

Research Article

Simulation-Based Genetic Algorithm towards an Energy-Efficient Railway Traffic Control

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The real-time traffic control has an important impact on the efficiency of the energy utilization in the modern railway network. This study is aimed to develop an energy-efficient railway traffic control solution for any specified railway. In other words, it is expected to define suitable driving profiles for all the trains running within a specified period through the targeted network with an objective to minimize their total energy consumption. How to optimize the train synchronization so as to benefit from the energy regenerated by electronic braking is also considered in this study. A method based on genetic algorithm and empirical single train driving strategies is developed for this objective. Six monomode strategies and one multimode strategy are tested and compared with the four scenarios extracted from the Belgian railway system. The results obtained by simulation show that the multi-mode control strategy overcomes the mono-mode control strategies with regard to global energy consumption, while there is no firm relation between the utilization rate of energy regenerated by dynamic braking operations and the reduction of total energy consumption.

1. Introduction

In modern railway system, most of the energy required by trains is supplied by the electric network. In recent years, the reduction of energy consuming has become one of the main concerns of the railway managers, and thus more and more projects have been kicked off in this domain, such as RailEnergy (cf., <http://www.railenergy.org/>) and GreenRail (cf., <http://www.logisticsinwallonia.be/en/greenrail/>).

In practice, a targeted railway network is composed of tracks, stations or junctions, and trains running within this network according to a seasonal timetable. Stations and junctions are normally defined as referenced operational points in the railway system, and they will be abbreviated as OcpRefs in the rest of this paper. The seasonal timetable defines for every day during a certain period, normally one year, which trains run along which track at which time. All the information previously mentioned above is determined by the railway system management committee and cannot be changed except when perturbations occur.

Nowadays, at the traffic management center, the working place where dispatchers monitor the real-time railway status and solve traffic problems when necessary, traffic information is normally visualized in track diagrams on large distant panels or on computer screens. Train dispatchers monitor the railway occupation status and control the network by automatic or manual remote interlocking system. As far as we are concerned, today's railway management systems are mainly focused on supporting train dispatchers in solving disturbances and conflicts when they occur, but few, though some work has been observed in the literature, such as the study of Lüthi [1], can help dispatchers make optimal decision in practice in solving those problems and provide real-time traffic control solutions with an objective to minimize the network energy consumption. In fact, when a targeted railway network is defined and distributed to the related staff, the railway staff generally works in an empirical way because few supporting systems have been employed in traffic management centers for improving dispatchers' capability to deal with such processes.

Since the energy consumption of the railway network depends on the real-time operations of the trains that run within it, the optimization about the driving profile of each train running along their journey within the network is really critical for an energy-efficient traffic control strategy. This study is aimed at proposing suitable driving profiles for the trains that run in one railway network so as to reduce the overall energy consumption of the targeted railway network. The proposed solution can be used as a decision-aid tool when the railway managers apply their traffic control strategies.

In order to take necessary real-time traffic control constraints into consideration, several hypotheses are used in this study.

- (i) All the trains running through their journeys must respect the seasonal timetable, which is defined by the infrastructure manager. In the seasonal timetable, the time needed by each train passing through each OcpRef is determined. In consequence, no safety constraint is considered in this study though safety-based driving behavior is very important [2].
- (ii) Speed limits are predefined for all railway tracks.
- (iii) The type of one train passing through a certain OcpRef can be “pass” or “stop,” which is also determined in the seasonal timetable. For the OcpRef of type “pass,” the train can pass by at any speed not higher than the predefined speed limit; for the OcpRef of type “stop,” the train must arrive at and leave from the OcpRef according to the indicated arrival and departure times with a short stay.

In one word, one traffic control strategy is defined in this study as a set of real-time driving profiles, where each driving profile corresponds to one train involved in train journeys predefined in the seasonal timetable. Each train’s driving profile, along the journey between two successive OcpRefs, is obtained by an industrial simulator provided by one well-known train manufacturer. This simulator has been approved and used by this company. Our objective is to optimize, from a global view, this set of driving profiles so as to minimize the total energy consumption for the targeted railway network within a certain period.

This paper is organized as follows: at first, a typical framework of the centralized railway traffic management system and the main idea of train synchronization are introduced, and then a brief review of the related work has been made. In Section 4, definitions of mono-train driving and multi-train traffic control strategies are described. Afterwards, the proposed genetic algorithm for generating energy-efficient traffic control strategy is detailed in Section 5. The sixth part consists of simulated results for different scenarios with different traffic control strategies. At the end of the paper, conclusions and some further discussions are made with possible ideas and methods for future researches.

2. Railway Traffic Management System and Train Synchronization

The railway traffic control is a dynamic process undertaken by the train dispatchers to manage the railway in real time. In general, the railway traffic management system is centralized and has two fundamental components: traffic management center and traffic management territory [3]. Trains moving within a territory are supervised and controlled by the associated train dispatcher at the traffic management center.

Regarded as the kernel of the railway traffic management system, the dispatchers at the traffic management center are responsible for the regulation of railway traffic within their associated territory with the help of traffic control system, which helps the dispatchers to observe the status of the their associated territories (e.g., the occupation of line sections, location of trains, position of switches and aspects of signals, etc.) and collect necessary information in a continuous manner. Ideally, the traffic control system should also be able to help dispatchers to make decisions and communicate with both the upper level decision makers and the front line level operational staff in accordance with the rules and the regulations predefined by the railway authority. As mentioned in Figure 1, the train dispatchers supervise the status of their associated territories with real-time data collected by the traffic control system from the associated territories (e.g., availability of railway lines, stations and sidings, the status of switching between different operation systems (OSs), performances of signals and railway traffic, etc.). Additional information about the real-time traffic status may be collected or transferred by personal communication equipment. When unplanned events (e.g., trains’ unscheduled stops, new trains added to the current schedule, etc.) occur, the involved train dispatcher tries to configure and solve the problem, according to predefined rules and regulations of the railway traffic management, within acceptable time. When necessary, this train dispatcher has to communicate with the associated decision makers before making the final decision and transferring it to all involved people.

