

Automatic Train Control Algorithms with Regulation Restrictions Adaptive to System State Changes

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Abstract— Centralized automatic train control algorithm is proposed which allows effective adjustment of each train's departure and running times or intervals when there are unscheduled delays. The novelty lies in that it employs three sets of methods, called regulative characteristics, which contain relationships between regulation restrictions (minimal station dwell times and train running times). These relationships are obtained a priori from the simulation of train circulation on the detailed railway or metro line model, saving later onboard real-time processing requirements, which is especially useful for those train control systems which are being only partially modernized. In the traditional algorithms these regulation restrictions are frequently considered fixed, while the changes of system's state do affect them, so the usage of the values recurrently updated by the regulative characteristics allows to have more flexible running and station times for every train on the line. The efficiency of the new algorithm is additionally increased by the usage of forecasting of station dwell times and train running times based on the history of these values for each train or station. Proposed algorithm decreases the quantity of undesired stops between stations, allowing to save energetic resources spent on repeated train acceleration and to raise, in general, the quality of the transportation process algorithm has been tested on Mexico Metro Line simulator confirming efficiency increase of 3% for the worst case scenario and up to 10% for the best cases (busiest state of the line plus additional temporal speed limits).

Keywords— Railway transportation, Automatic Train Control, Metro, Regulation Algorithms, Centralized Control, Forecasting.

I. INTRODUCTION

Centralized Automated Train Control (ATC) together with Automatic Train Operation (ATO) systems allow modern railways to increment traffic density in order to satisfy the raising passengers affluence while maintaining the desired quality of the transportation process in urban and suburban rapid railways. While the problem of rising passenger affluence in all kind of urban and suburban transport is being addressed from different points of view [1-7, 12-22] over the years, many efforts were spent on the subject of automation of the train control [1, 8-17]. In the core of any ATC-ATO system lies a family of algorithms which operates mainly with the values of train running and station well times. Normally [1, 13-25], there is at two level hierarchy present: the higher level calculates the timing difference between the desired and executed scenario (which is normally based on a schedule, an interval or both). The timing difference is caused by per turbations. If the per turbation is considered compensable, the higher level calculates the operating values (running and station times) for each train on the line. If the perturbation is non compensable, new scenario (schedule or interval or both) is generated. The lower level then executes the control commands generated by the higher level. The way in which the higher level calculates the operating times depends on a strategy concerning preferential usage of available timing resources (station time resource preference, running time resource preference or hybrid) and on algorithm type: there are algorithms based on schedule which operate with astronomical times, and algorithms based on intervals that use relative times, while hybrid algorithms use both [1, 10]. All ATC-ATO algorithms have basic regulation restrictions, such as minimal station well time (or minimal station time), minimal interval departure interval and minimal running time. Their absolute minimal values are dictated by line and rolling stock physical parameters and traditionally considered as fixed. However, these values can be considered as restrictions which depend on current system state, meaning that the changes of departure intervals and running times of all the trains in the line caused by perturbations affect them (moving them towards more restrictive values). In this article we present the algorithm which considers the modifications in the regulation restrictions caused by system state changes based on method, also presented in the article, of regulative characteristics of the station-to-station blocks, where the regulative characteristics are families of curves that relate train control parameters and are obtained a priori on the railway line simulator. Such approach allows saving processing time for further onboard real-time calculations. Analytical calculations for

complete train and line model may involve up to several dozens of differential equations. This kind of calculations is time consuming, especially due to the non-linear nature of the line and train parameters. In many cases, experimental modeling is recommended over analytical calculation of the functions, especially for many ATC-ATO systems which are being only partially upgraded (such as, for example, Mexico City Metro system). We also show the effectiveness of the proposed algorithm by simulating its application on a detailed computer model of Mexico City Metro Line and present results with several quality criteria of transportation process improvement [1, 23, 25]. Parameters of the line, such as curves, grades, train type, blocks lengths and quantity between stations, among others, are considered within the detailed model of the developed simulator.

Proposed algorithm lowers the quantity of undesired stops between stations, allowing saving energetic resources spent on repeated train acceleration, for which the saving energy via train regulation is a known strategy [19-28]. The new algorithm performs best in schedules with high density and high repeatability, so it might be best suitable for metro lines or relatively short suburb lines. However, some of the principles described here might be applicable to longer railway lines.

II. TRADITIONAL ALGORITHMS EXAMPLES

In order to show the importance of considering regulation restrictions as dependable on system state changes, we shall analyze two ATC-ATO algorithms: one based on schedule and another based on intervals.

2.1 Algorithm based on schedule

One of the simplest algorithms based on schedule compensates train's arriving time deviation by modifying train's station dwell time, and compensates train's departure time deviation by modifying station-to-station running time. For example, in case of late arrival of the focused $[n]$ train, its real arrival time is greater than the planned:

$$\Delta T_{Aj}[n] = t_{Aj}^R[n] - t_{Aj}^P[n] > 0 \quad (1)$$

where $t_{Aj}^R[n]$ is the real actual time of n -train arrival on the j - station; $t_{Aj}^P[n]$ is the planned arrival time for n -train onto j -station; $\Delta T_{Aj}[n]$ is the deviation of the arrival time for n -train on the j -station.

Now, the only two timing resources the algorithm has for the train to compensate the late arrival and get back on schedule is either to shorten the station dwell time or to shorten the running time to the next station. At first, the algorithm will attempt to get back into schedule by shortening only the station time. The train will run at the commanded departure time equal to the time planned by schedule $t_{Dj}^C[n] = t_{Dj}^P[n]$ in compliance to the regulation restrictions on minimal station time (T_S^{\min}) and minimal departure interval (T_{DI}^{\min}) between the focused train and the ahead train $[n-1]$:

$$t_{Dj}^C[n] - t_{Aj}^R[n-1] \geq T_S^{\min} \quad (2)$$

$$t_{Dj}^C - t_{Dj}^P[n-1] \geq T_{DI}^{\min} \quad (3)$$

These restrictions are defined by the safety system of the line, also called Automatic Train Protection (ATP). If both restrictions are satisfied, then the timing resource of the station dwell time is enough for getting back on schedule, so, only train's station time is shortened; running time to the next station would not be changed, the perturbation (late arrival) for the focused train would be compensated.

