully scheduled train waiting times that allow for train synchronization to the timetable (see below).
2. Interrupt the circulation of a train in order to move it in a siding yard. The corresponding command is activated when the train is already in a station and is not obstructing the operation of the residual trains. The number of remaining available siding tracks of the specific station alters automatically. This command is designed to modify the timetable during the day.
3. Speed-up or slow-down of the simulation clock at any time, so that users can observe the system performance on screen at their own convenience.
4. Screen view of additional information concerning the headways between consecutive train departures in a selected station. This information can be used for the calculation of the train reverse procedures (see below).

The programme simulates the typical train operations (acceleration, braking, dwelling for passenger boarding/alighting) as well as the turn-out procedures at the terminal stations. Each simulated train is described by the following parameters:

1. Itinerary. In the current case study, the trains are assigned to two itineraries, one end to end (Piraeus–Kifisia) and the other between two intermediate stations (Tavros–Patisia). Hereafter, the terms 'end-to-end' itinerary and 'intermediate' itinerary will refer (respectively) to these itineraries.
2. Time of initial departure (hours, minutes and seconds).
3. Starting station and direction of the initial trip.
4. Duration of the round trip.
5. Length of time at the turn-out track of the turn back stations. Since this time duration, T_{int}, is not known

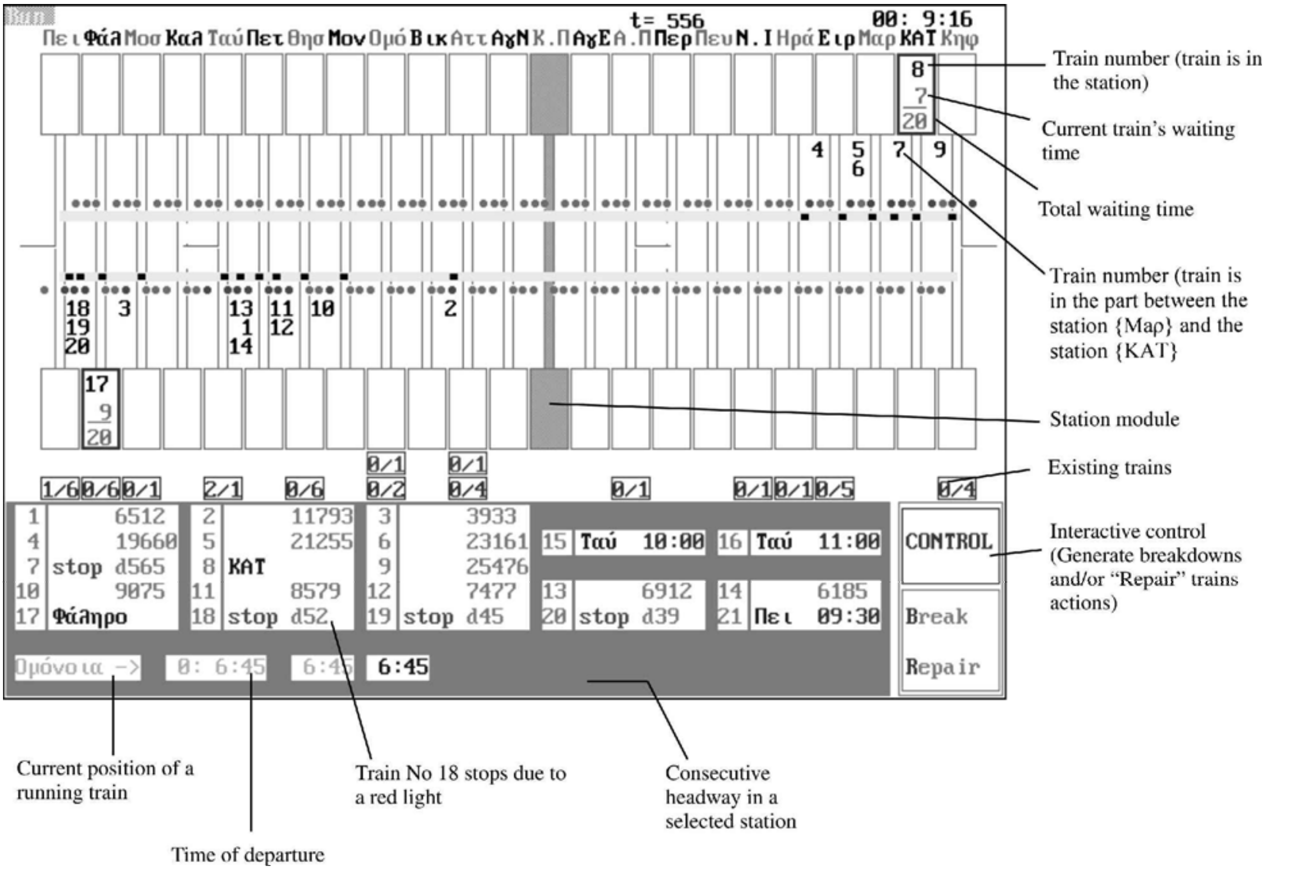


Fig. 3 Graphical output of the simulation model

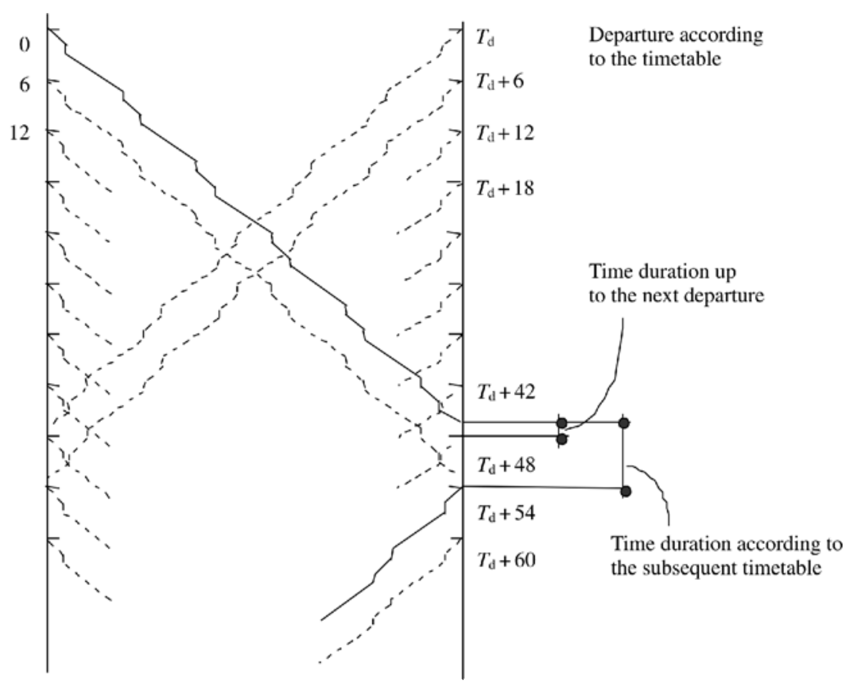


Fig. 4 First step towards the formulation of the timetable

in advance, an initial value is temporarily given which is then modified in order to allow the synchronization of the two itineraries.

The formulation of the timetable requires a systematic (sometimes based on trial and error) approach that consists of the following two steps.

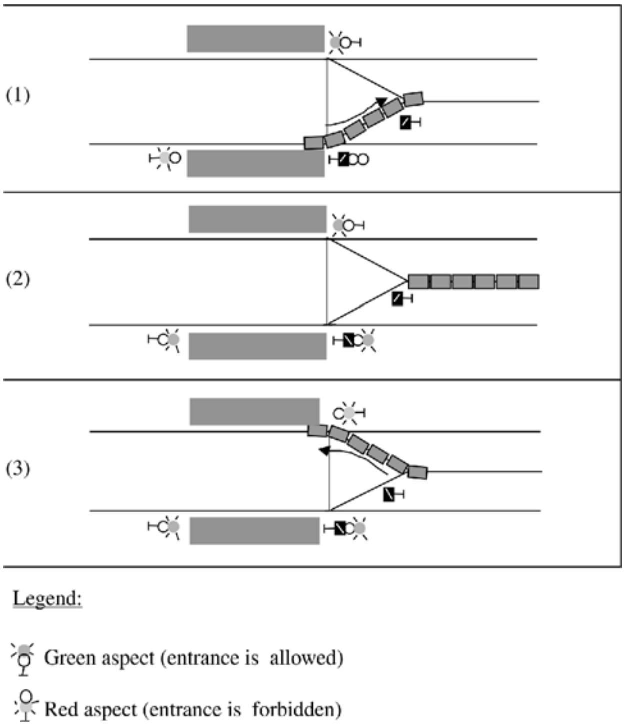


Fig. 5 Turn back procedure and associated signal aspects

In the *first step*, the trains associated with the 'end-to-end' itinerary are departing, scheduled under constant headways (that therefore define the slots of the timetable). Figure 4 presents graphically two groups of trains departing under a headway of 6 min. The first group starts from station A at time 0. The second group starts from station B at time T_d. The time T_d is initially set at zero and, if necessary, is modified later on. When the first departing train from station A arrives at station B, it undertakes the next or the subsequent slot. More specifically, if the remaining time duration between the moment of the train arrival and the moment of the next departure is sufficient for the boarding of the passengers and the driver's short break, then the train undertakes this slot. Otherwise, the train is assigned to the following slot of the timetable.