The main and traditional objective of the traffic control is not only to avoid conflicts between trains but also to restore the disrupted railway traffic as soon as necessary. In recent years, the third objective has arisen: synchronizing trains’ real-time operations so as to reduce the railway energy consumption in a dynamic perspective.

Although it seems that the traffic control center is not a major energy-consuming part of the railway system, it plays an important role in railway energy consumption management because the decisions made by dispatcher(s) impact directly on real-time operations of running trains, which are considered as the biggest energy-consuming units.

In addition, it is only the traffic control center that could make the decision from both global and dynamic perspectives so that train drivers would be able to “synchronize” their actions for not only avoiding unnecessary energy consumption but also reutilizing the energy produced by the dynamic braking nearby.

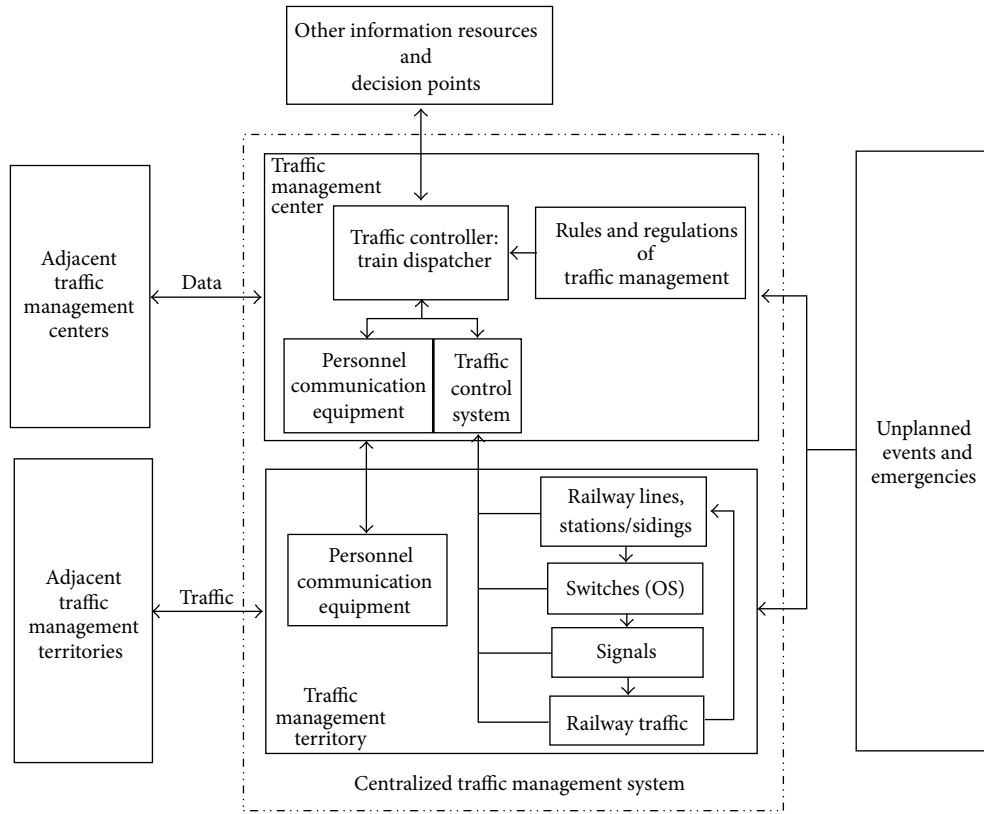


FIGURE 1: Interrelationship amongst the main components in the centralized traffic management system.

Train synchronization management is mainly concerned with the interactions between different trains in order to minimize the total energy consumption of the targeted railway network.

An ideal train synchronization solution should respect at first necessary constraints, such as the network security and the train punctuality, and meanwhile it should also minimize the network energy cost from a global perspective.

In the modern railway network, most of the trains are equipped with electric braking equipment. Dynamic braking is a general term used to describe the use of an electric motor as a generator to dissipate energy. This type of braking is more precisely described by one of the two terms: regenerative braking and rheostat braking. In regenerative braking, the electricity can be either transmitted through overhead catenary wires or an electrified third rail or can be stored onboard through the use of a flywheel, battery, or other energy storage system while Rheostat braking occurs when the produced electrical energy is run through resistors and dissipated as heat energy [4], since dynamic brakes only produce a retarding force when the wheels are rolling, and this force decreases as the rotational speed approaches zero. The wheel will be providing less and less braking force when its rotation slows down and finally the braking force becomes zero when it stops turning all together [5]; the dynamic braking is used to slow down the train rather than stop it. As shown by the two examples in Figure 2, when the regenerative braking is realized, the current generated by

the regenerated electric energy can be utilized by the trains running in the same substation over the same time period (such as those periods indicated by two-way arrows with solid lines). If no traction operations are produced in that period, the regenerated energies are lost in the electricity network except that some special devices are equipped to reserve them (such as those periods indicated by two-way arrows with dashed lines). In consequence, it is important to dynamically synchronize operations of trains running in the same substation so as to benefit as much as possible from the regenerated energy.

In general, a traffic control strategy is represented by a set of driving strategies that are defined for the trains that run within the targeted railway network. Two different traffic control strategies for three trains are shown in Figure 2, where the intervals indicated by two-way arrows (both dashed and solid lines) are the periods during which energies are generated by dynamic operations (descending arrows with solid lines) because trains run at a higher speed than their thresholds (vd_1 , vd_2 , and vd_3 , resp.) in those periods. Energies regenerated within the intervals indicated by the solid line two-way arrows can be reutilized by nearby trains for their traction operations (ascending and horizontal arrows), while those regenerated within the intervals indicated by dashed line two-way arrows cannot be reutilized by the nearby trains because no traction operation is produced. Neither energy consumption nor energy regeneration is observed during coasting phases (descending arrows with dashed lines).

