Simulation analysis of transmission-based signalling systems for metro applications

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Abstract

Transmission-Based Signalling (TBS) Systems offer Metro administrations major operational benefits in terms of improved line capacities, improved traffic regulation and possible reductions in journey time. Other benefits include large reductions in track equipment and associated cabling, improved maintenance facilities, and the capability to overlay onto existing Fixed Block installations.

Whilst the steady-state headway-performance of Moving Block based TBS systems is well understood, the dynamics of train performance when signalling interaction occurs has received little attention. Here analytical studies are difficult because of the non-linearities associated with both the safety algorithms and the control system. The paper describes simulation models that identify the basic control problems and their potential effect on train performance.

1. Introduction

This paper examines the basic control aspects associated with Transmission-Based Signalling (TBS) Systems that implement Moving Block control and protection for Metro applications. The use of simulation models is described, which are aimed at assessing both the steady-state headway performance and the dynamics of train performance when disturbances occur. Potential control problems are identified, and control algorithms are discussed targeted at improving the performance without incurring excessive penalties in either journey-time or minimum steady-state headway.

The work described in the paper has been carried out as part of the development of the WESTRACE Train Control System (WTCS). Westinghouse Signals Limited will supply this system to London Underground Limited for the signalling of the Jubilee Line Extension and existing line. This will represent the first application of radio-based Moving Block Signalling on a heavy metro[1]. The system is based on joint work by Westinghouse Signals and DIMETRONIC, S.A. within the BTR Rail Group.

2. TBS System Characteristics

2.1 Performance Objectives

One of the main performance objectives of TBS is to provide higher line capacities than are possible with conventional Fixed-Block Speed-Signalling (FBSS) systems, for the same (or better) journey time performance. To achieve this, TBS approximates a 'vehicle-following' law referred to by Thomas[2] and Pearson[3] as Pure Moving Block (PMB). This law requires that each train must regulate its speed in order to maintain a distance of separation from the train ahead, that is not less than its safe instantaneous braking distance. In line with traditional signalling practice, this assumes implicitly that the train ahead can, potentially, stop instantaneously.

2.2 PMB Characteristics

2.2.1 **line capacity** The line capacity that can be achieved with a PMB-based control system represents the theoretical maximum that is possible for a railway line given the assumption that, in the worst case, trains may stop instantaneously. Within this constraint, no other form of signalling can achieve the same level of capacity, for a given level of train performance.

For metros, it is the time-components associated with station stops that usually dictate the achievable minimum headway. There are situations, however, where the physical layout at terminal stations represents the constraining factor. At intermediate stations, for given values of dwell time, train length and departure acceleration, the minimum headway achievable with PMB depends primarily on both the approach-speed and the braking capability of the train. It is assumed that a communication system exists that reports to each train the location of the rear of the train ahead continuously.

With FBSS it is the spacing constraints dictated by the block layout that constrain the achievable headway. Although it is possible to produce improvements in headway by increasing the number of speed-levels (aspects) and as a result increasing the resolution of train-detection, this is at the expense of track equipment and system complexity. In any case, as is explained in a paper by Gill and Goodman[4], the realistic return in headway-improvement becomes diminishingly smaller as the number of speed-codes is increased.

The capacity characteristics of both PMB and FBSS are illustrated in the computed curves of figure 1, for typical metro rolling stock characteristics. This shows the line capacity, in terms of trains per hour, plotted against running speed for:

(i) theoretical PMB
(ii) a 5-aspect FBSS system signalled for a maximum speed of 100 km/h with intermediate speed levels of 86, 71 and 50 km/h.

For the purpose of this comparison, plain track is assumed with no station stops, and on which all trains travel at the same running speed. It can be shown that the relationships are similar when a station stop is modelled, in both cases the line capacities being reduced considerably.