In the *second step*, the trains associated with the 'intermediate' itinerary are departing, scheduled under constant headways arranged just between the headways of the 'end-to-end' itineraries. If, for example, 00:40, 00:46 and 00:52 are three successive departures of trains assigned to the 'end-to-end' itinerary, the 'intermediate' itinerary trains must depart at 00:43 and then 00:49. In this way, the station will be served by trains every 3 min.

The critical point for the above timetable formulation is the synchronization of the train after the turn back procedures in the terminals that define the 'intermediate' itinerary. Figure 5 presents the turn back procedures in the turn-out track of a station:

1. The train is entering in the turn-out track (upper part of Fig. 5). This action requires the track not to be occupied by another train. During this step, no other train can enter the station platform.
2. The train has fully entered in the turn-out track (middle part of Fig. 5). The station platform is now free to accommodate the following train. The driver stops the train and moves to the cab at the other end of the train. In order to enter the station platform (in the reverse direction), the train is required to wait for a green signal indicating that the platform is not occupied by another train.
3. The expected signal aspect becomes green (and the signal aspect prior to the station is switched to red). The train enters the platform (lower part of Fig. 5) and stops to allow the boarding of passengers.

The timing of the turn back procedure must take into account the timing of the associated trains in operation. Figure 6 shows a characteristic situation where train A cannot be placed between train B and C (having $3+3=6$ min headway) as its exit from the turn-out track will force train B to stop. The stopping of trains outside the stations, particularly when this occurs inside a tunnel, is undesirable, as passengers may feel anxiety. It is probably preferable that train A waits in the turn-out track until the next available slot. Unfortunately, the waiting time of train A at the turn-out track is subject to limitations owing to the approaching train D, which will also have to enter the turn-out track (only one train can be accommodated).

Therefore, the formulation of an effective timetable will require some iterations where various T_d and T_{int} values can be tested.