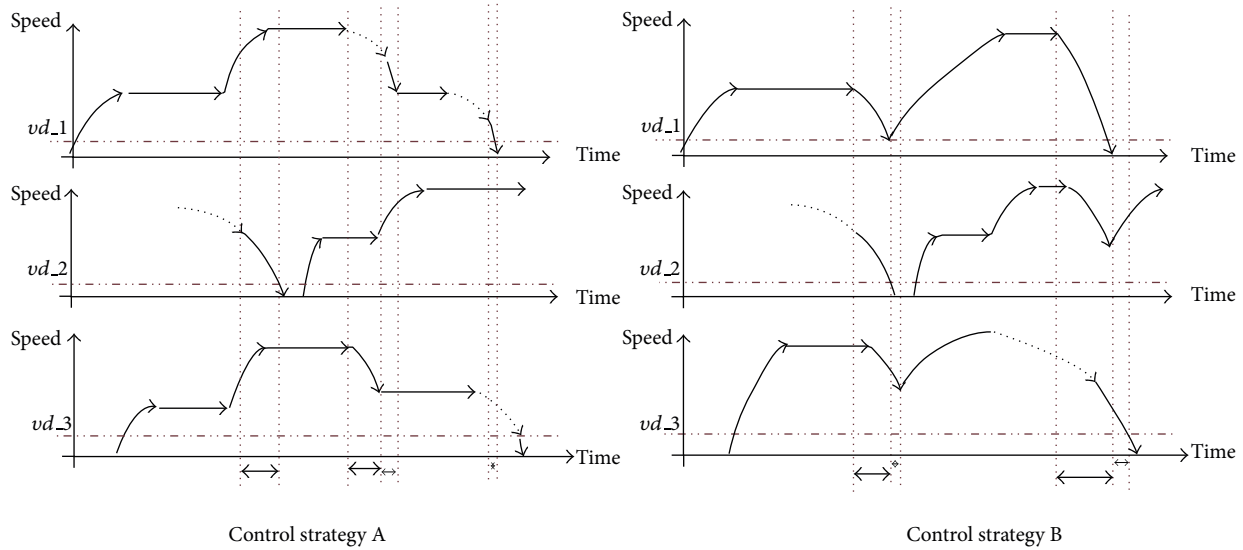


FIGURE 2: Two different control strategies for three trains.

It is observed in Figure 2 that the control strategy A may consume less energy than that of the control strategy B because more regenerated energies are utilized by the traction operations of the trains nearby; in other words, the train synchronization efficiency of control strategy A is higher than that of the control strategy B. Since most of the modern trains are equipped with dynamic braking devices, an energy-efficient traffic control strategy should not only reduce the single train's energy consumption but also increase the efficiency of the train synchronization. The objective is to minimize the global energy consumption of the targeted railway network.

3. A Brief Review of the Related Work

Although railway traffic control is an important topic in the modern railway management system, few results about the studies on railway traffic control, especially real-time energy-efficient traffic control for general railway system, have been published in the literature. The complexity of the railway traffic control system, related to the dynamic characteristic of the real-time train synchronization problem, can be regarded as the main reason.

According to the literature, the majority of the recent studies on railway traffic control are focused on avoiding conflicts within the railway network (e.g., [6–10]) or rescheduling trains for reducing negative impacts of disruptions (e.g., [11–14]). As one of the most lately raised topics in the railway traffic control, no clear definition can be found in the literature about real-time train synchronization, and few publications are dealing with the exact problem.

Nevertheless, some published results are observed in the literature about implicit train synchronization within a targeted railway network with an objective of minimizing the global energy consumption [15–22], though limitations are always observed.

- (1) Most of the studies simplify the problem by using average pacing velocities [15, 16] or constant speeds [17–20] to estimate the energy consumption of the trains along their journeys.
- (2) Some studies took into account the acceleration time between two different speeds when changing from one section to another but still suppose a constant speed for the train within the time interval [18].
- (3) Many studies were focused on avoiding train conflicts to reduce energy consumption [16, 18] while considering only the time reservation or margins of speeds instead of proposing driving profiles.
- (4) Determining time reserves first, and then optimizing the speed profiles in the second stages is considered reasonable and observed in several studies [17, 19, 21], while those studies consider the driving profile either in an independent way [17] or by means of setting constant speed for each section along the journey [19], or adjusting train running time instead of defining suitable driving profiles so as to reduce power peaks [21].
- (5) Although a well-developed integrated real-time rescheduling framework may help to save energy by reducing the number of unnecessary signal influences [1], the reutilization of the energy regenerated by dynamic braking was not considered.

In one word, a set of studies have been focused on the energy-efficient train scheduling, but few of them take into account both the train synchronization and the specific driving profile. For example, although Albrecht [21] took into account the energy regenerated by dynamic braking for the calculation of energy consumption, he just tried to modify the running time alongside the journey instead of proposing proper driving strategies for train drivers to reduce the power peak.

In fact, the railway energy-efficient traffic control is one of the most difficult optimization problems because not only the velocity profile for each running train should be dynamically defined but also all mandatory constraints keep changing. In addition, the energy consumption depends not only on the driving strategies but also on the infrastructure's condition (slope, curve, etc.), driving environment (tunnels, bridges, or open air), and the train's configuration (locomotive, weight, etc.). In this study, these impacts are considered as parameters for calculating energy consumption of the train with a specified driving strategy by using an industrial simulation tool.