If the condition (2) is violated (calculations demand station time to be shorter than the minimal restriction), it means that the timing resource of the station dwell time is not enough to get back on schedule. The generated departure time would be ignored as it appears to happen earlier than the minimal station dwell restriction time, thus, the train must depart upon fulfilling this minimal station time:

$$t_{Dj}^C[n] = t_{Aj}^R[n] + T_S^{\min} \quad (4)$$

$$t_{Dj}^C[n] = t_{Dj}^R[n-1] + T_{DI}^{\min} \quad (5)$$

At this moment, if either the condition (2) or (3) is violated, then the timing resource of shortening station time is not enough for getting back on schedule and the running time resource must be used. So, the station dwell time deviation would be compensated by modifying the running time $\Delta T_{Rj}^C[n]$ on the next station-to-station block:

$$\Delta T_{Rj}^C[n] = t_{Dj}^P[n] - t_{Dj}^R[n] \quad (6)$$

while also fulfilling the restriction on minimal running time T_{Rj}^{min} :

$$T_{Rj}^P[n] + \Delta T_{Rj}^C[n] \geq T_{Rj}^{min} \quad (7)$$

which is also a minimal restriction defined by the safety system of the line. If the calculated running time is greater than the minimal running time, then by executing it the train gets back on schedule by the time of arrival to the next station. Otherwise, if the commanded running time appears to be smaller than the minimal, the minimal running time must be executed.

If the timing resource is not enough to return to the planned schedule, then the perturbation is considered non compensable and the effective way of controlling the line is by using the algorithm based on intervals (which uses relative times instead of astronomical time) [1, 26].

2.2 Algorithm based on intervals

The interval algorithm is effective when the perturbation is greater than the timing resource that the algorithm has for the train to get back on schedule. The timing resources that the interval algorithm has for the train delay are the same: shortening the station time or shortening the running time. So, if the strict schedule is unreachable than sliding the schedule table ahead in time is the way of controlling the line, and the intervals, instead of astronomical timing, can maintain the slid schedule together. The general interval algorithm modifies the station time in order to compensate the deviation of arriving interval $\Delta T_{Aj}^C[n]$, while it modifies the running time in order to compensate the deviation of departure interval $\Delta T_{Dj}^C[n]$:

$$\Delta T_{Sj}^C[n] = L_1\{\Delta T_{Aj}^C[n], \Delta T_{Sj}^C[n-1], \Delta T_{Sj}^C[n-2], \dots, \Delta T_{Sj}^C[n-m]\} \quad (8)$$

$$\Delta T_{Rj}^C[n] = L_2\{\Delta T_{Dj}^C[n], \Delta T_{Rj}^C[n-1], \Delta T_{Rj}^C[n-2], \dots, \Delta T_{Rj}^C[n-l]\} \quad (9)$$

where L_1, L_2 are special operators which depend on the strategy, and m, l – the quantity of a head trains considered in the control command generation. For example, in the simplest interval algorithm which considers only one ahead train, the departure command is calculated as:

$$t_{Dj}^C[n] = t_{Dj}^R[n-1] + T_{Sj}^P[n] + \Delta T_{Sj}^C[n] \quad (10)$$

Where $t_{Dj}^C[n]$ is the commanded departure time for the n-train, $t_{Dj}^R[n-1]$ – real departure time of the ahead [n-1]-train, $T_{Sj}^P[n]$ – planned station time of the n-train, $\Delta T_{Sj}^C[n]$ – commanded compensation of the station time.

So the commanded departure time is made up from the sum of real departure time of the last departed train [n-1] added by the planned station time of the focused train [n] plus the commanded compensation of the station time modification. All the mentioned, once again, while the minimal station time and minimal departure interval are respected (conditions (2) and (3)). Otherwise the station and running times to be commanded are defined by the most restrictive of two conditions ((4) and (5)), as in the section 2.1. Then, the running time is modified according to (9) for $l = 1$:

$$\Delta T_{Rj}^C = -\Delta T_{Dj}^C[n] + k_1 \Delta T_{Rj}^C[n-1], 0 < k_1 < 1 \quad (11)$$

where $\Delta T_{Rj}^C[n]$ – is the modification to the running time that is to be commanded for the n-train towards the j-station;

$\Delta T_{Dij}[n]$ - is the deviation in the departure interval of the n-train (that is waiting to be departed);

$\Delta T_{Rj}^C[n-1]$ - is the modification of the running time that was commanded to the ahead train [n-1], and k_1 is a weight coefficient. The calculated modification must alter the commanded running time for the focused train, as long as the minimal running time condition (7) is respected. Otherwise minimal running time must be executed.

As we can see, both examples use fixed regulative restrictions of minimal station time and minimal running time marked by the absolute minimum defined by the safety system of the line. However, in the dense traffic of contemporary urban and suburban railway systems, and especially metro lines, even little timing perturbations on the line become a cause of raising the threshold of these minimal restrictions. For example, the late departure of ahead train would cause a restrictive signaling ("red light") on the arriving of the next running train, if its minimal departure interval and/or its minimal running time values are not raised above those absolute minimal values defined by the safety system. In the next paragraph we present a method to calculate and use special regulative characteristics of station-to-station blocks, which allows the effective raising of this minimum and lowering the probability of restrictive signaling ("red lights") of the safety system of the line, so the circulation without "red lights" appearing for the ahead trains would represent a nonrestrictive circulation.

III. INTRODUCTION OF REGULATIVE CHARACTERISTICS

In order to consider the way in which the system state changes affect the regulation restrictions, three functions, called special regulating characteristics of station-to-station blocks, are proposed. The characteristics are non-linear functions that establish the relations (curves) between involved variables of train circulation and are to be obtained *a priori* during experimental simulation process on the line's model to be later used in the ATO-CTC algorithm database. The values of the functions are defined by non-linear aspects of the line: station-to-station block curvature and profile, train acceleration characteristics, etc. [1, 12, 15, 17]. Due to this nature, experimental modeling is preferred over analytical calculation of the functions.

