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Dynamic Coast Control of Train Movement with Genetic Algorithm

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Abstract

Railway service is now the major transportation means in most of the countries around the world. With the increasing population and expanding commercial and industrial activities, a high quality of railway service is the most desirable. Dwell time control at stations and fixed coasting point in an inter-station run are the current practices to maintain the train service in most metro railway system, however a flexible and efficient train control and operation cannot be accomplished. Coast control is an economical approach to balance run-time and energy consumption in railway operation if time is not an important issue at off-peak hours. Coast control of train operation within inter-station runs offers certain flexibility to manoeuvre between run-time and energy consumption and hence it has become one of the biggest challenges for most metro railway operators around the world. This paper presents an application of genetic algorithms (GA) to search for the appropriate coasting point(s) and investigates the possible improvement on fitness of genes. Single and multiple coasting point control with simple GA are developed to attain the solutions and their corresponding train movement is examined. Further, a hierarchical genetic algorithm is introduced here to integrate the determination of the number of coasting points and a fast mutation scheme, Minimum-Allele-Reserve-Keeper (MARK), is then adopted as a genetic operator to ensure fast convergence.

1. Introduction

Modification or installation of a new signalling system to improve the service quality not only increases the capital cost, but also affects the normal train service and hence the passengers' activity. Traffic management to enhance an existing line capacity is one of the best approaches with the limited resources. Regenerative braking and coasting are the most commonly used approaches to reduce energy consumed by trains. The former requires efficient traffic regulation and train coordination to ensure

that energy recovered from a braking train finds a way to supplement a motoring train nearby. The latter allows simple and independent control on trains and is thus more popular with the operators. Coast control of train movement within inter-station runs offers a certain flexible and economical measure to manoeuvre between run-time and energy consumption. However, identifying the necessary starting points for coasting under the constraints of current service conditions is no simple task because train movement is attributed by a large number of factors, most of which are non-linear and inter-dependent. Under a typical flat-out inter-station run, a train is travelling very close to the maximum permissible speed throughout the trip. The running time is the shortest and the energy consumption is the highest. When coasting is allowed [1], the traction motors are turned off once the train has accelerated above a certain speed. The momentum of the train then carries it through and the brake is still needed to bring the train to a stop at the next station. Inter-station run-time is longer but energy saving is possible as the train spends less time on motoring.

During rush hours or imminent recovery from disturbance to service, flat-out inter-station runs are necessary. On the other hand, when time is not of the utmost importance, certain measures can be introduced to reduce the energy consumption, at the reasonable expense of the travelling time and coast control is one of the possible approaches to juggle the run time and energy consumption in an inter-station run. Nevertheless, the current practices in most metro systems is to start coasting at a fixed distance from the departed station. The coasting points are pre-determined and therefore only optimal with respect to a nominal operational condition of train schedule, but not the current service demand which varies throughout the day. Single coasting point is common in most metro systems to achieve the regulation of train schedule since inter-station distances are usually short. A quick and reasonable solution can be obtained with simple search techniques. Bi-section method is currently applied in practice in locating the coast control problem as this method is not limited by the track geometry along the line and it only depends on the distance in an inter-station run.

Train movement is governed by a large number of factors, such as track geometry, signalling, traction equipment characteristics, power supply system and speed restriction [2-4]. Some of them are position-dependent whilst the others are speed-dependent. As the coasting control is to alter the speed profile of the train at a particular position, formulation of an analytical model to connect the coasting points and their corresponding run-time and energy consumption and then applying appropriate optimisation techniques is very much impractical, if not entirely

impossible. Further consideration of uncertainties, like human behaviour and equipment delay, only makes matters more complicated. Having ruled out an analytical approach, heuristic search methods are the potential candidates to attain the optimal coasting points according to the real-time operational conditions.

Genetic algorithms (GAs) have already found successful applications in railway operation [5-6] and a preliminary attempt of applying GA on coasting control has shown promising results [7], where the number of coasting points was pre-determined. This paper presents utilising GA to search for coasting point(s) in an inter-station run with the aid of a single-train movement simulator, which takes into account all factors attributed to train movement. This study, however, allows the number of coasting points to be part of the solution and thereby a more flexible train schedule control can be obtained. With real-time control, when a train stops at a station, there are about 30 seconds or less to derive the location of the coasting point for the next inter-station run according to the current service demand. A fast solution is important for real-time control or supervision of the operation. This paper thus adopts a fast-converging GA, Minimum-Allele-Reserve-Keeper (MARK) [8], for real-time operations to improve the trade-off between computation time and the quality of the solution. GA may not be able to provide the best solution in such a short time interval when compared with classical searching methods, but it can present a solution any time, whose fitness is improved if more time is given for further evolution.

2. Problem formulation

Figure 1 shows the speed profile of a flat-out run between two stations with four possible coasting points. It is evident that different coasting points alter the speed profile dramatically. As the motoring time is shortened because of coasting, energy saving is possible at the expense of run-time. **Figure 2** illustrates the possible time differences for four coasting points. In general, the run-time can be further extended when an early coasting point is so required. Depending on the traction drive system, an energy saving of 30% can be attained with only a 5% increase in run-time [5].

