Transactions on the Built Environment vol 6, © 1994 WIT Press, www.witpress.com, ISSN 1743-3509

Invited Paper

Models and tools for simulation and analysis of metrorail transit systems

R. Minciardi[a], S. Savio[b] & G. Sciutto[b]
[a] *Dipartimento di Informatica, Sistemistica e Telematica, Università degli Studi di Genova, Via all'Opera Pia, 13-16145 Genova, Italy*
[b] *Dipartimento di Ingegneria Elettrica, Università degli Studi di Genova, Via all'Opera Pia, 11a-16145 Genova, Italy*

Abstract

The traffic and electrical analysis of a metrorail transit system may be successfully performed only by means of simulation tools; an analytical approach is in fact possible only introducing heavy simplifications due to the complexity and the mutual interaction of the phenomena, often non-linear, which determine the behaviour of the system. This is particularly true when the problems of determining a suitable schedule for the train traffic and of sizing the electrical network of an underground railway system are faced. In this paper two different simulators, that can be used to analyze the feasibility and the quality of the solutions to the above two problems, are presented. The first one is a stochastic event-driven simulator which allows the performance analysis of a given schedule and is able to represent the system kinematics and the safety constraints; the second one is an integrated system simulator which allows the electrical analysis of the network during the movement of the trains along the track.

1 Introduction

Analysis and management of metrorail transit systems are a subject of growing interest, from different methodological viewpoints [2,5,6,7,8,9,10,11]. The analysis of such systems is generally devoted to the evaluation of their performances, with respect to the different choices operated during the three different system design phases: in the first *high-level* phase the design guidelines of the system are outlined on the basis of urbanistic, social and economic considerations; in the second phase the traffic management procedures and the macrodesign of the subsystems are performed; in the third one the detailed design of all the components is carried on.

The above mentioned three different phases define a three-levels hierarchy, where each level is dealt with by neglecting the lower ones and taking as constraints the solutions defined by the upper ones.

The problems approached in this paper refer to the second design phase: in particular, the authors are interested in developing a procedure to determine the schedule of the trains over the whole track and over a certain time horizon, in testing the on-line control policies which have the function to react to stochastic disturbances, in analyzing the electrical behaviour of the whole transit system, which might represent a constraint for the above two points. In this connection, the development and use of effective simulation tools are a fundamental step for the achievement of acceptable solutions.

In fact, the determination of the overall train schedule can reasonably take place by means of a specific software tool, not described in this paper and in the following called the scheduler, based on the solution of a mathematical programming problem, which can be stated with reference to a set of specified objectives and, more important, using a simplified system model with respect to the real system.

The simplification is necessary since it is not possible to take into account the whole system complexity in developing the train schedule, especially as regards train dynamic real performances and electrical power network behaviour; as a consequence, a schedule determined by use of the above mentioned scheduler has to be validated, both for its feasibility and quality, by use of simulation tools based on models which are closer to the real system.

Moreover, simulation tests have to be performed also with the purpose of analyzing the application of on-line control policies for the movement of the trains. Such policies have the function of converting into control actions the deliveries of the schedule, taking into account the specific system status observed on-line.

For such reasons, a simulation tool, in the following called the traffic simulator, has to be applied to test the performances of the schedule (and then of the scheduler) and of the control policies. The traffic simulator has to evaluate such performances essentially as regards the kinematic aspets of the problem, and therefore it can be simply based on a kinematic model of the system, neglecting all dynamic, energy and electrical aspects. In this way a considerable simplification is achieved, especially because the model and the traffic simulator become strictly event-driven and therefore, in the realization of the traffic simulator, one has not to deal with the typical continuous simulation issues, such as, for instance, differential equations integration.

More specifically, the considered kinematic model is made up of two different phisical entities: the trains and the transportation network. The network is composed by tracks, stations, and deposits, and, in turn, tracks are subdivided in track circuits (TCs), each of which is characterized by length, slope, bending and maximum speed, acceleration and jerk. The track circuits are used to impose physical safety constraints for the train runs, since the presence of a train on one of them prevents the entrance of other trains. Besides, it imposes speed limits on the neighbouring track circuits.