The use of the first regulating characteristic will allow nonrestrictive train circulation (no "red lights") upon the perturbation of late departure of the ahead train from the ahead station. In other words, it will prevent a train from being stopped by the "red light" between stations if the train ahead is late departing from the station ahead. This situation is typical when the passengers behavior on the station delays train's departure. The regulative characteristic defines the minimal departure interval for the focused train [n] as a function of running time and station time of the ahead train [n-1] on the station-to-station block ahead:

$$T_{DIj}^{min}[n] = f\{T_{Rj}[n-1], T_{Sj+1}[n-1]\} \quad (12)$$

where $T_{Rj}[n-1]$ – running time of the ahead train on the station-to-station block ahead,

$T_{Sj+1}[n-1]$ – station dwell time of the ahead train on the ahead station.

The method to calculate one by one the points of the characteristic curve comprehends the following sequence around the station-to-station block which is being studied in the simulator:

- 1) Process of running and dwelling experimental trains on the simulated block initializes with the absolute minimal values of the function defined by the safety system (minimal station dwell time, minimal running time, etc), these minimums will be raising their values to form the non-linear function of the regulative characteristic; the station-to-station block is limited by the focused station j and ahead station j+1; a virtual depot is created right before station j; a sequence of trains are to be commanded out of the depot towards the station j and then towards the station j+1, the dwelling and running times of the trains are to be changed during the experiment in order to find the relations that will allow nonrestrictive circulation; another virtual depot is created after the ahead station j+1, trains are to be virtually disappeared into the second depot, because only one station-to-station block is analyzed at a time, so the circulation ahead of j+1 station is not to be studied at this iteration of the process;
- 2) First train of the sequence arrives from a virtual depot to the first station of the block, then the train executes the minimal station time and departs from the first station executing minimal running time, after arriving to the ahead station it executes minimal station time on it and departs towards a second virtual depot, where it disappears;

- 3) While the first train performs its running between station j and station $j+1$, the second train arrives from the virtual depot to the first station and executes minimal departure interval before it departs towards the ahead station with minimal (the fastest) running time commanded; now, the second train has two possible outcomes: either it arrives successfully to the $j+1$ station, or it is stopped by a “red light” on the block;
- 4) If the second train meets the restrictive signaling (“red light”) on the station-to-station block, then the set of commanded values is not suited for nonrestrictive circulation and should not take part of regulative characteristic, it is rejected and the process is ready for the next iteration;
- 5) The experiment repeats itself with increased value of minimal departure interval until the second and following trains (up to a reasonable number, for example, 5 following trains) arrive to the second station without any restrictive signaling on the way. At this time one point of one curve of the regulative characteristic is found and saved, i.e. the minimal departure interval for the following trains when the ahead trains perform with the current running time and the current dwelling time on the ahead station;
- 6) At this point the experiment increases the minimal running time by a user-definable step (for example, 5 seconds) and the whole sequence repeats itself until the next raised minimal departure interval is found and saved, becoming the second point of the first curve of the characteristic; the experiment follows until the whole range of running times is studied and the minimal departure intervals for the whole set of running times is found forming a first complete curve of the characteristic that corresponds to only one ahead station dwell time;
- 7) Now the experiment repeats itself with increased value of ahead station dwell time executing again through the whole set of running times, thus, obtaining the second complete curve of the characteristic, point by point; here, the increase in the departure time of the ahead train is simulating the perturbation that is causing the train’s delay and the maximum value for this delay equals to the maximum perturbation delay that is being studied in the simulation experiment; for example, if a dwell time of 5 minutes is selected, then the perturbation delay of 5 minutes is simulated and the experiment will run the whole sequence within this range for the matter of ahead station dwell time;
- 8) Finally, the complete family of curves is obtained each of them corresponding to a particular ahead station dwell time, while relating a range of running times and departure intervals and, thus, a complete first regulative characteristic is obtained for the particular station-to-station block which is being studied. Later, the experiment must be repeated for each station-to-station block of the line.
- 9) The points of the characteristic are obtained for one station-to-station block at a time, but when complete family of regulation characteristics obtained for the line it provides the necessary data for the algorithm’s variety which considers any number of ahead trains in its calculations.

“Fig. 1” illustrates the first regulative characteristic graphically (a simplified example with reduced range) for one station-to-station block. The family of curves forming the complete first regulative characteristic should be calculated within the widest practical range of each involved value that corresponds to the practical perturbation timing. This way the later usage of the characteristic in the controlling algorithm will allow circulation without restrictive signaling upon typical perturbations.

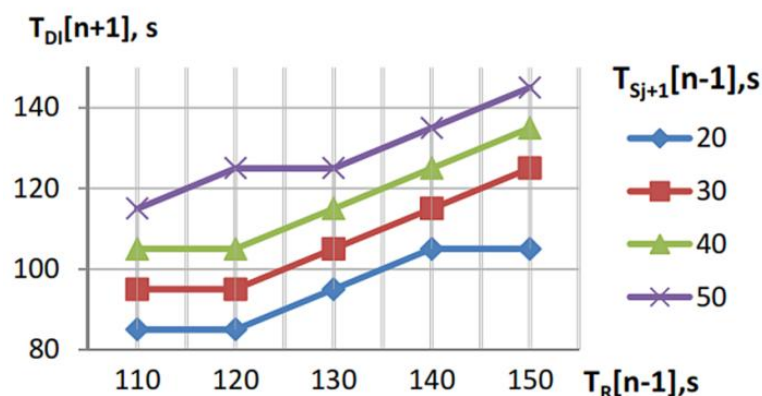


FIG. 1. EXAMPLE OF THE FIRST REGULATIVE CHARACTERISTICS FAMILY FOR A LIMITED RANGE OF STATION TIMES, RUNNING TIMES AND DEPARTURE INTERVALS.

