A Comparison Study of Fixed and Moving-Block Signalling in Rapid Transit Railways

Mohammad T.H. Beheshti[1], Mohammad H. Miran Baygi[2]
1-Assist. Prof. of Department of Electrical Engineering, Tarbiat Modarres University
2-Assist. Prof. of Department of Electrical Engineering, Tarbiat Modarres University

***P.O. Box 14115-143, Tehran, Iran.**

mbehesht@modares.ac.ir
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Abstract: An important task in the initial design stages of rapid-transit type systems or "metros" is the allocation of signals and control points. These are placed so as to achieve a specified minimum time-separation between trains (headway), whilst minimizing the amount of signalling equipment but maintaining the highest level of safety. Conventional signalling and control systems are based on the fixed-block principle, whereby the track (or guideway) is divided into sections of predetermined length. A train is only allowed to proceed into a block when that block and usually the next one is clear of traffic. With the moving-block concept, a train can follow a preceding train at a safe braking distance behined the tail of the train.

In this paper, the transient performances of the two signalling systems are compared. A multi-train simulator which was originally developed at Birmingham University (U.K.) with a fixed-block algorithm, has been adopted and modified to accommodate the moving block algorithm. Both signalling systems were applied to Singapore Mass Transit Railway (MTR) and the results were compared in terms of train movement and transient performances including headway and station delay under safety and speed restrictions. Results have shown that with a pure moving-block system a considerable improvement in transient performance can be achieved.

Keywords: Signalling, Metro, fixed-Block, Moving-Block

1- Introduction

On economic, social and environmental grounds many cities throughout the world are now looking for rapid-transit type systems as providing the most clean, safe and efficient way of moving large number of people. Whilst densely operated metros have existed since the begining of nineteen century, current activity centres on cities in developing countries.

There are currently about 70 metro-type systems in operation world-wide. The difference in population and distribution of population of cities around the world, has led to a diversity of metro system packages. With more people migrating to the city areas, as is the case in many developing countries, the pressure palced on the metro system, in terms of maximizing passenger-throughput, becomes more acute. The number of passengers that can be moved through a stretch of track per unit time, depends primarily on the train characteristics and the signalling system. In this latter respect, two parameters are used to describe the effectivencess of the signalling system: the minimum headway and the line capacity. The minimum headway defines the minimum time-separation between two trains, such that their progress is not impeded by the signalling system [1]. The line capacity is the reciprocal of the minimum headway and is defined as the maximum number of trains that can pass through a stretch of track perunit time. The minimum headway and line capacity depend on the adopted signalling, but is also greatly affected by the amount of time trains wait at platforms. By assuming a fixed station-wait, the line capacity can be calculated fairly easily. However, particularly when passenger flow rates are high, the station wait varies considerably and can only be modelled accurately by assuming some statistical distribution function derived from empirical data.

In general, the line capacity can be increased by increasing the complexity of the signalling system. On rapid transit rail ways, the type of adopted signalling system can have a great effect on the line capacity. In this paper, the performances of the two signalling systems with regards to the headway and station waiting time for Singapore MRT railway system have been compared. A multi-train simulator, which has been initially developed to study fixed-block signalling, has been used and modified to accommodate both fixed and moving block signalling for Singapore Mass Transit Railway system.

2- Automatic Train Control System

The main objective of automating the motion of a metro train is to transfer the task of the driver to a control system. A train is required to accelerate from a station, maintain the maxinum allowed speed, coast (no power) if necessary and brake into the next station very accurately. Therefore the control system is required to have continuous control of motoring, coasting and braking.

As a train proceeds along the line, it must be supplied with several sets of data including geographical data and signalling instructions [1,2]. Geographical data are those data which are related to the geographical features of the line and include speed restrictions, gradients and positions of stations on the line. Signalling instructions are issued according to the occupancy state of any section of the line and whether a train should motor or brake accordingly. Apart from these two sets of data, special instructions need to be provided to indicate if a train should coast and be delayed in leaving a station. The control system is therefore formed from three corresponding subsystems. These are: Automatic Train Operation (ATO), Automatic Train Protection (ATP) and Automatic Train Supervision (ATS) [1,3].

