COMPUTER ELABORATION OF TIME-TABLE
FOR SINGLE RAILWAY LINE

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ABSTRACT

This paper presents an introduction of computer techniques for the elaboration of railway time-tables. A single track line section is treated.

A short survey on data-processing organization is given including the automatic preparation of output data: the drawing of train diagram and the printing of train data.

Particularly, the method for solving the time-table problem is formally described and the appropriate criterion function is presented.

INTRODUCTION

The most considerable part of researches having for subject the introduction of data-processing techniques for the elaboration of a railway time-table have for their starting point the final product - the train diagram. This problem being obviously very large is however, due to its complexity, generally dealt with only partially. The most considerable contributions in this field are listed in references herewith under items (1), (2), (3), (4) and (5). Our way of taking into consideration this problem is quite similar. Aiming to master as large part of the problem as possible, we have started with the purpose of mastering the implements for line sections. This is only a part of the field that can be considered. Obviously there remains open the question what completion of the entire data-processing and programming package would be optimal, or where the desired automatization level occurs. Whether it would be worth trouble to embrace the largest possible area at any rate or it would be necessary to take into account the proportion between the cost of product and its efficiency. This paper has for its subject the task which is to automatize the last phase of operation - elaboration of train diagram and train schedule on line section. Should we adopt in the course of time a kind of two-phase processing, fig.1 represents the following: our actual level of results is represented by shaded areas, while within the elaboration of time-table for a part of railway network the first phase would represent the rough processing determining the tasks for line sections, while the detailed elaboration of time-tables for line sections would be embraced by the second phase.

Figure 1.

The choice of adequate methods is not quite simple, since each Railway accentuates in the first place its own specific problems, and there is a lack of uniformity of attitudes in that field. There are some opinions that the universal solution would not be efficient. Even if we treat only single line section there are numerous possible solutions yet not easy to be estimated. Then we apply additional conditions and rules thus entering the field of heuristics and with this renouncing the optimum (except in the case it is occasionally found). Due to the existence of numerous solutions we apply the Monte Carlo technique of random testing. The next characteristic is the look-ahead method for solving conflicting situations. These would be the three basic characteristics of method applied.

The input data are quite heterogenous and their preparation is hard to be automatized. A part of data was collected from appropriate services, some were prepared by means of a programming package in use with Yugoslav Railways, the paper listed in references herewith under item (6) gives a good survey of the latter.

The output data represent the train diagram and the data on trains necessary for the time-table booklet officialy in use (e.g. the post of engine-driver is provided with the booklet ...). Both are represented on fig.6 and 7. With the exception of intermediate controls and corrections the way to the final product is automatized. The drawing embraces marks for minutes, numbers of trains and lines which represent the train trajectory. The fig.7 represents the output schedule for one train, fig.6 reproduces the drawing with an OFF-line plotter.

The fig.2 gives the rough flow chart of elaboration. It can be seen that it consists of two parts. The first part is the preparation. The time when to effect the preparation has not been determined, it can be effected much in advance or just before the execution. The second part is the execution in a limited sense to be effected when there is necessity of a new final product. The first correction has for its purpose to re-process those data which have been modified and to choose the trains for line section. Thus an incomplete work file is prepared, it represents only a basis for elaboration of time-table, since during the optimization the file is completed in such a way that we can obtain from it the necessary informations for drawing train diagram and printing.

———— AUTOMATED WORK
----- HUMAN WORK

DATA AND NOTATION

To facilitate the understanding of the applied method we shall list here- under the necessary notations and partially present the data which are being used. The input data have been classified in accordance to the mode of preparation to those prepared by means of computer and the ones provided by adequate services. As for the execution itself there is a more useful classification of data, namely data used in the optimization process and data used for preparation, printing or drawing. The first lot is more important and will be formally enumerated while other data are not so essential (e.g. for printing of train itinerary, for data needed for each single category of train such as: percentages of braked weight, maximum speeds etc., for estimation and printing of necessary elements on line sections where local passenger trains have to wait in stopping-places, a series of elements for previously effected simulations, various sizes for printing and drawing etc.).