Finally, to test the validity of the analysis carried out by means of such a discrete-event simulator, as regards the practical applicability of the schedule and of the control policies, also the energy and electrical aspects have to be taken into account, in order to obtain a solution which has a full meaning from all points of wiew.

In other words, once tested the feasibility and the quality of the schedule and of the policies, it is then necessary to analyze the whole system from an electrical point of view. The traffic management strategies determine the train running curve but the mechanical performance of the vehicles are function of pantograph voltage status: for this reason the electrical analysis of the whole network during the movement of the vehicles is mandatory, in order to evaluate if the optimal schedule is really attainable.

As previously mentioned, such an electrical analysis cannot be correctly performed in an analytical way due to the presence of non-linear events and to the complexity and interactions of all the phenomena: the electrical analysis of the system is in fact related to the solution of a load-flow problem where the trains power, absorbed during tractioning or delivered during braking (if regeneration is allowed), do not represent known terms, for they are function of the pantograph voltage. Therefore to solve analytically the problem heavy and convervative simplifications may be introduced, which may bring to wrong results or oversizing.

For this reason, it is mandatory the use of another system simulator, in the following called electrical simulator, able to analyze, in an integrated way, the electrical behaviour of the traction network during the movement of the trains, both in normal and fault conditions [1,3,4]. On the basis of a macromodelling of the track, of the Electrical Substations (ESSs), of the onboard drives and of the signalling system, the code gives, at each integration step, information about the electrical status of the system, solving, after a linearization procedure, an equation system of the type $A\,\underline{x} = \underline{u}$, where $\underline{x}$ represents the unknown vector (train pantograph voltages), A is a constant matrix (function of trains position) and $\underline{u}$ is the known vector (Electrical Substation no-load output voltages).

In the following two sections, the traffic and electrical simulators, both developed at the University of Genova, and the relevant models will be shortly described.

2 The traffic simulator

This section is devoted to the presentation of the main characteristics of the simulation tool for the traffic management and control, which has been mentioned in the introduction. The development of such a tool has been based on the choice of a model which has been defined having the objective of representing in detail all kinematic and topological issues present in an underground railway network, but purposely neglecting all modelling aspects related to the dynamics of the moving vehicles, and to the energy issues of the electrical system. A pure discrete-event model has been adopted for the development of the considered simulator. This means that the system evolution is described in terms of discrete events, such as the arrival of the head of the train to the beginning of a track circuit, the exit of the tail of the train from a track circuit, the arrival of the train to a station, and so on.

Of course, the adopted model has to take into account the safety constraints that are relevant both to a-priori upper bounds for the speed, the acceleration, and the jerk, and to the bounds imposed by the signalling system. Further constraints are relevant to minimum dwell times of the trains at the stations.

The simulator that is described in this section can have essentially two functions. The first one is that of analyzing the performance of a given network, from a general viewpoint. The second one is that of analyzing the feasibility and the quality of a given schedule and the performances of the on-line control policies. The schedule is actually an input to the simulator and has to be found separately (off-line) by means of a dedicated tool. As previosly mentioned, the development of the schedule is generally carried out referring to a model simplified with respect to the model considered in the simulator, and thus any schedule has to be validated on the simulator.

A train schedule is made up of a set of values for the off-line decisional variables which describe the behaviour of each train in the system. Such variables consist essentially in the leaving times from the terminal stations, the minimum dwell times at the stations, and the times in which trains enter or leave track circuits.

Such time instants are the inputs to the traffic simulator, which tries to implement the tentative schedule taking into account the system dynamic, and indicates the adjustments to bring to the schedule proposed.

The traffic simulator is based on a model which allows the underground railway to have a general topology, in which one can distinguish the three following kinds of different elements: track circuits, which are components oriented according to the direction of the train movement, i.e., monodirectional elements; terminal stations, where trains can reverse; deposits, where trains can be 'parked' for an indefinite time.

