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Peak Power Demand Reduction Under Moving Block Signalling Using Expert System

T.K. Ho and K.K. Wong

Abstract: The concept of moving blocking signalling (MBS) has been adopted in a few mass transit railway systems. When a dense queue of trains begins to move from a complete stop, they can re-start in very close succession under MBS. The feeding substations nearby will likely be overloaded and the service will inevitably be disturbed unless substations of higher power rating is facilitated. By introducing starting time delays among the trains or limiting the trains' acceleration rate to certain extent, the peak energy demand can be contained. However, delay is introduced and quality of service is degraded. We present an expert system approach here to provide a supervisory tool for the operators. As the knowledge base is vital for the quality of decisions to be made, this study focuses on its formulation with the balance between delay and peak power demand.

1 Introduction

Fixed-block signalling (FBS) has been widely adopted in railway systems for more than a century because of its simple and safety-effective concept of one physical block of track occupied by no more than one train at a time [1-2]. To increase line capacity with FBS, it is possible to have shorter block lengths but the installation and maintenance cost of the signalling and track equipment may not be justified by the increased line capacity. The coarse positional resolution of the trains is another drawback.

The demand on the headway becomes so heavy in the metro systems of some major cities that FBS is not able to handle without operating with the full capacity of the infrastructure. Moving-block signalling (MBS) was proposed a few decades ago [3] to provide more room for headway reduction. Theoretically, two successive trains are separated by a distance equivalent to the braking distance for the train behind to brake to a complete stop from its current speed, as well as a safety margin. The separation is reduced to the bare minimum and hence the headway is improved to the limit for the given operating speed and train characteristics, such as train length and braking rate. MBS operations rely on the continuous bi-directional communication links between trains and controllers which can be distributed at track-side locations as well as being centralised. The positional resolution of the trains is therefore much higher than that under FBS. Most successful implementations of MBS systems are not exactly utilising the concept in its original form [4-7]. The communication is not absolutely continuous, but the ‘sampling frequency’ is adequately high to provide near-continuous communication with respect to the maximum train speed. It is regarded as pseudo-moving-block signalling. The communication links are realised by track conductor loops of a certain length. The boundary of two loops is identified by transposition and the loop length defines the resolution of train position, and hence accuracy of speed restriction for the train behind and minimum headway.

Because the trains can get closer to each other under MBS, a dense queue may form when the leading train stops at a station, or other reasons, for an unexpected period of time. With the assumptions that traction controllers are not capable of ramping down their demand to create a self-regulated condition and no specific traffic-regulation strategies are imposed from the ATS control centre, the trains behind may start when its separation from the rear of the accelerating train ahead becomes greater than the minimum ATP safety distance. As a result, soon after the leading train has started to move again, the whole queue of trains accelerates in close succession. It is feasible from the operational point of view but the instantaneous increase of power demand will be too much for the power system to bear. The feeding substations in the vicinity may be overloaded. In the worst case, the circuit breakers, set for earth-fault detection, will be tripped and the service will be disturbed as a result. One possible solution is to raise the power ratings of the feeding substation but the additional cost cannot be justified by the fact that overloading is not expected to occur very often and the substations are usually operated well below its ratings. Indeed, the peak demand can be reduced by regulating the train movement and spreading the demand to the adjacent substations.

Takeuchi and Goodman have investigated the starting behaviour of a queue of trains within simple metro systems under pure MBS [8]. Two peak demand reduction strategies: starting time delay (STD) by which the starting of each train behind is delayed; and accelerating rate limit (ARL) where the acceleration of each train behind is limited to certain extent, were proposed. Simulation results show ARL achieves better peak demand reduction under certain traffic conditions. Further improvement can be attained when different values of ARL are used for the trains behind according to how far they are at the back of the queue. This study was carried on further to evaluate the combination of STD and ARL [9] with performance indices including peak demand reduction, total energy saving, delay propagation and total arrival time delay. Even though the exclusive use of the graded ARL technique is still suggested to be the best solution to this re-starting problem from the viewpoints of the defined performance indices, the combination of both techniques has the merit of better total energy saving.

Power demand and delay are two conflicting criteria in railway operation and the tilt of balance varies with traffic conditions, service demands and time of operation. Unsurprisingly, no single technique can provide the optimal solution for this re-starting problem in general. To complicate matter further, MBS has so far been applied in metro systems in which only a single type of trains serves the passengers and the track topology is simpler. Some new mainline systems, where mixed traffic must be allowed and complex rail network is needed, are investigating the possibility of using MBS. The West Rail of KCRC in Hong Kong is one example. Because different types of trains have their own equipment characteristics and operation schedules, more variables are introduced to the selection of peak energy demand and delay minimisation techniques to restart a queue of trains. An analytical model to relate various system parameters, such as traction equipment, train distribution, substation locations, to peak energy demand and delay is anything but simple. Intelligently combining different techniques in accordance with the current operational demand is an alternative to maximise the advantages of MBS.

This study is to investigate the performance of various techniques and their combinations on peak power demand and delay reduction; and their balance under various operational requirements and traffic conditions by computer simulation. An advisory system is then built to assist the operations, automatic or otherwise, to restart a queue of trains under MBS in either metro or mainline systems while satisfying the current operational requirements and traffic conditions. The time given to find the solution is limited as the trains may start to move very soon. A large amount of parameters are involved in the decision-making process and some may come with uncertainty and ambiguity, expert knowledge and common sense on railway operation will therefore be needed to hasten the solution-searching process. An expert system approach is therefore adopted to develop this advisory system. Expert system is one of the early products from the artificial intelligence and has been used extensively in numerous areas. The deployment of expert systems is not yet very common in railway applications but more examples have emerged in recent years. Successful applications have been found in adapting different fixed-block signalling specifications to a multi-train simulator [10], AC supply system control on an electrified line [11], scheduling and timetabling [12-13], as well as other applications on traffic management [14] and service distribution [15] in road transportation.

We describe the application of an expert system to find the appropriate train control measures for re-starting trains under MBS while reducing the peak power demand. The formulation of the knowledge base for the expert system from the consideration of various system parameters will be presented and the performance will be evaluated by computer simulation.

2 Restarting with fixed block and moving block signalling

With FBS, the track is divided into a number of sections called blocks and each block cannot be occupied by more than one trains at any one time. The presence of a train within a block, or the occupancy of a block, is detected by means of electrical track circuits or similar form of train detection. With speed-signalled systems, a train may proceed to a vacant block, subject to the speed restriction relating to the number of vacant blocks ahead. The line capacity is thus determined by the minimum number of blocks between two successive trains while they do not interact with each other via the signalling system. The resolution of a train’s position is rather coarse as it depends upon the length of block it occupies.

