OPTIMIZING THE RUNNING PERFORMANCE OVER RAILWAY TRACKS USING SIMULATION TECHNIQUE

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ABSTRACT

Simulation models are being increasingly used as a planning tool to examine upgrading strategies. These models, however, need often considerable amount of capital and time to simulate real railway tracks. The paper presents a simulation process, developed by the authors, that can be used to investigate, with a degree of confidence, the effect of modifying the elements of a railway system on the movement behaviour of trains. Programmed for computer, the proposed process enables the planner to evaluate a wide range of upgrading alternatives in a short time and to select the most feasible solution which optimizes certain operating conditions. Ways in which the process can best be used and its limitation are illustrated by applying it to simulate the operation on the Abou Kir railway under different upgrading philosophies.

INTRODUCTION

The current techniques used for studying the movement of trains over a railway track can virtually be classified into three categories: analytical methods, optimization algorithms, and simulation models.

The analytical methods are based on algebraic expressions employed to determine the relationships between travel time and railway system attribute. These algebraic expressions can be used for the rough investigation of the interdependence between track capacity and system characteristics. The analytical methods are very simple in application, however, they are less accurate, as they do not take all system characteristics into consideration [7].

Optimization algorithms deal often with the problem of scheduling trains over an existing railway track to optimize certain operating criteria, such as minimizing total delays and fuel consumption. The formulation of the optimization problem, the objective functions and their constraints is usually very complicated [10].

Simulation is the technique of replacing an actual "railway" system by a "railway" model which should be similar from various viewpoints to the real one. Simulation gives the response of the railway model to proposed changes in the system parameters, individually or collectively. It should be carried out accurately at a great level of details [3].

According to the available literature, the weaknesses of the simulation models in common use can be summarized as follows [6]:

- the models are often established for a specific railway track, and they are always incompatible with other tracks,
- excessive data is always needed for applying a simulation model, and
- simulation of a railway model requires long calculating time and large computing expenses.

This paper presents a new simulation process which is developed to overcome the weaknesses of the traditional techniques. The intention of the process is to simulate and to test the effects of different changes in the parameters of a railway system in order to determine the most feasible parameters which optimize some operating criteria.

Because of the large number of repetitive calculations and the volume of data involved in the simulation, the paper illustrates an interactive computer system, designed to allow more rapid implementation of the conceptual process.

Finally, the proposed simulation process is applied to the railway line "Alexandria / Abou Kir" to examine the effect of some upgrading measures. However, it must be emphasized that the goal of the application here is only to examine the efficiency and practical capability of the proposed process.

SIMULATION PROCESS

Process Overview

The paper is created in response to the difficulties inherent by simulating the movement of trains over a railway track. It is recognized that railway operation is an indivisible system and, that projected changes to any single operating element potentially affect some others. This leads to the concept of "planning alternatives". A single alternative contains a combination of options. Then, analyzing alternatives is needed to examine system response to all combinations of many individual options.

Figure (1) simply illustrates the basic components of the proposed simulation process and its overall structure. The parameters of the railway model (basic design) should firstly be defined in terms of track alignment, rolling stock, and operating conditions. Through the simulation process, the running performance of each type of trains between the different stops is determined, and the timetable needed to cover a certain travel demand is prepared. The following overall performance characteristics are also calculated:

- running time,
- average speed,
- commercial speed,
- fuel consumption, and
- service frequency.

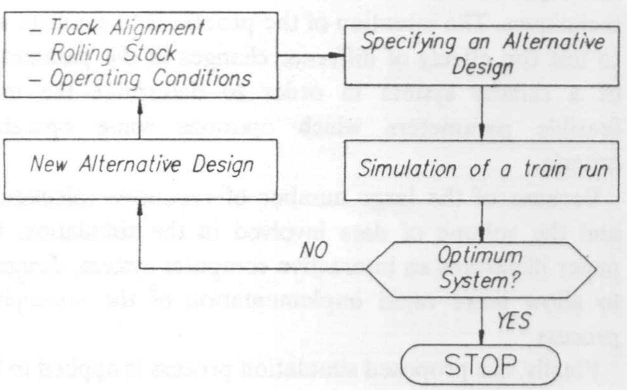


Figure 1. Overall structure of the simulation process

By selectively altering the parameters of the basic design, and repeating the simulation process, a lot of alternative designs can be generated and evaluated according to their performance characteristics. The most feasible design is the optimized solution that includes the operating conditions which minimize running time and fuel consumption, and simultaneously maximize average speed and service frequency.

Methodology

The proposed process deals with the simulation of a railway track at two levels; asynchronous and synchronous levels.

At the asynchronous level, a four-step procedure is developed for the global determination of the speed profile along the railway track (Figure 2). At the first step the speed profile is generated according to the maximum design speed (due to track alignment). At the second step the speed profile is modified by considering the maximum speed which can be achieved by a particular train. The purpose of the last two steps is to identify the acceleration and deceleration points.

The purpose of the asynchronous simulation is to determine accurately the running performance between stops. The asynchronous simulation is based on the well known "Discrete Event Simulation" method [11]. It uses iterative computational cycles based on both distance and speed increments, as shown in Figure (3). The movement of trains between two sequential stations is generally divided into three segments (acceleration, steady speed and braking segments).

During acceleration, the speed increases successively until the train reaches a maximum speed V_m (point 2). Because train acceleration is highly speed dependent, and the maximum speed can not previously be determined, acceleration distances and times are computed step-by-step at small speed increments δV (e.g. $\delta V = 2$ Km/h). It is important here to emphasize that V_m does not allow the absolute maximum permissible speed. It is the maximum feasible speed which guarantees a minimum running time and fuel consumption, taking into account the accelerating and decelerating characteristics as well as the distance between every two sequential stops.

The steady speed segment extends from the end of the acceleration segment (point 2) to the beginning of the braking segment (point 4). The speed becomes uniform as

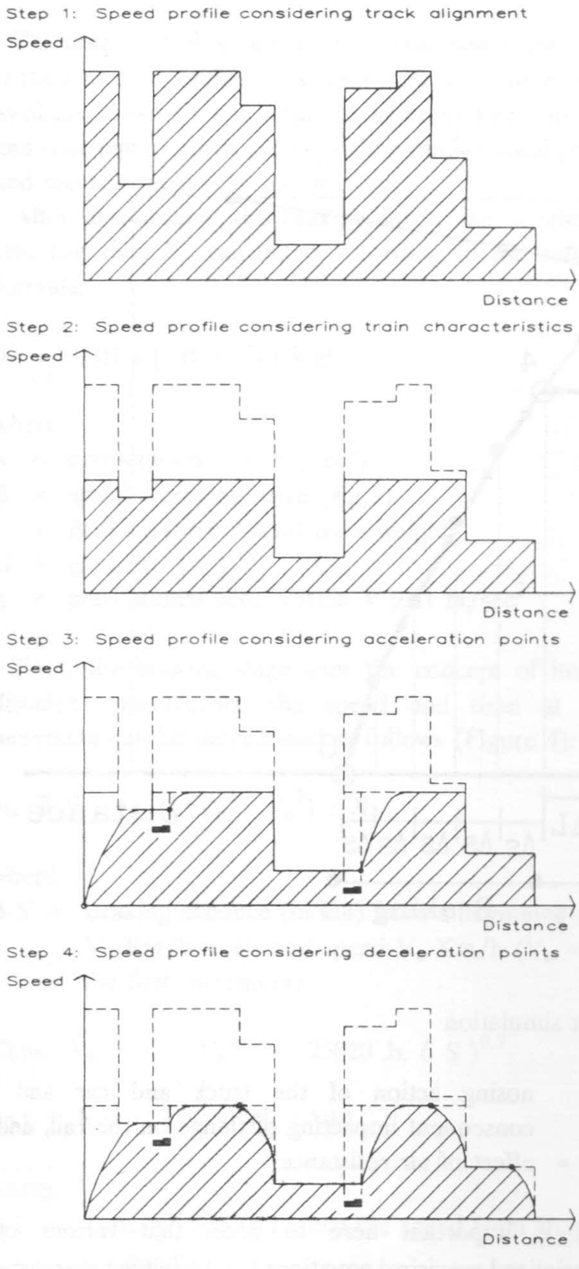


Figure 2. Simulation at asynchronous level

long as the resistance is constant and there are no speed restrictions. According to the actual track resistance, the changes in speed and time can iteratively be calculated at small distance increments δ L.

