Computer Physics Communications 143 (2002) 1–10

Computer Physics Communications

www.elsevier.com/locate/cpc

Computer simulation and modeling in railway applications ☆

T.K. Ho [a,*], B.H. Mao [b], Z.Z. Yuan [b], H.D. Liu [b], Y.F. Fung [a]

[a] *Department of Electrical Engineering, Hong Kong Polytechnic University, Kowloon, Hong Kong*

[b] *School of Traffic and Transportation, Northern Jiaotong University, People's Republic of China*

Abstract

An electrified railway system includes complex interconnections and interactions of several sub-systems. Computer simulation is the only viable means for system evaluation and analysis. This paper discusses the difficulties and requirements of effective simulation models for this specialized industrial application; and the development of a general-purpose multi-train simulator. © 2002 Elsevier Science B.V. All rights reserved.

PACS: 89.40.+k; 02.60.Cb; 89.20.+a

Keywords: Computer simulation and modeling; Software development; Computer-aided engineering tool; Industrial applications

1. Introduction

Railway is one of the most popular means of mass transportation. Every railway system is unique in terms of its technical specifications and available services as it is built in accordance with its own social demands, financial resources, geographical restrictions and sometimes political considerations. An electrified railway system is a complicated system with a number of interacting sub-systems. To further perplex the design, the sub-systems are full of variety. For instances, DC motors with DC–DC chopper converter or inverter-fed three-phase induction motors can be used for traction drive; signaling system may apply the fixed-block or moving-block concepts. Because of the high cost of building a new railway system or redeveloping an existing one, it is necessary to assess all functions and features of the system in depth in order to justify the cost; to specify the system parameters, to identify possible hazards and safety issues in operation and to evaluate the options for improvement. Computer simulation is now conceived to be the most flexible and cost-effective tool to serve these purposes.

A complete railway system simulation must consist of a hierarchical structure consistent with the operation requirements, system configurations and component design. In a railway simulator, each train has to satisfy the equations of motion, for which the traction characteristics, resistance to motion and line geometry are considered. Train control requirements are usually communicated to the trains by track-train data link and the trains interact through both the signaling and power supply systems. The diversity of the tasks to satisfy the above features imposes strict constraints on the development of whole-system simulators.

The variations and characteristics of the major components of a railway system, which requires careful and substantial modeling in the simulation, will be discussed here. A whole-system simulator has been de-

☆ Paper presented of the Conference on Computational Physics 2000, "New Challenges for the New Millenium", Gold Coast, Queensland, Australia, December 3–8, 2000.

* Corresponding author.

E-mail address: eetkho@inet.polyu.edu.hk (T.K. Ho).

PII: S0010-4655(01)00410-6

veloped for general studies of multi-train operation in a railway system. It is designed to cater for various types of evaluation and analysis on railway systems of a wide range of specifications and operation conditions, but not tailor-made for one particular system or application. The models, structure and functions of the simulator will then be presented.

2. Railway system

An electrified railway system is a closely-knitted integration of a number of sub-systems which interact continuously with each other and influence the train performance directly. The major sub-systems are signaling, power supply and traction drives. They have their own specifications and variations in different railway systems to meet their corresponding requirements.

2.1. Signaling

Signaling is concerned with the safety of train movement and regulation of traffic flow. There are two basic principles in signaling, the block safety signaling theory to maintain a safe separation between two successive trains; and the interlocking of points and signals to protect trains at track stations and junctions.

With the more commonly used fixed-block signaling [1], the track is divided into blocks of fixed length and the trains are detected occupying one or more blocks. A train is allowed to enter a block if that block is clear of other trains and if its speed is low enough for the train to stop before the entrance to an occupied block. In order to improve headway (train frequency), moving-block signaling has been introduced so that a hypothetical, instead of physical, block exists between two successive trains [2]. The block length is defined by the current speed and braking rate of the train behind. Train movement is regulated by the signaling system and hence train movement simulation relies on appropriate modeling of the signaling functions.

Despite the relatively simple operation principles, the implementation of a signaling system is anything but simple. Because of the requirements and constraints on different railway lines, such as speed restrictions, line capacity, mixed traffic and even climatic conditions, no two signaling systems are implemented in the same way. There are always some special features within the signaling system. For example, an overlap distance is introduced in the British Rail to provide extra protection to trains [3]; point-machine defrosters have to be deployed in Sweden to keep the mechanical parts moving smoothly under severe weather etc.

2.2. Power system

The power supply in electrified railway system is characterized by the unique requirements on power transmission, harmonics content and movement of the load, and electromagnetic compatibility in the vicinity.