Under normal operation the task of ATO is to run the train from one station to another; stop the train at a station, and open or close the doors which would otherwise be done by the operator. As a train travels along the line it receives ATO speed instructions. The value of the speed received is compared with the actual speed obtained from a tacho-generator. This enables the ATO to regulate the motors and brakes accordingly.

The ATP system overseas the motion of the train, and causes the brakes to be applied due to the signalling conditions or if the train exceeds the maximum allowed speed. This system is designed to observe the fail-safe standard and has higher priority over the other two subsystems as the safety of trains should never be compromized. The ATP system ensures that the trains observe speed limits and prevents unsafe train movements (for example prevents two trains entering the same track section or prevents conflicts at junctions). As a train proceeds along the line, it receives valid ATP speed limit codes. If the ATO system operates correctly, the speed of the train should always be below the ATP speed limit.

The ATS system monitors and coordinates the train movements and performance against a schedule held on a central computer. The main tasks performed by ATS include:

- Addition or deletion of trains to or from service according to the prestored schedule or in response to abnormal events,
- Assignment of routes for trains in accordance with the normal schedule requirements and in response to abnormal events,
- Updating train service information for display to passengers and staff including announcement of arrival and departures from the platform,
- Monitoring positions and operational status of trains, and regulating flow of trains in the system with regards to velocity adjustment to reduce energy consumption and temporary speed restriction to protect work crew or other strategies,
- And monitoring the status of ATO and ATP systems. This can provide early warning of any vehicle failure enabling corrective actions to be taken.

3- Signalling Theory

An important parameter in adopting a particular signalling system is the anti-collision protection that the system can provide. The separation between any two trains must at least be equal to

the instantaneous braking distance of the control train at all times [4]. The signalling system must ensure that all trains obey this and take necessary action if a train fails to do so. Another important parameter is the minimum achievable headway, which is defined as the minimum separation in time between successive trains such that the progress of trains is not disturbed by signalling [1,4,5]. The reciprocal of the minimum headway is the line capacity which is defined as the maximum number of trains passing through a stretch of track per unit time [1,4]. This reveals the relationship between the minimum headway and passenger throughput, and that improving the minimum achievable headway improves the passenger throughput.

If the instantaneous headway between two trains is below the minimum headway then the two trains will interact through signalling somewhere along the line. This means that the second train will have to brake to a lower speed and maintain this speed for some time before it is allowed to accelerate back up to the line speed. This might have similar effect on trains further behind resulting in unforseen delays.

Localised disturbances such as delays cause trains to interact through signalling. Those trains which operate close to the minimum headway are those which experience the effect most [2]. Period of recovery from a disturbance plays an important role. This depends on the type of signalling system, and is different for different systems.[1,6,7]

3-1- Fixed Block Signalling

This is the traditional and most widely used type of signalling. The track is divided in to a number of blocks of equal or different lengths. Only one train is allowed to occupy a block at any time. Occupancy state of a block is detected by means of a track circuit arrangement. Associated with each block is a code or aspect which indicates whether that block is free of traffic [2]. If a block is occupied the aspect or signal associated with it will be red. Additional aspects are used to give forewarning of a red signal. When a train clears a block "b(i)" and enters block "b(i+1)", a certain distance known as overlap needs to be travelled in the new block before the signal associated with that block changes sign. In a 2-aspect arrangement the signal changes directly from red to green whereas in multiple aspect arrangement the signal changes to lower restricted aspects (yellow and double yellow) before changing to green.

Figure 1 shows the ATP code sequence together with the braking envelope of the train for a 4-aspect fixed block signalling [1].The envelope moves as the train proceeds along the line. The code in each block consists of two figures. The left figure denotes the maximum safe speed that a train can have in a block and the right figure indicates the speed known as the target speed that the train should attain before entering the next block. Under normal operation, trains operate well above the minimum headway and can proceed with the maximum safe speed. However, when signal interaction is about to occur, the affected trains are required to aim for the target speed which is reduced successively as 80, 65,40, 0 km/hr for a particular line. The maximum safe speed defines an limit that upper a train should not exceed, otherwise, this will result in an "ATP trip" meaning that the emergency brakes are activated and the train is brought to a halt.