When a train stops for a station or whatever reason, train(s) behind, if any, will stop at least a block away, so is the separation between any two trains further behind. A queue forms but it spreads over a long section of track because of this compulsory block-length separation. Even when the first train starts to move, the second train cannot start until the first one clears the block it was occupying. The same applies to the trains behind. Hence, there is an intrinsic time delay imposed to the starting process of the queue of trains. With this time delay, the train in front has established a certain speed and its power demand may have subsided before the train behind starts and accelerates with the maximum power demand. The instantaneous power demand comes in a number of phases as each train moves on in turn and there is no need for the supply system to cater for the need of the simultaneous starting of a few trains. Besides, when the queue is longer, it is more likely that the power demand is shared by more feeding substations.

On the other hand, two trains are only separated by a safety margin when they stop under MBS. A dense queue is resulted if more trains are brought to a stop. The time interval of the starting and then drawing the maximum power among the trains will be very short. More trains on the queue will only add to the toll of the instantaneous power demand. It does not take too many trains to push this sudden rise of power demand to exceed the ratings of feeding substations in the vicinity. The installation and maintenance costs of the substations are directly linked to the power ratings. The provision of higher ratings to solve this particular problem with MBS is not necessarily justified when there may be other possible solutions. It is definitely not a feasible solution for the existing lines which are to be re-signalled to MBS.

Takeuchi et al conducted a thorough investigation on FBS and MBS under steady-state and perturbed traffic conditions through mathematical analysis and simulation studies [16]. Pure Moving Block signalling has been proven to produce the best performance in both cases. However, MBS suffers from the inherit problem of high peak demand for a queue of re-starting trains. To tackle this problem, starting time delay (STD) and acceleration rate limit (ARL) have been adopted to reduce the peak demand with certain degree of success [8-9, 16]. They impose delays to successive trains during the re-starting process through manipulating the time schedule and tractive effort respectively. The reduction of peak demand is however at the expense of headway because of the delays introduced, which may reduce the ability of MBS to recover from a disruption. As a result, the relationship between peak demand reduction and headway deterioration under both STD and ARL has to be investigated before their advantages can be fully taken.

Nevertheless, an analytical model to link peak demand and delay together may not be a technically viable option because there are so many inter-dependent parameters and uncertainties involved. Some of the parameters are system-related, such as train weight, tractive equipment characteristics, power system ratings and service headway whilst the others vary in different re-starting situations. The numbers of trains on the re-starting queue, mixture of the trains and feeding substation locations may have different implications on the application of STD and ARL. The relative position of the train queue to the substations is another crucial factor. When the trains stop mid-way between two substations, the peak demand will be evenly shared and overloading at the substations may be avoided. It is of course a different scenario when the trains have to start very close to a particular substation.

As the re-starting process may start any time after a queue forms, a complicated model, however accurate, is not particularly helpful for the quest of a quick solution, which may be a graded application of STD or ARL or even a combination of both. Human experts of substantial relevant background and experience are capable of making such real-time decisions, just like traffic warden at a road junction or even a signalman in the past. The optimal solution may not be forthcoming all the time from a human expert. A reasonable, sensible and consistent solution is what it is required as a supervisory tool for the operators. While it is impossible to post human experts along the rail line, an expert system approach is employed to emulate the expert's decision-making capability with a software program.

3 Expert system

An expert system is a computer program that utilises knowledge and inference procedures to solve problems which require human expertise in a specific domain of applications [17-18]. For complex systems where simple 'blind' search technique is inadequate, knowledge-guided search has emerged and led to the idea of expert system. The knowledge required in an expert system consists of facts and heuristics. The facts are the well-known and widely accepted information or practices of a particular field. The heuristics are some rules of good judgment or good guess for decision making in that field. They are normally less publicised but they usually work well and result to a quicker and/or better solution in most cases. Different experts may have their own sets of heuristic rules based upon their experience in the field.

There are two basic components in an expert system, a knowledge base and an inference engine. The domain knowledge required for the expert system is placed in the knowledge base. It may be in the form of rules or other appropriate formats, depending on the knowledge representation. The inference engine is the problem solving strategy which organises and controls the steps taken towards the solution. The most popular paradigms are the top-down (goal driven) and the bottom-up (data driven) approaches [19-20].

It is also desirable to have a user-friendly interface to enable the users to communicate with the system under a comprehensible and comfortable environment. A natural language interface would be particularly helpful for non-expert users. However, a window environment with dialogue boxes, menu-driven controls and sufficient help messages is enough to make the interaction simple and smooth. An explanation module may also be included as an option, allowing users to examine the reasoning underlying the solution given by the expert system. Fig.

1 gives an overview of the functional blocks within an expert system. The expert system in this study is developed with Visual Basic and run on IBM compatible PCs.

3.1 Knowledge base

Most of the expert systems have the knowledge represented in one of the three forms, production rules, semantic network and predicate logic. They apply a number of rules, graphs and clauses respectively to match a particular pattern denoting the problem to be solved. In this expert system, the most popular format, production rule, has been adopted as it resembles better with the experts' experience and hence provides a natural representation.

The basic principle of production rules is to formulate the relations between the patterns of data presented to the system and the resulting action(s) the system should take. In addition to the knowledge base, the expert system also consists of a global database to keep a record of the problem status and a rule interpreter to decide when and how to apply the rules.

The rules are made up of two components, conditions and actions:

If A_1 & …… & A_m, then B_1 & …… & B_n

It means that 'if the conditions A_1 and … and A_m are satisfied, then perform the actions B_1 and … and B_n.

The production rules are tried in turn to match the pattern in the global database. The appropriate rule is then executed and the actions taken generate another pattern in the global database. The procedure then repeats until a solution is found. As the number of rules increases, simply examining every rule becomes a tedious job. Meta-rules may be introduced and they can select a particular set of rules to execute next. Meta-rules are distinguished from ordinary production rules that they guide the reasoning towards the solution, rather than performing the reasoning.

3.2 Inference engine

An inference engine executes the procedures of applying the knowledge. With the production rules, the inference engine compares the IF part of the rules against known facts in the global database in order to determine if the THEN part, i.e. new facts, can be inferred. In this expert system, the initial facts are the system constraints and operating conditions and the ultimate inferred action is a re-starting policy. The inference strategy adopted is therefore forward chaining with data-driven rule searching.

Unlike most conventional software programs in which the algorithms and control of the program flow are mixed together, the knowledge base and inference control within the expert system must be physically and functionally independent so that they can be developed, modified and refined without imposing any limitations or alterations on one another. It is indeed in consistent with how a human expert operates.