DC power supply is mainly used in metro systems where the lines are shorter, trains are lighter and train speed is lower. DC power is of course obtained from the utility AC supply through transformer/rectifier substations. However, only the behaviour of the DC side imposes an influence on train movement. Hence, simulation can be confined within the DC side, which is relatively simpler. On the other hand, AC supply technology encounters problems of transmitting high level of power required by trains over long distance and electromagnetic compatibility with the surroundings. As a result, catenary feeding systems with booster transformers or auto-transformers have been developed to improve transmission efficiency and system regulation and to reduce earth-current leakage and electromagnetic interference. Inevitably, the feeding system is complicated by the introduction of additional overhead conductors [4].

2.3. Traction equipment

Railway traction drives must allow for flexible speed control as the train speed varies over a wide range. DC traction motors meet this requirement easily with DC–DC chopper or AC rectifier drives and hence they have been used in most railway systems. AC induction motors enable saving on maintenance and overhaul cost, operate at high maximum speeds and provide inherent regenerative braking capability. However, speed control involves variable-voltage, variable-frequency input, which was not viable until the development of advanced high-rating thyristors a couple of decades ago. Hence, AC traction drives have become more popular in recent years [5].

As DC and AC traction drives operate on different principles and the supply can be in DC or AC, power electronics circuits of different configurations are required to provide the necessary speed control. To attain a thorough model of a drive system, it is necessary to begin the analysis from the secondary side of the step-down transformer which is directly connected to the input of the power electronics circuits.

3. Simulation models

3.1. Train movement

Train movement is the calculation of the speed and distance profiles when a train is traveling from one point to another according to the limitations imposed by the signaling system and traction drive characteristics. As a train runs on the track, its movement is also under the constraints of track geometry and speed restrictions. The data structure representing the track geometry and signaling system modeling are therefore critical to achieve effective simulation. Besides, the models to denote the evolution of train movement also play an important role in the flexibility of applying the simulator on different studies.

As fixed-block signaling was solely used until a decade or so ago, data representation and storage are mostly in the shape of two-dimensional arrays with the rows of the arrays denoting the signaling blocks with fixed block signaling. The track-based data include block identity, gradients, speed restrictions, coasting points and signal aspects etc. within the signaling block. The major advantage of this structure is easy referencing. However, only a single data type (e.g., floating-point numbers) is allowed within the array, which is inflexible for accommodating the diversified nature of data. Besides, the array structure does not offer any representation of track layout, except that the adjacent rows in an array may depict a sequence of adjacent signaling blocks. When it is necessary to describe the track connections within a complicated railway network, the array structure must be enhanced or additional data structures are needed. Further, the size of the arrays required vary with applications, a number of ‘supposedly’ large enough arrays are usually defined. In other words, excessive amount of memory space is reserved in the simulator in order to meet the demands of most applications.

Object-oriented approach provides the solution for the above deficiency. It has been successfully applied in railway network and signaling modeling [6]. The network structure is represented by a number of ‘node’ objects jointed by ‘link’ objects. The nodes can be stations, junctions, points and termini whilst the links are the tracks connecting the above features and they are directional. They have their own data structures characterizing their properties, and the data structures accept mixed data types. Fig. 1 illustrates how a section of track is represented by the nodes and links. Train movement is realized by moving the train from one node to the next through a permitted link, which contains the necessary information for the movement calculation. Similarly, trains and signals can be encapsulated in their respectively defined classes. Various types of trains and signals are further defined by subclasses through inheritance and the functions operating on them are allowed to be re-used through polymorphism. The object-oriented approach is particularly useful for the moving-block signaling because the signaling blocks do not exist physically and the modeling of continuous communication among trains (objects) can be made possible.

Depending upon the level of details required, there are two major approaches to simulate train movement, time-based and event-based models. In time-based models, the time span is divided into evenly-spaced intervals and train movement is evaluated at each interval. This approach is conceptually analogous to how the trains move along the track in reality, hence it is easier to design. Despite its simplicity, a time-based model requires a highly computational demand as a significant amount of information has to be produced during every update. This demand can only be justified in applications where full details of train movement are needed. Energy consumption and signaling layout design [7] are typical examples. Event-based models, on the other hand, express the progress of train movement by the occurrence of a sequence of pre-defined events, such as arrival at and departure from stations [8]. Since the events are linked together through the interactions among trains via signaling or power system, one event, as the consequence of a previous one, will trigger another to happen. As a result, a chain of events reflects the progress of the trains. Computational effort can be substantially reduced because the calculation of exact train movement between two