In some cases, when the spacing between two sequential stops is very small, the trains can reach the maximum speed (at point 5) and then apply the brakes to stop at the next station (point 3). In such cases, steady speed segments do not exist.

The braking segment starts with V_m, from which the speed decreases gradually until the train stops at point 3. The total braking distance can be calculated for each particular train type. Thus, speed and time changes can be determined on the basis of small distance increments δ S.

The proposed simulation process depend on several mathematical and algorithmic models; namely power-system model, resistance model, brake model, and departure time model.

Power-System Model

The power-system model can simulate both diesel-electric and fully electric propulsion systems. It calculates the running performance attributes during acceleration at each prespecified speed increment, i.e. rolling resistance, tractive effort, and running speed. Other function of the power-system model is to compute the fuel consumption.

As input, the model requires information concerning the resistances along the track layout (grade and curve resistances) as well as the specification of the total power system in terms of tractive-effort curve, rolling resistance curve, and energy demand curve (if available).

The power-system model can also be used to calculate fuel consumption for diesel-electric locomotives, on request, by applying the following expression [9]:

$$FC = 0.05 \int_0^t [(TR \times V) / (CV \times e)]\, dt + B \times T_B$$

where

FC = Fuel consumption during a time interval t (in kg)
TR = instantaneous tractive effort at speed V (in kg)
CV = calorific value of diesel fuel (about 9000 kcal. per kg fuel)
e = thermal efficiency (about 40 %)
B = fuel consumption by idling run (in Kg/min.)
T_B = braking time (in min.)
0.05 = conversion factor

Simpson rule [2] is applied to perform this integration, and to sum up the area under the time/fuel consumption curve.

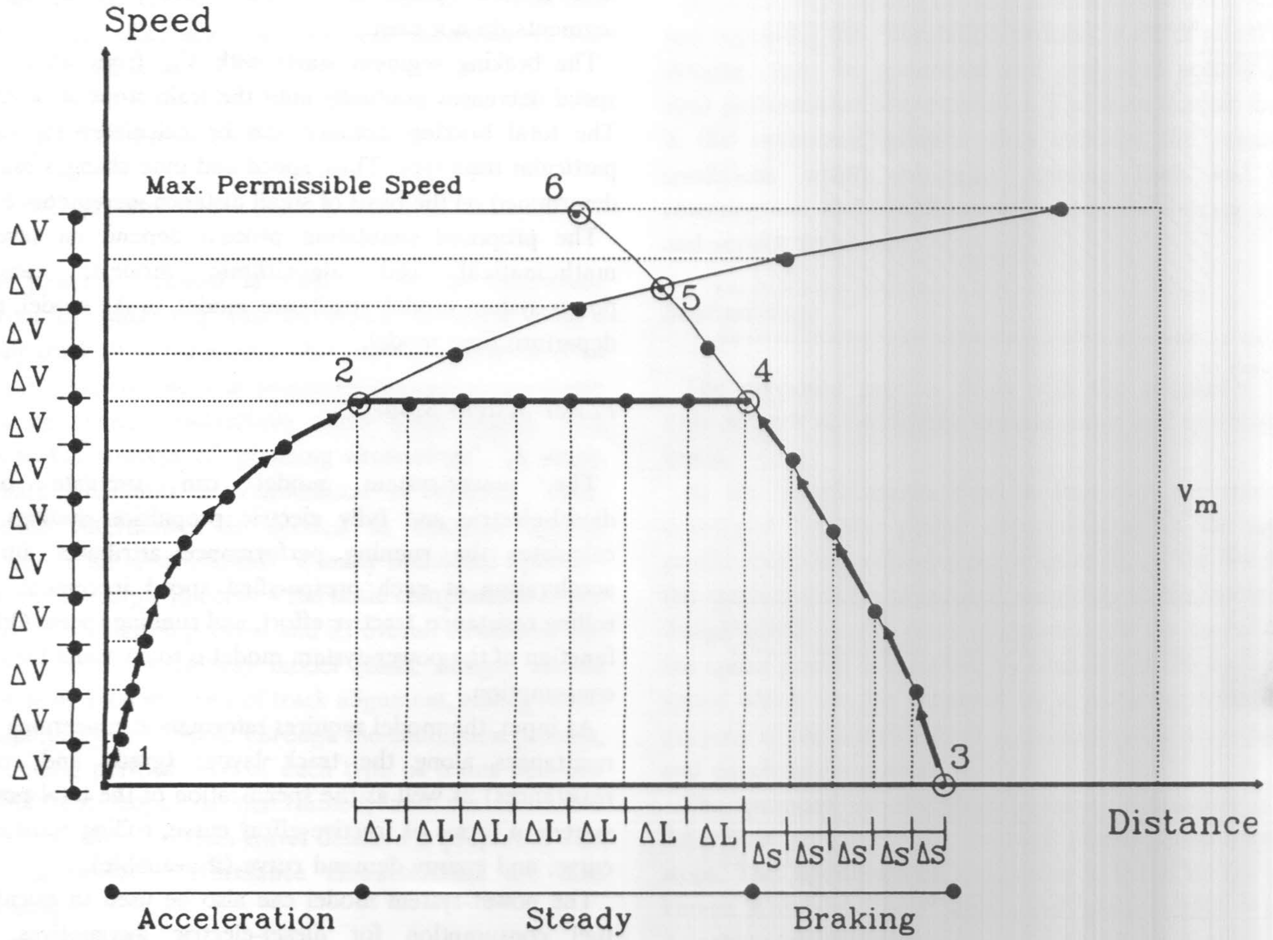


Figure 3. Discrete Event simulation

Resistance Model

Aerodynamic and mechanical resistance to the forward motion on level track is computed by using an equation with the general form [4]:

$$R = a + bV + cV^2$$

where
R = train resistance on level track,
V = running speed,
a = mechanical or friction drags that at least partly weight dependent,
b = all effects that depend on the first power of the speed, such as flange resistance caused by the nosing action of the truck and car and the consequent impacting of flange on the rail, and
c = effect of air resistance.

It is important here to note, that various other specialized empirical equations for describing aerodynamic and rolling resistance are available for application. The use of any equation requires the verification of its accuracy and the calibration of its results with the specific railway track.

Resistance due to track grade and curvature is added to the resistance on level track. Curve resistance is taken as 0.36 kg/(ton.degree of curvature), and grade resistance as 1 kg/(ton per thousand of grade).