3.3 User interface

Communication between the users/experts and the expert system is made possible through the user interface. A user supplies the information and data of the problem and then obtains the solution with the aid of the interface. Fig. 2 and 3 give the examples of the input and output interfaces respectively. The former allows the system requirements and operational conditions to be inputted whilst the latter displays the peak power demand reduction measure recommended by the expert system.

4 Acquisition of knowledge base

The rules and facts in the knowledge base are the core of the expert system. They are the knowledge usually acquired from human experts. However, human experts are not available in this application because no signal engineer has ever been engaged in this capacity. As a result, the knowledge base has to be established through experiences with practical traffic conditions and knowledge, as well as common sense, of railway operation. In this section, a number of tests are carried out with the aid of a whole system simulator [21] in order to investigate the effects of various system parameters and peak power demand reduction measures on the power demand during the re-starting process. A specific test-bed is used to generate the rules here to demonstrate the application of expert system. Different systems may produce different sets of rules similarly and the rules can be inserted in the knowledge base directly.

4.1 System constraints and operational parameters

As illustrated in Fig. 4, a queue of three trains T_1, T_2 and T_3 is intentionally put to a halt between two substations S_A and S_B. It is a dc supply system with a nominal voltage of 1.5kV and S_A and S_B are 7km apart. The peak power demands at S_A and S_B and the time required for the last train (i.e. T_3) to clear S_B during the re-starting process under the following conditions are attained. The results are then used to formulate the rules and facts in the knowledge base.

4.1.1 Weights of trains: With mixed traffic, trains for different services are running on the same line and the weights they carry may vary significantly. A lighter train can go away from a re-starting queue quicker so that the peak demand may spread over more substations whilst a heavy one may limit the acceleration of the trains behind. This test takes the case of equal-weight on the three trains as a reference and assumes identical traction equipment characteristics. To exaggerate the possible effects of train weight on peak demand, one of the train weights is reduced to half or doubled. The results are summarised in Table 1 and the case of equal weight is used as the reference.

The peak demand increases when the weight distribution is uneven (as reflected by the negative values on percentage reduction). If the heaviest train is not the first on the queue, the peak demand goes further up. A heavy train tends to accelerate slowly and the signalling influence from the train in front gradually diminishes. The train then accelerates freely without any limitation and draws the maximum necessary power. It is therefore recommended that a queue of trains with mixed weights should be divided into two so that the heaviest train heads the second queue. A time delay can be introduced between the two queues to spread the peak demand over farther distance, but of course it may impose delays on the trains. Indeed, the heaviest train is usually the one heading a queue in metro systems as more passengers board the train after longer period of waiting.

4.1.2 Re-starting location: The re-starting location of the first train with respect to the two sandwiching substations plays an important role on the distribution of the peak power demand to the substations nearby. In this test, the relative position of T_1 to S_A and S_B is defined by $K = X / Y$ so that $0 \le K \le 1$, as illustrated in Fig. 4. The peak demand distributions on the two substations are shown in Table 2 with K=0 as the reference. As the distribution for the first half of K should be roughly a mirror image of that for the second half, only the cases with K ranging from 0 to 0.5 are given here.

Unsurprisingly, imbalance of peak demand on S_A and S_B is the most apparent when K=0 (reference case) and rapidly subsides when K approaches 0.5. In order to denote the extent of urgency of peak demand reduction according to the relative position of trains within the expert system, the inter-substation distance is divided into a number of regions which are defined in Table 3. More regions may lead to better control resolution, but only when such resolution is required.

4.1.3 Safety margin: Table 4 (the first case taken as the reference) shows that safety margin between trains does not carry significant impact on peak power demand. There is a slight tendency of peak demand reduction when safety margin increases because the trains are farther apart and peak demand is spread around. However, excessive safety margin introduces unnecessary delays to the train service.

4.1.4 Train length: From Table 5 where the case of equal length is taken as the reference, there is no clear relationship between peak power demand and lengths of trains as the trains still draw the maximum power simultaneously during re-starting. Longer trains only make the queue longer and possibly allow more substations to share the peak demand.

4.2 Peak power reduction measures

Performance of the two peak demand reduction measures, STD and ARL, are investigated with this 3-train, 2-substation test-bed. As combinations of the two measures provide more control options for the operators, the effects of various combinations on peak demand reduction are also examined.

4.2.1 Starting time delay: Peak demand reduction at S_A and S_B under different combinations of starting delay times on T_2 and T_3, with K=0, are summarised in Table 6. The case of no starting time delay is taken as reference. Peak demand keeps falling with increasing starting time delays and the demand reduction is particularly obvious on S_A. While the starting times of the trains T_2 and T_3, which are closer to S_A, are well separated, the demand on S_A does not pile up simultaneously and hence the peak demand reduction on S_A is more apparent. However, the overall run-time suffers as a result of extra time delay, which may lead to unwanted deterioration of quality of service.

With different values of *K*, Tables 7, 8 and 9 show similar pattern. As *K* gets closer to 0.5, the peak demand is already better balanced over S_A and S_B. Even though further reduction on peak demand is possible, it is justified by the extra time delay.

4.2.2 Acceleration rate limit:

Table 10 illustrates the peak demand reduction when the acceleration rate of T_2 and T_3 are refrained to various fractions of full motoring. The case of all trains at full power is used as the reference. Demand reduction is possible but not as significant as when STD is adopted. However, a reasonable demand sharing between S_A and S_B is maintained, as indicated by a positive reduction on S_A and a negative one on S_B. Although the peak demand from each train decreases with subdued acceleration, a train spends more time on motoring before it reaches the maximum permissible speed. It is more likely to have trains motoring simultaneously and hence the accumulative power demand is still considerable. Besides, the acceleration rate cannot be set in practice as freely as in the simulation because of its dependency upon the traction drive system characteristics. The control space of this peak demand reduction measure may be rather limited. On the other hand, the delays introduced to the trains with ARL are not too excessive as the overall run-time is only extended slightly.

As illustrated in Tables 11 and 12, further increase of *K* produces similar results. However, the peak demand sharing is already quite even when *K* approaches 0.5, substantial reduction on acceleration rates only sees the peak demand shifting toward S_B and induces unbalance peak demand.

4.2.3 Combined measures:

Combinations of STD and ARL to different extents are applied to various operational conditions and the results for *K*=0 are given in Table 13. The case of no STD and ARL is used as the reference. Peak demand is reduced considerably in most cases and the demand on the two substations is better balanced. Having attained control on time delay and acceleration rate, the control space becomes two-dimensional. It is therefore more flexible for the operators to exert the necessary actions according to the operational conditions. The only drawback is that the overall run-time is stretched extensively because both measures impose delays to trains.