3-2- Moving Block Signalling

If the number of aspects in fixed block signalling scheme is increased and therefore the block length reduced, the positional resolution becomes finer. This in turn enables the headway to be improved. If the number of aspects tends to infinity, the block length will tend to zero. Trains will then be separated only by the instantaneous braking distance of the second train [3,4,8,9]. This arrangement is known as moving block [6].Instead of one-way communication from track to train in the traditional signalling layout, the moving block scheme is implemented using a wide-band continuous data link based on a two-way flow of information. With such a system, every train reports its position and speed at regular intervals to a central computer. The central computer issues commands to trains according to their positions and speeds [3,9].

4- The Multi-Train Simulator

This simulator has been developed in theuniversity of Birmingham for studying the system performance characteristics in a two-road rapid transit type of railway [1]. It has two distinct jobs, that is to model the running of trains and to establish the power flow conditions so as to calculate the total energy consumption. The main core of the program consists of three parts. They are the Movement Simulator A (MVSIMA), the Power Network Solution (PWRNET) and the Movement Simulator B (MVSIMB). MVSIMA establishes train mode according to updated train velocity and position. PWRNET calculates power and energy consumption of train and MVSIMB establishes train performance and updates train position and velocity.

A fixed block signalling layout has been accommodated into the movement parts of the simulator according to ATP codes and signals shown in Figure 1. Trains proceed along the line according to instructions imposed by this signalling layout.

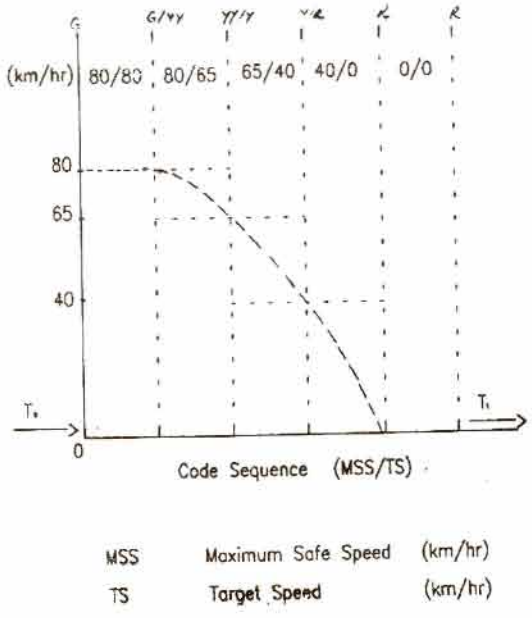


Fig1 ATP Code Sequence

4-1- MVSIMA

All parts of the simulator operate within a loop which is used for incrementing time. With prespecified trains position and velocity and setting or resetting the signals correctly according to the previous update, MVSIMA checks the new position and velocity of each train against the signal control points, station braking profile and speed restrictions. The mode of each train for the new update period can then be determined. There is a main loop within MVSIMA for incrementing train number enabling trains to be proceeded one by one. The structural diagram of program MVSIMA is shown in Figure 2.