As for resolution methods, decomposition methods (e.g., [17, 19, 21]), heuristics (e.g., [17, 18, 20]), and meta-heuristics (e.g., [16, 22]) are mainly used as optimization methods in the literature, while some other methods, such as simulation (e.g., [15, 20]), local strategy (e.g., [15]), and fuzzy rule-based methods (e.g., [14]) are also observed. In fact, even if some real-time traffic control issues can be theoretically solved by some exact methods when all the parameters are determined, the considerable running time of exact methods makes them impractical in real application because of the complexity of such problems. That is why there is no room for time-consuming method in this case, and most of the researchers are interested in meta-heuristics or heuristics. The decomposition idea looks efficient, but the problem raised is how to reduce the error amplification during the resolution procedure. Furthermore, it is important to find an efficient decomposition perspective.

In order to obtain real-time energy-efficient traffic control strategy within reasonable execution time, we are focused on heuristic and meta-heuristic methods. Furthermore, encouraged by the good performance of methods based on genetic algorithm (e.g., [21, 22]), we have developed a method based on genetic algorithm and simulation output to solve the traffic control problem.

4. Construction of Traffic Control Strategies

As previously mentioned, a traffic control strategy consists of driving strategies defined for all the involved trains. With a given driving strategy, the train driver will be informed about the details of the driving profile suggested to him during the following journey. In fact, a driving strategy is mainly determined by two important parameters.

- (i) Traction coefficient: coefficient of pulling effort of train's engine. When the engine performs a full traction effort, the coefficient is 1; otherwise, it is a real number between 0 and 1.
- (ii) Driving mode: it represents a rule used to determine a sequence of driving operations, such as traction, coasting, cruising, and braking operations, which are performed by the driver along the trajectory.

In this study, a traffic control strategy is defined as a set of mono-train driving strategies applied to all the trains involved in train journeys observed in the targeted railway network. According to the literature, several energy-saving

mono-train driving strategies have been proposed by using dynamic programming [23] or evolutionary algorithm [24]. Since the energy consumption depends not only on how a train performs but also on the environment, such as the railway network conditions, it is impossible to define a universal optimal driving strategy for any train under any conditions, and it takes considerable time to calculate for each train its optimal strategy under the specific conditions, which are not suitable for real-time multi-train control problem because the details of the updated driving strategies have to be sent to train drivers in a short time; otherwise, the decisions will be no more available because all the trains are running all the time within the network and their situations change rapidly. Furthermore, since some empirical driving modes are normally proposed by experts, who are working in the railway system, to train drivers, those driving modes have been already realized and known well by them. In consequence, the proposed traffic control strategy proposed in this study is based on empirical driving modes, which can save time of calculation and are familiar enough to get accepted by train drivers.

It should be mentioned that empirical driving modes mostly based on the maximum principle as Howlett and Pudney stated [25], and the experimental results of Miyatake and Ko [23] mentioned that the maximum principle is not quite appropriate for the use of power recovery, and therefore a power-reduced driving mode, where the traction effort is reduced to 80%, is constructed to each studied empirical driving mode with an aim at getting solutions with acceptable quality.

4.1. Empirical Mono-Train Driving Modes. In this study, the three most used empirical mono-train driving modes are employed.

- (i) Mode 1: cruising mode. Only one universal sequence of the train operations is observed within any of the railway segments that compose the journey: traction, cruising, and braking operations whereby the driver has to reduce the train's speed.
- (ii) Mode 2: coasting mode. Starting with a traction operation, the driver performs alternatively traction and coasting operations along a specified journey, where upper and lower bounds of the running speed are specified. The conditions involved in operation changes are as follows.
 - (a) If the speed of the train is lower than the upper bound, the traction operation is implemented until the speed reaches the upper limit, and then the coasting operation is applied until the speed of the train reaches the lower bound, where the train will be powered again. These two kinds of operations are implemented alternatively until the train passes into a section with different upper and lower bounds of the speed. A braking operation may take place if the coasting operation is not enough to reduce train's speed to the upper bound of the speed at the next section.