Notation:

c	category of train
d	solution of conflicting situation
e	estimation of energy consumption for traction
f	criterion function
g	physical weight
i	station or section between two neighbour stations
j	direction
k	level in the tree of conflicting situations
l	locomotive type
n,m,v	train
p	distance statistical data
q	conflict of two trains
r	weighted value of train
t	time
u	mode of running between two stations
w	sample of solution of conflict tree
x	binary switch
y	stop switch
α	coeff. of prices
γ	decision coeff. for "obvious" conflicting situations
δ	unit step function

ϵ	interval for choice of time segments
λ	number of tracks in station
θ	time statistical data
$\Delta\tau^{\text{int}}$	time intervals needed for trains in traffic
$\Delta\tau^r$	running time
$\Delta\tau^s$	minimum waiting time
τ^l	time limit for locomotive delay
τ^t	time limit for train delay
τ^o	time after the train is available at initial station

CRITERION FUNCTION AND TRAIN WEIGHTING

The criterion function reflects a relation between incomes and expenses, i.e. we shall make efforts in obtaining the best possible results for a line section. The criterion function is constructed in such a way as to facilitate the comparison of two trains as well as of two different time-tables. It seems to us that it is essential to introduce train weighting in the criterion function. The mode of train weighting will be given priority treatment. Although it is difficult to estimate incomes and expenses, (these can be determined from various analysis), the main problem consists in how to determine or take into account the train priority class which has no quantitative indicator. The strict appliance of priority treatment for the higher priority train must be sometimes given up especially on particularly busy section where it is difficult to operate the desired volume of traffic. Therefore we take simultaneously all trains into treatment and try to keep a certain proportion between the running time and waiting time by means of train weighting. From statistical data it is possible to determine a relationship among the following quantities:

actual running time	θ_1
actual traveling time	θ_2
actual distance	p
category of train	c

The value r_c is determined for each group of trains of the same category which were in operation during the period of time for which we have the available data:

$$r_c = p / (\theta_2 - \theta_1) \quad (1)$$

The value of r_c obtained for some categories of trains can be found in fig.3.

Figure 3.

The value r_c can be explained as the average number of km lost due to unit waiting time. This gives the possibility of valuating the waiting time of a train by means of the lost gross transport operation, and can be included into the criterion function. If we want, notwithstanding the statistical data, to obtain better relative results with trains of category c we can increase the value r_c over the one obtained from p, θ_2 and θ_1 . It is essential to try to estimate how a unit of waiting time reduces the income since this does not represent a productive transport operation. We can apply here the undimensional fraction r_c/r_0 where r_0 is constant and represents the weight for some fictitious category of train having $\theta_2 = 2 \cdot \theta_1$, i.e. the waiting time equal to the running time.

According to the notation we can write t_{n,i,j_n} for departure time and $t_{n,i,1-j_n}$ for arrival time for train n , at station i respectively. For some other elements in the criterion function we introduce the matrix for stopping $[y_{n,i}]$:

$$\begin{aligned} t_{n,i,j_n} = t_{n,i,1-j_n} &\Rightarrow y_{n,i} = 0 \\ \text{otherwise} &y_{n,i} = 1 \end{aligned} \quad (2)$$

and the function:

$$u = 2 \cdot y_{n,i+2j_n-1} + 1 \cdot y_{n,i} \quad (3)$$

which illustrates the mode of passage on a line section between two neighbour stations. The range of values $u \in \{0,1,2,3\}$ represents the following:

$u=0$ no waiting either before departure or upon arrival,
 $u=1$ waiting only upon arrival,
 $u=2$ waiting only before departure,
 $u=4$ waiting before departure and upon arrival.

Coefficients α^a , $a \in \{1,2,\dots,6\}$ represent:

- α^1 income per gross ton km,
- α^2 expense per gross ton minute,
- α^3 expense per minute of locomotive delay,
- α^4 expense per minute of train delay,
- α^5 expense per kwh for traction energy,

α^6 expense per stopping.