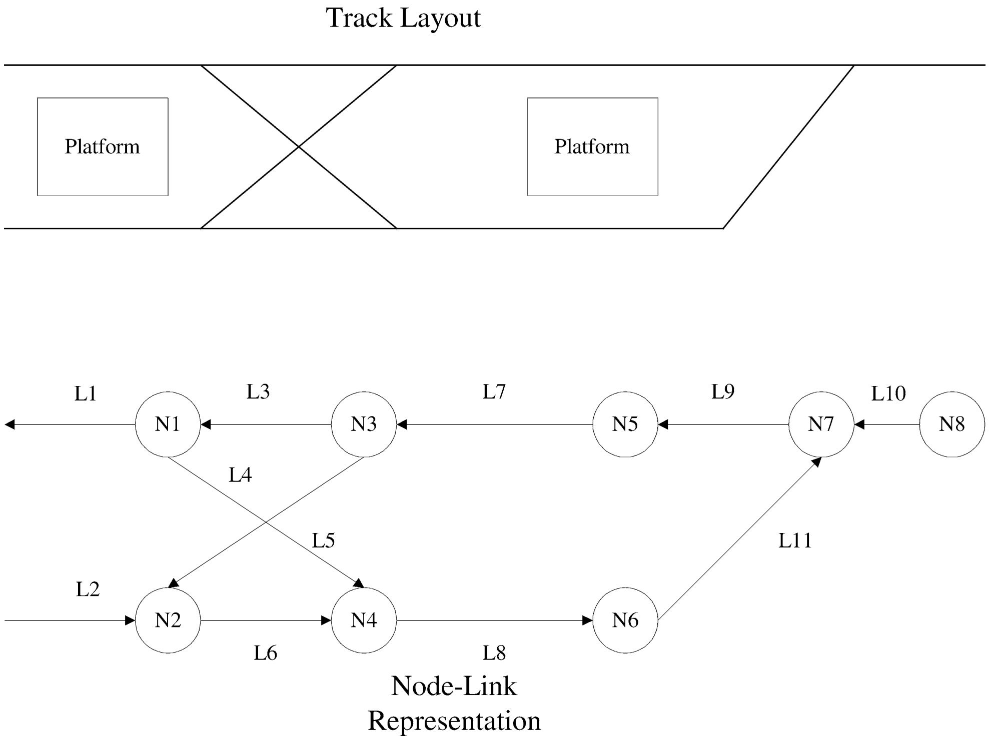

Fig. 1. Node-link model of railway track.

events is skipped. Nevertheless, this apparent advantage may be overshadowed by the fact that the updates of train movement are not carried out synchronously. It is possible that the processing of an event is postponed because the event to trigger it has not yet occurred, or it is processed with certain assumptions and it will be re-processed if the assumptions are found invalid later.

3.2. *Traction power supply*

An electrified railway line is a huge electrical circuit with feeding substations as sources and trains as moving loads. The voltage seen by a train may vary with time and it then determines the traction performance, which in turn affects train movement. Thus, it is necessary to attain the voltages at certain nodes of this circuit at consecutive time intervals, which requires circuit analysis and the solution of a matrix equation. Efficient algorithms are essential for the power network simulator to produce accurate results within reasonable computation time.

DC supply systems may use overhead lines as supply and rails as the return paths (a third rail is used as supply in some cases). Modeling is quite straightforward as all the conductive components are safely assumed linear. The feeder substations are modeled as a voltage source (with nominal line voltage) in series with a source resistance (i.e. a V-R model). The only complication is to denote the capability of a substation on power reception when regenerative braking is allowed, the V-R model is replaced by a simple resistive load when the current is proved to be flowing in the opposite direction.

Power supply for AC traction is obtained from the utility supply through traction feeder substations. Traction currents are often so contaminated by harmonic content that the current return-path has to be conditioned by return conductors, booster transformers or auto-transformers in order to avoid interference with communication systems and electrolytic corrosion. The complete conductor arrangement of the feeder system then becomes tedious. The V-R model is still valid for the substations, but the feeder-conductors along the line carry different portions of the traction current when a train is moving in the vicinity. Careful modeling is required to take into account of the electromagnetic interference effects on different harmonics of the power supply, as well as other frequencies used in the signaling system. The physical sizes, relative resistivity, permeability and geometry of the conductors, relative permittivity of the medium and earthing conditions are essential for the feeder system model. Further, as the rail is of unique shape, calculation of impedance is far from easy. It can be treated as a single cylindrical steel conductor with different cross-section areas for a wide range of frequencies [9].