4.3 Formulation of knowledge base

According to the results in previous sections, rules in the knowledge base can be built. The rules are organised in five sets, designated to various functions in this application. Priority is given in the order of when they should be triggered during the process of formulating a solution. Supported by the facts on train positions, number of trains, train characteristics and service requirement, the rule-sets are initiated and the appropriate rules are fired to bring the reasoning toward the possible solution.

The 5 rule-sets are classified as in Table 14 and the inference flow is illustrated in Fig. 5. The expert system thus starts with identifying the heaviest train, followed by splitting the queue into two groups according to the total number of trains in the queue and usually the heaviest train leads the second group. Introduction of time delay between the train groups is possible and it is at the discretion of the user. Having allowed the user to indicate preference on either shorter time delay or more peak demand reduction as a result of the recommended measure, the expert system goes on to devise the appropriate measures within the 'Time-delay Assignment' and 'Acceleration-rate Assignment' rule-sets.

The 'Time-delay Assignment' and 'Acceleration-rate Assignment' rule-sets are divided into a number of classes and groups, which contain various extents of time-delay and acceleration-rate, in order to suit operation conditions and user requirements on time delay and peak demand reduction. They can be updated and/or deleted flexibly with respect to any changes in the system conditions and operation requirements.

5. Results and discussions

5.1 Testing

This section demonstrates the functions and versatility of the expert system by putting it through similar traffic conditions with different operational requirements. The tests have been undertaken in the same set-up as for the test-bed because the rules are generated from the 'experiences' there. Demand reduction percentages at the substations and overall run-time are the basic performance indicators. The performance of the expert system has been investigated when the operational concern focuses on peak power demand reduction, time delay reduction or both, as envisaged in three tests here. There are three levels of time delay and peak demand reduction: high, medium and low, to allow the user to indicate the requirement on the two performance concerns. They will be used to determine the extents of application of any re-starting measures. The case of K=0 for the leading train with no action from expert system, which is the worst case with highly unbalance demand on S_A and S_B (case A in the tests), is taken as the reference. The operational requirements of the three tests are listed below and the results of various cases are given in Tables 15, 16 and 17 respectively.

Additional time delay can be introduced between train groups by the user if the train queue is divided into two groups and more. The results also show its impact. As the reduction of accelerating rate of a train depends upon traction equipment, it may not be set to any arbitrarily low value. The user may specify such a threshold that the acceleration rate should not fall below whenever ARL measure is adopted.

Test 1
Performance concern: Peak demand reduction
Level of peak demand reduction: High
Priority to the heaviest train: No
Total number of trains in the queue: 5
Number of trains in group (if grouping required): 3

Test 2
Performance concern: Time delay reduction
Level of time delay reduction: High
Priority to the heaviest train: No
Total number of trains in the queue: 6
Number of trains in group (if grouping required): 3

Test 3
Performance concern: Both peak demand & time delay reduction
Level of peak demand reduction: High
Level of time delay reduction: High
Priority to the heaviest train: No
Total number of trains in the queue: 5
Number of trains in group (if grouping required): 3

In Test 1, peak demand reduction is the prime concern. The five trains are divided into two groups, with two trains in the first group and three in the second. From the results, only STD measures are recommended and they lead to either peak demand reduction on both S_A and S_B or a spread of loading from S_A to S_B (as reflected by a negative peak demand reduction on S_B, coupled with a positive reduction on S_A). The overall run-time is however longer as a result. When a time delay is introduced between the two train groups (cases D, E, G and I), the peak and unbalance loadings are further improved in general at the expense of extra time delay. The expert system recommends no action (cases G, H & I) when the train queue re-starts mid-way between S_A and S_B. The power demand should be quite evenly distributed between the two substations in these cases.

On the other hand, the operational focus is placed on time delay reduction in Test 2. The six trains are also divided into two groups, with three trains each. ARL measures are therefore the resulting actions. Peak demand reduction is not evident in most cases but unbalance loading on S_A and S_B has been alleviated with significant increase of loading on S_B. The overall run-time is very comparable in all cases and even the introduction of time delay between the two train groups only imposes slight delay. However, such delay between the two groups (cases B, D, F and H) does not help reduce the peak demand, if not otherwise.

Test 3 entertains the two conflicting requirements in time delay and peak power reduction. Various combinations of ARL and STD measures are recommended for different cases. Unsurprisingly, the two ends cannot be met simultaneously and no overwhelming superiority is attained. Compromise has to be made instead. Peak demand reduction is not always possible as in Test 1 and even when it is possible, only a limited extent of reduction is realised. Nevertheless, this lesser concession on peak demand reduction is well compensated by a better sharing of peak demand between S_A and S_B; and a more acceptable overall time delay imposed on the trains. The combination of ARL and STD also allows any time delay between the two trains groups (cases B, D, F and H) to achieve further peak demand reduction while keeping the overall time delay down.

5.2 Implementation

The expert system is an independent supervisory tool with direct interface with the ATS control centre. It is not safety critical and its recommended actions, if adopted, are safeguarded by the ATP. Two sets of input are required, static and dynamic. The former consists of track layout, substation locations and ratings which can be inserted as facts to the knowledge base; whilst the latter contains traffic conditions and operational requirements which are attained from the ATS via the bi-directional communication links between trains and controllers.

As numerical calculation is kept to minimal within the inference engine, a modest microprocessor platform with a fair size of memory for the knowledge base is adequate to satisfy the hardware requirement. An AI-specific programming language or any advanced high-level language can be used for software implementation. An expert system shell will of course quicken up the development process.

6. Conclusions

We have presented an expert system approach to reduce peak power demand in a railway system when re-starting a queue of trains under moving block signalling scheme. Based on the studies with STD and ARL measures, their adoption and the extent they should be applied have to be assigned with respect to the system conditions and operation requirements in order to take their full advantages. An expert system has been built to make such assignments and its knowledge base is derived through the simulated 're-starting experiences' in a trial traffic scenario. As peak demand reduction is often accompanied by an extra time delay imposed on the train queue, the balance between demand reduction and time delay is the key performance indicator.

The expert system is then asked to make recommendations in a number of tests with different priorities on performance. The results show that it is capable of providing appropriate advices according to the operational requirements in all cases of the tests. The expert system also enables better sharing of peak demand between substations and holds the balance between peak demand and time delay reduction in response to the user's request. The re-starting queue of trains is usually divided into groups before the expert system is applied to each group. A deliberate time delay between these train groups provides another possible means to further reduce peak demand.