As already pointed out, the model considered is purely kinematic; in this model, the influence that the movement of a train has on the following trains is carefully modelled. Such an influence is represented by imposing speed limitations on the movement of the following trains on the line. First of all, each track circuit can host only a train at the same time. Moreover, five different speed codes are assigned, by the signalling system, to the five track circuits that are upstream with respect to the last track circuit occupied by the train. Each code represents an upper bound for the speed of the trains following the one that has determined the code imposition. The signalling and control system are assumed to communicate with trains at any time.

In addition, the physical topology of the line is taken into account by defining for each track circuit the maximum values of speed, acceleration and jerk, in both the regular and anomalous conditions of the line.

The traffic simulator is totally based on a discrete-event model. The structure of such model has been presented in detail in [12]. Some of the classes of events that may take place during the simualtion, and that give raise to the state transitions are:

- arrival of the head of a train at the beginning of a track circuit;
- arrival of the tail of a train at the beginning of a track circuit;
- closing of train doors;
- arrival of a train at a station;
- end of a train reverse;
- end of the entrance of a train in a deposit;
- end of the stay of a train in a deposit;
- end of simulation.

In addition to such classes of events, further event types (simulation initialization, end of simulation, line degradation, etc.) are taken into account. In connection with the occurrence of an event of a certain class, the simulator has to schedule future events. For this purpose, it is essential that the simulator knows the train schedule and makes use of suitable control policies. Both the schedule and the control policies can thus conceptually be considered as "inputs" to the simulator.

Once a given schedule has been "adjusted" by using the traffic simulator, in its "deterministic version", it can be interesting to evaluate the quality (for instance, the robustness) of the resulting schedule, by taking into account the stochastic features of the considered system. For this reason, the simulator is provided with a wide range of possibilities to model stochastic phenomena. Stochastic disturbances may be point-disturbances (such as, for instance, a line breakdown), or systematic disturbances (such as, for example, the perturbations in the dwell times at the stations, or in the times needed to cover certain distances). Finally, during a simulation run, a wide set of statistics are automatically collected (such as, for instance, the aggregated train delay).

3 The electrical simulator

In the present paragraph a software tool for the analysis of the electrical behaviour of a DC fed metrorail transit system is presented. As well known, the mechanical performance of an electrical onboard drive is a function of the pantograph voltage value: for this reason the proposed simulator performs an integrated mechanical and electrical analysis.

Only from a conceptual point of view, the simulator may be divided in two main parts: the first one performs traffic management and solves the trains movement equations while the second one, in this paragraph described with the relevant models, is devoted to the resolution of the electrical network.

Transactions on the Built Environment vol 6, © 1994 WIT Press, www.witpress.com, ISSN 1743-3509

The problem, in its simplest formulation as it will be shown in the following, is to solve a DC electric circuit, fed by voltage ideal generators (Electrical Substation no-load voltages) and made up of resistive linear components (ESS equivalent resistances, contact wires and rails) and non-linear components (trains), whose absorbed or delivered power is a function of pantograph voltage.

The problem may be therefore catalogued as a DC load flow problem and the solution method has to be based on a iterative procedure for the linearization of the trains electrical equations.

At each integration step, as shown in Figure 1, the solution algorithm, based on node analysis, defines a trial set of pantograph voltages $\underline{V}_t$ to calculate voltage dependent train powers, linearizes train equations, and solves a linear equations system, whose unknown variables are train pantograph voltages: the new set of values of the unknowns $\underline{V}_n$ is compared with the trial one and, if the difference is greater than a predefined tolerance *eps*, the last set of values $\underline{V}_n$ is utilized as trial set $\underline{V}_t$ and the above procedure is repeated till the convergence process is over.