While the first regulative characteristic allows nonrestrictive circulation despite departure delays on the ahead station, there is other kind of perturbations that should be considered on the line, that is – additional speed limit. Sometimes the additional speed limit is introduced when partial segments of the line are being under maintenance. Another reason is during precipitations (rain or snow) on the open segments of the line that specially applies to metro lines which are partially located underground and partially on the ground, as is the case of Mexico City Metro which was used for main simulation example.

The use of the second regulative characteristic of station-to-station block will allow non-restrictive circulation upon additional speed limit introduction between stations. The characteristic defines the minimal departure interval as a function of additional speed limit introduced on the block and station time of the ahead train on the ahead station:

$$T_{Dlj}^{min}[n] = f\{V_{ADj}, T_{Sj+1}[n-1]\} \quad (13)$$

where V_{ADj} – additional speed limit over station-to-station block j ,

$T_{Sj+1}[n-1]$ – station time of the ahead train on the ahead station.

The method of calculation follows the similar sequence as with the first regulative characteristic: the minimal departure interval is tested for a range of increasing additional speed limits while maintaining constant station time for obtaining one curve of the characteristic, then the experiment repeats itself for a range of ahead station dwell times, same range being used as in the first regulative characteristic. Later in the algorithm, the minimal departure interval will be selected from the second regulative characteristic if there have been an introduction of additional speed limit, or from the first characteristic if no additional speed limit is being assigned to the station-to-station block. “Fig. 2” illustrates the example of the reduced range of the function graphically.

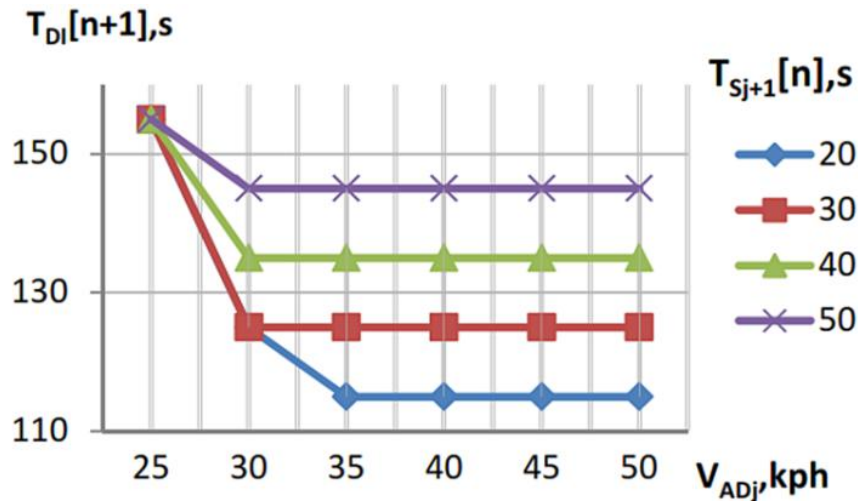


FIG. 2. EXAMPLE OF THE SECOND REGULATIVE CHARACTERISTICS FAMILY FOR A LIMITED RANGE OF SPEED LIMITS, STATION TIME AND DEPARTURE INTERVALS.

While the first and second regulative characteristics allow us to effectively select the new minimal departure interval, the third characteristic helps to choose the new minimal running time. It defines the minimal running time as a function of departure interval $T_{DI}[n]$ (previously selected either from the first or second characteristic), running time of the ahead train $T_{Rj}[n-1]$ and ahead station dwell time:

$$T_{Rj}^{min}[n] = f\{T_{DIj}[n], T_{Rj}[n-1], T_{Sj+1}[n-1]\} \quad (14)$$

“Fig. 3” illustrates the function graphically. The method of calculation is similar to the first and second characteristics, but, as the third characteristic is a function of three arguments, the simulating sequence requires the whole extra set of iterations for the additional argument. The resulting family of curves is three-dimensional, but for the similarity with the first and second

characteristics it is presented graphically as several two-dimensional families of curves located side by side on the same plane of coordinates (“fig. 3”).

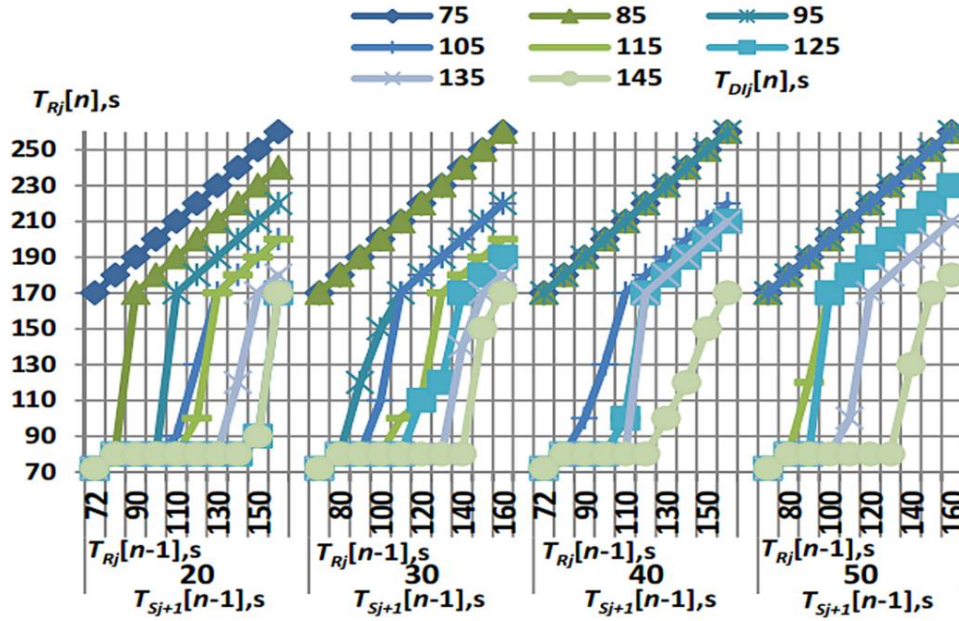


FIG. 3. EXAMPLE OF THE THIRD REGULATIVE CHARACTERISTICS FAMILY FOR A LIMITED RANGE OF RUNNING TIMES, AHEAD TRAINS RUNNING TIMES, DEPARTURE INTERVALS ORGANIZED IN GROUPS OF STATION DWELL TIMES.