This study reveals the feasibility of applying expert system on this railway operation problem with a simple and small-scale test-bed. A more complicated re-starting case with more trains and system constraints involved should however not hinder the effectiveness of an expert system approach. Even though every railway system is unique on its own characteristics and the re-starting problem under MBS is heavily system-dependent, the same expert system is still a generic supervisory tool for the railway operators because of its intrinsic separation of knowledge and inference. Different system conditions and operation requirements merely mean a change of knowledge base while the basic structure of the expert system remains. Further works therefore include development of an expert system shell, with which any system-dependent knowledge base can be slotted in flexibly.

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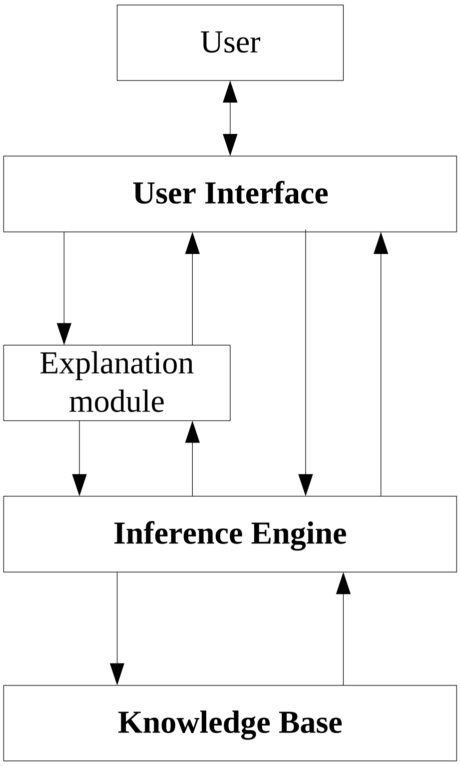
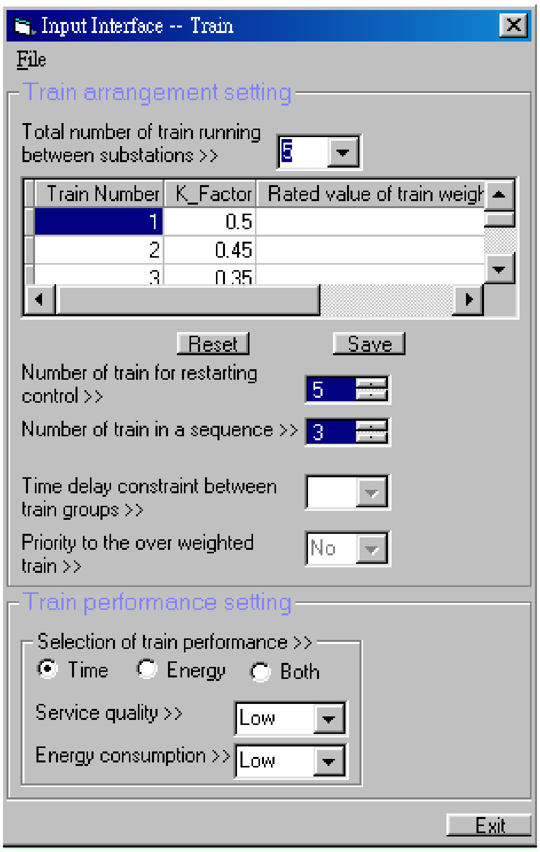


Fig. 1 Structure of an expert system



Train arrangement setting

Total number of train running between substations >> 5

Train Number	K_Factor	Rated value of train weig
1	0.5	
2	0.45	
3	0.35	

Number of train for restarting control >> 5

Number of train in a sequence >> 3

Time delay constraint between train groups >>

Priority to the over weighted train >> No

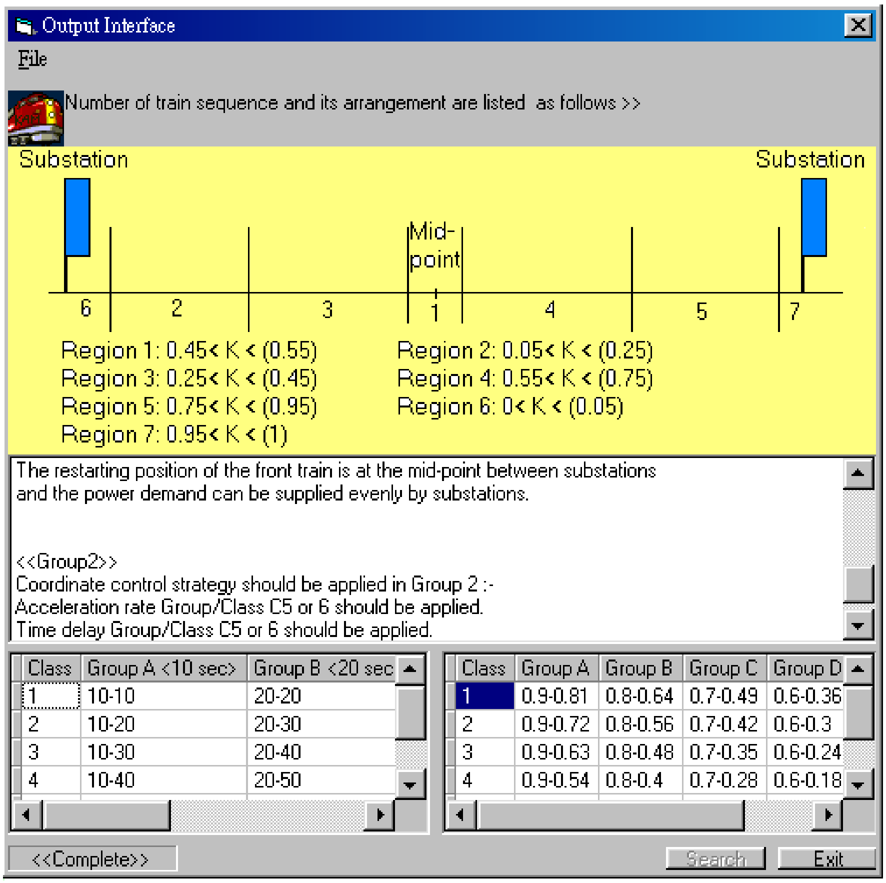
Train performance setting

Selection of train performance >>
● Time ○ Energy ○ Both

Service quality >> Low

Energy consumption >> Low

Fig. 2 Input interface



Number of train sequence and its arrangement are listed as follows >>

Region 1: 0.45< K < (0.55)
Region 2: 0.05< K < (0.25)
Region 3: 0.25< K < (0.45)
Region 4: 0.55< K < (0.75)
Region 5: 0.75< K < (0.95)
Region 6: 0< K < (0.05)
Region 7: 0.95< K < (1)

The restarting position of the front train is at the mid-point between substations and the power demand can be supplied evenly by substations.