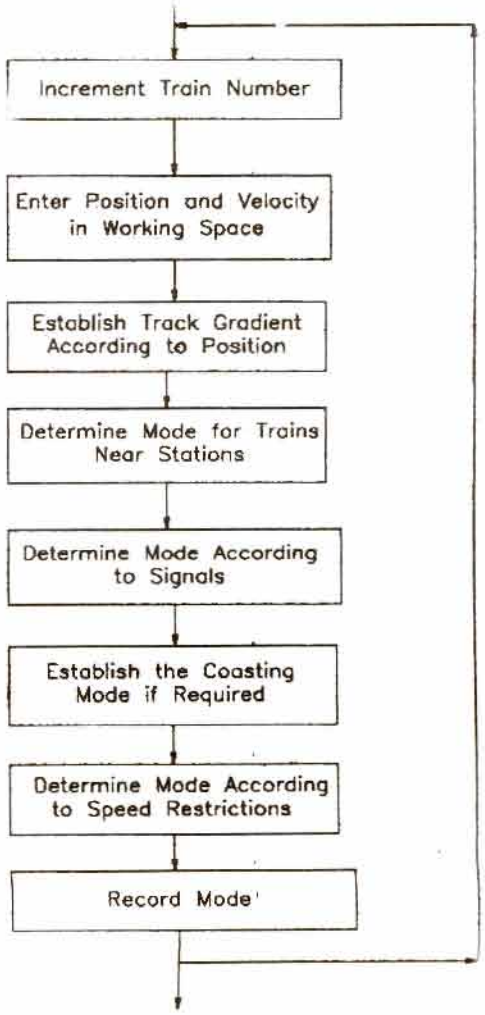


Fig. 2 Structure of MVSIMA

4-2- MVSIMB

Having determined the mode of each train, MVSIMB calculates the required traction effort and updates the velocity and position of each train accordingly. The calculated new position and velocity together with the status of signals are then passed to MVSIMA. An outline structure of MVSIMB is shown in Figure 3.

4-3- Data Arrangements in the Simulator

The track and train-based data are stored in two arrays, "block" and "train" respectively. The

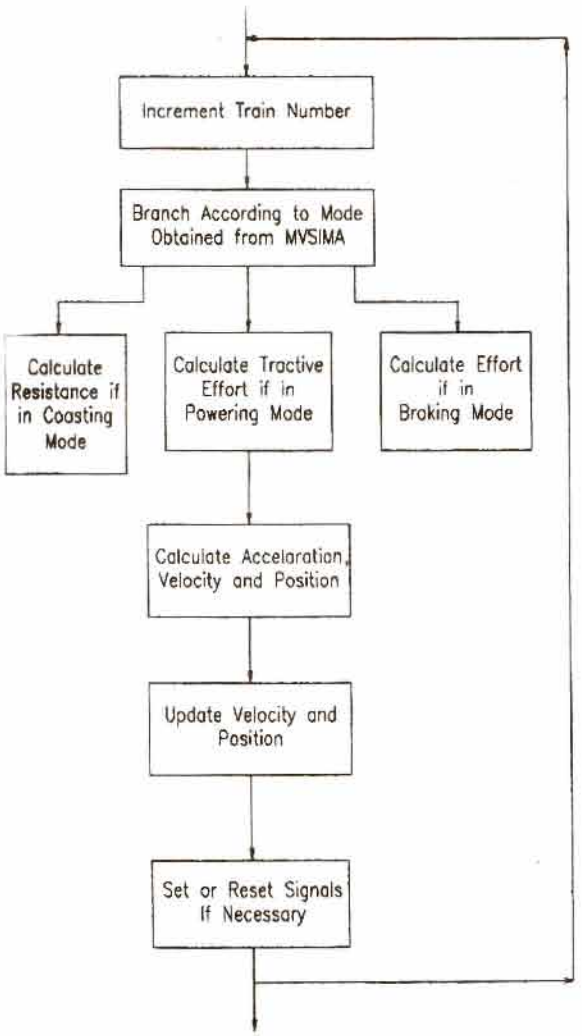


Fig. 3 Structure of MVSIMB

track is treated as being divided in to blocks in accordance with fixed block signalling. The "Block" array contains the control points and features associated with each of these blocks. On the other hand the "TRAIN" array contains the train related data most of which is updated for each update period.

4-4- Accommodating Moving Bolck Algorithm into the Simulator

In order to model a moving bolck signalling system it is required to find an algorithm which gives the instantaneous braking distance of a train as it proceeds along the line. Practical constraints such as equipment reaction delays and jerk conrol periods, also needs to be considered. A suitable algorithm has been given by [1,2,4]:

$$f(V,G_{av}) = v(t_r + t_c + t_j) + \frac{(v-\Delta v)^2}{2(b_s + \frac{g.G_{av}}{(1+r)})} +$$

$$\Delta v t_j - 0.5 b s t_j^2 + \Delta s$$

where:

f is the minimum allowed separation between trains as a function of both velocity and gradient,

t_c is the transmission cycle time,

t_r is the ATO equipment reaction delay,

t_j is the period of jerk limiting

b_s is the minimum service braking rate

Δv is the change in speed during jerk limiting.