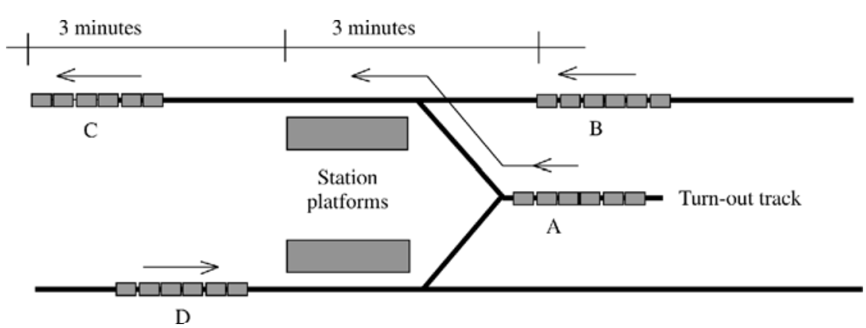


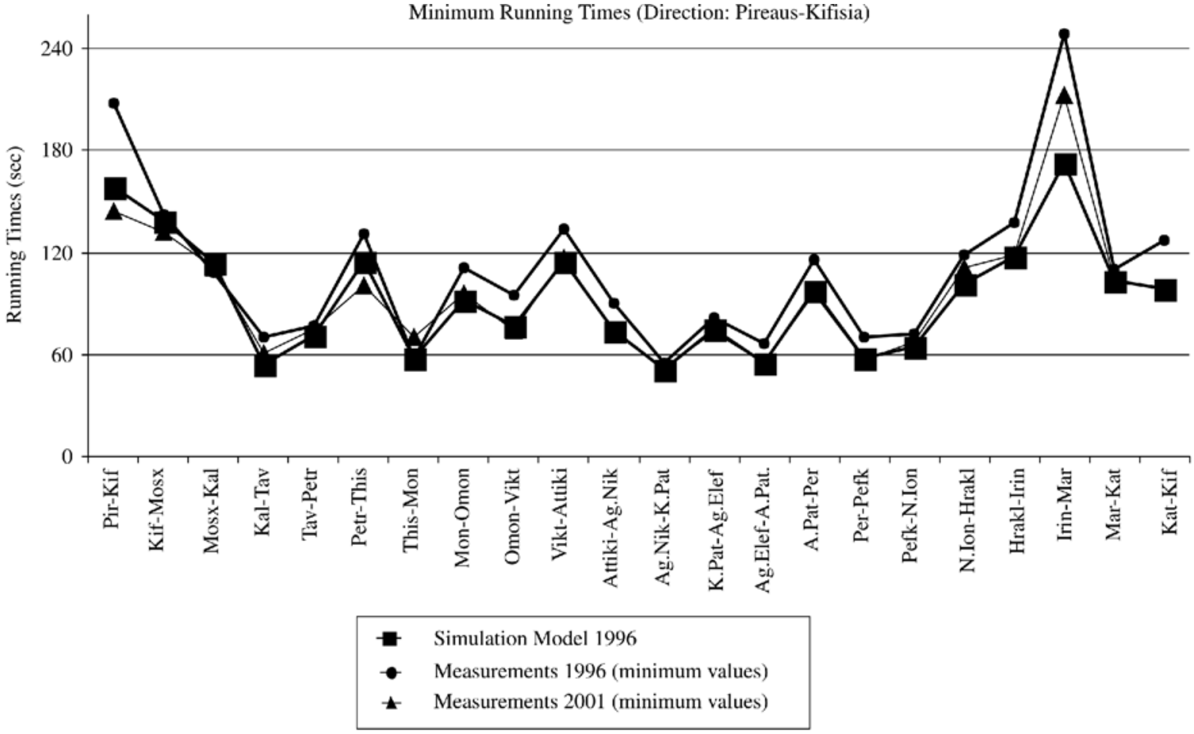
Fig. 6 Typical problem of synchronizing the trains in the turn-out tracks

Table 1 Measured and simulated running times on the ISAP line (years 1996 and 2001)

Piraeus–Kifisia		Measurement under typical conditions—1996 (average values) (s)	Measurement under optimum conditions —1996 (s)	Measurement under typical conditions —2001 (average values) (s)	Results of simulation model (s)
Piraeus	Faliro	230	213	201	158
Faliro	Mosxato	151	135	143	139
Mosxato	Kallithea	120	110	115	114
Kallithea	Tavros	73	66	71	54
Tavros	Petralona	85	80	84	71
Petralona	Thisio	136	126	138	115
Thisio	Monastiraki	65	57	67	58
Monastiraki	Omonoia	114	101	106	92
Omonoia	Viktoria	96	85	91	77
Viktoria	Attiki	139	114	127	115
Attiki	AG. Nikolaos	93	80	88	74
AG. Nikolaos	K. Patisia	64	56	65	51
K. Patisia	AG. Eleftherios	92	81	86	75
AG. Eleftherios	A. Patisia	72	63	71	55
A. Patisia	Perissos	118	108	116	98
Perissos	Pefkakia	73	61	68	58
Pefkakia	N. Ionia	78	70	77	65
N. Ionia	Hrakleio	126	115	130	102
Hrakleio	Irini	144	152	145	118
Irini	Marousi	254	193	259	173
Marousi	Kat	123	103	108	103
Kat	Kifisa	139	105	143	99
Total time (min)		43	38	42	34
Time differences from simulation results (min)		9	4	8	
Time differences (%)		27	11	23	

Kifisia–Piraeus		Measurement under typical conditions—1996 (average values) (s)	Measurement under optimum conditions —1996 (s)	Measurement under typical conditions —2001 (average values) (s)	Results of simulation model (s)
Kifisia	Kat	122	100	116	100
Kat	Marousi	124	107	108	94
Marousi	Irini	237	203	271	154
Irini	Hrakleio	145	112	138	102
Hrakleio	N. Ionia	133	113	128	91
N. Ionia	Pefkakia	83	69	72	62
Pefkakia	Perissos	68	61	65	55
Perissos	Patisia	117	107	117	85
Patisia	EG. Eleftherios	68	60	67	53
AG. Eleftherios	K. Patisia	88	76	84	69
K. Patisi	AG. Nikolaos	62	57	61	50
AG. Nikolaos	Attiki	126	78	89	68
Attiki	Viktoria	140	120	127	116
Viktoria	Omonoia	115	88	97	73
Omonoia	Monastiraki	116	101	101	91
Monastiraki	Thisio	63	59	62	58
Thisio	Petralona	152	126	134	103
Petralona	Tavros	99	79	88	65
Tavros	Kallithea	67	61	68	52
Kallithea	Mosxato	124	116	111	101
Mosxato	Faliro	178	160	156	131
Faliro	Piraeus	235	167	253	177
Total time (min)		44	37	42	33
Time differences from simulation results (min)		11	4	9	
Time differences (%)		34	12	27	