Brake Model

The brake system model simulates the behaviour of both friction and air brakes. The approach for computing the available braking force is the use of brake-force, distance, and time equations derived from the fundamental physical and mechanical system parameters.

After determining the braking force, the deceleration rate can then be calculated according to the following formula:

$$b = 0.001 \times [(B + G) \times g]$$

where

b = deceleration rate (m/sec^2)

B = specific braking force (Kg/t)

= Braking force / total train weight

G = gradient (%.)

g = gravitational acceleration = 9.81 m/sec^2

Since, the braking stage uses the concept of iterative distance increments, the speed and time at every increment can be determined as follows (Figure 4):

$$\text{as, } \delta S = (V_b^2 - V_e^2) / 2b$$

where

δS = Braking distance (in km) from a beginning speed V_b Km/h to an end speed V_e Km/h (V_e = 0 at the first increment)

$$\text{Thus, } V_b = (V_e^2 + 25920 .b. \delta S)^{0.5}$$

$$\text{and } \delta t = \delta S \times 60 / VM$$

where

δt = Time needed to reduce the speed from V_b to V_e (in minutes)

$VM = (V_e + V_b) / 2$

It is important to note, that V_b of the first increment will change to be V_e of the second increment. The previous calculations are repeated for each distance increment δS until reaching the maximum speed V_m using backward iteration.

The total braking distance S_B and total braking time T_B are then calculated as follows:

$$S_B = \sum_{1}^{n} \delta S \text{, and}$$

$$T_B = \sum_{1}^{n} \delta t$$

where

n = number of increments

Departure time model

This model attempts to simulate the operation over an actual railway track very closely. It permits the preparation of the graphic timetable which describes train movement against time over any railway configuration.

The departure time model can be summarized as follows:

- Calculate the occupancy times of the various track segments for each train type.
- Based on the actual demand, identify the number of trains for the following train sequence cases: Slow/Fast, Fast/Fast (or Slow/Slow), and Fast/Slow.
- Determine the headway hN between train N and the next train N+1.
- Compute the average buffer time, the average headway, and the service frequency [8].
- Determine the departure time for each train by using the following equation [13]:

$$dtN = dtN\text{-}1 + (aN \times havr)$$

where

dtN = Departure time of train N

dtN-1 = Departure time of the earlier train N-1

havr = Average headway

aN = random value calculated according to the following distribution (Erlang-Distribution) used by Potthoff [12]:

$$aN = e^{[-2\, hmN \sum_{0}^{1} (2\, hmN) / n!\,]}$$

hmN = hN / havr

n = Counter

- Arrange the trains in a rhythmic interval timetable graph.

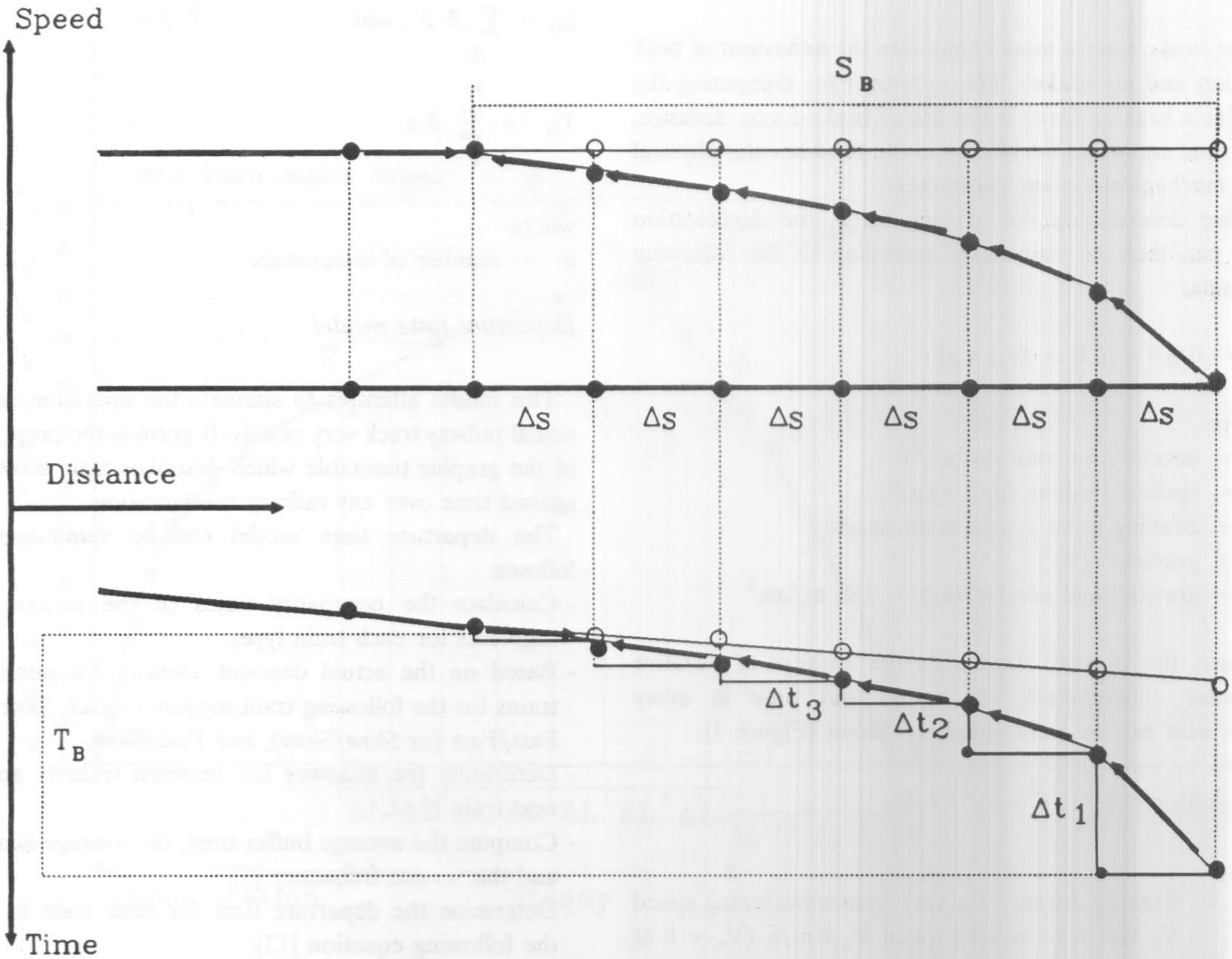


Figure 4. The brake model

INTERACTIVE PLANNING SYSTEM

The simulation of a railway track requires excessive amount of data and needs a long computing time for the development and evaluation of alternatives.

Due to the multiple variables which exist by railway simulation, a man-computer interactive system (called SIMULA) is developed. It is a menu- driven system, that takes the planner step-by-step through the simulation process. In an uncomplicated fashion, it enables him to generate and evaluate different alternative designs. After the evaluation, the planner can modify these alternatives to come closest to his objectives.

The structure of SIMULA system is illustrated in Figure 5. It includes three modules and a control system which makes the decisions, regarding the working progress within each module and the cooperation between the different modules.

The first module (DATA INPUT) is a data editor which can be used to enter either new data set (basic design) or modify existing data set (generate alternatives). It introduces the characteristics of the railway system elements (track alignment, rolling stock, and operating conditions) as well as the travel demand (demand distribution by the period of the day) to the computer. The input data is stored automatically on a computer disk, from which it can be printed or displayed on the screen.