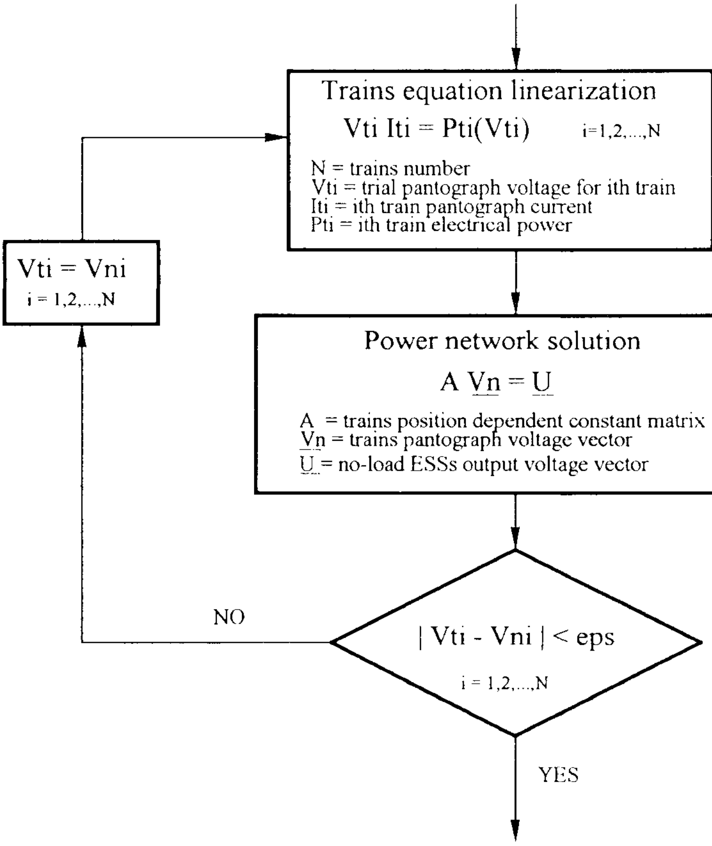

Figure 1: Power network solution algorithm.

At the end of the convergence process all the electrical quantities of the system are known; it is then possible to evaluate the power delivered by the Electrical Substations (ESSs) and to update correctly the mechanical status of all the trains, now being known the mechanical power available.

The load-flow solution guarantees the consistency of mechanical and electrical results, being the convergence process based on the control of train pantograph voltages.

As far as modelling concerns, the authors present the models of the two subsystems whose behaviour and mutual interaction influence the electrical status of the system: Electrical Substations and onboard drives.

The electrical scheme usually utilized in metrorail transit system for the Electrical Substations which fed the DC contact wires, is made up of a three phase transformer, with two secondary windings, and a 12-pulse diode rectifier.

The DC output voltage static characteristic of a 12-pulse rectifier for railway applications is shown in Figure 2 (3600 V rated DC voltage, 1500 A rated DC current, 5400 kW rated DC power); it is worth noting that the first part of the curve is a linear function of the current delivered by the Electrical Substation and it may be described by the following relationships:

$$V_d = V_{d0} - \frac{3}{2\pi} X_c I_d \tag{1}$$

$$V_{d0} = \frac{3\sqrt{2}}{\pi} V \tag{2}$$

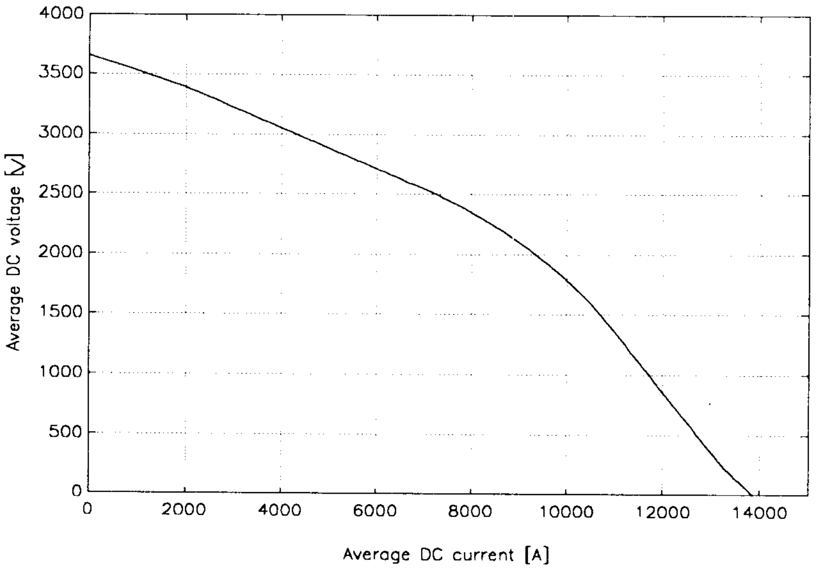

Figure 2: Electrical Substation DC output voltage characteristic.

where:

V_d = ESS DC output voltage;
I_d = ESS DC output current;
V_{d0} = no-load ESS DC output voltage;
V = RMS AC phase to phase voltage;
X_c = commutation reactance.