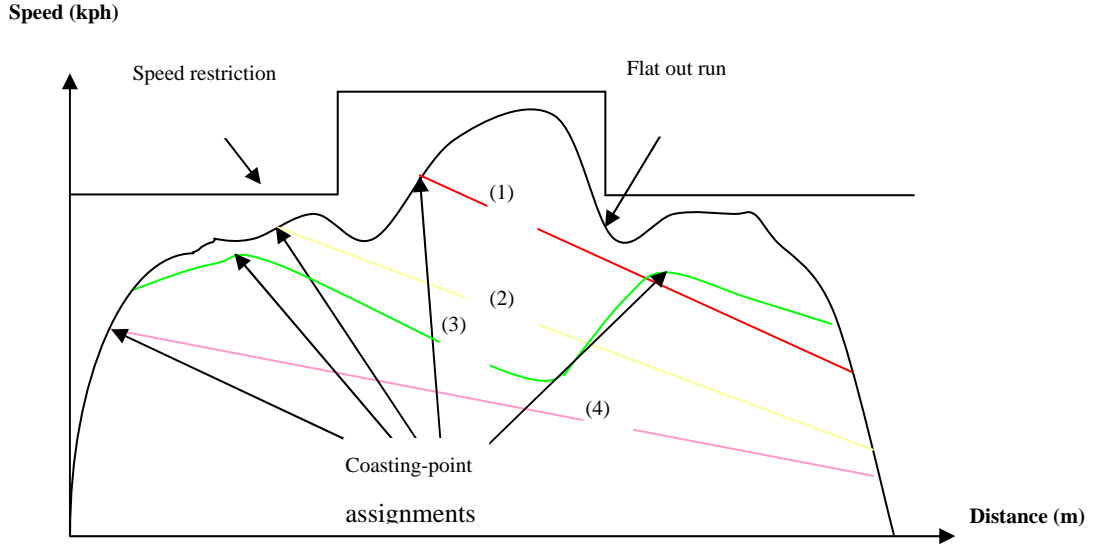


Figure 1: Speed profiles of flat-out run and some possible coasting-points

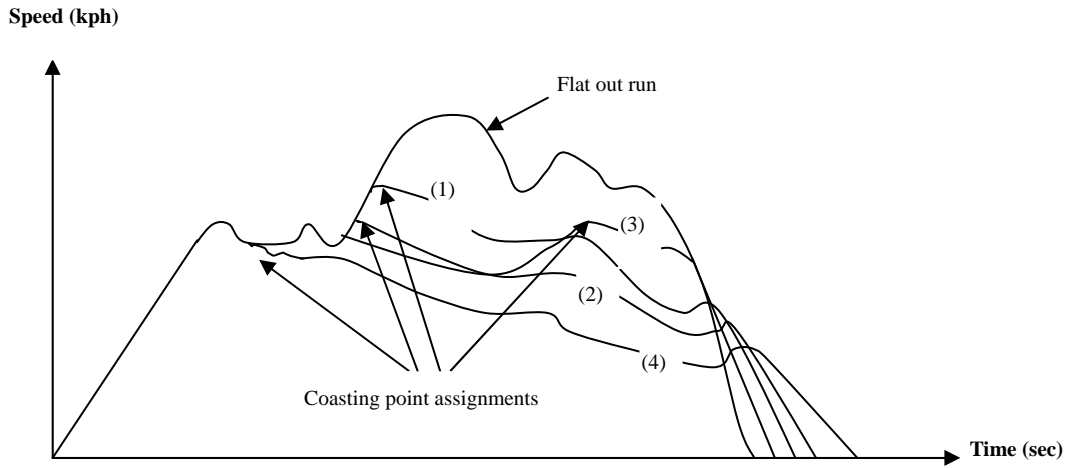


Figure 2: Run-time extensions with some possible coasting points

A single coasting point is usually adequate for service regulation in a metro system because of the short inter-station runs. With a single coasting point control, the run-time decreases and energy consumption increases monotonically if the coasting point shifts from the starting station to the next. The optimal coasting point to trade off run-time and energy consumption can be attained by simple optimisation techniques, except for some extreme track geometry and speed restrictions, because there are no local optima clouding the global one.

Inter-station distances vary even within the same railway line and multiple coasting points may be required for a longer inter-station run. Nevertheless, there are no specific rules on the number of coasting points, which inevitably turns the solution space for coast control multi-dimensional. Hence, the problem becomes more complicated and an analytical approach is not practical for real-time applications.

Figure 3 shows the solution space of a typical 2-coasting point control. From **figure 4**, V_{rm} is the operation parameter for multiple coasting point identification. When the train speed falls below this specific value from coasting, it is allowed to re-motor to ensure sufficient momentum to go on. It should be noted the train spends more time in motoring mode and hence consume more energy when multiple coasting points are allowed. The location of the first coasting point inevitably affects that of the second and so on. Further, the solution space for the next coasting point varies with the location of the previous coasting point.