The MetSim simulation model provides an efficient tool that facilitates the calculations, provides the necessary information (e.g. actual train departure and headways at the stations) and allows for sensitivity analysis under user-defined scenarios. Furthermore, the model collects and provides statistical information (number of passing trains per station and hour, travel distance for each train, etc.). These results are displayed



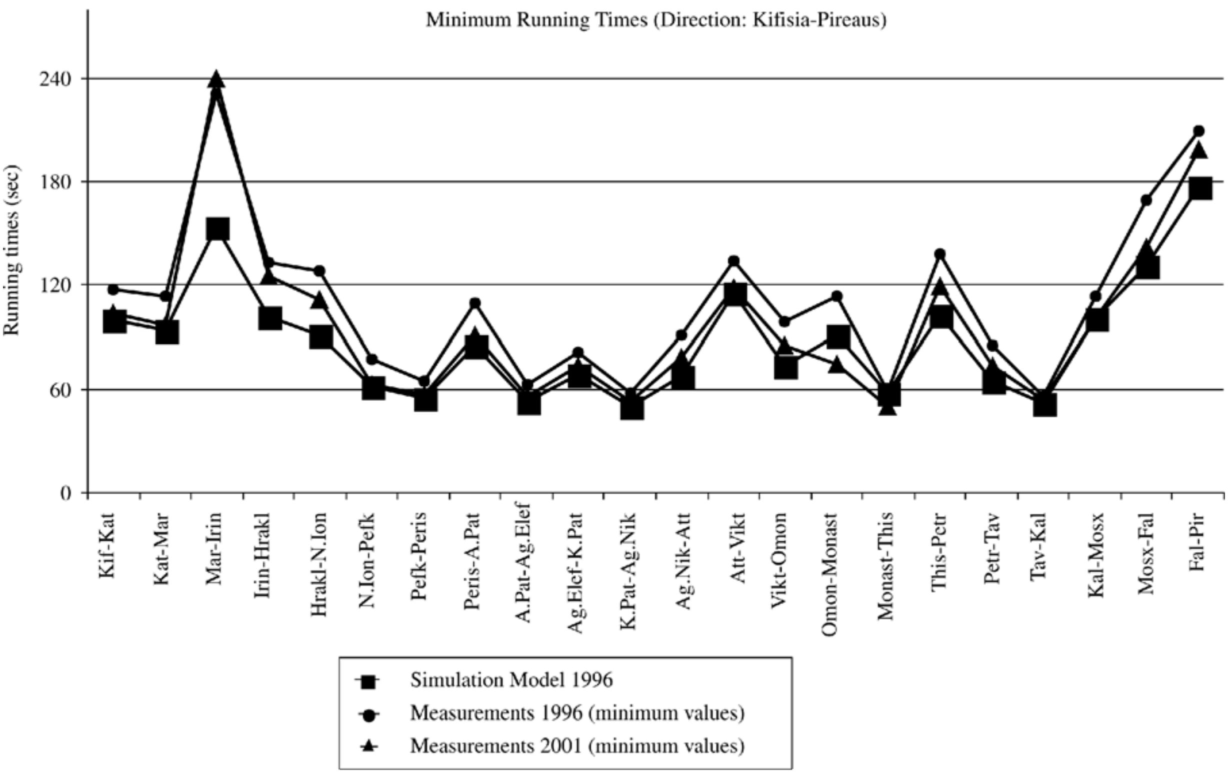


Fig. 7 Minimum running time diagrams in various sections of the railway line

in table format that can be printed out or sent to a file for further elaboration. Nevertheless, the model cannot be used for on-line timetable rescheduling which requires a different approach [**15**].