3.3. Traction drives

The basic function of a traction equipment model is to provide traction effort output and current/power demands according to the given input parameters for the train movement and power network calculations. The DC supply voltage with respect to the rolling stock can vary from -30% to $+20\%$ of the nominal value. A voltage sensitive drive model is, therefore, essential in achieving accurate electrical and mechanical representations for the conventional DC traction equipment. However, for the modern three-phase induction motor drive, the voltage fluctuation on the train pantograph (or collecting shoe) is less significant with the advanced pre-conditioning front–end technology. The voltage at the DC link can remain at a fairly constant level.

Two voltage-sensitive drive-modeling approaches, namely, the detailed [10] and simplified [11], have been widely used. When the information of motor terminal characteristics, winding resistance and reactance is available, it is often desirable to model a drive with the detailed approach. However, at a feasibility study or preliminary engineering stage, it is not always possible to gather all the necessary information to model a new drive comprehensively. The simplified drive modeling approach based on data fitting and numerical techniques provides a much more practical alternative as it only requires the high level information, such as traction effort vs. train speed curves, which are generally much easier to obtain.

To integrate into the same electrical circuit with the power system, the traction systems are also represented by the V-R model. However, the values of V and R vary with the speed and operational mode of the train. Either the detailed or simplified methods can therefore be employed to synthesize, usually off-line, the look-up tables of V and R over the whole range of operation conditions.

3.4. Power network solution

With the models of power supply and traction equipment available, the circuit of the electrified railway line is established for the calculation of voltages and currents at various points of interest. Because of the size of the circuit, the power network solution is the most time-consuming step of railway simulation. The V-R models for substations and traction equipment are thus crucial to the simplified structure of the circuit, which in turn has an impact on the computational demand and hence the simulation speed.

There are two major approaches to solve the power network. In the first approach, load flow calculation [12], the power network simulator is quite often separated from the train movement simulator. The traction power network simulator, as a stand-alone module, takes in the train movement results, such as train locations and train power demands etc. from data files or intermediate storage. This approach, from a programming viewpoint, provides a much easier interface between the train movement and traction power simulators. It does, however, provide no direct reflections of voltage variations back to the train movement calculations. With modern three-phase drives, the traction drive is less dependent on supply voltage than is the case with DC motors, but all drives have a designed 'graceful degradation' response to reduced traction voltage. Thus, if the performance limits of the total system are to be properly examined, feedback of the power network solution to the traction performance calculations becomes essential.

For the second approach, the direct matrix method [13], a matrix equation is formulated from the electrical circuit using either mesh or nodal analysis. The latter is more suitable complex networks, because it is often easier to identify nodes than loops in non-planer networks. From a programming perspective, automatic network set-up procedures and advanced network graph techniques are easier to implement with the use of the nodal approach. Fig. 2 shows the circuit

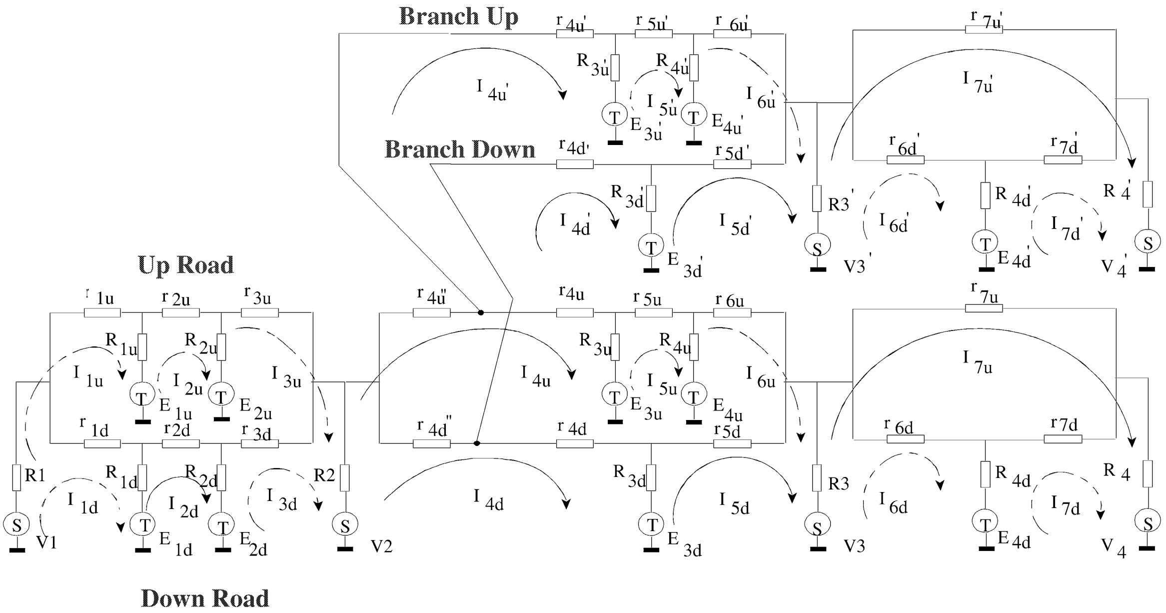

Fig. 2. Simplified power network with branches.