In order of appearance the expressions in the criterion function have the following meaning: 1.) estimate of income per train from gross effected transport work, 2.) estimate of expense or lost income for gross weight-time where the running time is not weighted while the waiting time is weighted with r_c/r_o , 3.) estimate of expense due to locomotive delay, 4.) estimate of expense due to train delay, 5.) estimate of expense due to the energy consumption for traction, 6.) estimate of additional expense for those stoppings that have been subsequently introduced.

The criterion function is:

$$f = \sum_n f_n \quad (4)$$

where

$$\begin{aligned} f_n = & \alpha^1_{c_n} \cdot P \cdot g_n - \\ & - \alpha^2_{c_n} \cdot g_n \left(\frac{r_n}{r_o} \sum_i (t_{n,i,j_n} - t_{n,i,1-j_n}) + \sum_i (t_{n,i_a,1-j_n} - t_{n,i,j_n}) \right) - \\ & - \alpha^3_{l_n} (t_{n,I \cdot j_n + 1 - j_n, 1 - j_n} - \tau_n^1) \cdot \delta(t - \tau_n^1) - \\ & - \alpha^4 (t_{n,I \cdot j_n + 1 - j_n, 1 - j_n} - \tau_n^t) \cdot \delta(t - \tau_n^t) - \\ & - \alpha^5 \sum_i e_{c_n, 1 + u_{n,i}, i} - \\ & - \alpha^6 \sum_{i, \Delta \tau \neq 0} y_{n,i} \end{aligned}$$

$\delta(t)$ represents unit step function, $i \in \{1, 2, \dots, I\}$ stations and $i \in \{1, 2, \dots, I-1\}$ sections between two neighbour stations.

DESCRIPTION OF PROCEDURE

We take into consideration the 24-hour time-table embracing the N_o set of trains. The solution would represent the determination of matrix elements $t_{n,i,j}$ along with fulfillment of condition (13). The procedure can be simplified in such a way as to treat each train n N_o only in the look-ahead method (and in the computer central memory). Consequently the

time-table cycle of 24 hours will not be closed and it is therefore necessary to point out two facts:

-the first train to be treated, that is, the reference time t_0 before the beginning of the procedure, must be chosen in such a way to facilitate the conclusion of the time-table cycle and to choose within a set of trains of sufficiently high priority class,
 -upon the end of the procedure there remain some unsettled conflicts (in our case studie there remained two to five conflicts), which are solved within the correction work, provided we give priority to trains from the beginning of the cycle and thus assure there are no further influences to the already settled trains.

The notation for stations $i=1, i=2, \dots, i=I$ rises in the direction $j=1$ of increasing number of kilometers. The section between two neighbour stations i and $i+1$ is marked $i'=i$. If j_n determined the direction of train n , it can be seen that at the departure of train n from the station i the section i' has been passed:

$$i' = i + j_n - 1 \quad (5)$$

and that the following station i_a is:

$$i_a = i + 2 \cdot j_n - 1 \quad (6)$$

We then subsequently treat one part after another of the time table represented by sub set NCN_0 of trains:

$$t_0 - \epsilon_1 \leq t_{n, i_0, j_n} < t_0 + \epsilon_2 \quad \Rightarrow \quad n \in N \quad (7)$$

$$i_0 = 1 \cdot j_n + I \cdot (1 - j_n)$$

Where $\epsilon_1, \epsilon_2 > 0$ are according to experiences determined sufficiently large time intervals.

Each time a new train is inserted into the set N we set its "ideal" trajectory. This trajectory represents the determination of elements $t_{n, i, j}$ in such a way as if there were no other trains on the line section. In this case the train n departs from its initial station i_0 at a moment τ_n^0 when available. The waitings are determined only in those stations where the minimum allowed waiting time is greater than zero:

$$\begin{aligned} \Delta \tau_{n,i}^s > 0 &\Rightarrow y_{n,i} = 1 \\ \text{otherwise } y_{n,i} &= 0 \end{aligned} \quad (8)$$

and

$$t_{n,i_a,1-j_n} = t_{n,i,j_n} + \Delta \tau_{c_n,i',1+u_{n,i}}^r \quad (9)$$

where $i_a = i + 2 \cdot j_n - 1$ and $i' = i + j_n - 1$.