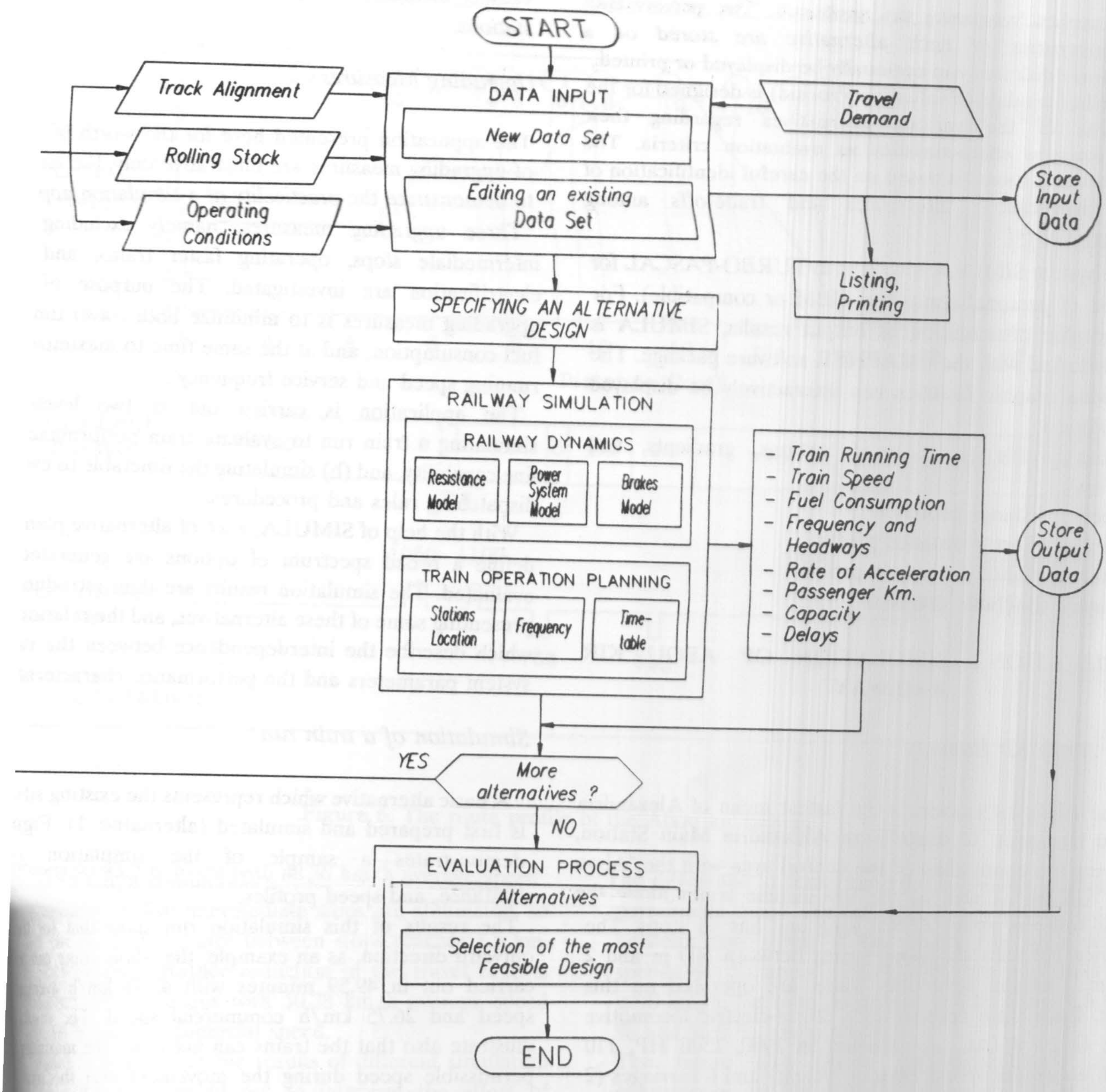


Figure 5. The Structure of the SIMULA system

The second module (Railway Simulation) is divided into two main routines. The first one contains the railway dynamic calculation models (power-system, resistance and brake models) and the second deals with train operation planning (station location, frequency determination, and timetables creation).

After specifying an alternative design and carrying out the second module, a lot of statistical output measures (operating performance characteristics) such as travel time, average speed, commercial speed, fuel consumption, and service frequency are produced. The performance characteristics of each alternative are stored on a computer disk and can optionally be displayed or printed.

The last module (Evaluation Process) is designed for the analysis of the various alternatives regarding their performance characteristics as evaluation criteria. The evaluation process is based on the careful identification of the significant differences and trade-offs among alternatives [5].

The system SIMULA is written in TURBO-PASCAL for the use of personal computers (IBM or compatible). For the graphic presentation of output results, SIMULA is closely linked with the GRAPHER software package. The following graphic facilities can interactively be displayed and plotted:

- Route profile (location of stations, gradients, and curves),
- Speed / distance profile
- Tractive effort / distance profile
- Total resistance / distance profile
- Graphic timetable diagram.

APPLICATION : SIMULATION OF ABOU KIR RAILWAY

The Abou Kir Railway

The Abou kir railway is the fastest mean of Alexandria local transport. It starts from Alexandria Main Station, serving the connection of the central area with the "Abou Kir" suburb as well as the low-income zones along the southern urban axis.

The route is about 22 km long and has 16 stops. The distance between the stops varies between 500 m and 2 800 m. Eleven reversible trains are operated on this route. Each train consists of a diesel-electric locomotive (type G 22 W/AC, constructed in 1980, 1500 HP, 110 km/h maximum speed, 80 tons weight) and 6 carriages (2 two axle bogies, constructed in 1979, 100 km/h maximum speed, 40 tons weight, 1500 passengers capacity). The maximum permissible speed on the Abou Kir route is 70 km/h.

According to the formal timetable, 64 trains are scheduled per day (18 operating hours) for each direction. During peak hours the trains run at intervals of 15 to 20 minutes. At off-peak periods, the headway is 30 minutes.

Figure 6 shows the route profile of the Abou Kir railway, including the location of the curves, gradients, and stations.

Upgrading Measures

The application presented here for the worth of a range of upgrading measures are illustrative only, the aim being to demonstrate the practicality of a simulation approach.

Three upgrading measures, namely excluding some intermediate stops, operating faster trains, and route electrification are investigated. The purpose of these upgrading measures is to minimize both travel time and fuel consumption, and at the same time to maximize both running speed and service frequency.

The application is carried out at two levels: (a) simulating a train run to evaluate train performance and line capability, and (b) simulating the timetable to evaluate dispatching rules and procedures.

With the help of SIMULA, a lot of alternative plans that define a broad spectrum of options are generated and evaluated. The simulation results are then introduced by presenting some of these alternatives, and the relationships which describe the interdependence between the railway system parameters and the performance characteristics.

Simulation of a train run

A basic alternative which represents the existing situation is first prepared and simulated (alternative 1). Figure 7 demonstrates a sample of the simulation output (performance characteristics); i.e. tractive effort, total resistance, and speed profiles.

The results of this simulation run show that for the outward direction, as an example, the whole route can be carried out in 49.59 minutes with 45.71 km/h average speed and 26.75 km/h commercial speed. The results illustrate also that the trains can not reach the maximum permissible speed during the movement over the small distances between stations.