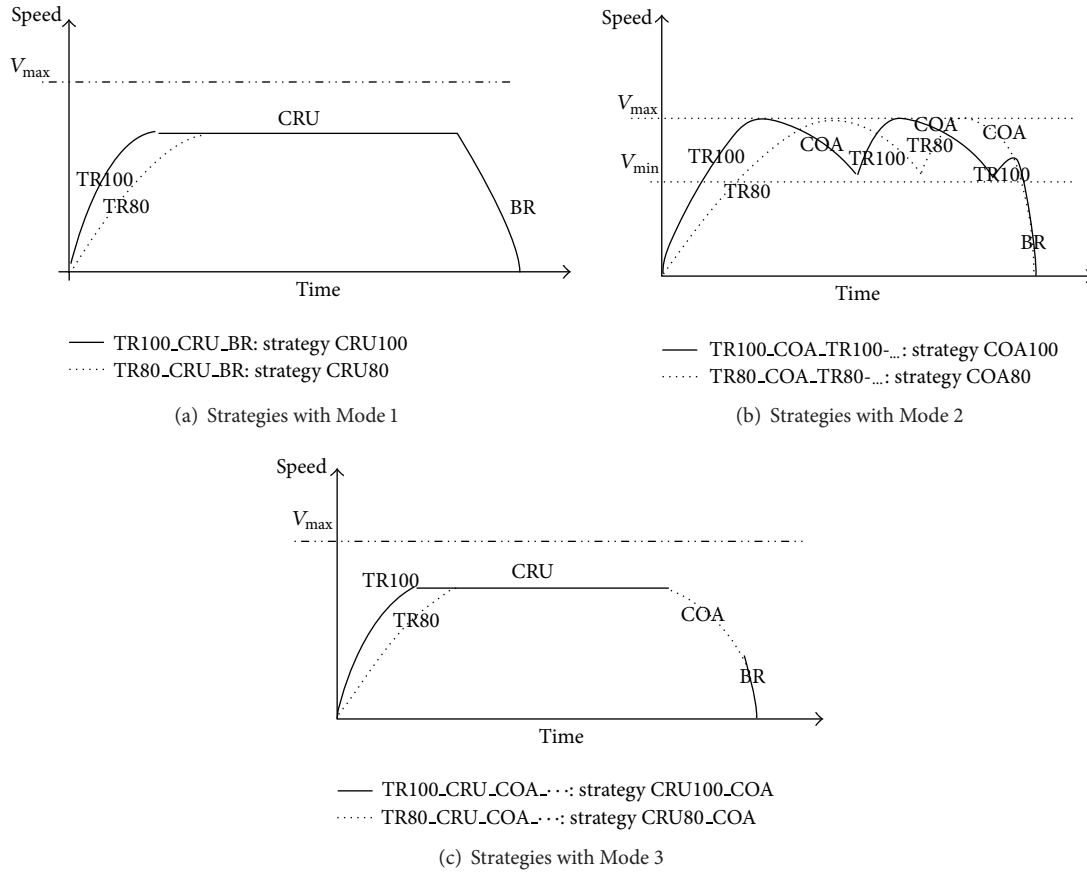


FIGURE 3: Mono-train driving strategies.

In that case, the braking operation will force the train to reduce its speed to a reasonable value.

- (iii) Mode 3: Cruising-coasting mode. In general, a train running with this mode is conducted by a set of operations in the order of traction, cruising, and coasting within each segment of its journey. Braking operation can be only observed when the train shows a risk of exceeding the upper bound of the speed limit or when it is beyond the capacity of the coasting operation to slow down the train to the specified arrival speed at its destination.

It is obvious that one train may have different driving profiles with different traction efforts even with the same mono-train driving mode. According to the practice, the two most performed traction efforts are applied to generate mono-train driving strategies: full traction effort (100%) and reduced traction effort (80%).

As shown in Figure 3, six combinations of mono-train driving mode and traction efforts are defined as basic mono-train driving strategies for generating multi-train traffic control strategy in this study by combing three basic empirical modes with two possibilities of traction effort, respectively: CRU100, CRU80, COA100, COA80, CRU100_COA, and CRU80_COA, where the first three letters represent

the involved driving mode and the numbers stand for the rate of traction effort. For example, CRU100 represents the combination of Mode 1 and full traction effort.

4.2. Traffic Control Strategies Based on Empirical Mono-Train Driving Strategies. Considering that the mono-train driving strategies used for different trains during their journeys can be either universal or different, in this study, seven traffic control strategies in total are defined: six of them are monomode strategies, where one universal driving mode is defined for all the trains during their journeys, and the remaining one is multimode strategy, where different mono-train driving strategies, selected among six mono-train driving strategies mentioned previously, are used to generate driving profile for the trains observed in the targeted network.

5. The Genetic Algorithm for Generating Energy-Efficient Traffic Control Strategy

5.1. Framework of the Proposed Genetic Algorithm. As shown in Figure 4, the procedure of the proposed genetic algorithm, used for generating energy-efficient traffic control strategy, is as follows.

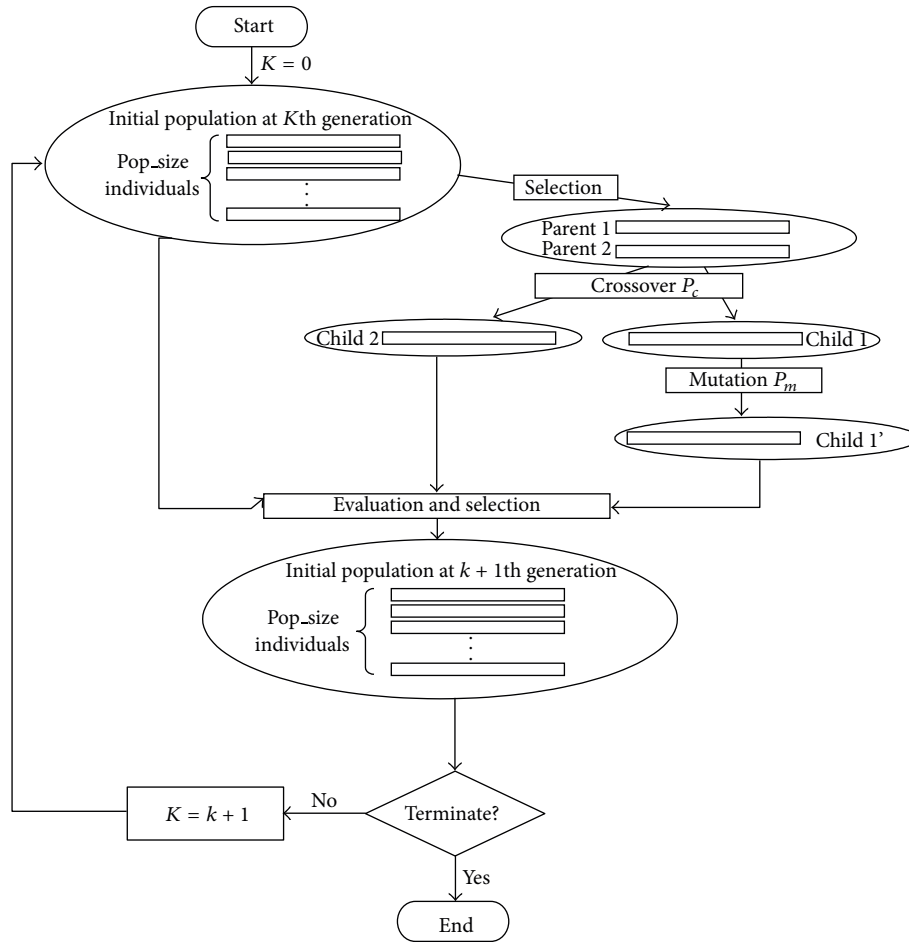


FIGURE 4: Framework of the proposed genetic algorithm.