We can see that the train with the ideal trajectory would have the smallest traveling time and as a rule will have the biggest f_n (though the value of the expression for the consumed traction energy does not decrease). When condition (13) is fulfilled new waitings and deformations of train trajectory are introduced.

For each $t_{n,i,j}$, ($n \in N$) occurring after t' the following relation must be valid:

$$t' < t_{n,i,j} \quad (10)$$

Therefore if a segment of the time-table, treated through the set N embraces also midnight, a simple linear transformation is required. Obviously this must be taken into account when forming the final data for the set N_0 of trains.

To ascertain the existence of a conflict for train n on section i between two neighbour stations we must check whether condition (13) has been fulfilled.

$$\begin{aligned} t_{v,i_a,j_v} \geq t_{n,i_a,j_n} > t_{v,i_a,1-j_v} &\Rightarrow x_{st}(v) = 1 \\ \text{otherwise } x_{st}(v) &= 0 \end{aligned} \quad (11)$$

According to fig.4:

$$\begin{aligned} (t_1 < t_I < t_2) \vee (t_{II} < t_4 \ \& \ t_5 < t_{III}) \vee (t_7 < t_{IV} < t_8) \vee \\ \vee (t_{11} < t_I < t_{12}) \vee (t_3 < t_{II} \ \& \ t_{III} < t_6) \vee (t_9 < t_{IV} < t_{10}) &\Rightarrow x_r = 1 \\ \text{otherwise } x_r &= 0 \end{aligned} \quad (12)$$

we have:

$$(\lambda_i > \sum_{\substack{v \in N \\ v \neq n}} x_{st}(v)) \ \& \ x_r = 0 \quad (13)$$

If condition (13) has been fulfilled we set $x_c = 0$, otherwise $x_c = 1$. The times t_b , $b \in \{I, II, III, IV\}$, representing the running of the second train v through section $i+j_n-1$ between two neighbour stations:

$$\begin{aligned} t_I &= t_{v,i,1-j_n} \\ t_{II} &= t_{v,i,j_n} \\ t_{III} &= t_{v,i+2j_n-1,1-j_n} \\ t_{IV} &= t_{v,i+2j_n-1,j_n} \end{aligned} \quad (14)$$

The time limits t_z , $z \in \{1, 2, \dots, 12\}$ are given in fig.4 and are obtained by means of time intervals needed for trains in traffic:

$$t_z = t^{\text{dep/arr}} \pm \Delta \tau_{i,j_n}^{\text{int}} \quad (15)$$

where $t^{\text{dep/arr}} \in \{t_{n,i,j_n}, t_{n,i,1-j_n}\}$ and $\text{int} \in \{1, 2, \dots, 5\}$ for five different intervals.

Therefore:

$$x_c = 1 \quad \Rightarrow \quad m = v \quad (16)$$

m is the second train in conflict, or the "conflicting" train to the train n on the section $i+j_n-1$.

In order to find what are the consequences of solving that conflict we form the binary conflict tree (see fig.5) so that for the chosen number of levels K in the tree we look for $Q = 2^K - 1$ nodes and form the tree by means of the sequence $q \in \{1, 2, \dots, Q\}$. One node of the tree corresponds to each single conflict. For each conflict $q < 2^{K-1}$ we look for the next two conflicts where the first and second trains are:

conflict	q	$2q$	$2q+1$
first train	n	n	m
second train	m	m_{2q}	m_{2q+1}

The trains m_{2q} and m_{2q+1} are the "new-conflicting" ones.

Figure 4.

The solution of each conflict in the sense of fulfilling condition (13) can be effected in such a way as to give priority to the train n , for which we set the indicator $d=1$, or to give priority to the second train m and set the indicator $d=0$. Therefore $d \in \{0,1\}$.