IV. FORECASTING STATION AND RUNNING TIMES FOR THE AHEAD TRAINS

As we can notice from the equations of “section 3”, two arguments of the regulative characteristics require special attention: station time of the ahead train on the ahead station $T_{Sj+1}[n-1]$ and running time of the ahead train $T_{Rj}[n-1]$. In the conditions of dense traffic these values are not always known at the moment of departure of the train for which the regulative characteristics are to be selected. Thus, a forecasting of these values is proposed, based on historical values that these magnitudes presented. In the proposed model for station time, the deviation of train’s departure is extrapolated upon known deviations of real departure times from planned departure times for a series of trains that have already passed the station:

$$T_{Sj+1}^*[n-1] = T_{Sj+1}^P[n-1] + F_{Sj+1}^*[n-1] \quad (15)$$

where $T_{Sj+1}^P[n-1]$ – planned station dwell time for the ahead train on the ahead station,

$F_{Sj+1}^*[n-1]$ – forecasted deviation of ahead train’s departure time from the ahead station,

$T_{Sj+1}^*[n-1]$ – forecasted station time of the ahead train on the ahead station.

Least square method of first and second order was used for forecasting the deviation based on progression of different series of passed trains:

$$F_{Sj+1}^*[n-1] = \sum_{i=0}^M F_{Sj+1}^R[n-2-M+i]L^i \quad (16)$$

Where $F_{Sj+1}^R[n-2-M+i]$ are the historic values of real deviations for the variable that is being extrapolated;

$M+1$ – is the quantity historic trains ahead that are being taken into account for the extrapolation method;

L^1 – is the operator of least square method of first order (when $l = 1$) or second order (when $l = 2$).

There is a necessity of assessing the inaccuracy of the forecasting method, in order to do that we must study the level of correlation of the values $F_{Sj+1}^R[i]$ for a number of historic ahead trains. A set of typical correlations was used:

$$R_1(k) = \sigma^2 \frac{\sin \omega_0 k}{\omega_0 k} \quad (17)$$

$$R_2(k) = \sigma^2 e^{-\alpha^2 k^2} \quad (18)$$

$$R_3(k) = \sigma^2 e^{-\alpha |k|} \quad (19)$$

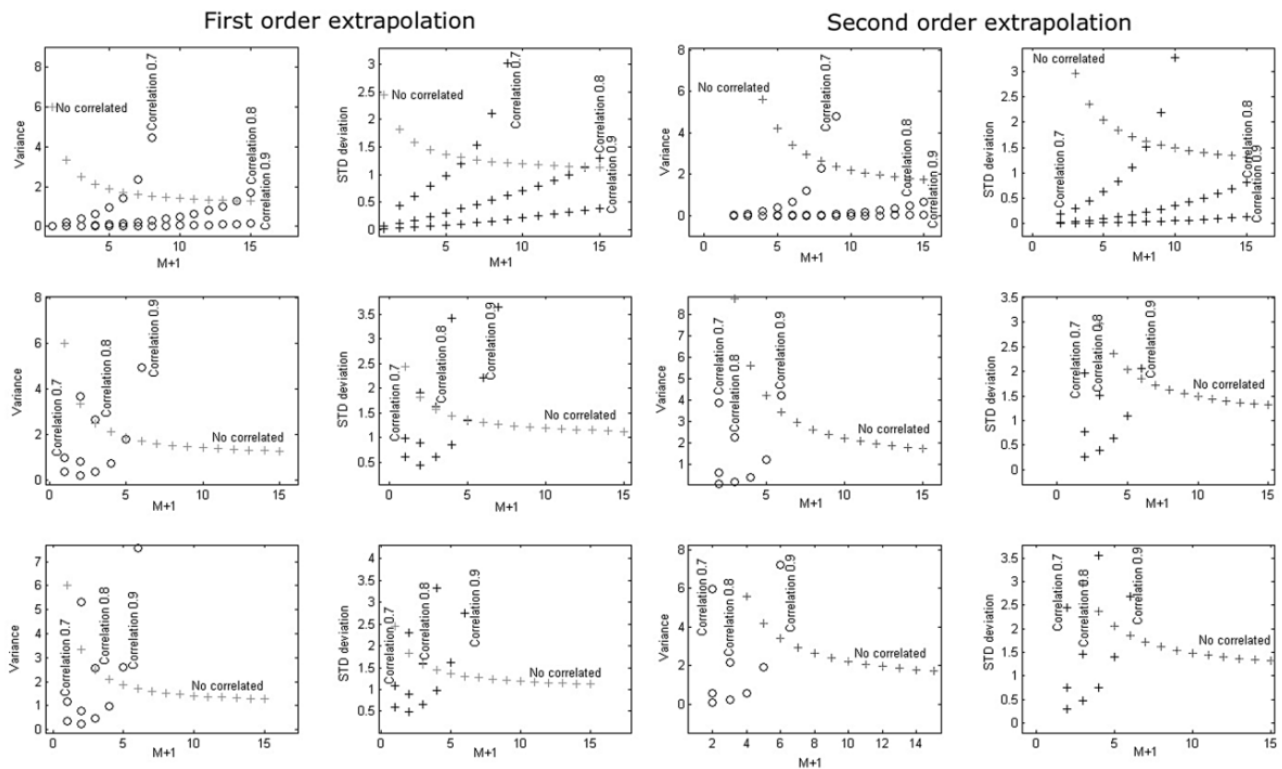


FIG. 4. INACCURACY ASSESSMENT OF DIFFERENT CORRELATIONS WITH THE 1st and 2nd ORDER EXTRAPOLATIONS: 1st row $R_1(k)$; 2nd row $R_2(k)$; 3rd row $R_3(k)$.