The simplest model of an Electrical Substation is therefore made up of an ideal voltage generator with a linear series resistive component but this model is correct only if the DC current does not exceed its rated value, which approximately represents the end of the linear field. For this reason a more accurate model is based on the implementation of the whole static characteristic inside the simulator. In this case, a new non-linearity is then introduced, and a further linearization procedure has to be adopted also for ESSs DC output voltages.

As far as vehicles models concerns, it is to say the models able to represent the trains in terms of mechanical effort as a function of their speed, the simplest one is built on the basis of the rated mechanical characteristics and does not take into account the dependence of the performances on the pantograph voltages. This simplified model may be utilized only when the power network and traffic configuration is such to guarantee a maximum pantograph voltage drop, which allows the DC drive to provide the rated mechanical performances.

A slightly more detailed model represents the train on the basis of the rated mechanical characteristics but with the introduction of a maximum current limitation which allows to simualte only a linear dependence of the performances on the pantograph voltages.

Both the above models may be therefore cause of electrical and mechanical errors, for the DC load-flow problem and the mechanical equations are solved taking into account trains with powers greater than the real ones: the electrical errors may bring to ESSs oversizing and wrong evaluation of pantograph voltages, while the mechanical ones to wrong evaluation of train running curves and times required to cover the whole track.

To overcome this problem, a complete macromodel of the drive must be adopted, based on the steady-state equations of the electrical machine utilized and on the actions performed by the control.

Taking into account a chopper fed DC drive, it is possible to write the following equations, which describe the electrical and mechanical steady state behaviour of the electrical machine:

$$\alpha V_p = R_a I_a + \omega L_{af} I_f \tag{3}$$

$$C_m = L_{af} I_f I_a \tag{4}$$

where:

α = chopper duty cicle;
V_p = pantograph voltage;
R_a = motor armature resistance;
I_a = motor armature current;
ω = motor angular speed;
L_{af} = equivalent coupling inductance;
I_f = field current;
C_m = mechanical torque.

On the basis of such equations it is possible to determine, once known the pantograph voltage, the mechanical characteristics of the train, as shown in Figure 2; it is worth noting that each characteristic may be divided into three different fields.

In the first one, the armature and field currents are kept constant and equal to their rated values (I_{ar} and I_{fr} respectively), the chopper provides voltage regulation and the torque is constant; the motor speed corresponding to the end of this field may be calculated setting $I_a = I_{ar}$, $I_f = I_{fr}$ and $\alpha = 1$. In the second one the field current is regulated as the inverse of the motor speed, till its minimum allowed value I_{fmin}, the chopper duty cicle is constant and the armature current kept to its rated value; the torque presents an hyperbolic behaviour and the motor speed corresponding to the end of this field may be calculated setting $I_a = I_{ar}$, $I_f = I_{fmin}$ and $\alpha = 1$. In the third one, no regulation may be performed and the motor follows its natural characteristic, whose behaviour may be determined setting $I_f = I_{fmin}$ and $\alpha = 1$.