The conflict $q=1$ represents the basic conflict, while other $q \in \{2,3,\dots,Q\}$ represent the survey area. We wish to determine d_1 along with estimating the consequences of such a decision on the survey area. There are 2^Q possible solutions for such a tree and we cannot survey them all. For that reason we effect samplings using the sequence of pseudorandom numbers $\{p_v\}$, $p_v \in \{0,1\}$.

For $q=1$ (the basic conflict) we set:

$$\begin{aligned} f^1 > f^0 &\Rightarrow d_1 = 1 \\ \text{otherwise} & d_1 = 0 \end{aligned} \quad (17)$$

where

$$f^1 = \sum_w f(d_w^1) \quad f^0 = \sum_w f(d_w^0) \quad (18)$$

and $w \in \{1,2,\dots,W\}$ is the index which illustrates one sampling. Upon each sampling the solution is evaluated and then cancelled in such a way as to set again the previous "ideal" train trajectories. The vector d_w which determines the solution takes $2W$ values (W -times $d_1=1$ and W -times $d_1=0$):

$$\begin{bmatrix} d_w^1 \end{bmatrix} = \begin{bmatrix} 1 \\ d_2 \\ d_3 \\ \vdots \\ d_Q \end{bmatrix} \quad \begin{bmatrix} d_w^1 \end{bmatrix} = \begin{bmatrix} 0 \\ d_2 \\ d_3 \\ \vdots \\ d_Q \end{bmatrix} \quad (19)$$

For "obvious" solutions d_q is determined by:

$$\begin{aligned} \gamma_{c_n, c_m} < \Delta t = t_{m, i_\gamma, j_m} - t_{n, i, j_n} &\Rightarrow d_q = 1 \\ \gamma_{c_m, c_n} < \Delta t = t_{n, i, j_n} - t_{m, i_\gamma, j_m} &\Rightarrow d_q = 0 \\ (\text{for } j_n \neq j_m &\Rightarrow i_\gamma = i_a \text{ otherwise } i_\gamma = i) \\ \text{otherwise} & d_q = p_v \end{aligned} \quad (20)$$

We thus obtain that the number of possible solutions is reduced 2^{Q_d} times if among Q conflicts there are Q_d conflicts with "obvious" solutions. $[\gamma]$ is a $C \times C$ square matrix that contains those times which according to experience guarantee that it is not worth while to check another inferior alternative.

After d_1 has been determined, again all trajectories are set in the way they have been previous to sampling, except the conflict $q=1$ which has been solved since that moment and is not modified any more. The solution is in accordance with the chosen d_1 , of course.

The choice of the following conflict is done by choosing from the set N the train n having the departure time from station i nearest to the reference time t_o and at the same time that it is possible to obtain for (n,i) the conflicting train m :

$$(t_{\min} = t_{n,i,j_n} - t_o) \ \& \ (x_c = 1) \quad \begin{matrix} n, m \in N \\ n \neq m \end{matrix} \quad (21)$$

Along with the solution of conflicts $t_{\min}$ increases and we must take care that:

$$t_{\min} < t_{\text{critical}} \quad (22)$$

If $t_{\min}$ exceeds t_{critical} there remains the risk that we have not included on time some train from N_o in the set N . If this train had been in N it would have been included in one of the conflicts q . To avoid this, t_{critical} has to be chosen in such a way as to complete the set N early enough. Then a new reference time is set:

$$t_o = t_o' + t_{\text{critical}} \quad (23)$$

The trains that passed the entire line section are excluded from the set N since they will not be in further use.

We continue with this procedure until all trains have passed the line section. It is understood that, since within the last time segment there are no treatment of trains which have been solved already in the first one, some unsolved conflicts remain.