From the viewpoint of application, there is a wide range of locations to start coasting(s) and each will produce different run-time and energy consumption. In other words, given the required run-time, as set by the current service schedule or headway, locating the required coasting point(s) quickly is the essence of this searching problem.

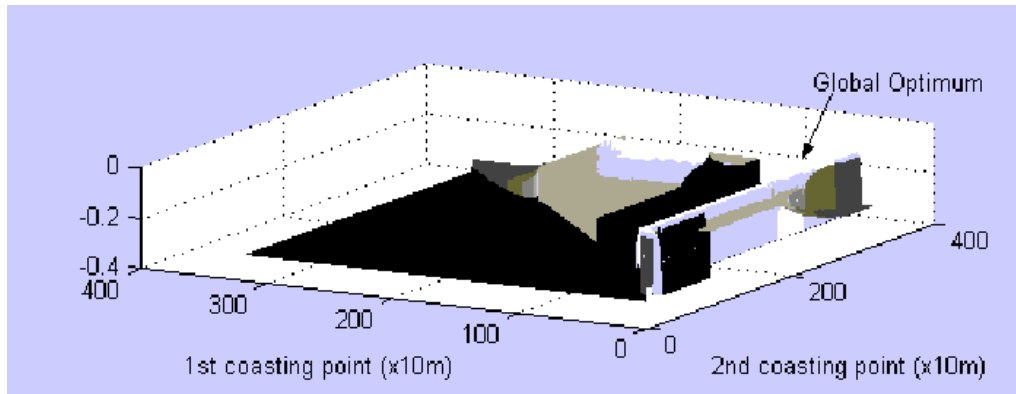


Figure 3: A typical solution space with 2 coasting points

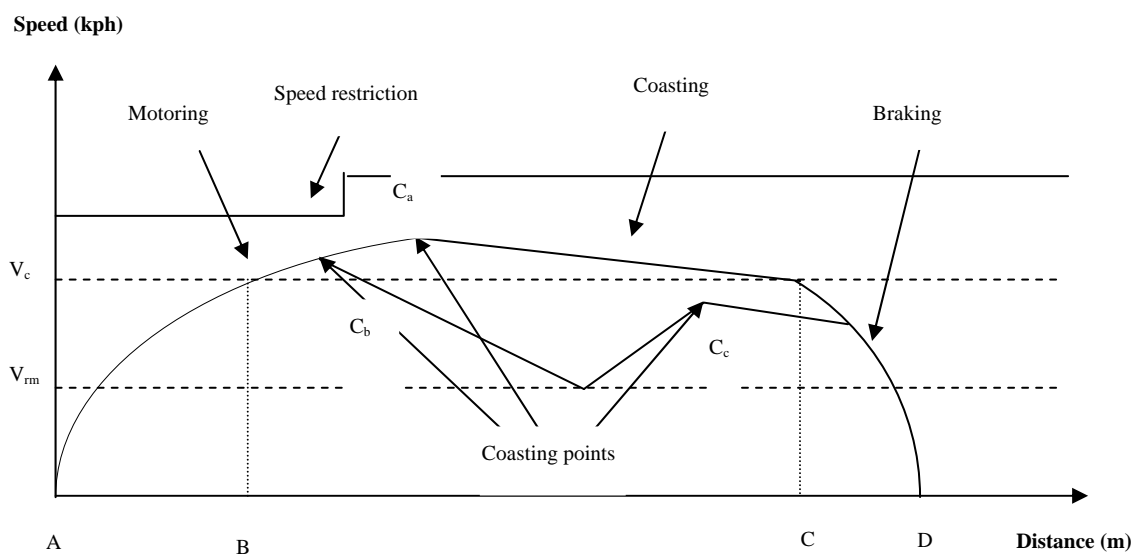


Figure 4: The range of possible coasting point

3. Train control

In general, time and energy demand are the two main parameters for the train service regulation in railway engineering and they are usually complement with each other, except for some extreme track layout. In the viewpoint of energy saving, coast control and regenerative braking are the two commonly approaches to obtain a flexible and efficient train operation in most current metro railway systems. With the application of regenerative braking, energy released from braking trains can be partly returned to the AC power supply system through inverters and partly absorbed by acceleration trains nearby. Efficient coordination among trains is required to ensure a low energy loss in lines and tracks from regenerative braking. Energy exchange between trains is limited within the same section of line since the railway line is usually made up of a number electrical line. A substantial energy saving with a limited delay of train operation has been shown in study [9]. Further, the railway equipment may cause damage because of a sudden rise of current if there are a number of trains operating in braking simultaneously. In practice, overvoltage on the nearby substation from regeneration can be avoided if the following measures can be taken.

1. the terminal voltage of driving system can be limited by a capacity and the system automatically switches to rheostatic braking once the energy returned from the braking trains is excessive.
2. the energy released from regenerative braking can be limited by controlling the conduction angle of the driving system and the tap position of the transformer.

Even regenerative braking provides a low peak energy demand on substation, an efficient coordination and regulation among trains is desirable to ensure the energy recovery between motoring and braking trains. An exact cost for the equipment of regenerative train operation and overvoltage protection are also essential to assure the safe and sound operation. Further, time delay is usually the co-product in the application of regenerative braking to procure a low peak energy demand on the power supply system.