representation of a typical DC traction power network with branches. It is not difficult to see that the railway traction power network is characterized by sections of ladder type networks infrequently cross-connected. For this characteristic topology, the sparse matrix technique coupled with efficient matrix elimination methods leads to an expeditious network solution, since it does not suffer from the fill-ins that the direct inversion of the coefficient matrix requires.

The coefficient matrix of the traction power network equation is usually of positive definite (PD), symmetric and sparse type. Many sparse matrix elimination techniques tailored for PD matrices, such as LL^{T} decomposition and Cholesky decomposition, are applicable. For the sparse techniques, the essence is the equation-ordering. There are generally two types of ordering method namely, static and dynamic ordering. Typical examples of static ordering for long and thin ladder type networks include the Cuthill and McKee algorithm [14] and reverse Cuthill and McKee algorithm [15], which make use of the property that the zero elements situated before the first non-zero element on any row always remain zero. For dynamic ordering, the minimum degree algorithm provides an efficient alternative for solving the network matrix. This is actually a heuristic algorithm for finding an ordering for the coefficient matrix which suffers low fill-ins when it is factored. Therefore, this scheme requires a simulation of the effects on the accumulation of nonzeros of the elimination process. In order to avoid direct elimination with actual values, a symbolic factorization is usually adopted to obtain the zero and nonzero structures of the factored matrix. As the numerical values of the matrix components are of no significance in this connection, the problem could be studied using a graph approach, instead of using an actual matrix factorization. The minimum degree algorithm is particularly suitable for solving medium to large networks, in which there are 200 nodes and more. For smaller networks, the minimum degree algorithm becomes a less efficient option, since a significant portion of the overall processing time is used in the symbolic factorization process.

4. General-purpose railway system simulator

Most of the existing railway simulators were developed specifically to solve one particular problem only or to study the performance of a particular part of the system. Different applications lead to different specifications of simulators. For a railway research group, it is impractical to develop a number of simulators to carry out various studies. A general-purpose multi-train simulator suite is therefore in great demand to deal with studies of various kinds and levels. This section briefly reviews the development of a multi-train simulator based on the models described, and its applications.

4.1. Structure

The simulator consists of a library of software modules modeling the features and variations of the sub-systems within a railway system. To cater for a particular application, appropriate modules are selected from the library and bound together to attain the simulator required.

This simulator suite contains a graphical input front–end, a number of categories of functions representing the sub-systems of a railway system and a common data-structure shared among the categories. Under the heading of each category, there are modules modeling functions of the sub-systems. To enhance the applicability of the simulation suite, different concepts and approaches of modeling the sub-systems can be incorporated. For example, in the signaling category, there are modules for both fixed and moving-block signaling schemes. In the power-system category, different modules are certainly needed for AC and DC railways. Such flexibility however requires intelligent supervision to ensure that the selections of modules within one sub-system category are compatible with those for others.

As illustrated in Fig. 3, the vast amount of data required for simulator is supplied through the input interface. It allows easy input with dialogue boxes and, in some cases, graphical input with typical mouse actions. Data integrity check is also incorporated to prevent the simulator from operating with foul data. A set of databases is necessary to systematically store data of different purposes. Function modules of different features and variations of the sub-systems are available within the simulator. They are defined and developed