DESCRIPTION OF RESULTS

As shown in fig.2 the elaboration is concluded with the drawing of a time-table diagram for single-track line section and the printing of train data. Figure 6 shows a part of the train diagram for single-track section Ljubljana Jesenice which is a part of one of the main lines connecting the middle and south-east Europe. The drawing is effected in three phases. Phase 1 consists of drawing those lines which represent the train trajectories. There exists the possibility of drawing with various thickness of pen as well as with continuous or broken line. The second phase consists of drawing the minute marks. The location for the inscription of minute mark is determined from $t_{n,i,j}$, (according to existing regulations the inscription is done only for minute digit for departure and arrival if the train is provided with waiting time, while the hour and ten-minute digit can be read from the time axis), and the small shift is subjected to the cosinus of the angle made by train line and time axis. Since the plotter drawing requires quite a lot of time, we used it only in the case when a certain alternative has been already corrected and approved. The survey diagram which is used for checking the results, conclusion of time-table cycle etc., is produced on printer in a simplified version. After the correction the programming statements for drawing are generated and set on the magnetic tape. The complete file with the statements and appertaining data consists of approx. 240,000 char. or approx. 3,000 char. per train. The comparatively large number of necessary characters is due to the fact that the plotter was not provided with enough powerful software support and it was necessary to write the elementary statements, this being one reason more why we decided in favour of automatic generating of program statements on the main computer (IBM 360/30 with 128 K).

The printing of train data for the time-table booklet is in our case effected almost simultaneously with the drawing of diagram. With the standard non-EDP procedure this would follow only upon the execution of the diagram. The reason for it was obviously in the fact that the graphic version is more easily surveyed by the constructor. Thus, the classical preparation of the time-table booklet was reduced merely to the transformation and transcription of data. The direct printing will dispense the diagram constructor from that time consuming operation. We proceed to give explanations for the reading of adequate train data from fig.7.


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*****
                                TAGERN EKSPRES
                                EKSPRESNI VLAK ST. 218
                                SPLIT ZAGREB LAMBEJANA JESSENICE MUNCHEN DOSTENDE

                                1 IN 2 NAZRED

                                Q 362= 700 Y

*****
                                2              3              4              5              6              7              8              9              10             11
*****
LAMBELJANA              ISF:35              11 52.5              75 7C
LAMBELJANA STSFA              1.5              54.0
VITKARICE              3.5              57.5
MERKODE              3.5              12 01.0
SKOFJA LOKA              4.5              05.5
KRANJ              6.5              12 12.0              3.0              15.0
TODARST              9.0              24.0
LPSCE, MLED              10.0              34.0
ZITOVNICA              4.0              38.0
SGOTVRSKI JAVORNIK              4.0              75
USF:35
JESSENICE              SF              3.0              12 45.0
*****
64.1 VOZNI CRG: 0 49.5              POKRANITI: 0 03.0              POVOVA KIR: 0 52.5
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EKSPRESNI VLAK ŠT.	= Express train No.
1 IN 2 RAZRED	= 1st and 2nd class
VOZNI ČAS	= Running time
POSTANKI	= Waiting time
POTOVANJE	= Traveling time

The heading gives the following data: number of train, its itinerary, locomotive and gross weight. The columns present the following data: 1.) length of section between stations, 2.) name of station, 3.) passing-loop marks, 4.) section running time, 5.) arrival time at the station, 6.) waiting time, 7.) departure time, 8.) special waitings, 9.) maximum speed, 10.) percentage of braked weight, 11.) minimal running time. The last row indicates: total distance, total running time, total waiting time and total traveling time.

CONCLUSION

Notwithstanding further prospectives in automatization of time-table elaboration on the larger field, the actual level is also acceptable. It is an aid in making some alternative time-tables and allows the influence of the constructor in the choice of data and corrections. The particular purpose of the task will be more evident if the EDP would be extended to the time-table for regional railway network.

The proposed method does not assure the achievement of an optimum as far as the criterion function is concerned, but it facilitates the quite prompt searching of a good solution. The possibility is open for a more detailed analysis of parameters K , W and γ , their influence on the speed and quality, as well as analysis of the proposed method for weighting of trains.

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