Effect of excluding intermediate stops

Several alternatives simulate the operation on the Abou kir Railway in case of eliminating some intermediate stops.

Alternative 2: three intermediate stops are excluded, so that the smallest distance between stops increases to be more than 1.0 Km. Consequently, the travel time

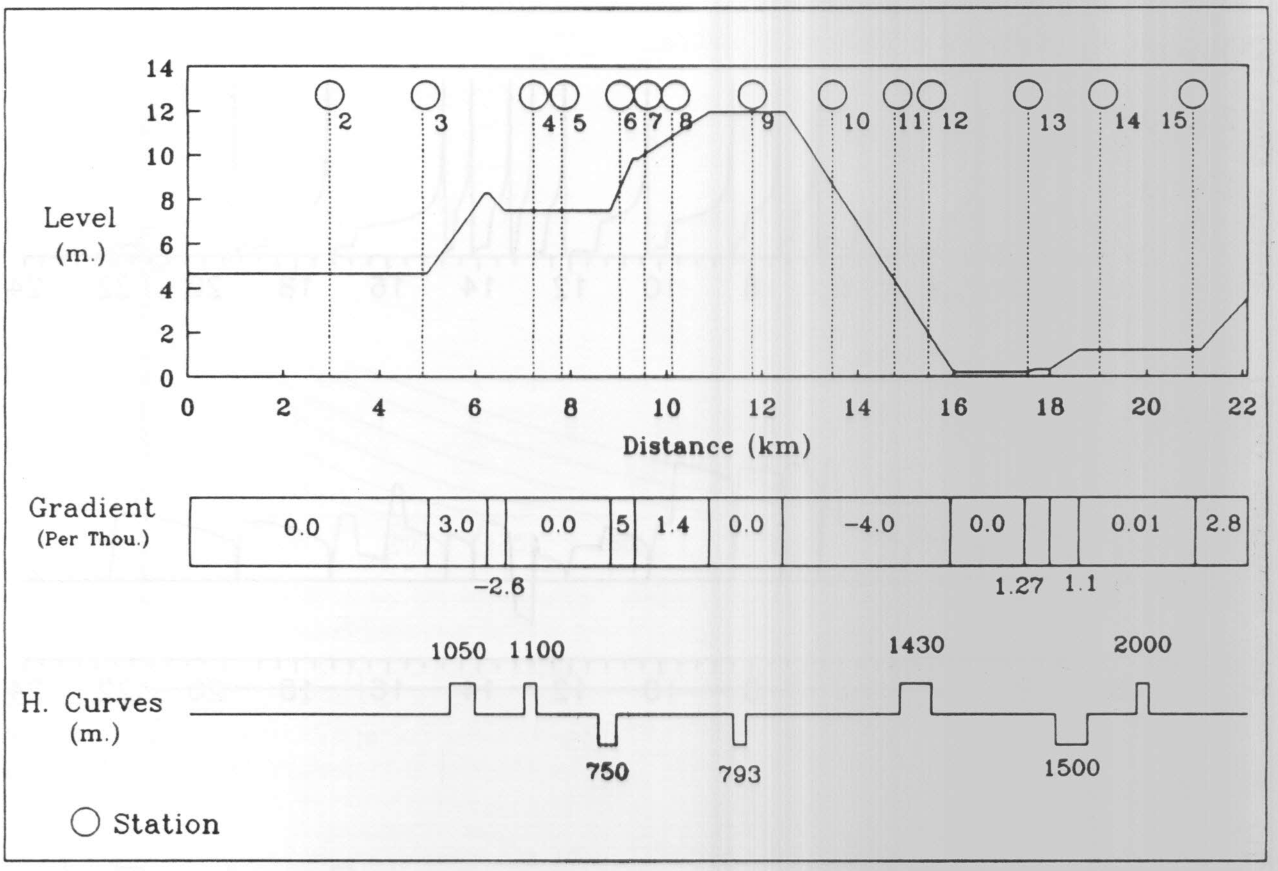


Figure 6. The route profile of the Abou kir railway

decreases to 43.0 minutes with 48.36 km/h average speed and 30.85 km/h commercial speed.

Alternative 3: five intermediate stops are eliminated, so that the shortest distance between stops reaches 1.5 km. In such manner, further reduction in the travel time is achieved; 38.14 minutes with 50.78 km/h average speed and 34.78 km/h commercial speed.

Figure 8 summarizes the results of different simulation runs, which are carried out to interpret the effect of varying the distance between stops on the travel time, and fuel consumption, as well as on the ratio "average speed to maximum speed". The main features are:

- The distance between two sequential stops limits the maximum running speed. The train can reach the maximum permissible speed, in the case of Abou Kir railway system, first when the distance between stops is longer than 1250 m.

The difference in travel time δ t increases gradually, if a train runs with speeds less than the maximum permissible speed. For instance, over a 1250 m. distance between two stops, if the trains run with different speeds; 60, 50, and 40 km/h, while the maximum speed is 70 km/h, the time difference will be about 1.3 %, 4.2 % and 16.6 %, respectively.

- The figure also shows the dependency of fuel consumption on the distance between stops in the case of running speeds; 40 km/h (open), 50 km/h, 60 km/h and 70 km/h (down). It can be seen almost linear, slightly convex increasing functions. The reason of increasing the fuel consumption by lower speeds is the longer travel time incurred. The fuel consumption is calculated here as the fuel demand is multiplied by the travel time.
- The relationship between distance between stops and