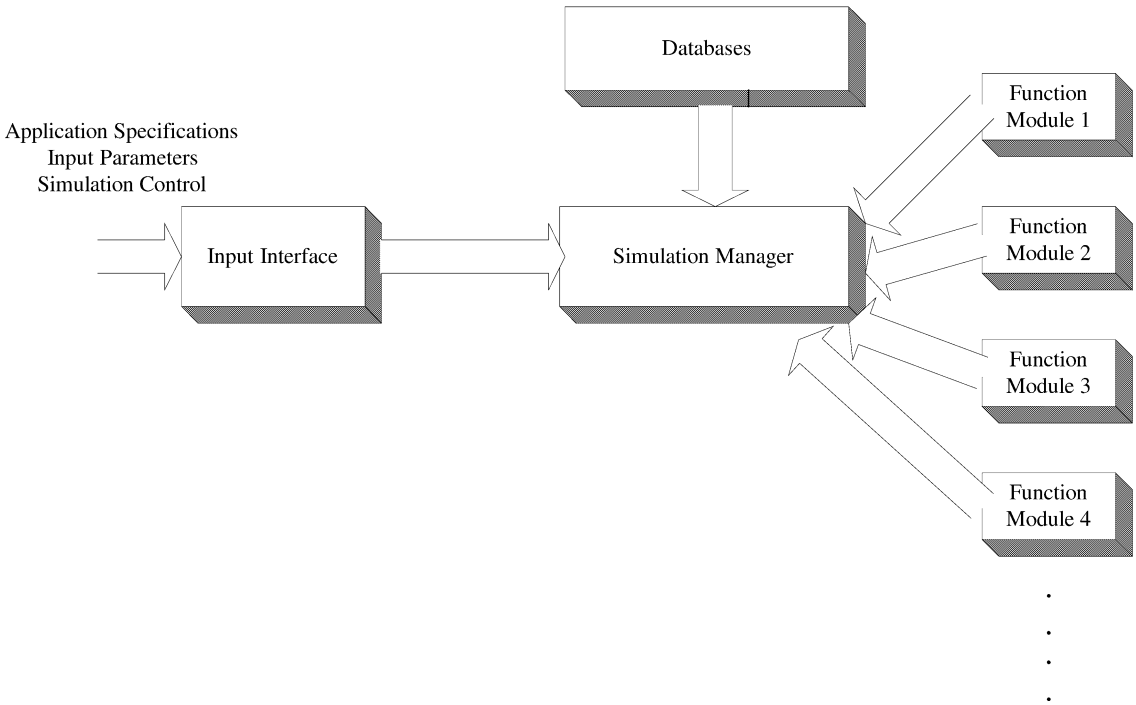

Fig. 3. Structure of the general-purpose railway system simulator.

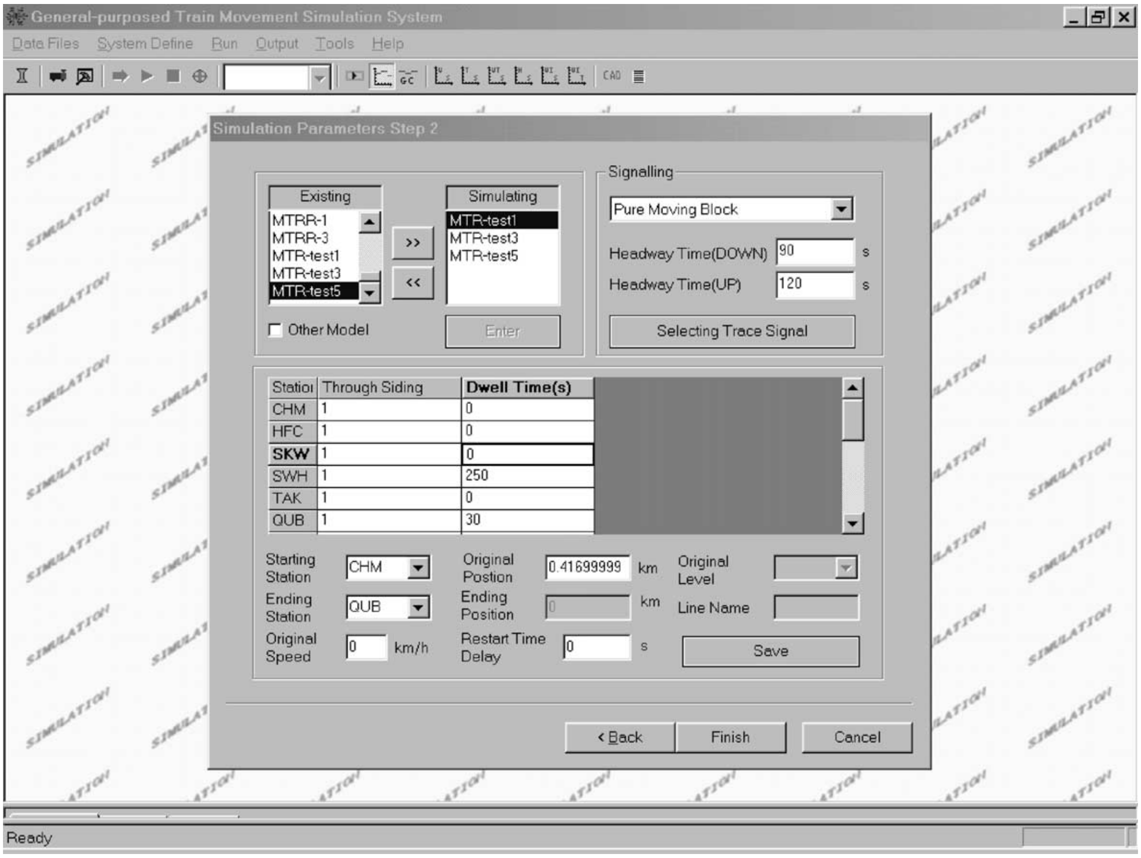

Fig. 4. An input interface.