Where σ^2 - is the dispersion of the deviations of $F_{Sj+1}^R[k]$, so the argument of the correlation is the list of historic ahead trains ($k=1, 2, \dots, M+1$) and each of them is treated as a moment of time. Assessment of the inaccuracy was performed for 1st and 2nd order extrapolations (fig. 4), each row contains the comparison of the forecasting accuracy for correlated and non-correlated data applied to three different correlation coefficients ($R_1(k) = 0.9, 0.8$ and 0.7 ; $R_2(k) = 0.9, 0.8$ and 0.7 ; $R_3(k) = 0.9, 0.8$ and 0.7) that correspond to each of the used correlation bonds. The investigated results here are the values of variance (1st and 3rd columns) and standard deviation (2nd and 4th columns). It can be noted that a number of historic ahead trains can be selected for particular correlation coefficient for which the standard deviation of the inaccuracy is lower than one, meaning the forecasting is effective. It can be appreciated how fast the standard deviation grows with the decrement of correlation coefficient. This allows to define the threshold value of $(M+1)$ historical ahead trains that are to be taken into account during extrapolation for which the standard deviation of the forecasted value of $F_{Sj+1}^R[n-1]$ is smaller than one. It can be seen from the graphics that the threshold of 1 is not crossed for $M+1 < 5$. Thus, the uncertainty assessment of the method recommends up to 5 ahead trains for effective forecasting of the deviation F.

“Fig. 5” shows the block diagram of the forecasting algorithm. Running times of the ahead trains are subjects for fewer perturbations as they do not depend on passenger’s behavior on the station, nevertheless their deviations also should be forecasted on the same basis in order to effectively satisfy the consideration of regulation restrictions dependence on the changes of the system’s state.

It is worth noting that the forecasting is not the core of the algorithm, but rather an accessory. Other forecasting techniques may and should be tested for further improvement of algorithms efficiency.

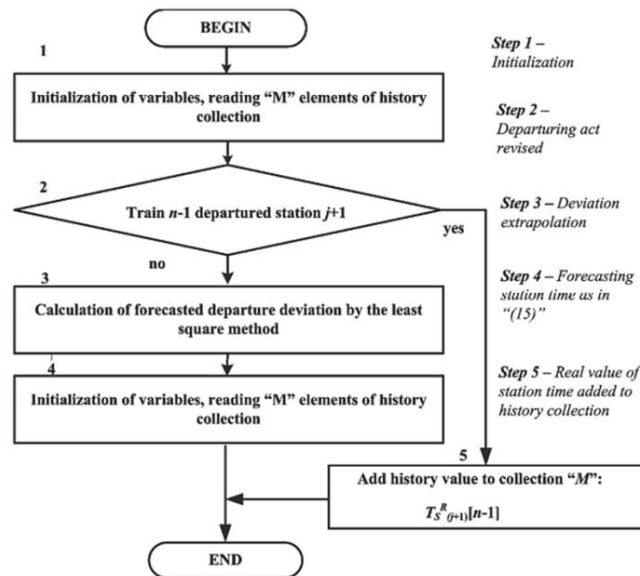


FIG. 5. BLOCK DIAGRAM OF THE FORECASTING ALGORITHM FOR THE VALUES OF STATION TIMES OF THE AHEAD TRAINS

V. THE COMPLETE ALGORITHM

The result of adding regulative restriction dependence on system’s state changes as well as forecasting of ahead station and running times to the traditional ATO-CTC algorithm is the new proposed algorithm. “Fig. 6” illustrates the block diagram of the simple schedule algorithm, discussed in the “Section II” updated with the proposed modifications. The blocks of the algorithm make reference to some equations presented earlier in the article.

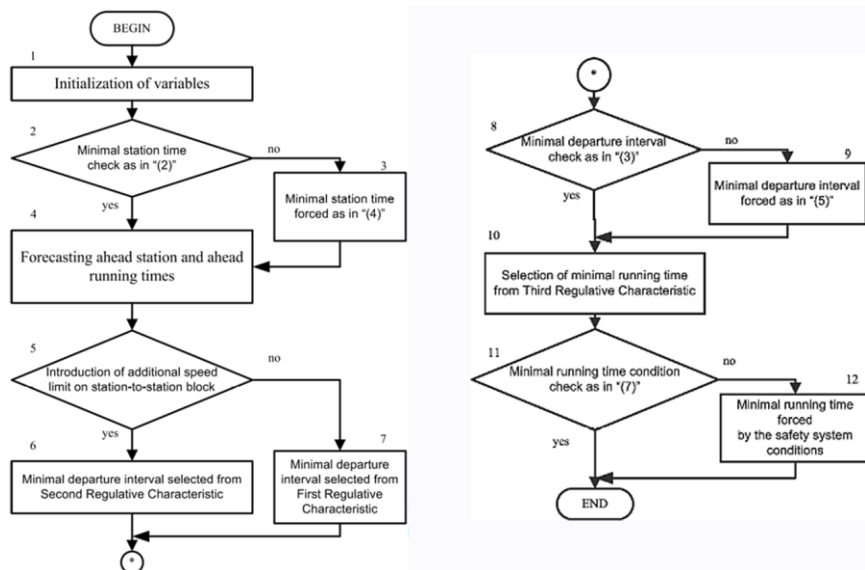


FIG. 6. BLOCK DIAGRAM OF THE ATO-CTC ALGORITHM BASED ON SCHEDULE UPDATED WITH REGULATIVE RESTRICTIONS DEPENDENCE ON SYSTEM’S STATE CHANGES AND THE FORECASTING OF AHEAD TRAINS STATION AND RUNNING TIMES.

During our investigation other versions of ATO-CTC algorithms were also updated with regulative restrictions dependence on system's state changes and forecasting of ahead trains and running times. This includes algorithms based on intervals, hybrid algorithms based on schedule and intervals, and subversions of these algorithms which use different timing resource priorities: station time resource priority, running time resource priority, fixed times, station time increasing only, and running time increasing only versions of the algorithms. By now, only those algorithms were tested which do not allow running time correction "on the go" (after the train has departed the station), because the simulation model resembled a real metro system of Mexico City and Moscow (which also resembles many other outdated control systems in the world). Adding the "on the go" running time correction possibility is now left for further improvement of presented algorithm and is anticipating further improvement of its efficiency.