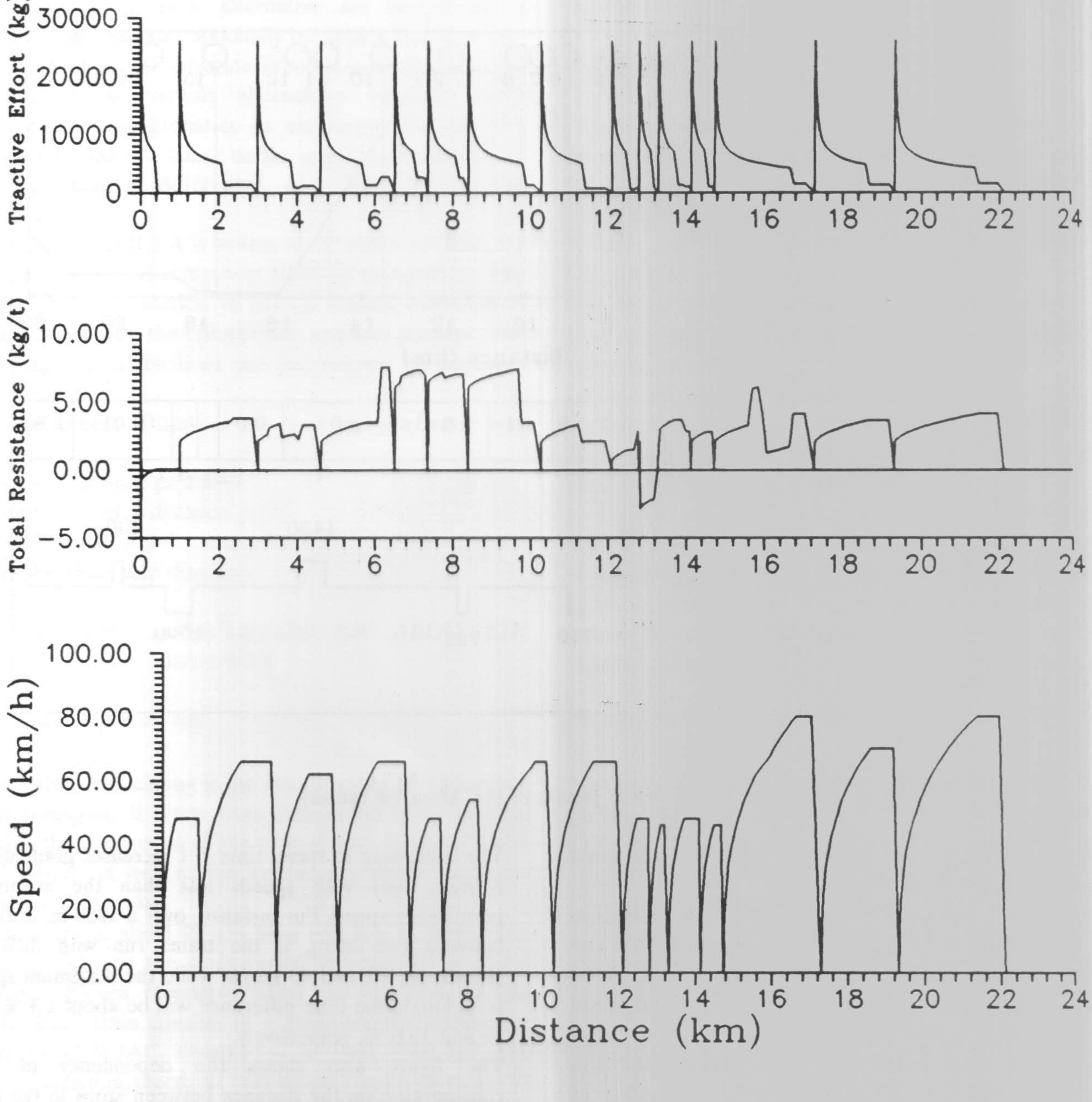


Figure 7. Sample of the simulation output (alternative 1)

average to maximum speed" ratio clearly proves that the nost feasible running performance (V_{avr}/V_{max} is naximum) can be achieved when the trains run over long listances between stops, particularly with lower speeds. However, the last circumstance affects negatively the other running performances (i.e. travel time and fuel consumption). For example, if a train runs over 2000 m. segment between two stops with a maximum speed 70 km/h the V_{avr}/V_{max} ratio will be 68 % . The ratio increases to 90 %, when the train travels with 40 km/h maximum speed. In this case, the fuel consumption rises to about 33 %, and the travel time extends about 30 % .