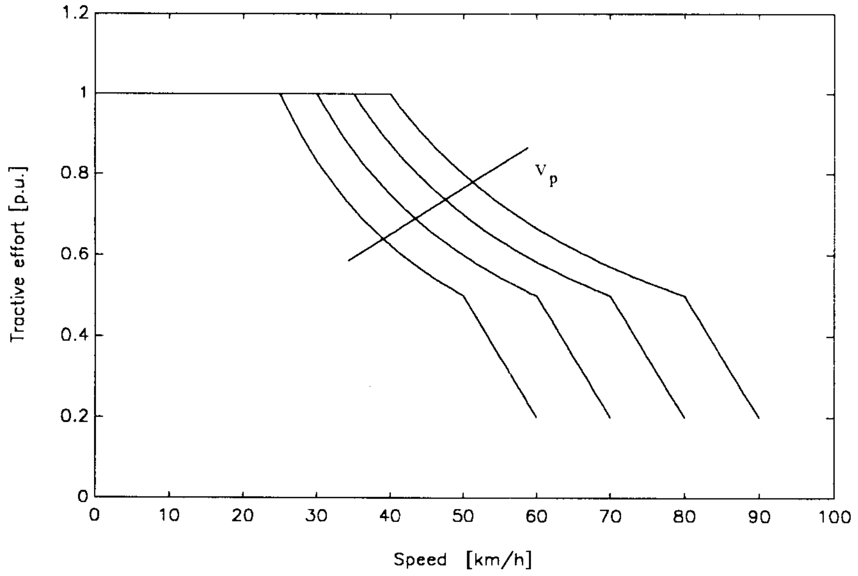

Figure 3: Pantograph voltage dependent DC drive mechanical characteristics.

This modelling procedure, which may be simply applied also to inverter fed AC drives, allows a correct simulation of trains, as far as voltage dependent mechanical performances concerns, and is equivalent to the model with maximum current limitation only if the motor operating condition falls in the first two fields.

4 Structure of an integrated software environment

In this paragraph, the authors describe how the two simulators may be jointly utilized for the design of a new transit system or when a modification is required in an existing metrorail to improve system performances.

This may be explained by means of Figure 4, where the described simulation tools are represented by two different blocks, together with other blocks representing different tools or procedures. Figure 4 shows an integrated environment for the synthesis of the traffic management system and of the electrical power network, and their performance analysis. The information flows among the procedures and the software tools are highlighted. For instance, it appears that the scheduler rewceives as input the information relevant to the track and track circuits configuration, and to the performance objectives. Moreover, the output of the analysis carried out by means of the discrete-event and electrical simulators may be usefully utilized for a possible correction of a previously determined schedule.

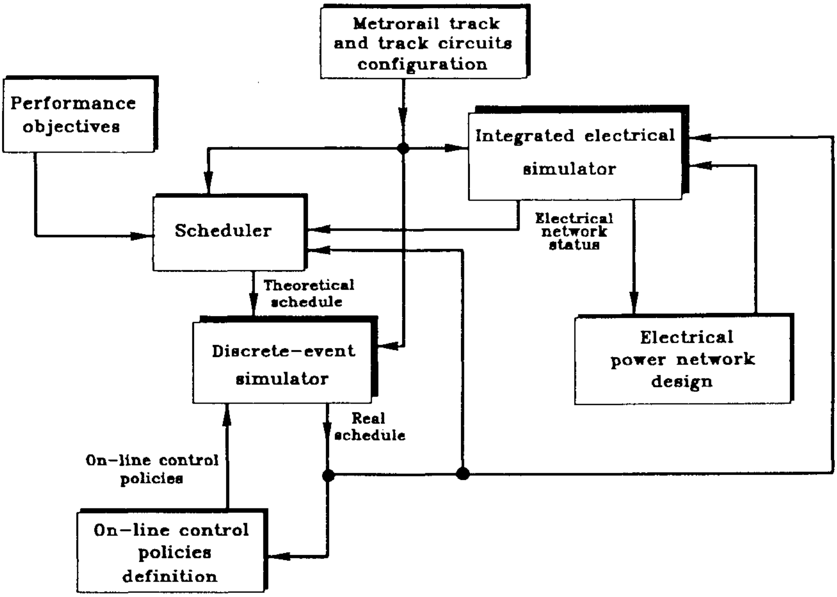

Figure 4: Integrated environment for traffic management system and electrical power network analysis and design.

The discrete-event simulator, which receives as input the information relevant to track and track circuits configuration, to the theoretical schedule, and to the on-line control policies, yelds a real schedule, i.e., the actual timetabling which results from the application of the theoretical schedule. In this case, the discrete-event simulator is applied in its deterministic version.

In turn, the real schedule is given to the electrical simulator in order to test its electrical feasibility. Taking into account the nature of the problematics to be solved, this test may give rise to the necessity of redefining the schedule or reviewing the electrical power network design, on the basis of the electrical infeasibility problems that may have been recognized.