Step 1. Construct an initial population. Each individual of the population represents a feasible traffic control strategy, that is, a set of feasible driving profiles proposed for trains involved in the targeted network within the specified period. All necessary constraints, such as the passing time noted in the timetable, and speed limits set along the line, are respected in each individual. The coding strategy of one individual is detailed in Section 5.2.

Step 2. Calculate each individual's fitness value. The fitness value is used to confirm that the smaller an individual's fitness is, the more likely it will be selected. In this study, the global energy consumption of a traffic control solution is used as its fitness.

Step 3. Select randomly two individuals by making a roulette wheel of the fitness array. These two individuals will be used as parents for the crossover operator.

Step 4. Recombine the selected parents with a predefined crossover probability, P_c , and generate two new individuals; if no crossover takes place, copy the original information of these parents to their children.

Step 5. Randomly select one newly generated child. Mutate it with a predefined mutation, probability P_m , to generate a new individual.

Step 6. Evolve the population for the next iteration by making roulette wheel selection.

Step 7. The individual, who has the best fitness among all the current individuals, replaces one individual, which is randomly selected from the current selected population. This step confirms that the present best individual will be a member of the new population.

Step 8. If the iteration number or the runtime reaches the predetermined limit or the current population is converged (its rate of convergence is larger than a predefined threshold), this procedure is terminated and the one with the best fitness is reported as the final traffic control solution; otherwise, go to Step 2.

5.2. Coding Strategy. Make a train journey represent a train running between two successive OcpRefs within a period specified in the periodical timetable. Suppose that N train

$V_s(0), C(0), M(0), V_f(0)$...	$V_s(i), C(i), M(i), V_f(i)$...	$V_s(N), C(N), M(N), V_f(N)$
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FIGURE 5: Structure of an individual representing a traffic control strategy for a railway network containing N train journeys.

journeys are observed passing through the targeted railway network in a constructed scenario. One traffic control strategy, named *sd* an individual, is coded as a structural array that consists of N elements. Each element, named as a gene, represents a specified train journey. At the operational level, the features of one train journey, such as positions of departure and arrival, running duration, and characteristics of railway lines along the journey and the used locomotive, are already determined, and thus the energy consumption of this train journey is determined. When all the train journeys are well defined, the global energy consumption of a specified traffic control strategy can be obtained by summing up the energy consumed by all train involved in the defined train journeys. It should be mentioned that because both network configuration and locomotives are planned in the tactical decision level while our study is focused on the operational level, only four of those parameters can be updated in this study to get an energy-efficient traffic control strategy. These variables are defined as follows:

$V_s(i)$: passing speed of train involved in the train journey i at the begin of its running section;

$V_f(i)$: passing speed of train involved in the train journey i at the end of its running section;

$C(i)$: coefficient of traction effort for train involved in the train journey i ;

$M(i)$: type of driving mode for train involved in train journey i .

According to the individual structure shown in Figure 5, the train involved in train journey i ($0 \leq i < N$) is planned to pass through its departure and arrival points at the speeds $V_s(i)$ and $V_f(i)$, respectively. During its journey, the rate of traction effort is $C(i)$, and the driving mode is $M(i)$.

5.3. Variation Operators. The aim of the variation operators is to maintain genetic diversity from one generation of a population to the next, while we overcome the infeasibility of the new individual generated by the variation operation with respect to the constraints.

In the proposed genetic algorithm, two kinds of variation operators are defined: one-point crossover and point mutation. When crossover occurs, a single crossover point on both parents' chromosomes is selected and the corresponding data beyond that point in either chromosome is swapped between two parents, while only the gene at the selected point is updated with the newly generated data for mutation.

Although more than one factor of the gene can be varied to generate a new one because each gene contains four elements (driving mode, rate of traction effort, and departure and arrival speeds), only one of them, randomly chosen, is varied within the allowed range at one iteration. The range of variation can be either the predefined candidate list or the

limited value. For example, the driving mode varies within the range of {CRU, COA, or CRU_COA}; the rate of traction effort can be either 1.0 or 0.8; the departure or arrival speed should be either fixed as zero at an OcpRef of type "stop" or varied from zero to the speed limitation at an OcpRef of type "pass."

Traditionally, after swapping the corresponding parts of two parents during crossover operation, two children are generated. When mutation occurs, one new individual is generated by updating the selected gene. Those newly generated solution can be used as candidate(s) for generating the new population. However, in this study, the traditional variation operators may generate infeasible solutions that do not satisfy any more some constraints. In consequence, some additional operations must be guaranteed that all the solutions generated by the variation operators are feasible ones.

Feasibility check is necessity when train's departure or arrival speed is updated. A feasible solution should satisfy the following constraints.

- (i) Constraint 1: the predefined running time should be respected.
- (ii) Constraint 2: each train's speed should be always below the speed limitation of the associated section.
- (iii) Constraint 3: the arrival and departure speeds of one train at an OcpRef should be the same.

Constraint 1 may be violated when the driving mode is transferred from CRU to COA or the rate of traction effort is reduced; in this case, the actual choice will not be accepted, and the other solution will be generated with different variation factor until Constraint 1 is satisfied. If there are no more candidates in the list, keep the original solution.

Constraint 2 can always be respected if the new value is generated from a bounded range.

The feasibility of the new solution with regard to Constraint 3 depends on both the selected variation element and the type of OcpRefs. If both OcpRef are of the type "stop," the new solution will have no chance to violate this constraint; if one OcpRef is of the type "pass," a state that the involved train can pass through this OcpRef without stop, a further check should be made by the comparison between the departure and the arrival speeds of the involved train at OcpRefs of the type "pass" in both new children generated by crossover operation (or the new individual generated by the mutation operation) with the arrival speed of this train in the preceding section and its departure speed in the following section, respectively. If train's departure speed is always equal to its arrival speed at the same OcpRef, the new solution is accepted as a feasible one; otherwise, replace the arrival speed or the departure speed of the involved train in the adjacent section by the corresponding value associated with the selected gene

TABLE 1: Brief configuration of different scenarios.