To achieve a flexible and efficient train schedule with the limited resources, dwell time and coast control are the two measures currently applied in most railway system. Dwell time control is the simple and easy means to maintain the train schedule, regardless of other system constraints and parameters, such as traction equipment characteristics and signalling constraints. Nevertheless, a flexible and low energy demand operation may not be attained with time reduction and extension at stations

alone. Coast control has therefore become popular for train service regulation in recent years because of its flexibility, efficiency and economy. A coasting speed lookup table has been developed for train service control in KCRC [10]. An audible system has been set up to detect train speed and loading and the coasting speed can then be determined in the built-in lookup table. The table stores the train loading, inter-station run time and coasting speed information. An alarm is given to operator starts a train to coast once the train speed exceeds the specific limit. The paper also shows that 3% energy reduction and 10% maintenance cost for braking equipment are the result. Although the coast control is limited with the specific railway system in this application, the result is very attractive and encouraging for operators. Further, an expert system approach of coast control has been proposed for the Singapore MRT system [11] to determine the coasting solution in which the loading effect and train voltage variation are also taken into account. An expert system is a computer program and it stores knowledge and utilises inference engine to solve problems which require human expertise in a specific domain of applications [12-13]. With the above coast control system, the advantage of dynamic coast control cannot be fully taken as the coast control action is limited by the development of the built-in lookup table and knowledge base accordingly. Moreover, the memory size of the coast control lookup table and knowledge base of the expert system and computation time increases if a more accurate result is expected. Thereby, a fully dynamic coast control is more desirable to identify the coasting point according to the current traffic condition.

4. Genetic algorithm

Genetic algorithm is a mathematical search technique based on principles of natural selection and genetic combinations [14]. In other words, the concept of natural evolution is used to solve problems in different areas. The possible solutions make up the population and better solutions, equivalent to fitter organisms in nature, are more likely to reproduce and pass on their genetic information to the next generation. It is expected that good solutions evolve over time just as organisms have evolved in nature.

4.1 Essential components of GA

To solve a problem using GA, the following are essential,

1. A system of encoding the possible solutions or chromosome structure
2. An initial population of solutions
3. A function to evaluate a solution's fitness
4. A method of selecting solutions for producing new solutions
5. Operators to create new solutions from those existing

The basic flow of GA is illustrated in **figure 5**. At the beginning, an initial population is generated. The fitter individuals have a better chance to evolve. Offsprings are then created by crossover and mutation. The crossover operation normally takes two parents and creates off-springs with a mixture of both parents' genetic information. Mutation alters the new solution in a totally random manner. The searching process repeats until the latest solutions satisfy the desired conditions or attain the maximum number of generations.

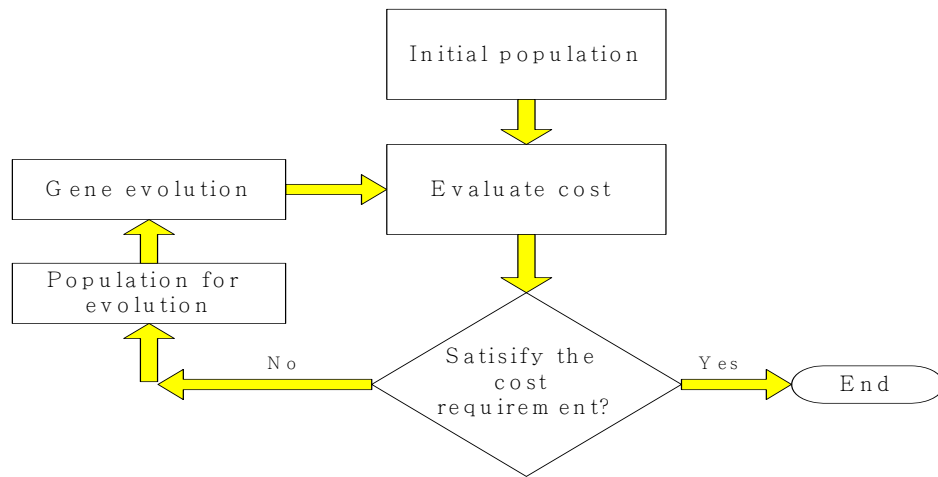


Figure 5: Flow of GA

4.2 Coast control with GA

With the application of coast control, coasting point(s) is/are searched for train service regulation in an inter-station run. Hence, coasting point can be represented in binary, octal, decimal and hexadecimal format for the ease of gene evolution. To ensure the new generation to be within the boundaries of solution space, gene is defined in binary format to represent the relative position to start coasting between stations in this application. Resolution on the coasting position representation depends on the number of binary bits used. In addition, the number of bits used for coasting point representation is directly related to the distance between stations, which is in general over a kilometre. Thereby, the resolution on the coasting position representation up to a metre is sufficient.

To evaluate the possible solution with coast control, an objective function is necessary. The objective function is to determine how close the chosen coasting point is to lead to the desired run-time and energy consumption and it is quantified in the equation (1).