<<Group2>>
Coordinate control strategy should be applied in Group 2 :-
Acceleration rate Group/Class C5 or 6 should be applied.
Time delay Group/Class C5 or 6 should be applied.

Class	Group A <10 sec>	Group B <20 sec
1	10-10	20-20
2	10-20	20-30
3	10-30	20-40
4	10-40	20-50

Class	Group A	Group B	Group C	Group D
1	0.9-0.81	0.8-0.64	0.7-0.49	0.6-0.36
2	0.9-0.72	0.8-0.56	0.7-0.42	0.6-0.3
3	0.9-0.63	0.8-0.48	0.7-0.35	0.6-0.24
4	0.9-0.54	0.8-0.4	0.7-0.28	0.6-0.18

Fig. 3 Output interface

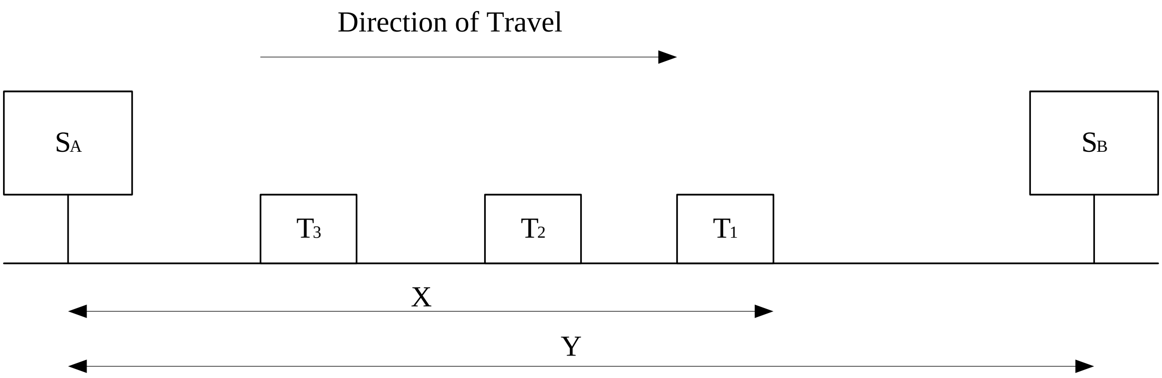


Fig. 4 Locations of trains and substations

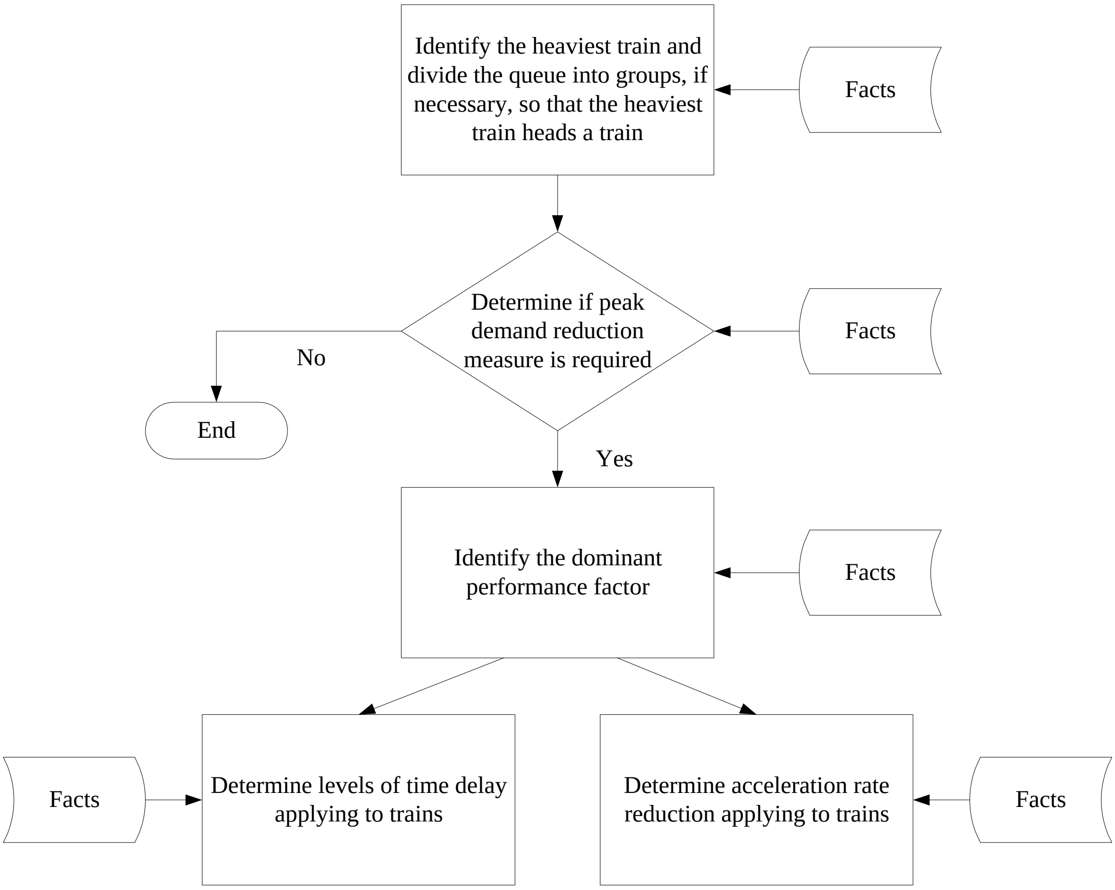


Fig. 5 Inference flow within the expert system

Ratio of train weight T_1:T_2:T_3	**Peak demand reduction on S_A (%)**	**Peak demand reduction on S_B (%)**	**Time for T3 to clear S_B (min)**
1:1:1	0 (6122.3 kW)	0 (3545.5kW)	13:35
2:1:1	-7.4	-10.4	14:06
0.5:1:1	-8.5	14.9	13:22
1:2:1	-14	-12.4	13:34
1:1:2	-15.5	-7.6	13:35

Table 1 Peak demand reduction with different train weights

K	**Peak power demand reduction on S_A (%)**	**Peak demand reduction on S_B (%)**
0	0 (6028.5 kW)	0 (3235.2 kW)
0.178	-2.3	-17.2
0.338	7.6	-21.9
0.5	26.6	-40.2