3.5 Model validation

The model validation was focused on the train cycle time as well as on the driving times of the trains between

Table 2 Minimum running times in ISAP line (years 1996 and 2001)

Piraeus–Kifisia		Simulation model—1996 (s)	Measurements—1996 (minimum values) (s)	Measurements—2001 (minimum values) (s)
Piraeus	Faliro	158	208	144
Faliro	Mosxato	139	142	132
Mosxato	Kallithea	114	108	111
Kallithea	Tavros	54	70	61
Tavros	Petralona	71	77	75
Petralona	Thisio	115	131	101
Thisio	Monastiraki	58	58	70
Monastiraki	Omonoia	92	111	96
Omonoia	Viktoria	77	95	74
Viktoria	Attiki	115	134	117
Attiki	Ag. Nikolaos	74	90	73
Ag. Nikolaos	K. Patisia	51	55	52
K. Patisia	Ag. Eleftherios	75	82	73
Ag. Eleftherios	A. Patisia	55	66	55
A. Patisia	Perissos	98	116	96
Perissos	Pefkakia	58	70	57
Pefkakia	N. Ionia	65	72	67
N. Ionia	Hrakleio	102	119	111
Hrakleio	Irini	118	138	119
Irini	Marousi	173	249	213
Marousi	KAT	103	110	104
KAT	Kifisia	99	127	98
Kifisia–Piraeus		**Simulation model—1996 (s)**	**Measurements—1996 (minimum values) (s)**	**Measurements—2001 (minimum values) (s)**
Kifisia	KAT	100	117	104
KAT	Marousi	94	114	97
Marousi	Irini	154	231	240
Irini	Hrakleio	102	133	125
Hrakleio	N. Ionia	91	128	112
N. Ionia	Pefkakia	62	77	63
Pefkakia	Perissos	55	65	57
Perissos	A. Patisia	85	110	91
A. Patisia	Ag. Eleftherios	53	63	56
Ag. Eleftherios	K. Patisia	69	81	73
K. Patisia	Ag. Nikolaos	50	58	53
Ag. Nikolaos	Attiki	68	91	78
Attiki	Viktoria	116	134	118
Viktoria	Omonoia	73	99	85
Omonoia	Monastiraki	91	114	74
Monastiraki	Thisio	58	59	50
Thisio	Petralona	103	138	119
Petralona	Tavros	65	85	73
Tavros	Kallithea	52	56	54
Kallithea	Mosxato	101	114	101
Mosxato	Faliro	131	169	142
Faliro	Piraeus	177	210	199

all successive stations. It was performed by measurements that took place before and after the first upgrade of the ISAP railway line and rolling stock (1996 and 2001 respectively). The measurements of 1996 (see Table 1) were obtained in two ways:

(a) under 'typical conditions' of operation where the trains were driven by their everyday drivers;
(b) under 'optimum conditions' where an expert (an ISAP director) drove the train at the bound of the performance envelop while observing all speed restrictions.

The comparison of the model output with the above measurements revealed relatively small differences from the real system response operating at 'optimum' conditions (10–15 per cent deviation) but high differences (25–35 per cent deviation) at 'typical conditions'. In the latter case, the deviation can be explained by the fact that the drivers overestimate the weaknesses of the railway line, mainly horizontal defects and track settlements (see reference **[16]** for an outline of the track settlement issue) and therefore hesitate to take advantage of the full capabilities of their trains. It should be mentioned that such behaviour is on the side of safety.

The reduced system performance reflects the indirect cost due to inferior track condition which can be offset by proper alignment of the line. The recent (2001) measurements collected during 'typical conditions' indicated a better (but still not satisfactory) match between simulation and actual data. Moreover, it is worth mentioning that the minimum actual times observed between the successive stations are very close to those predicted by the model (see Fig. 7 and Table 2). This is an important indication that the predicted times from the model can be achieved. It is expected that, when the upgrade of the ISAP line is complete, the deviations between the actual and the simulated data will be significantly reduced.

4 RESULTS

The investigation of the capacity of a single line requires significant computation, while the synchronization of the trains that enter the system after the turn back procedures in the intermediate stations requires additional effort. This paper presents a simulation-based modelling tool that, through a graphical and interactive environment, facilitates the calculations, provides the necessary information and allows for sensitivity analysis under user-defined scenarios that enable the investigation of the behaviour of the system when longer than anticipated delays or abnormal situations occur.

The model was developed and used within the framework of a research study investigating the enhancement of the capacity of the existing urban railway line in the city of Athens in order to comply with the new modern Metro lines. The validation of the model revealed that the observed minimum actual times between stations are very close to those predicted by the model. In particular, the deviations between the model and actual timings were found to be very limited when the train was driven too close to its recommended speed limits. The deviation between the associated average values observed at normal conditions and the model predictions can be explained by the existence of track defects and settlements that affect the average driver behaviour, causing the drivers to hesitate to take advantage of the full performance capabilities of trains.

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