independently so that they can be inserted, deleted or modified without affecting others. The core of the simulator is a Simulator Manager which selects, according to the application specifications, the appropriate function modules and arranges the necessary initialization for the simulation. Modules of the same function but different approaches should have the same protocol in order to maintain consistent interfaces with other function modules. The modularity is essential for the adaptability of this simulation suite.

4.2. Progress and further development

The development of the simulator has been divided into a number of milestones and the latest version contains the train movement under fixed-block and moving block signaling and their minor features, DC power supply systems and DC motors with chopper drives. The input interface now allows fully interactive data acquisition and the tedious data input process can be divided into a number of stages and stored in separate application-oriented files. One of the input interfaces is given in Fig. 4. The simulation results may be presented in graphical, textual and AutoCAD formats. The graphical output can be displayed as the simulation proceeds, an example is shown in Fig. 5. To save computational effort and to reduce simulation time, the real-time graphical output can be turned off and the analysis of output data is carried out upon the completion of simulation.

AC power supply network is now being implemented. The complexity of the model, which generally involves equations of very large matrices (typically, 200×200 to 1000×1000) of complex numbers,

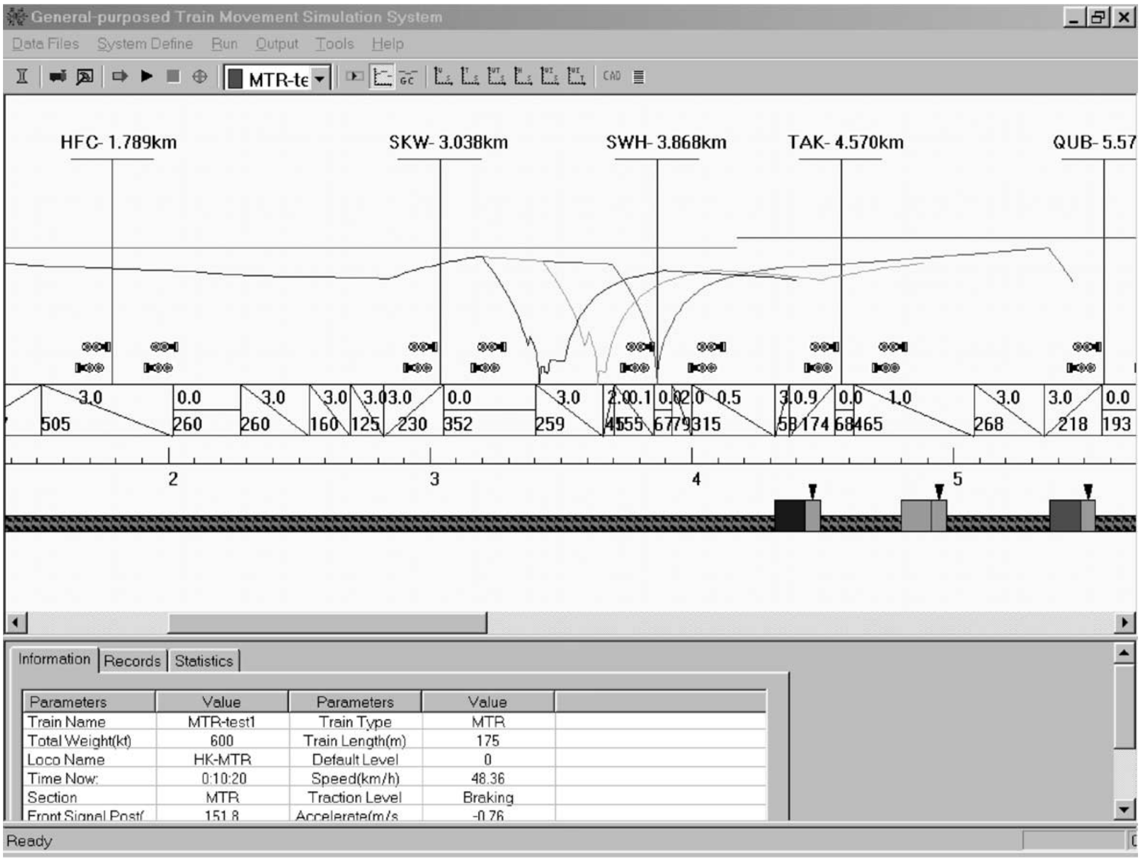

Fig. 5. Train speed profiles (simulation results).

leads to such a computationally demanding solution process that parallel computing by Streaming SIMD Extensions (SSE) [16] on a single processor or parallel algorithms on multi-processor platform has been contemplated.