Gav is the average gradient in the region of constant braking

r is an allowance for rotational inertia

g is the acceleration due to gravity, and

Δs is an allowance for initial acceleration.

Obviously as in the case of any practical situation, an additional safety margin needs to be included so that in the worst-case condition the following train comes to a halt a certain distance from the preceding train. Figure 4 shows how two trains are separated by the above algorithm. The algorithm with the required data was accommodated into the multi-train simulator. A software switch has been provided to switch between the two signalling systems.

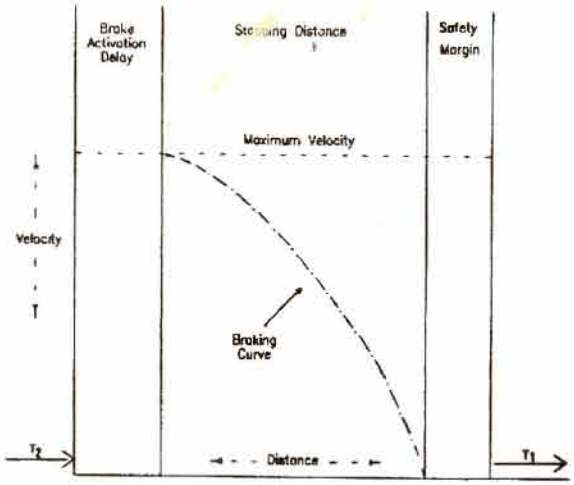


Fig.4 Min. Separation Between Two Trains in Moving-block Signalling

5- Results

This section contains the results of the simulation study of train performances under the two different signalling schemes. Some assumptions, such as train operating at a constant supply voltage and constant passenger loading, were made in obtaining the results. Singapore "MRT" was used as the data base for running the simulator. Trains proceeded along a line which consisted of twenty stations abreviated as CLE, BNV, QNT, CMW, ROH, TIB, OTP,MAX, RFP, CTH, DBG, SOM, ORC, NEW,NOV, TAP, BDC, BSH, AMK and YCK respectively, covering a total line distance of 26 kilometers.

The results produced by the simulator have been presented in graphical form of time/distance trajectories and have been classified into two groups. The first group has looked at the effects of reducing the entry headway, that is the time speration by which trains have entered the line, on the train performances. The second group, however, has been the result of investigating the transient performances of the two signalling systems under perturbed running conditions. By reducing the entry headway and running the trains under each of the two signalling systems it has been possible to establish the minimum headway for each case. On the other hand in producing disturbances into the two systems has enabled certain information to be obtained about the responses of these systems to such disturbances.

Figure 5 shows a typical time/distance trajectory obtained by running the simulator under fixed block signalling. With seven trains entering the line, the entry head way was set to 120 seconds. All trains proceeded normally without interfering. In the Figure only the central part of the line has been shown because any interaction through signalling was most likely to occur in this region.