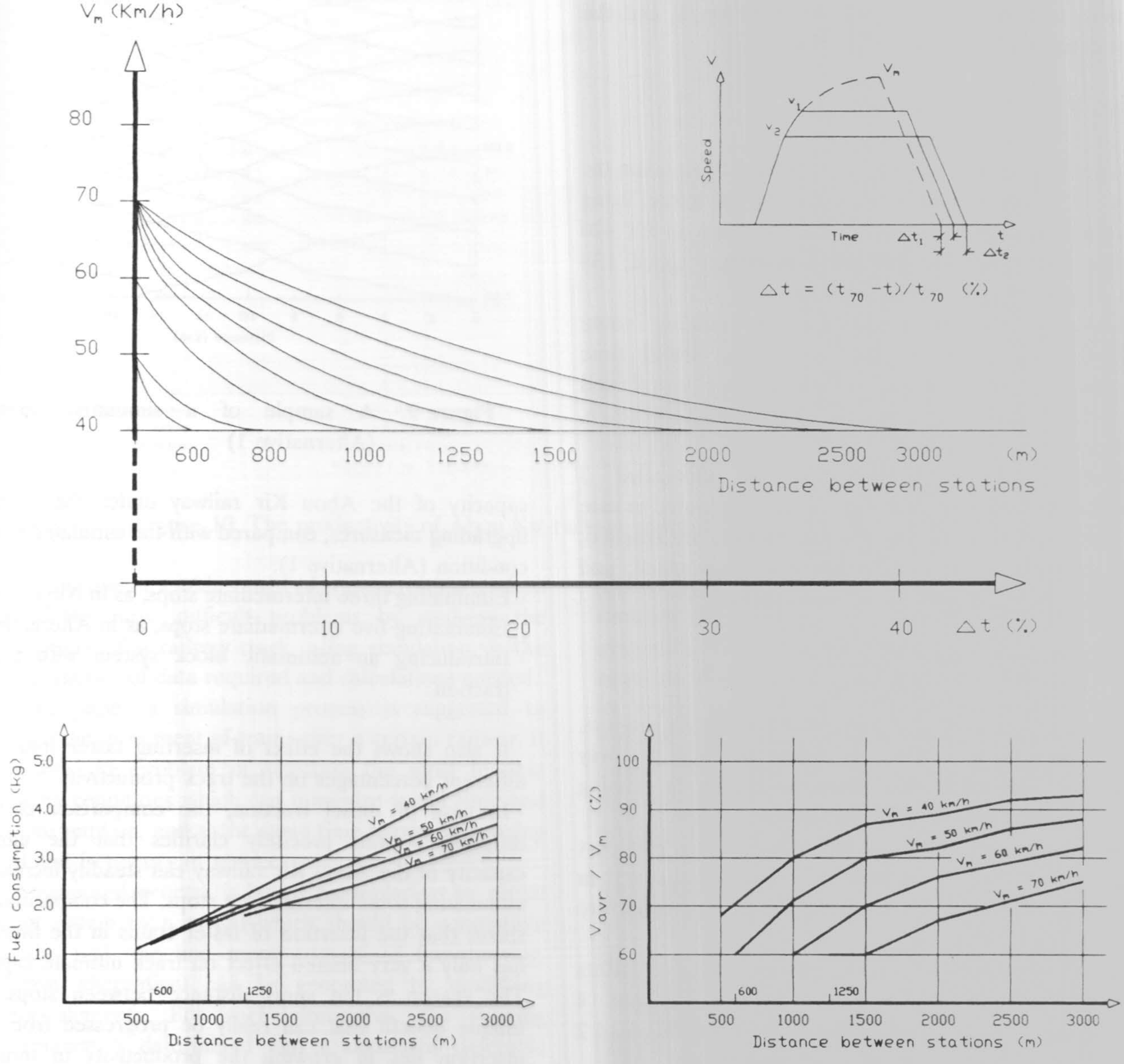


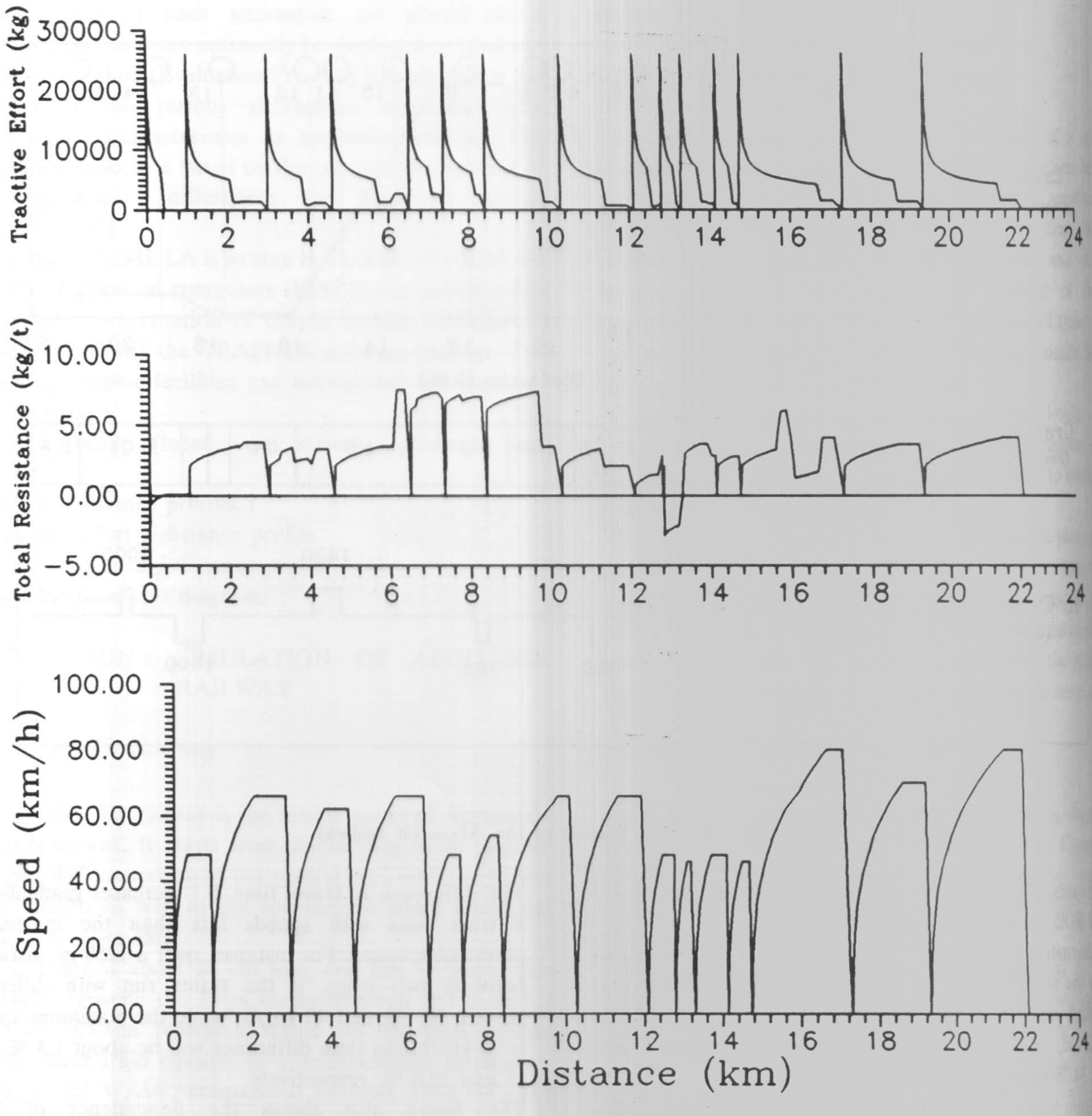
Figure 8. Effect of varying the distance between stop on the performance characteristics

Effect of increasing the motive power

Certain alternatives simulate the operation on the Abou kir Railway in case of replacing the present locomotives with others (2200 HP, 90 tons weight, 120 km/h maximum speed).

Alternative MP1: the existing situation is simulated by operating the new train. Compared with Alternative 1, the results show a slight reduction in travel time (3.07 minutes). The average speed reaches 50.26 km/h and the commercial speed increases to 28.52 km/h. As the horsepower of the locomotive used in this alternative is bigger than the first one, the fuel consumption is about 33% higher than the fuel demand in Alternative 1.

Alternative MP2: the situation of Alternative 3 (eliminating 5 stops) is also simulated by operating the



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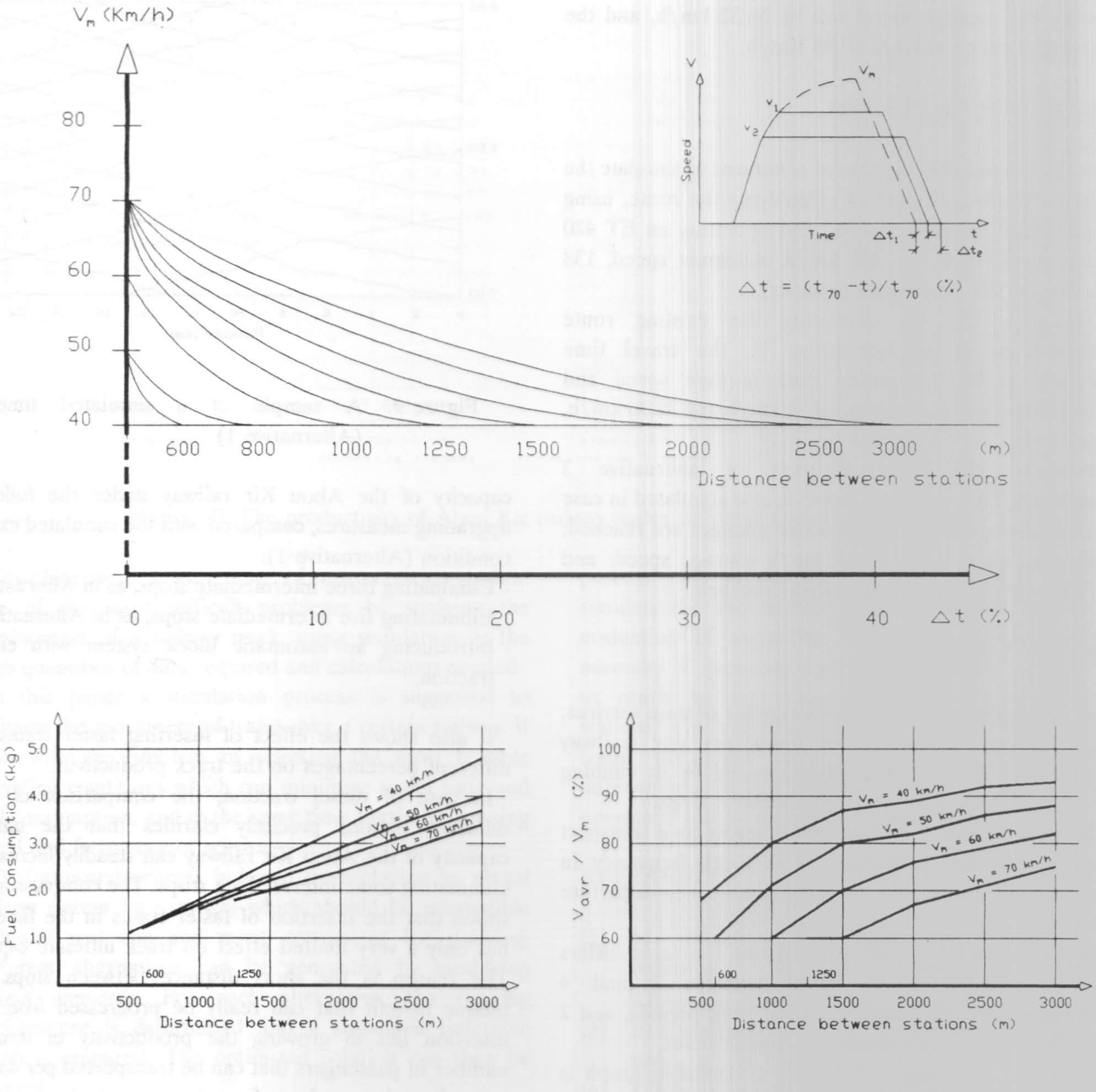

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Alternative MP2: the situation of Alternative 3 (eliminating 5 stops) is also simulated by operating the new train. In this case, the travel time will be 35.3 minutes, the average speed will be 56.32 km/h, and the commercial speed reaches 37.58 Km/h.