Finally, the on-line control policies are assumed to be initially tentatively defined (for instance, by suitable rules, based on specific knowledge domain), and iteratively adjusted, on the basis of the obtained real schedule.

5 Conclusions

The problems related to traffic management and electrical analysis of a metrorail transit system may be succesfully solved only using simulation tools, due to the presence of non-linear and complex phenomena, mutually coupled, which influence the behaviour of the system. For this reason, the authors describe in this paper two different simulators, developed at the University of Genova and devoted to the definition of real schedules and to electrical sizing of a metrorail, respectively. The two above simulators, based on different models and procedures, may be usefully utilized in an integrated environment, whenever it is necessary to design a new metrorail or modify an existing one: in the first case the real schedule, which is yielded by the traffic simulator, represents a fundamental input for the electrical simulator, in order to size the power network, while, in the second one, the electrical simulator is the validation tool for the real feasibility of a proposed schedule.

Aknowledgements

This work has been performed with the support of the Italian National Council of Research, within the special project on transportation systems *"Progetto Finalizzato Trasporti 2"*.

References

1. Mellit, B., Goodman, L.J., Arthurton, R.I.M.: Simulator for Studying Operational and Power Supply Conditions in Rapid Transit Railways. Proc. IEE, Vol.125, pp 298-303, 1978.

2. Cury, J. E., Gomide, F. A. C., Mendes, M. J.: A Methodology for Generation of Optimal Scedules for an Underground Railway System, IEEE Transactions on Automatic Control, Vol. AC-25, n.2, pp.217-222, April, 1980.

3. Goodman, C. J., Mellit, B., Rambukwella, N. B.: CAE for Electrical Design of Urban Rail Transit System. Computer in Railway Operation, Computational Mechanics Publication, Southampton Boston, 1987.

4. Rambukwella, N.B., Mellit, B., Goodman, C.J., Muniene, Z.S.: Traction Equipment Modelling and the Power Network Solution for DC Supplied Rapid Transit System Studies, IEE Conference on Electric Railway Systems for a New Century, London, Great Britain, 22 - 25 Deptember, 1987.

5. Barnard, R.E.B.: Design Principles of Automatic Control for the London Docklands Light Railway, Electric Vehicle Developments, vol.7, n.2, pp.52-54, April,1988.

6. Cesario, P., Nicoletti, D., Savio, S., Sciutto, G.: Train Running Curve Oriented to Electrical Energy Saving in Metrorail Transit System, XXXVI Convegno Internazionale delle Comunicazioni, Genova, Italy, 4-6 October, 1988.

7. Mellit, B., Passalacqua, R., Sciutto, G.: The Role of CAE Techniques in Traction Systems: State of Art and Trend, 2nd International Conference COMPRAIL '90, Roma, Italy, 27-29 March, 1990.

8. Galaverna, M., Pozzobon, P., Salvo, F., Savio, S., Sciutto, G.: Optimum Strategy for Traffic Management in Light Rail Transit System during Power Supply Faults, 11th IFAC World Congress, Tallin, Estonia, 13-17 August, 1990.

9.Van Breusegem, V., Campion, G., Bastin, G.: Traffic Modelling and Feedback Control for Metro Lines, IEEE Trans. on Automatic Control, vol.37, n.7, pp.770-784, July, 1991.

10. Kataoka., K., Komaya, K.: An Interactive Support System for Train Diagram Preparation - DIAPLAN, IEE Trans., vol.112-D, n.2, pp.153-162, February, 1992.

11. McKay, S.R., John V.I., Dawson, G.E.: Rapid Transit Performance Studies with an Interactive Train Operations Simulator, 3rd International Conference on Computer Aided Design, Manufacture and Operation in the Railway and other Advanced Mass Transit Systems, Washington D.C., 18-20 August, 1992.

12. Boccalatte, A., Di Febbraro, A., Minciardi, R., Paolucci, M., Pesenti, R.: Modelling and Simulating for Optimal Management of Underground Railway Systems, IEEE Conference on Systems, Man and Cybernetics, Le Touquet, France, October, 1993.