F is a non-negative quantity and a smaller value implies a fitter solution. The fitness function enables the adjustment of the relative weights on the two conflicting factors, energy consumption and run-time, within GA. Other definitions for F are equally valid if other considerations are taken into account.

$$F = W_T \left| \frac{T_g - T_D}{T_D} \right| + W_E \left(\frac{E_g - E_D}{E_D} \right) \quad (1)$$

where $W_T + W_E = 1$

W_T is the weighting factor for run-time

W_E is the weighting factor for energy consumption

T_D is the desired run-time

E_D is the desired energy consumption

T_g is the run-time achieved by the gene

E_g is the energy consumption attained by the gene

4.2.1 Single-coasting-point control

One coasting point is assumed in this application. The location of this coasting point and its distance from the departed station is encoded in binary form. When the locations of the start and stop stations are fixed, the number of binary bits required is known. **Table 1** shows the gene representation of single coasting-point control.

Inter-station distance (m)	Number of bits required	Gene representation of coasting point
1200	11	00111110100 (500m)

Table 1: Gene representation of single coasting point

4.2.2 Multiple-coasting-point control

Gene representation of multiple coasting point is similar to the single coasting point control. For the sake of simplicity, two coasting points are assumed (i.e. two genes) in the following descriptions and they are integrated in a single chromosome. Two types of gene representation of multiple coasting point control are proposed as in **Table 2**.

	Absolute distance representation	Relative distance representation

1 st coasting point (Gene 1)	011001000000 (1600m)	011001000000 (1600m)
2 nd coasting point (Gene 2)	100111000100 (2500m)	001110000100 (2500-1600=900m)
Chromosome	011001000000 100111000100	011001000000 001110000100

Table 2: Gene representation of absolute and relative coasting point

With the application of absolute distance representation, absolute distance of the locations of the first (Gene 1) and second (Gene 2) coasting points from the departed station are applied. Gene 1 and 2 then form a chromosome as the coasting solution. Nevertheless, the separation of the distance between the first and second coasting point is used to represent Gene 2 with the relative distance representation.

4.2.3 Hierarchical genetic algorithm (HGA)

Throughout the above discussions, the number of coasting point(s) required for service regulation is fixed. In general, it is difficult for the operators to determine the number of coasting points in an inter-stations run as the train movement depends on a larger number of factors. HGA approach [15] is adopted here to represent both the number and locations of coasting point in a chromosome. HGA can provide the coast control information in a hierarchical manner according to the traffic condition. Gene representation of HGA is similar to the multiple coasting point control but one more bit, Gene 3, is introduced to identify the number of coasting points required as shown in **Table 3**. HGA allows multiple coasting point control when this single bit is “1”. However, a single coasting point control is recommended when the bit is “0”. In other words, the availability of the second coasting point, Gene 2, is called for by this multiple coasting point control identifier.

1 st coasting point (Gene 1)	011001000000 (1600m)
2 nd coasting point (Gene 2)	100111000100 (2500m)
Multiple coasting point control identifier (Gene 3)	0/1
Chromosome	011001000000 100111000100 0/1

Table 3: Gene representation of HGA

5. Minimum-Allele-Reserve-Keeper (MARK)

Crossover and mutation are the two commonly used approaches to evolve new genes from parent(s) in GA. The role of crossover is to combine pieces of information together coming from different individuals in the population. Since crossover proceeds by recombining information from parents, the offspring it produces contain only the information that were already exist in the parents. Premature convergence is thus the result with crossover alone in evolution as crossover never creates new information to the offsprings, if the solution is trapped at the local optimum already in which depicts in **figure 6**. Further, GA increases the effort of search for the optimal solution with crossover when GA starts to approach to the optimum of the search space.

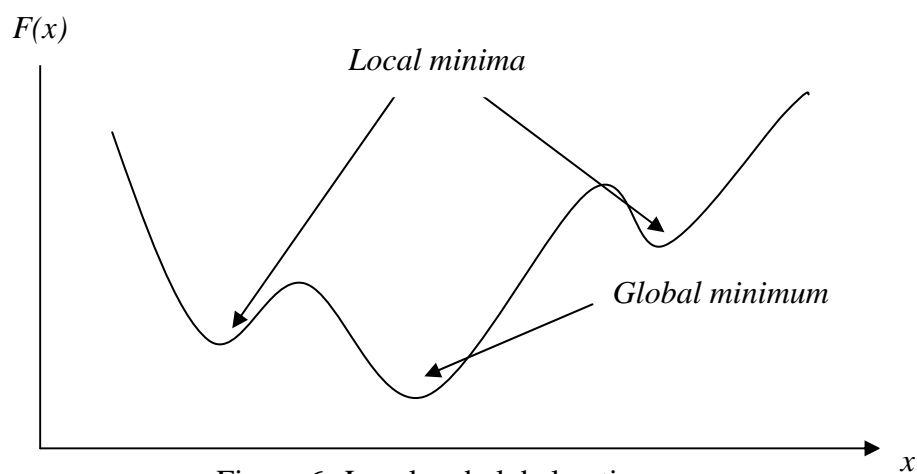


Figure 6: Local and global optimum

Mutation is the other general genetic operator for evolution in GA and it creates offspring by performing a random modification on an individual. Though the chance for the offspring to escape from the local optimum is improved in mutation, it also has a chance with a high probability from the population to exclude from the global optimum if the gene modification incurs in a major point that is far from the optimum. In other words, the classic mutation is too destructive when the GA begins to reach a good solution in evolution.