VI. EXPERIMENTAL MODELING RESULTS

New algorithms proposed here were tested on several lines of Moscow Metro simulator and Mexico City Metro simulator, also developed by the authors (screenshot presented at "fig. 7"). The selection of these metro systems is explained by the origin of the research (Moscow State University of Railway Engineering) from one side and PhD studies of one of the authors, supported by Mexican Agency CONACYT, on the other side. Moreover, there are similarities shared by both systems: high traffic density, organization of the circulation on the lines, red lights operation. However, there are also differences, which are, of course, considered in the detailed model. Mexico City Metro is a system with small number of blocks between stations, normally varying from 5 blocks for the closely located stations to 10 blocks for distant ones. Another difference is the operation of triple platform terminals in almost all Mexico's lines. One more diversity is in the fleet with rubber wheels for which additional speed limits are applied during rain on open sections. Algorithms were tested with different kinds of perturbation and traffic density. A series of quality criteria were used for the comparison of the algorithms, the following of them were selected as priority: quantity of emergency stops between stations and specific electrical energy consumption of the trains.

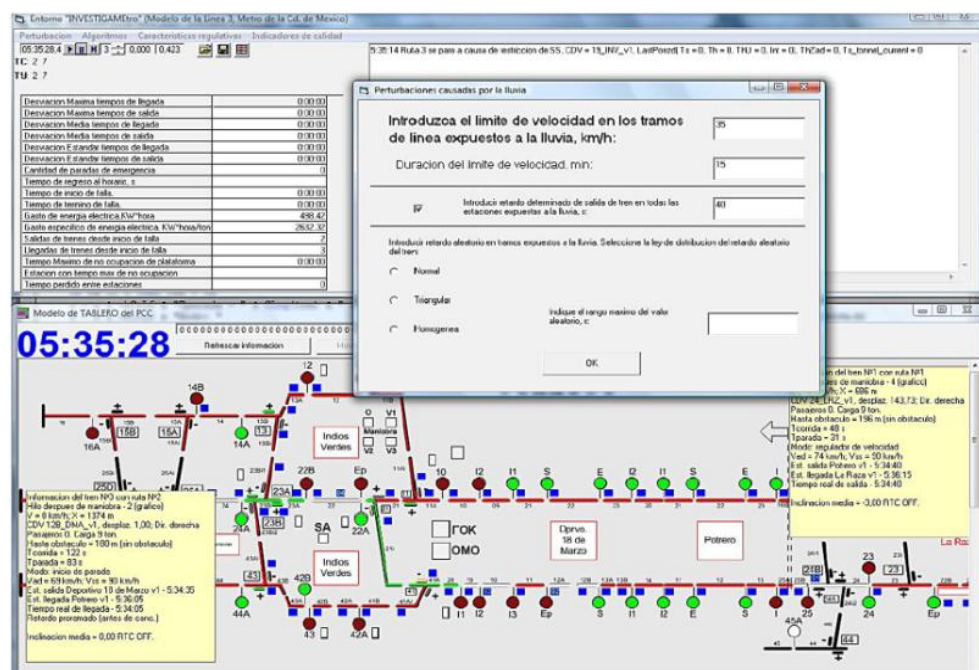


FIG. 7. FRAGMENT OF THE SIMULATOR INTERFACE.

"Fig. 8" illustrates circulation graphic representation of a fragment of the line where single timing perturbation of 20 seconds departure delay occurs in one of the stations. Horizontal axe shows the time. Vertical axe shows the stations proportionally distanced one from another in the way that correct circulation timing is illustrated as a 45° line. Emergency stops ("red lights") between stations illustrated as dots. As we can see, the response of a traditional algorithm produces three emergency stops, while the new version of the algorithm produces only one stop. In case of the new algorithm the first stop is unavoidable, as the moment of the first perturbation occurrence is unpredictable. However, new algorithm senses the system's change of state and adjusts its regulative restrictions (by raising the departure interval and/or the running time of the next train), which helps to avoid the next two emergency stops.

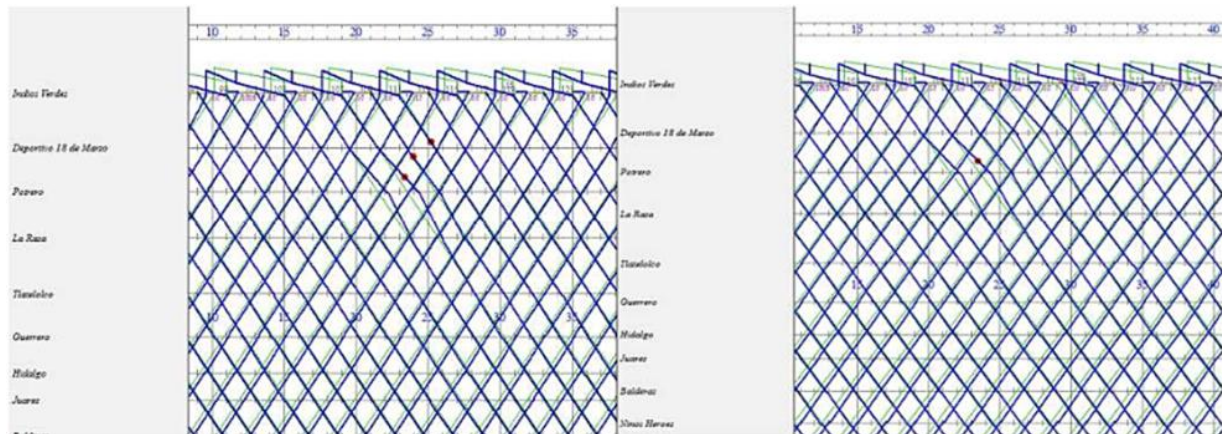


FIG. 8. EXECUTED CIRCULATION GRAPHIC OF THE FRAGMENT OF MEXICO CITY METRO LINE 3 WITH TRADITIONAL (LEFT) AND NEW (RIGHT) ALGORITHM USED.