4.3. Applications

Because of its generic nature, the simulation suite can be applied in literally most of the studies related to railway systems. To date, it has been used in the studies of the traffic control at conflict areas; energy consumption for trains re-starting under moving block signaling; train control optimization at inter-station runs and train service scheduling in both Hong Kong and China. The list will certainly go on when the current development is completed and all the modules are fully functional. This simulator is a pragmatic and viable tool for every railway operator who is responsible for the daily operation, disturbance recovery and risk assessment and management.

5. Conclusions

Railway system is a specialized multi-disciplinary engineering application. Its unique characteristics, requirements and social impact on transportation call for the imminent needs of a reliable, accurate and flexible tool to assess system performance in various aspects. This paper reviews the difficulties of the model development for electrified railway simulator. Variations of railway system functions and their implications on appropriate modeling have been briefly discussed. The accuracy and resolution of simulation results, computational time, flexibility for use, applicability and transportability of the simulator are largely determined by the models of various components of the railway system. Since a simulator is often employed when a railway line is still at the design stage, the simulation results cannot be verified by actual measurements. Hence, the nearly over-cautious concern on adequate and efficient modeling within the simulator is never an overstatement from simulator developers.

A general-purpose multi-train simulator has been developed with the appropriate modeling. It provides a generic computer-aided engineering tool for the railway operators and researchers to carry out studies without any modifications on the program-code level. It enables the users to focus on the concerns of the studies but without losing the realism of a total system model and thus preserving knowledge of the system implication.

Acknowledgement

This work has been supported by the Research Committee of the Hong Kong Polytechnic University.

References

[1] R.J. Hill, Electric railway traction, Part 4, Signalling and interlocking, Power Engrg. J. (1995) 201–206.
[2] M.J. Dockyear, Changing track — moving-block railway signalling, IEE Rev. (1996) 21–25.
[3] O.S. Nock, Railway signalling, A&C Black Publishers, 1980.
[4] R.J. Hill, Electric railway traction, Part 3, Traction power supplies, Power Engrg. J. (1994) 275–286.
[5] R.J. Kemp, Developments in electric traction, Power Engrg. J. (1989) 71–82.
[6] L.K. Siu, C.J. Goodman, An object-oriented concept for simulation of railway signalling and train movements, in: COMPRAIL'92, Vol. 2, 1992, pp. 545–556.
[7] D.C. Gill, C.J. Goodman, Computer-based optimisation techniques for mass transit railway signalling design, IEE Proc. B 139 (3) (1992) 261–275.
[8] T.K. Ho, C.J. Goodman, J.P. Norton, An event-based traffic flow model for traffic control at railway junctions, in: Aspect'95, International Conference on Advanced Railway Control, 1995, pp. 163–170.
[9] J.C. Brown, J. Allan, B. Mellitt, Calculation and measurement of rail impedence applicable to remote short circuit fault currents, IEE Proc. B 139 (4) (1992) 295–302.
[10] C.J. Goodman, B. Mellitt, N.B. Rambukwella, CAE for the electrical design of urban rail transit systems, in: COMPRAIL'87, 1987, pp. 173–193.
[11] J.G. Yu, R.W. Struand, L.R. Denning, A general motor modelling method for transit system simulation studies, in: COMPRAIL'94, 1994.
[12] S.N. Talukdar, R.L. Koo, The analysis of electrified ground transportation network, IEEE Trans. Power Appl. Systems 76 (1) (1977) 240–247.
[13] B. Mellitt, C.J. Goodman, R.I.M. Arthurton, Simulator for studying operational and power-supply conditions in rapid-transit railways, Proc. IEE 125 (4) (1978) 298–303.
[14] E. Cuthill, J. McKee, Reducing the bandwidth of sparse symmetric matrices, in: Proc. 24th Nat. Conf. Assoc. Comput. Mach, ACM Publishers, 1969, pp. 157–172.
[15] A. George, J.W.H. Liu, Computer Solution of Large Sparse Positive Definite Systems, Prentice-Hall, Englewood Cliffs, 1981.
[16] G. Conte, S. Tommesani, F. Zanichelli, The long and winding road to high-performance image processing with MMX/SSE, in: Proc. 5th IEEE International Workshop on Computer Architectures for Machine Perception, 2000, pp. 302–310.