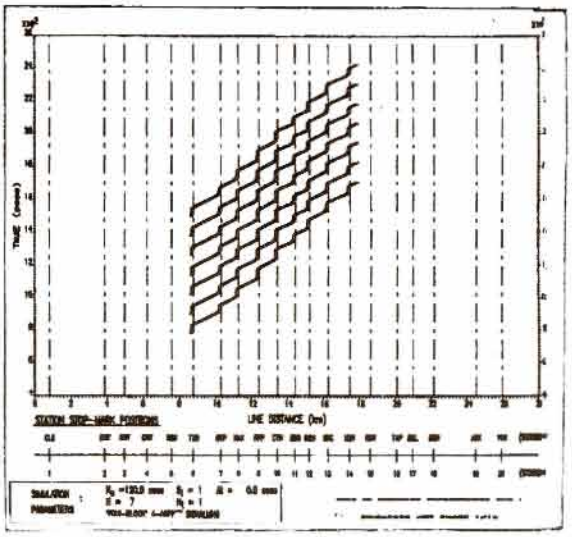


Fig.5 A typical Time/Distance Trajectory Under Fixed-Block Signalling

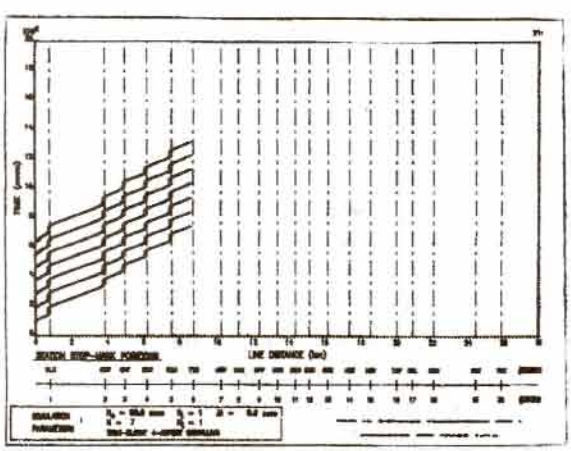
5-1- Effects of Reducing the Entry Headway

5-1-1- Results With Fixed Block Signalling

With the entry headway of 120 seconds, trains proceeded normally with the instructed speeds (Figure 5). With the same number of trains, when the entry headway was lowered to 90 seconds, shown in Figures 6 and 7, some of the trains began to interact through signalling immediately after entering the line. Except the first train, all trains were instructed to brake. Regarding the rest of the journey, trains proceeded normally without significant disturbances. Increasing the headway to 92 seconds resolved the above problem.

5-1-2- Results with Moving Block Signalling

With the same number of trains on the line and entry headway of 90 seconds all trains proceeded normally under the moving block signalling conditions. Reducing the headway to 80 and 75 seconds still did not affect the normal running of trains. This verified the expectation that, with trains being allowed to be separated by a relatively shorter distance the headway at which the interaction will take place would be decreased. With 70 seconds entry headway (Figure 8), trains began to interact through signalling near RFP and CTH.



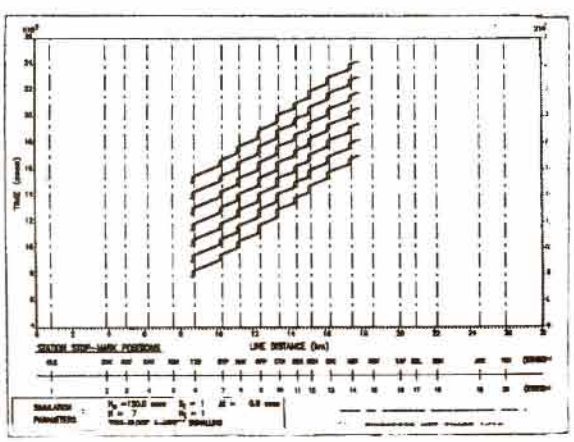


Fig. 6 &7 Simulation Result Under Fixed-Block Signalling with 90s Headway

From this, it was clear that the minimum headway was slightly more than 70 seconds, about 72 seconds, but considerably lower than that achieved with fixed block signalling.

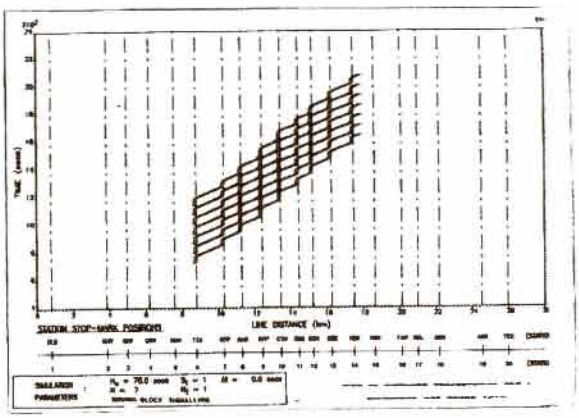


Fig. 8 Simulation Result Under Moving-Block Signalling

5-2- Effects of Disturbances on the System Performance

The performance of trains moving through the two signalling systems were investigated following the introduction of a perturbation. This took the form of a deliberate delay imposed at a specific station, and involving a specific train. This was equivalent to increasing the station waiting time for a particular train. The interesting parameters to note, were the way in which trains responded to the delay and the time they spent to recover from it.