To obtain solution with a fast convergence in evolution for real time control, a fast mutation scheme, Minimum-Allele-Reserve-Keeper (MARK), is introduced as a genetic operator. With MARK operation, a minimum reserve (MARK rate) of each binary value at the same bit positions must be kept within the population. In other words, the chromosomes of each generation have a minimum number of '0' and '1' at each bit position. Since it makes minimal disturbances to the population and provides

modification on an individual like classic mutation, a fast convergence with less destructive can be accomplished in evolution. Hence, MARK avoids excessive bit-inversions and it also provides the routes for offspring excluding from local optima.

With MARK, the minimum amount of “1” and “0” are governed by a rate α . A_c and B_c are the ratio of “1” and “0” at a specified column in the mating pool respectively. The operation of MARK is illustrated in **Table 4** and it now assumes that 0.2 of MARK rate at each column in the population is expected. It can be seen that the Mark rate in A_1 and B_3 below the specific value, a single “1” and two “0” in column 3 and 1 are randomly selected and mutated respectively.


Gene						Gene				
	0	1	1	0	<div>Evolution</div> <div></div>		0	1	1	0
	0	0	1	1			0	0	1	1
	0	1	1	0			1	1	1	0
	0	1	1	1			0	1	1	1
	0	0	1	0			0	0	1	0
	0	0	0	1			0	0	0	1
	0	1	1	1			0	1	0	1
	0	0	1	1			0	0	1	1
	0	0	1	1			1	0	1	1
	0	1	1	1			0	1	1	1
A _c	0	0.5	0.9	0.7		A _c	0.2	0.5	0.8	0.7
B _c	1	0.5	0.1	0.3		B _c	0.8	0.5	0.2	0.3

Table 4: Mark operation

6. Software implementation

The single train simulator and GA-based coasting-point identification process are the two major components in coast control of train operation [16]. The architecture within GA is not excessively complicated for finding the solution, and hence computing demand is not unreasonably high, particularly when the number of coasting points does not exceed two, which can be usually attained within a minute from the simulation. Thereby, the train simulator with the function of coasting identification have been implemented in Visual Basic (VB) with the provision of a good interface

even it lacks strong support to numerical computation.

The principal loop in the train simulator is the incrementing time. At the beginning of each update period, it is assumed that the position and speed of the train are known. The movement simulator is used to examine these new position and speed with respect to track-based data, in order to determine the possible train modes (motoring, coasting and braking) for the duration of the next update period. Once the train mode is established, the performance of the train must be calculated, taking into account track details, train speed and position. This requires a representation of track gradient and curvature, motor efficiency and train loading. Finally, the calculated speed and position of train is updated and will then be used as the initial values for the next time update. The structure of the single train simulator is given in **figure 7**.

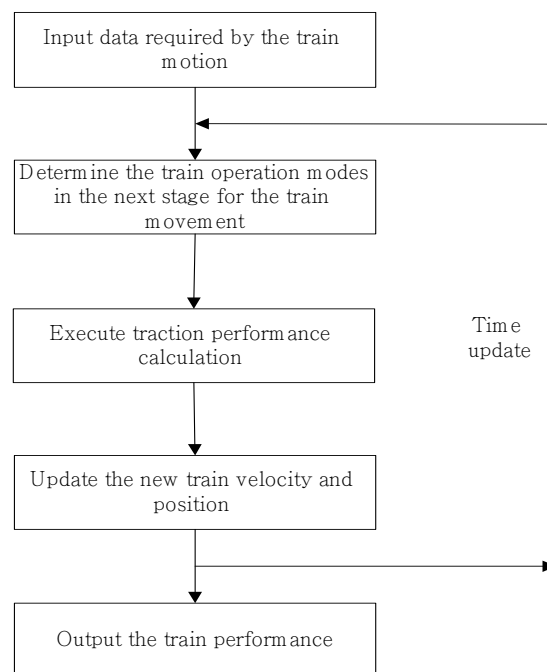


Figure 7: Single train simulator

Once the train performance with the “flat-out” speed against position profile is attained from the train simulator, the coasting-point identification module starts. A new gene (coasting point(s)) will be reproduced if the train output performance does not fulfil the fitness requirements. The same process repeats until either the new coasting point(s) satisfies the expected requirements or the maximum number of generations set by the user is reached. The structure of the module is shown in **figure 8**.