Table 2 Peak demand distribution with relative positions of the trains

K	**Region**
$0.45 < K \leq 0.55$	1
$0.05 < K \leq 0.25$	2
$0.25 < K \leq 0.45$	3
$0.55 < K \leq 0.75$	4
$0.75 < K \leq 0.95$	5
$0 < K \leq 0.05$	6
$0.95 < K \leq 1$	7

Table 3 Regions between two substations

Safety margin (m)	**Peak demand reduction on S_A (%)**	**Peak demand reduction on S_B (%)**	**Time for T3 to clear S_B (min)**
20	0 (6086 kW)	0 (3530 kW)	11:49
40	-0.4	12.4	11:52
60	1.6	7.1	11:54
80	1.5	7.5	11:56
100	2	7.1	12:00
120	-10.7	-1.3	12:04
140	1.8	17	12:05
160	3.2	17.3	12:07
180	3.6	17.9	12:10
200	4	18.5	12:12

Table 4 Peak demand with different safety margins

Ratio of train length T_1:T_2:T_3	**Peak power demand reduction on S_A (%)**	**Peak power demand reduction on S_B (%)**	**Time for T3 to clear S_B (min)**
1:1:1	0 (6122.3 kW)	0 (3545.5 kW)	12:45
0.5:1:1	1.88	-6.2	12:40
1:0.5:1	-0.35	-15.5	12:38
1:1:0.5	-0.2	1.3	12:42

Table 5 Peak demand with different train lengths

Starting time delay on T_2 and T_3 (sec)	**Peak power demand reduction on S_A (%)**	**Peak power demand reduction on S_B (%)**	**Time for T_3 to clear S_B (min)**
0-0	0 (6028.5 kW)	0 (3235.23 kW)	11:53
10-10	-17.81	16.98	11:58
10-20	7.27	17.51	11:56
10-30	7.27	4.62	11:57
10-40	7.27	-2.62	11:59
10-50	5.86	-4.13	12:04
10-60	7.27	-1.62	12:15
20-20	2.98	1.86	11:56
20-30	10.53	-0.98	11:58
20-40	16.68	1.2	12:05
20-50	18.65	2.08	12:15
20-60	22.9	-3.73	12:25
30-30	12.5	4.58	12:05
30-40	17.96	6.36	12:15
30-50	22.38	0.11	12:25
30-60	25.89	-2.81	12:35
40-40	19.82	3.13	12:25
40-50	24	-2.81	12:35
40-60	31.76	13.71	12:45
50-50	33.89	16.63	12:45
50-60	33.89	29.74	12:55

Table 6 Peak power demand reduction with STD (K=0)

Starting time delay on T_2 and T_3 (sec)	**Peak power demand reduction on S_A (%)**	**Peak power demand reduction on S_B (%)**	**Time for T_3 to clear S_B (min)**
0-0	0 (6169.5 kW)	0 (3793.1 kW)	11:54
10-10	-15	-14.6	11:56
10-20	13.9	13.8	11:55
10-30	13.9	6.6	11:56
10-40	1.3	4.4	11:56
10-50	7.7	6	12:04
20-20	6	6.4	11:56
20-30	13	5.9	11:57
20-40	14	7.2	12:04
20-50	18	8.3	12:14
30-30	13.6	10	12:04
30-40	17.7	11	12:14
30-50	20.9	7.3	12:24
40-40	19.1	9.5	12:24
40-50	24.7	10.8	12:34
50-50	37.2	24.3	12:44

Table 7 Peak power demand reduction with STD (K=0.178)

Starting time delay on T_2 and T_3 (sec)	**Peak power demand reduction on S_A (%)**	**Peak power demand reduction on S_B (%)**	**Time for T_3 to clear S_B (min)**
0-0	0 (5570.3 kW)	0 (3944 kW)	11:55
10-10	-18.9	-22	11:56
10-20	11.4	10.8	11:56
10-30	11.4	-0.7	11:56
10-40	6.1	-9.1	11:58
10-50	4.8	-7.4	12:04
20-20	3.4	1	11:56
20-30	9.8	1.1	11:58
20-40	16.6	0.2	12:04
20-50	16.5	-2.4	12:14
30-30	11.5	3.4	12:04
30-40	16	0.9	12:14
30-50	19.7	-3	12:24
40-40	17.6	-1.3	12:24
40-50	21.1	-2.5	12:34
50-50	35.7	15.9	12:44

Table 8 Peak power demand reduction with STD (K=0.338)

Starting time delay on T_2 and T_3 (sec)	**Peak power demand reduction on S_A (%)**	**Peak power demand reduction on S_B (%)**	**Time for T_3 to clear S_B (min)**
0-0	0 (4427.5 kW)	0 (4534.5 kW)	11:54
10-10	-20.4	-19.7	11:56
10-20	9.8	6.3	11:56
10-30	9.8	-0.9	11:57
10-40	6.3	-12.5	11:57
10-50	5.1	-11.2	12:04
20-20	3.8	1.4	11:57
20-30	9.7	1.9	11:58
20-40	16.1	-2.8	12:04
20-50	16	-4.9	12:14
30-30	11.3	-0.3	12:04
30-40	15.6	-2.2	12:14
30-50	19.1	-5	12:24
40-40	17.1	-3.8	12:24
40-50	20.4	-4.6	12:34
50-50	35.1	16	12:44

Table 9 Peak power demand reduction with STD (*K*=0.5)

Acceleration factors on T_2 and T_3	**Peak power demand reduction on S_A (%)**	**Peak power demand reduction on S_B (%)**	**Time for T_3 to clear S_B (min)**
1-1	0 (6122.3 kW)	0 (3545.5 kW)	11:55
0.9-0.81	2.9	-7.4	11:54
0.9-0.72	3.4	-8.4	11:56
0.9-0.63	8.2	-2.5	11:53
0.9-0.54	5.4	-8.5	11:55
0.9-0.45	8	-11.7	11:55
0.8-0.64	5	-12.5	11:55
0.8-0.56	4.2	-7.1	11:54
0.8-0.48	7.2	-15.6	11:57
0.8-0.4	12.3	-16.1	11:56
0.7-0.49	4.1	-22.5	11:59
0.7-0.42	3.5	-25.1	11:58
0.7-0.35	0.1	-28.6	12:01
0.6-0.36	5.7	-23.8	11:58
0.6-0.3	-10.2	-19.6	11:56
0.5-0.25	1.2	-43.4	12:10

Table 10 Peak power demand reduction with ARL (*K*=0)