“Fig. 9” illustrates line’s behavior with traditional and new algorithms upon multiple timing perturbations on several stations during 15 minutes period of time. As seen before, new algorithm detects the system’s change of state and manages to avoid the majority of emergency stops. In fact, the quantity of emergency stops equals the quantity of trains which already left the station and cannot already correct its departure interval to avoid the emergency stop ahead. This means that the reached emergency stops quantity is the minimum for an algorithm with no running time correction “on the go”.

Emergency stops quantity reduction decrements the times train has to accelerate on the station-to-station block. “Fig. 10” shows the specific energy consumption rates upon repetitive timing perturbations for a variety of eight traditional and eight new algorithms (marked with *). As we can see, the new family of algorithms shows noticeable consumption reduction. In fact, energy savings reached from 3 to 10%, depending on the kind of perturbation, the density of the traffic and the algorithm tuning used.

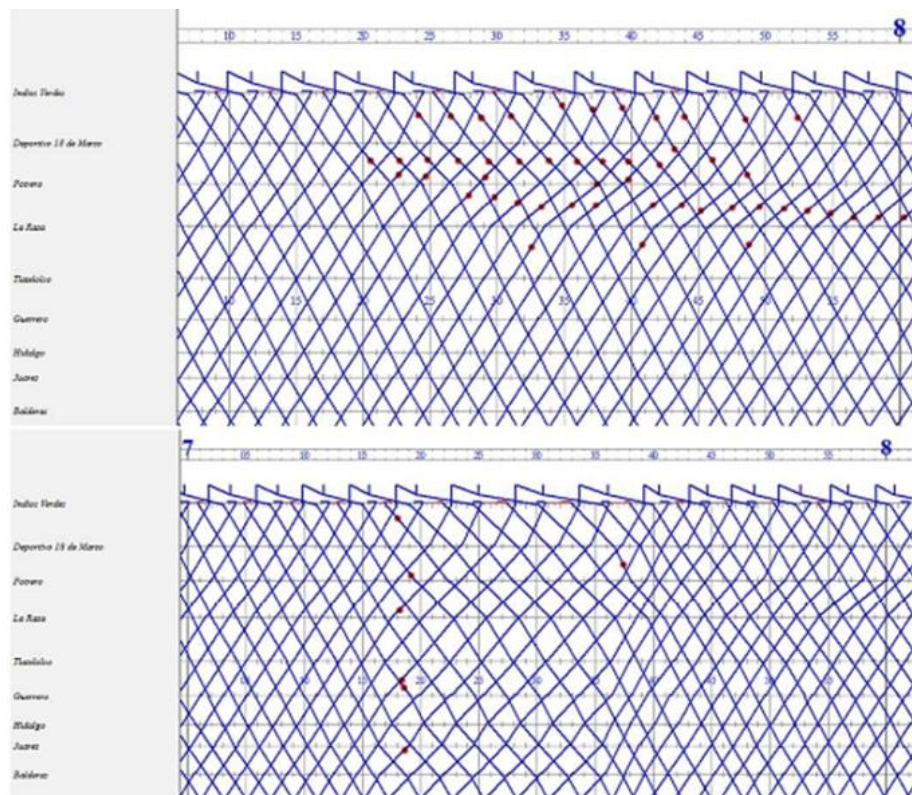


FIG. 9. EXECUTED CIRCULATION GRAPHIC OF THE FRAGMENT OF MEXICO CITY METRO LINE 3 WITH TRADITIONAL (UP) AND NEW (DOWN) ALGORITHM USED.

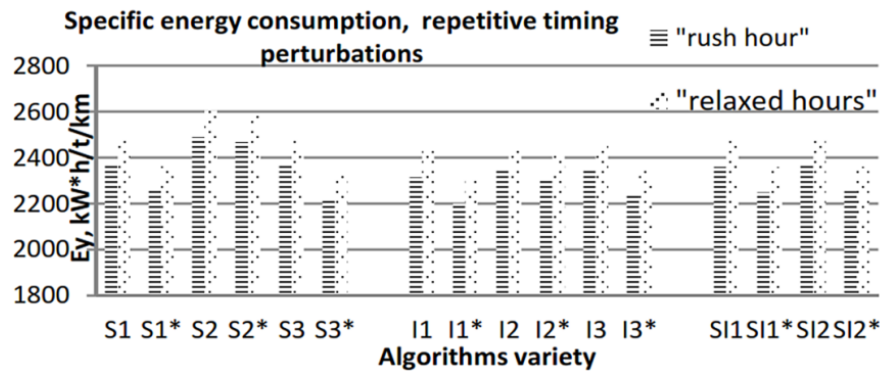


FIG. 10. SPECIFIC ENERGY CONSUMPTION COMPARISON FOR A FAMILY OF TRADITIONAL ATO-CTC ALGORITHMS AND NEW PROPOSED ALGORITHMS (MARKED WITH *) BASED ON SCHEDULE (S), INTERVALS (I) AND HYBRID VERSIONS.

VII. CONCLUSION

Results and methods conceived are mostly applicable for metro lines and can be kept for suburban railway lines with the stations located close to each other, so there is small deviation in running times and there are small differences in service patterns so that the dwell time can be forecast.

The core block of the new algorithm is based on the regulative characteristics, which are calculated *a priori* on the line simulator, while the forecasting only improves its efficiency in the conditions of highly dense traffic (that is when sequential perturbations are most likely correlated between each other). It might be noted that the usage of other forecasting techniques [2, 22, 28] could be adopted and studied in order to work within regulative characteristics methodology. In any case, following the presented methodology, the great majority of calculations are performed only once every time there is a constructional update on some station-to-station block, for which the regulative characteristics must be also updated, because the simulation parameters would change. This leaves few calculation cycles to be performed “on the go” and makes the new algorithm particularly suitable for real-time regulation especially on outdated control systems with no great calculation-power onboard, which is the popular case of partial modernization. On the other hand, energy saving and general transportation process quality improvement makes presented algorithms recommendable for practical usage.

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