Number of scenario	Main station	Period	Number of train journeys
1	Gent-St-Pieters	07h00–07h30	52
2	Gent-St-Pieters	11h00–11h30	58
3	Namur	07h00–07h30	39
4	Namur	11h00–11h30	22

when necessary so as to ensure that the train's arrival speed is the same as the departure speed when it passes through an OcpRef.

Considering that the mutation operator used in this study is much more complex than the traditional point mutation, the steps taken by the dedicated mutation operator are detailed in the following for a better understanding.

Step 1. Set the initial candidate list of variation factors. Theoretically, the set should contain all the four elements of the gene, that is, $\{V_s, M, C, V_f\}$. However, the candidate list may be reduced according to the types of OcpRefs associated with the selected point because once an OcpRef is of the type "stop," the train must execute "stop" at this point, that is, its speed being fixed as zero. In consequence, V_s and V_f at the OcpRef of the type "pass" should be excluded from the list of candidates for variation operator.

Step 2. Randomly select one element from the candidate list for the mutation operation.

Step 3. Vary the selected element to construct a new solution.

- (i) If M is selected as variation factor, the driving mode of the selected gene will be replaced by another driving mode randomly selected among three basic empirical driving modes from 1 to 3.
- (ii) If C is selected, the selected gene's actual traction effort will be updated by a value randomly selected from 1 and 0.8.
- (iii) If V_s is selected, the selected gene's actual departure speed will be replaced by a randomly generated value, which is positive and respects the speed limitation.
- (iv) If V_f is selected, the arrival speed of the involved gene will be updated with a positive value randomly generated between 0 and the corresponding speed limitation.

Step 4. check the feasibility of the newly generated solution; if the solution generated at Step 3 is feasible, the mutation operator is terminated. If an infeasible solution is generated, it may result from a reduced traction effort or the change of speeds at OcpRef of the type "pass." The corrections are made as follows:

- (i) If C is varied from 1 to 0.8, first make $C = 1$, and then exclude M from the candidate list for variation operation. If the candidate list becomes empty, this

operation will be terminated without variation; otherwise, go to Step 2 with a reduced candidate list.

- (ii) If V_s or V_f is selected as variation factor, update the V_f of the involved train in the precedent section or its V_s in the following section to avoid the conflict caused by defining different speeds for the train at the same OcpRef. Once the speed conflicts are solved, the mutation is terminated with a feasible solution.

6. Experimental Results

6.1. Data. Experimental data used in this study are supplied by the Belgian railway infrastructure manager who handles the train traffic control in Belgium. Most of the Belgian railway lines are electrified. The majority of the electrified railway lines use 3000 volt (DC) overhead power supply, and only some high-speed lines are electrified at 25000 volt (AC). Since the high-speed lines are separated from the normal lines by using special railways and this study is focused on the normal lines, all the experimental data used here are concerned with railway lines electrified at 3000 volt (DC). In addition, because of the loss of energy when it is transported in the wire, it is reasonable to suppose that the energy produced by the dynamic braking of one train can only be reutilized by the trains with a distance of less than 30 kilometers from it.

In this study, as shown in Figure 6, two railway networks are constructed by selecting railway lines around two railway stations in Belgium, Gent-St-Pieters and Namur. The former is a main station in a relatively dense network, while the latter is a normal one according to the periodical timetable of the year of 2011. For each defined railway network, two sets of train journeys are selected for the specified periods: train journeys observed from 07h00 to 07h30 and those observed from 11h00 to 11h30. In consequence, as shown in Table 1, four scenarios are in total constructed with train parts selected and cleaned according to different conditions and constraints. It should be mentioned that since the distance between the two selected stations is far more than 60 km, it is possible to construct two distinct railway networks by using tracks around these two stations, as shown in Figure 6.

The parameters of the genetic algorithm are set as follows:

- (i) crossover probability: 0.8,
- (ii) mutation probability: 0.1,
- (iii) rate of convergence: 95%,
- (iv) maximum runtime: 2 minutes,
- (v) maximum number of iterations: 500.

6.2. Numerical Results. Four scenarios, mentioned in Section 6.1, are tested with six monomode control strategies and one multimode strategy. Since genetic algorithm is a meta-heuristic, the final solution obtained is rather an approximate solution than an optimal one, and therefore ten trails are executed for each scenario.

As shown in Table 2, only two kinds of traffic control strategies can be feasible solutions for all constructed scenarios within all trials: one uses CRU100 strategy as the universal

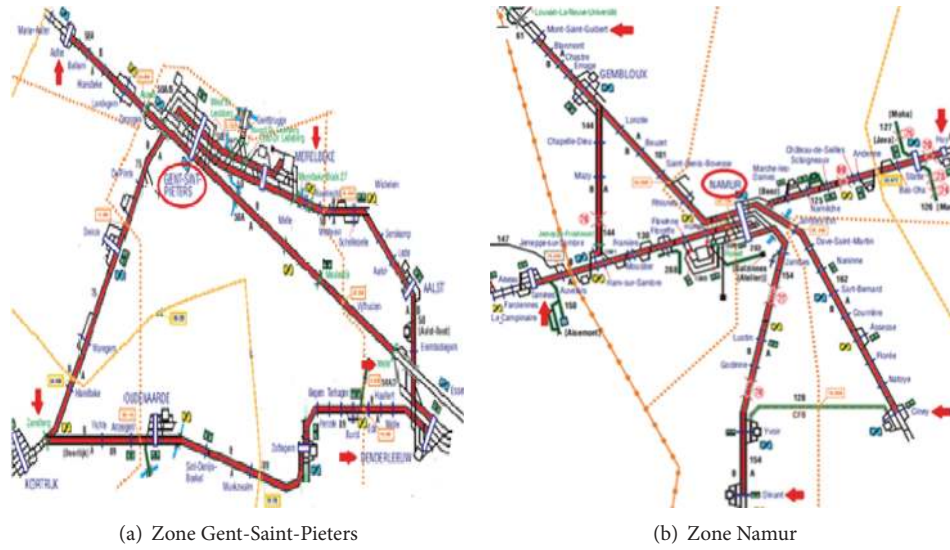


FIGURE 6: Railway networks constructed around two selected stations in Belgium.