Effect of route electrification

Two additional alternatives are generated to simulate the Abou kir Railway in case of electrifying the route, using an automatic signaling system, and operating an ET 420 electric train (2400 Kw, 140 km/h maximum speed, 138 tons weight, 992 passengers capacity).

Alternative E1: by simulating the existing route configuration (as in Alternative 1), the travel time decreases to 49.59 minutes, both average speed and commercial speed increase to 63.51 km/h and 32.36 km/h, respectively.

Alternative E2: The situation of alternative 3 (eliminating 5 intermediate stops) is also simulated in case of route electrification. Remarkable changes are reached; 29.63 min. travel time, 73.78 km/h average speed, and 44.77 Km/h commercial speed was reached.

Timetable simulation

The railway supply consists of a number of train services, that is to say, a number of trains per day (railway productivity). Each train is characterized by its running time over the different segments between stops.

The investigation following below refers to a transport supply constructed on the basis of an hourly frequency. In that case all trains run to fixed times; i.e. departure minutes.

For the Abou Kir railway, the existing timetable offers service frequency which varies between 3 and 4 trains/hour in each direction during peak periods, and 2 trains/hour in each direction at off-peak times.

Regarding the existing situation, a timetable graph is created, using the "time departure model" described earlier. Figure 9 illustrates a sample of the simulated timetable produced. Then, a lot of alternatives which presents different upgrading strategies is generated and analyzed. It is not the primary purpose of this paper to discuss the actual simulation results. However, Figure 10 gives an indication of few results based on several simulation runs that assess the effect of some upgrading measures on the railway productivity.

The values presented in Figure 10 shows the ultimate

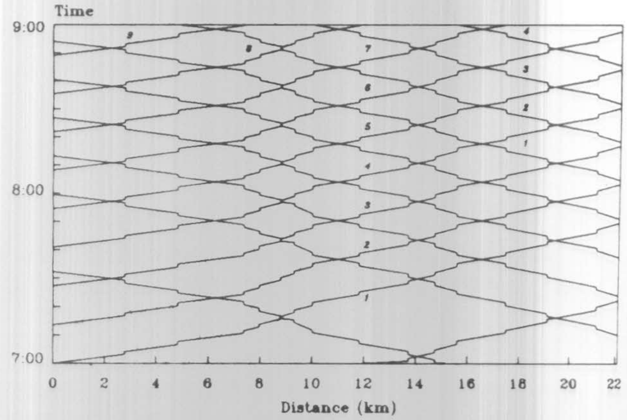

Figure 9. A sample of a simulated timetable (Alternative 1)

capacity of the Abou Kir railway under the following upgrading measures, compared with the simulated existing condition (Alternative 1):

- Eliminating three intermediate stops, as in Alternative 2.
- Eliminating five intermediate stops, as in Alternative 3.
- Introducing an automatic block system with electric traction.

It also shows the effect of inserting faster trains with different percentages on the track productivity.

In case of diesel traction, the comparison of these different options precisely clarifies that the ultimate capacity of the Abou Kir railway can steadily increase by eliminating some intermediate stops. The comparison also shows that the insertion of faster trains in the timetable has only a very limited effect on track ultimate capacity. The reason is the short distance between stops. The unique benefit that can really be progressed from such insertion lies in growing the productivity in terms of number of passengers that can be transported per day; i.e. expanding the number of carriages per train due to the greater motive power.

The results do not directly tell how the railway ought to operate, or in this instance, the investments required. This is still a matter of further engineering judgment and economic appraisal using the simulation results.

CONCLUSIONS

The improvement of railway operation has long been a

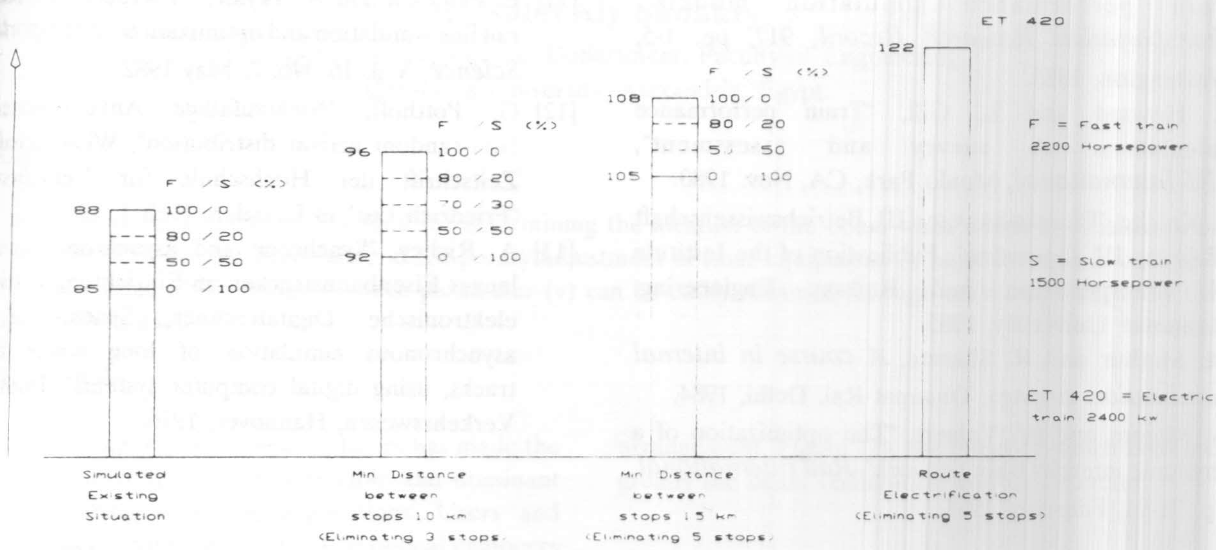

Figure 10. The productivity of Abou Kir railway under different upgrading strategies

major objective of a wide range of transportation studies. One of the most difficult problems by studying the development of a railway track, using simulation, is the large quantities of data required and calculations needed.

In this paper a simulation process is suggested to optimize the movement of trains over a certain railway. It deals with the problem of selecting the most feasible operating conditions which can minimize travel time and fuel consumption, and at the same time maximize running speed and frequency of service.

The proposed process is based on replacing an actual railway system by a model which should be compatible with the real one and more convenient for studying. Different alternatives can be generated by modifying system elements. For each alternative, the running performance is determined and a simulated timetable graph is prepared. The optimized solution can then be selected.

In the suggested simulation process only one or two elements are changed from each simulation run, so that the effect can be clearly seen. Simulation does not directly give an "optimal" result. However, successive simulations can iterate towards an optimum solution.

An interactive computer system is then designed in order to facilitate the application. The program can deal quickly with large amount of data, with adequate accuracy.

To test the practicability of the proposed simulation process , the supporting computer system is applied to simulate the movement on the Abou Kir railway. The evaluation of upgrading alternatives demonstrates the necessity of excluding several intermediate stops in order to reach an approximately uniform speeds between stations. The evaluation also shows that inserting faster trains does not have a significant effect on the improvement of this regional railway, i.e. on revising the operation and increasing the productivity.

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