Acceleration factors on T_2 and T_3	**Peak power demand reduction on S_A (%)**	**Peak power demand reduction on S_B (%)**	**Time for T_3 to clear S_B (min)**
1-1	0 (5554 kW)	0 (3973 kW)	11:55
0.9-0.81	8	-10.4	11:55
0.9-0.72	7.2	-11.3	11:54
0.9-0.63	11.6	-11.5	11:56
0.9-0.54	10.7	-9.3	11:56
0.9-0.45	14	-14.1	11:55
0.8-0.64	5.1	-15.3	11:56
0.8-0.56	7.6	-12.8	11:55
0.8-0.48	4	-20.4	11:57
0.8-0.4	11.8	-19.9	11:56
0.7-0.49	11	-25.2	11:59
0.7-0.42	12.7	-27.2	11:58
0.7-0.35	14.1	-31.5	12:01
0.6-0.36	19.3	-32.5	11:58
0.6-0.3	3	-27.1	11:56
0.5-0.25	15.1	-49.5	12:10

Table 11 Peak power demand reduction with ARL (K=0.338)

Acceleration factors on T_2 and T_3	**Peak power demand reduction on S_A (%)**	**Peak power demand reduction on S_B (%)**	**Time for T_3 to clear S_B**
1-1	0 (4410.9 kW)	0 (4560 kW)	11:54
0.9-0.81	8.9	-4.9	11:55
0.9-0.72	8.3	-4.1	11:56
0.9-0.63	11.6	-6.7	11:55
0.9-0.54	11.1	-7.7	11:55
0.9-0.45	14.2	-12.4	11:57
0.8-0.64	4.8	-8.6	11:56
0.8-0.56	8	-8	11:57
0.8-0.48	3	-20.3	11:57
0.8-0.4	12.3	-15.1	11:55
0.7-0.49	10.4	-17.2	11:59
0.7-0.42	12.2	-20.6	11:58
0.7-0.35	14	-24.9	12:01
0.6-0.36	18.6	-29.9	11:59
0.6-0.3	0.2	-27.7	11:56
0.5-0.25	14.1	-41	12:10

Table 12 Peak power demand reduction with ARL (K=0.5)

Combined measures		**Peak power demand reduction on S_A (%)**	**Peak power demand reduction on S_B (%)**	**Time for T_3 to clear S_B (min)**
STD	**ARL**			
0-0	1-1	0	0	11:55
10-10	0.9-0.81	-5.9	-12.6	11:56
10-20	0.9-0.72	13.4	10.7	11:56
10-30	0.9-0.63	32.9	20.1	12:58
10-40	0.9-0.54	12.8	1.85	12:11
10-50	0.9-0.45	13.4	13.2	12:31
20-30	0.8-0.64	14.7	4.47	12:05
20-40	0.8-0.56	35.9	31.82	13:26
20-50	0.8-0.48	30.1	14.6	12:38
30-40	0.7-0.42	29.9	18.7	12:45
30-50	0.7-0.35	27.9	20.6	13:05

Table 13 Peak power demand reduction with combined STD and ARL

Rule-set	**Fact(s) required**	**Priority**
Train-weight identification & train grouping	- Weight of each train - Number of trains in a queue	1
Strategy-activation	- Restarting location (i.e. *K*) of the first train	2
Performance selection	- Headway or timetable - Power system rating	3
Time-delay assignment	- *K* of the first train - Level of quality of service required	4
Acceleration-rate assignment	- *K* of the first train - Level of power reduction required	4

Table 14 Classifications of the rule-sets

Case	**K of the 1st train**	**Expert system recommendations**	**Time delay between train groups (sec)**	**Peak demand reduction on S_A (%)**	**Peak demand reduction on S_B (%)**	**Time for last train to clear S_B (min)**
A	0	N/A	0	0 (7213.4kW)	0 (4279.9kW)	14:48
B	0	1st group: no action 2nd group: time delay C4	0	5.1	5.7	15:24
C	0.25	1st group: no action 2nd group: time delay B3	0	3.7	-3.1	14:48
D	0.25	1st group: time delay B3 2nd group: time delay B3	20	9.7	-9.5	15:05
E	0.25	1st group: time delay B3 2nd group: time delay B3	40	12	0.35	15:24
F	0.3	1st group: no action 2nd group: time delay A2	0	7.6	-6.6	14:48
G	0.3	No action recommended	60	14.7	-2.4	15:22
H	0.5	No action recommended	0	24.3	-35.3	14:48
I	0.5	No action recommended	10	24.3	-33.9	14:53

Table 15 Recommended actions from expert system and their results in Test 1

Case	K of the 1st train	Expert system recommendations	Time delay between train groups (sec)	Peak demand reduction on S_A (%)	Peak demand reduction on S_B (%)	Time for last train to clear S_B (min)
A	0	N/A	0	0 (7213.4kW)	0 (5087.6kW)	17.05
B	0	1st group: acc rate C4 2nd group: acc rate C4	20	-18.4	-15	17.13
C	0.25	1st group: no action 2nd group: acc rate B3	0	3.7	13.3	17:04
D	0.25	1st group: acc rate B3 2nd group: acc rate C4	20	-37.3	-26.4	17:16
E	0.3	1st group: no action 2nd group: acc rate C4	0	-19.4	-4.7	17:06
F	0.3	1st group: time delay A2 2nd group: time delay C4	20	-12.7	-25.8	17:11
G	0.5	1st group: no action 2nd group: acc rate B3	0	8.7	-14.4	17:06
H	0.5	1st group: no action 2nd group: acc rate B3	20	3.3	-21.4	17:09

Table 16 Recommended actions from expert system and their results from Test 2

Case	K of the 1st train	Expert system recommendations	Time delay between train groups (sec)	Peak demand reduction on S_A (%)	Peak demand reduction on S_B (%)	Time for last train to clear S_B (min)
A	0	N/A	0	0 (7212.7 kW)	0 (4279.9 kW)	14:48
B	0	1st group: time delay C4 & acc rate C4 2nd group: time delay C4 & acc rate C4	0	10.3	-6.06	16.52
C	0.25	1st group: time delay B3 & acc rate B3 2nd group: time delay B3 & acc rate B3	0	-3.68	-3.1	14:48
D	0.25	1st group: time delay B3 & acc rate B3 2nd group: time delay B3 & acc rate B3	30	-0.13	-10.37	16:06
E	0.3	1st group: time delay A2 & acc rate A2 2nd group: time delay C4 & acc rate C4	0	12.13	-47.3	15:41
F	0.3	1st group: time delay A2 & acc rate A2 2nd group: time delay C4 & acc rate C4	30	20.29	-20.46	15:44
G	0.5	1st group: no action 2nd group: time delay B3 & acc rate B3	0	10.74	-31.72	15:42
H	0.5	1st group: no action 2nd group: time delay B3 & acc rate B3	30	11.17	-38.54	15:40

Table 17 Recommended actions from expert system and their results from Test 3