TABLE 2: Energy consumed at pantographs.

Number of scenarios	Total energy consumed at pantographs (unit: kwh)			Total energy consumed at pantographs for traction operations (unit: kwh)		
	CRU100	CRU100_COA	MULTI	CRU100	CRU100_COA	MULTI
1	5972.17	3935.95	3932.58	6670.52	4404.61	4396.08
2	9444.85	—	7642.59	10163.06	—	8230.83
3	3828.01	3040.84	2744.41	4527.23	3575.10	3288.28
4	2059.21	1410.12	1263.64	2460.54	1676.83	1505.93

mono-train strategy and the other is a multimode control strategy (MULTI), where each train part has its proper mono-train driving strategy. The traffic control strategy, where CRU100_COA is used as the universal mono-train strategy for all the train parts, can obtain feasible solutions for most of the constructed scenarios but not for all. In comparison with total energies consumed by feasible solution obtained with different traffic control strategies, MULTI traffic control strategy can always obtain the solutions with minimal energy consumption (about 70% of that consumed by solutions obtained with CRU100 traffic control strategy).

It is observed that the total energy consumed at pantographs is less than the total energy consumed at pantographs for traction operations for all the obtained solutions; that is, the energy regenerated by dynamic braking operations is more or less used among different trains.

A further analysis is made about the relation between the reutilization of energy generated by dynamic braking operations and the total energy consumption.

As shown in Table 3, it is observed that high utilization rate of energy regenerated by dynamic braking operations is observed in all solutions. However, there is no firm relation between the utilization rate of energy regenerated by dynamic braking operations and the reduction of total energy consumption.

TABLE 3: Reutilization of energy regenerated by dynamic braking operations.

	Rate of total energy consumption to energy consumed by traction operations (%)	Utilization rate of energy regenerated by dynamic braking operations (%)
CRU100	87.68	92.32
CRU100_COA	86.17	81.75
MULTI	87.42	80.25

In consequence, it is concluded that a proper combination of different mono-train driving strategies can help reduce the total energy consumption of the targeted network. A high utilization rate of energy regenerated by dynamic braking operations is not necessary for minimizing the total energy consumption. The proposed method can propose a set of energy-efficient driving profiles for train parts observed in the targeted network according to experimental results.

7. Conclusions and Perspectives

This study is aimed to propose a method that can obtain an energy-efficient traffic control strategy for any targeted

railway network. Since little work observed in the literature to optimize the synchronization of trains' operations though it is very important in the real world, we are focused on this aspect in this study. In addition, considering that the time consuming method is not practical for real-time traffic control, a method based on genetic algorithm is proposed to generate a proper traffic control solution within reasonable runtime.

According to the experimental results, it is concluded that the proposed method can generate energy-efficient traffic control solution, where the driving profile of a train part is defined by a suitable mono-train driving strategy that can be different from the driving strategy used by another train part in the same railway network.

Furthermore, it is concluded that although a high utilization rate of energy regenerated by dynamic braking operations can always be observed in the energy-efficient traffic control solution, the optimization of mono-train driving profile is more important than the reutilization of energy generated by dynamic braking operations because a higher value of the latter is not necessary for a traffic control solution to have the minimal total energy consumption.

In one word, in order to minimize the total energy consumption of a targeted railway network, it is important to not only propose ecodriving driving profile for each train part but also synchronize the operations of different train parts to introduce a high utilization rate of the energy regenerated by dynamic braking operations.

It should be mentioned that this study does not yet consider the estimation of the disturbances in the railway network though the quality of the solution depends on the input parameters that predict the real status of the railway network. Therefore, it is interesting to develop the future study based on the prediction of the status of railway network at the point of time when the proposed solution would be implemented.

In addition, some other objectives such as punctuality are also important in practice, and therefore multi-objective optimization should be an interesting research topic as well. The driving modes of trains should be provided in a real-time manner, whereas it takes the current algorithm considerable execution time to get results. In consequence, it is important to reduce the running time of the algorithm. In fact, the parallelization of the algorithm may be helpful to find good results in a reasonable timeframe.

Furthermore, several works about synchronization of trains in mass transit systems are observed in the literature. Though much more constraints should be taken into account in the open railway system, the approaches proposed in the former can give some ideas about train synchronization for the latter, thus how to get benefit from the successful experiences in the mass transit systems will be another interesting topic of research in the future.

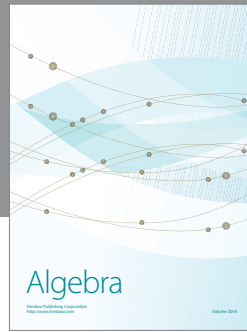
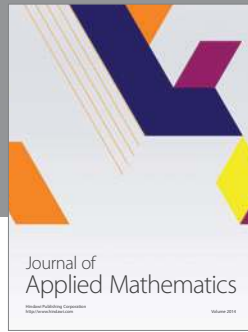
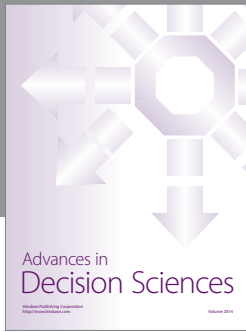
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