5-2-1- Results with Fixed Block Signalling

With seven trains being entered on the line, a delay of 130 seconds was imposed at CTH, involving the second train. The entry headway was set to 90 seconds very close to the minimum headway. As shown in Figure 9, the delay caused a "ripple back" on all trains following the second train. It took quite a long time for trains affected by the delay to recover and proceed as normal afterwards. The effect was such that the sixth and seventh trains interacted through signalling immediately after leaving station MAX which was at a relatively long distance from CTH. By reducing the entry headway while maintaining the same delay at CTH, trains performed exactly in the same way in the central region. The reason was that, with reducing the entry headway below the minimum headway, trains interacted before achieving the first station and maintained their time separation

close to the minimum headway (92 seconds) for the rest of their journey.

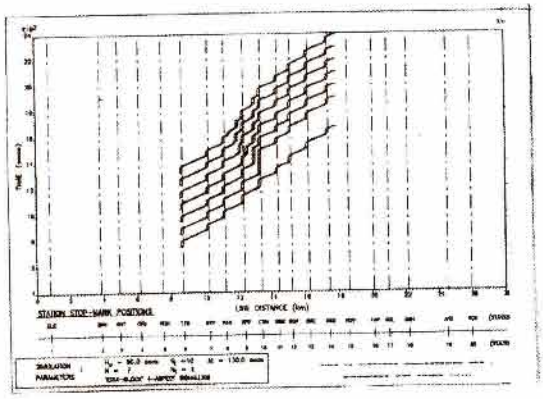


Fig. 9 Fixed-Block Signalling Result with Station Delay

5-2-2- Result with Moving Block Signalling

In order to compare the two signalling systems with respect to their responses to station delays, the same delay of 130 seconds was imposed at CTH involving the second train. Having set the entry headway to 75 seconds close to the minimum attainable headway, trains responded to the delay in the way shown in Figure 10. All trains except the first one were affected by the delay but only in the vicinity of the station. All trains following the second train came to stand-still one following the other with a separation equal to the safety margin (25 meters). The period of recovery from the delay was considerably shorter than that when fixed block signalling was used.

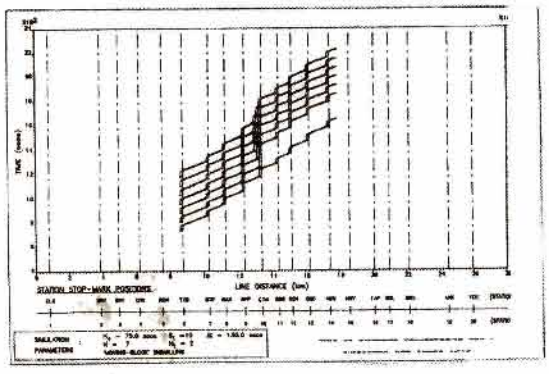


Fig. 10 Moving-Block Signalling Result with Station Delay

6- Concluding Remarks

From the simulation study of the two signalling systems for Singapore MRT it is clear that the moving block system has exhibited a considerable improvement in the minimum attainable headway (72 seconds) which can be obtained with the fixed block system (92 seconds). With the fixed-block signalling conditions trains face the problem of signal interaction before reaching the first station when the entry headway is below the minimum headway. With the moving block signalling the interaction takes place in the middle of the line. The moving block signalling system has also shown considerable improvement to localised disturbances compared with the fixed block layout. With the delay imposed at stations towards the middle of the line, trains demonstrated some ripple back effect under both signalling conditions. However with moving block signalling, trains experienced the effect at or in the vicinity of the affected station. Also the period of recovery from the delay has been shorter than that of fixed block signalling.

This paper has highlighted the benefit of adopting a moving block control system for Singapore MRT. There are other aspects of the two signalling systems which can be studied further using the simulator. The period of updating the information in the simulator itself is an important parameter which should be studied carefully. Disturbances in the form of delay can be placed on trains on their journey from one station to the next, rather than at a station. Trains can be allowed to coast while in motion; trains can also be allowed to enter the line at specific stations and it will be important to see how the signalling system will respond to such strategy.

Among many, these are just some few examples of what can happen on the line and how the control system will resopnd to them. Obviously there are other cases which may arise according to the type of communication and power systems employed for a particular metro system.

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