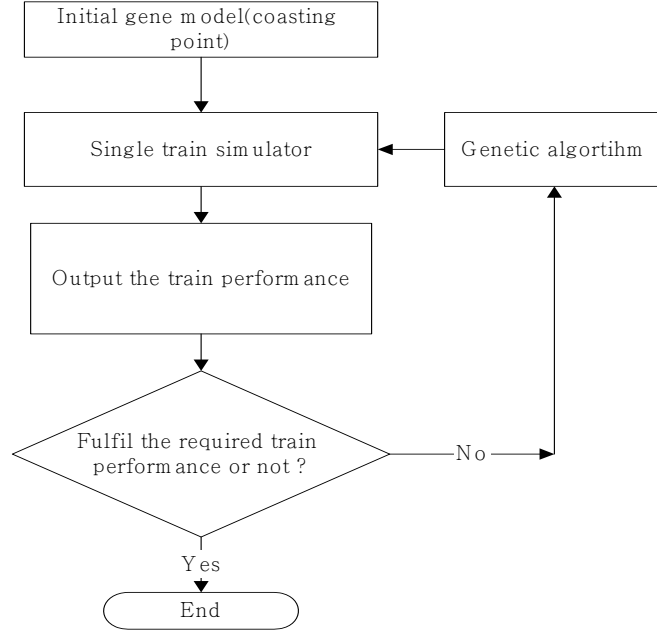


Figure 8: GA based coasting point identification module

7. Results and discussions

7.1 Simple GA based coast control

This study investigates the application of a single and multiple coasting point control on train operation with simple GA according to a specified traffic conditions. Two cases are considered here in which the track geometry is different and the operation conditions are listed in **Table 5**. With GA, a fitness of 0, which means the outcome providing exactly the desired solution, with a maximum number of iterations set at 20 is required in all cases.

	Case I	Case II
Inter-station distance	9km	
Run time extension	10% more than that in flat out run	
Track	Downhill slopes	Uphill slopes

Table 5: Operation conditions

With the aid of the train simulator, the results are summarised in **Table 6**. From the results, it can be seen that a simple GA-based coast control can provide solutions with an acceptable fitness in both cases. A single coasting point control is more applicable for an inter-station run with downhill slopes as it provides a lower fitness in case I. With downhill track, a train tends to maintain its speed during coasting and hence it

favours one coasting point. Nevertheless, a train loses speed quickly during coasting with uphill track and it usually needs re-motoring and then another coasting is required. Though a quick and near-optimal solution can be provided by a simple GA based coast control, there is no specific rule in obtaining the number of coasting points for the regulation of train schedule.

	Single coasting point		Multiple coasting point	
Case	I	II	I	II
Fitness	0.0015	0.0186	0.0079	0.0008

* The computation time is within 10 second in all tests.

Table 6: Inter-station runs with uphill and downhill slopes

7.2 HGA

A 3.2km long inter-station run is chosen and the other operation requirements are given in **Table 7**. With GA, a fitness of 0 with a maximum number of iterations set at 100 is required in all cases.

	Case I	Case II
Inter-station distance	3.2km	
Run time extension	30% more than that in flat out run	
Energy consumption	30% less than that in flat out run	
Track	Downhill slopes	Uphill slopes

Table 7: Operation conditions

Different inter-station runs with uphill and downhill tracks have been examined to obtain the number and location(s) of coasting point(s) with HGA and the results reveal that it provides the solution with acceptable fitness. An even lower fitness value can be achieved with a larger maximum number of generations. **Figure 9 and 10** show that the average fitness of the coasting solution attained from the HGA is better than that by a simple GA with fixed number of coasting points in both cases. From the previous study, it also illustrates 1 coasting point is preferred in Case I because of the downhill track, whilst the track in Case II mainly consists of uphill slopes and hence re-motoring and further coasting point are necessary. **Table 8** summarises the

percentages of coasting point selection and HGA selects the correct number of coasting points in more than 70% of the cases. Hence, a greater flexibility of coast control of train operation can be accomplished with HGA.

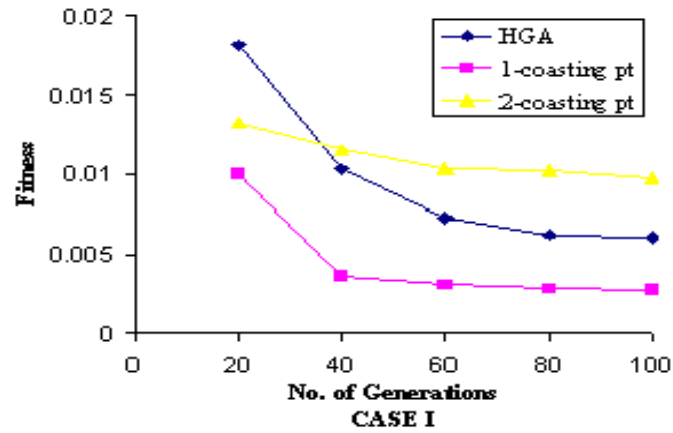


Figure 9: Average fitness of an inter-station run with downhill slopes

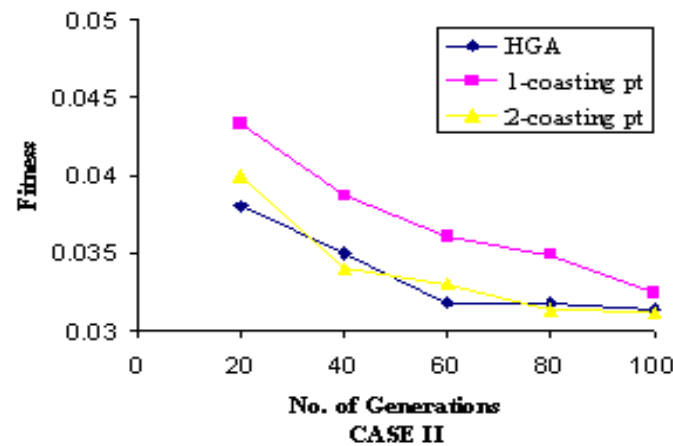


Figure 10: Average fitness of an inter-station run with uphill slopes

	1-coasting point	2-coasting point
Case I	70%	30%
Case II	28%	72%

Table 8: Percentage of coasting point selection

7.3 MARK

This study explores the performance of MARK operation in GA. The inter-station conditions and operation requirements remain in which are given in **Table 7**. The track layout characteristic is shown in **Table 9**. The evolution method applied in GA in this application is depicted in **Table 10**

Section (m)	Slopes (%)
0 ~ 850	0
850 ~1300	-1
1300 ~ 1700	-0.31
1700 ~ 2600	0.3
2600 ~ 2850	1.98
2850 ~ 3200	-0.36

Table 9: Track layout

Genetic operator	
Crossover point	2
mutation	0 ~ 40%
MARK	0 ~ 40%

Table 10: Evolution method in GA

Figure 11 and Table 11 illustrate the fitness with different mutation and MARK rates and their corresponding numerical result of the test respectively. In **Figure 11**, the darker area implies a lower fitness. Simulation result shows that the fitness is gradually reduced when the percentage of mutation adopted in evolution is increased, and if no MARK is introduced. Further, the fitness is even better when only MARK is given in the test. Tests have also been undertaken to investigate the effect of various extents of MARK and mutation on chromosome fitness. **Figure 11** reveals that the introduction of MARK provides significant enhancement with the same number of generations when mutation manages a gradual improvement on fitness. The reason is the solution escapes from the optimum is limited with MARK operation in evolution and the efficiency of MARK on convergence can then be assured.

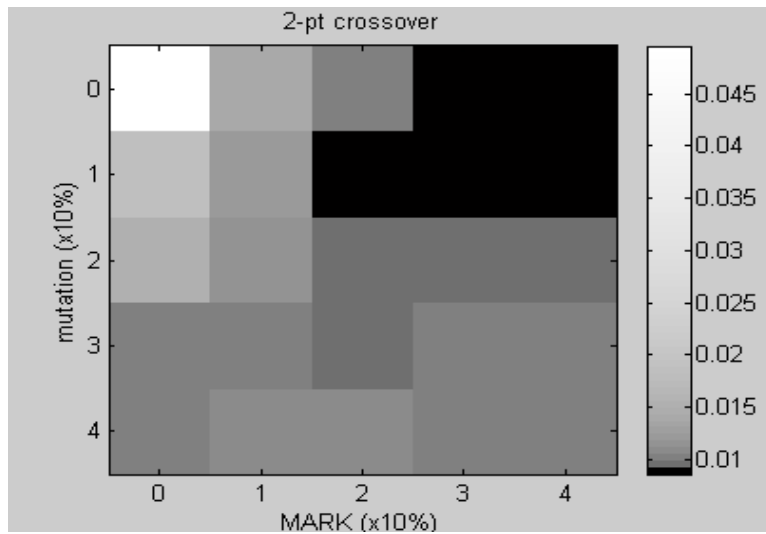


Figure 11: Fitness values with different mutation and MARK rates

Mutation (%)	MARK rate (%)				
	0	10	20	30	40
0	0.0496	0.0138	0.0101	0.0086	0.0086
10	0.0184	0.0119	0.0089	0.009	0.0089
20	0.0154	0.0116	0.0098	0.0095	0.0097
30	0.0104	0.0103	0.0097	0.0099	0.01
40	0.0102	0.0109	0.0106	0.0104	0.0102

Table 11: Fitness values with different mutation and MARK rates (numerical data)

8. Conclusions

A GA-based coast control of train operation has been presented and the results show successful provision of the coasting solution for the regulation of train schedule with the aid of the train simulator. The application of HGA has been proposed to obtain the number and locations of coasting points according to traffic condition, which can be incorporated into coast control for train operation. Simulation results reveal that a greater flexibility in train movement control can be achieved with HGA and it is more likely to optimise train operation with respect to run-time and energy consumption requirements in an inter-station run. The results also show that track geometry and the distance between stations are the key factors to determine the number of coasting point required in an inter-station run. Further, a fast mutation scheme, MARK, has been introduced and MARK operator has been successfully incorporated to ensure quick convergence in the HGA, which meets the demand of this real-time application. In practice, dynamic coasting control has not yet been commonly adopted in train service regulation and the GA-based controller has the potential to maintain the train service in railway system. The controller can be integrated in the on-board Automatic Train Operation (ATO) system and the coast control command for the next inter-station run can be obtained when a train stops at a station.

Acknowledgements

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