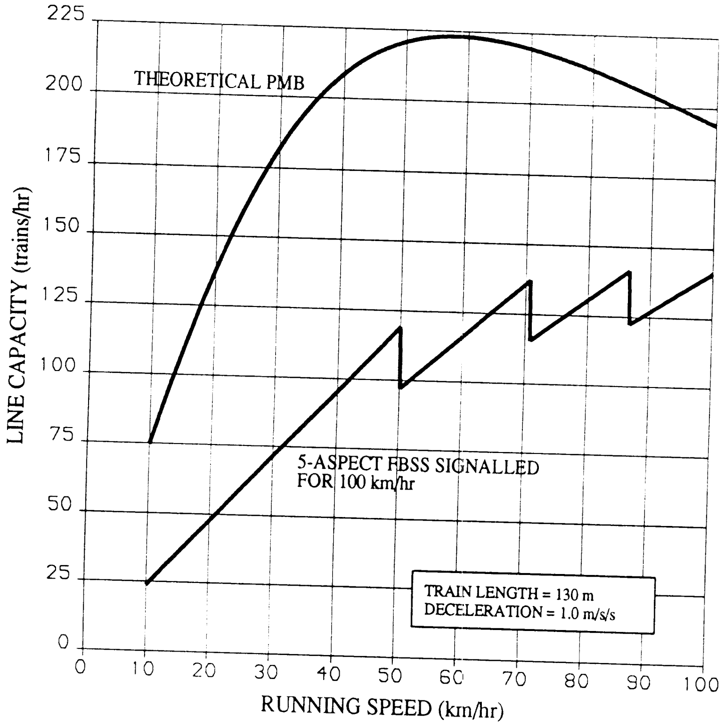

Figure 1 - Line capacity characteristics

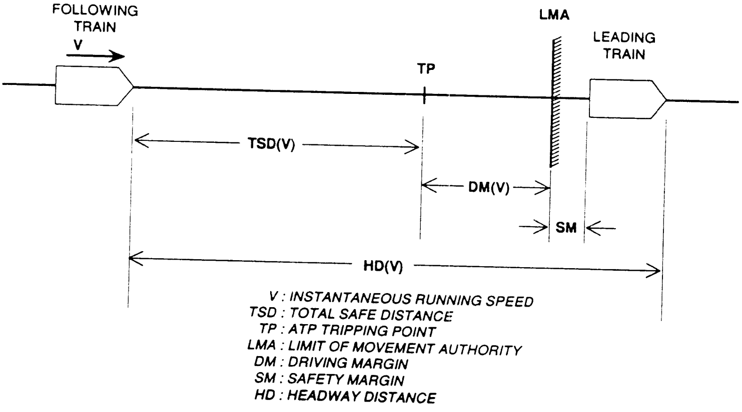

Figure 2 - Minimum headway - distance components

Discontinuities occur in the FBSS relationship because at running speeds just below the three intermediate speed levels, the train is permitted to move one block closer to the occupied block. The headway is maximised only when trains run at the design speed. With PMB, every running speed is, in effect, a design speed. The capacity of PMB is maximised at a single running speed; in this case about 60 km/h. It can be shown that at this speed the braking distance is equal to the train length. The existence of an optimum running speed can be exploited by enforcing it at headway-critical locations, such as station approaches. At all other locations, the running speed can be maximised in order to minimise the journey times, thereby minimising the required fleet size.

2.2.2 journey-time performance With conventional FBSS systems, the set of speed levels is determined from a consideration of both headway and journey-time performance. For railways having numerous multi-valued speed restrictions, particularly characteristic of older tube lines, it is necessary to carry out a simplification due to the limited number of speed levels that are practicable. This involves both truncating the speed restriction to the nearest available speed level, and moving the boundary of the speed restriction to the nearest block boundary. The combined effect of this can be a degradation in potential journey time. A PMB-based system, by contrast, does not involve any compromise on journey-time potential. It permits trains to be driven either automatically or manually close to the absolute profile of civil restrictions and line speeds, subject to the capability of the traction equipment.

2.3 Implementation Considerations

Fundamentally, the implementation of PMB requires the following:

(i) an inter-train position feedback system; and
(ii) a dynamic real-time prediction of required braking-distance.

The steady-state line capacity that can be realized depends primarily on the following practical constraints:

(i) the frequency with which each train reports its location;
(ii) the time taken for position-reports to be processed and transmitted to trains; and
(iii) the frequency with which the prediction of required braking-distance is repeated.

The effect of the first two constraints is to degrade the achievable headway by an amount equal to the delays involved. The effect of the third constraint is to degrade the headway by an amount equal to the travel-time between consecutive predictions.

Past analyses of PMB systems in the steady-state have mostly assumed a single braking system. As demonstrated by Bergmann[5], the inclusion of a second brake model leads to some quite involved analysis, resulting in conditional relationships. Conventional metro rolling stock employs two braking systems: a controlled service brake and an emergency brake. The former is designed to achieve comfortable and efficient brake applications using load-weighing, jerk control, slide protection and dynamic blending

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between pneumatic and electric (regenerative or rheostatic) braking. The latter gives a direct application of pneumatic braking, bypassing any control circuits apart possibly from load-weighing.

Service braking is requested by either a manual driver or an Automatic Train Operation (ATO) system. The braking is applied with varying levels and removed as and when required. Emergency braking is requested by an Automatic Train Protection (ATP) system, and is normally irrevocable until the speed has been reduced either to zero or a very low value.

The distinction between ATO and ATP is the distinction between control and protection respectively. The Westinghouse WTCS implementation of approximated-PMB, is founded on the principle of maintaining physical and functional separation between the control and protections systems. The ATP system maintains an envelope of safe speed and distance continually, within which the ATO system is free to regulate the train speed. Any infringement of this envelope is detected by the ATP which requests an emergency brake application immediately.

The minimum permitted separation between successive trains depends primarily on the assumed worst-case emergency braking performance. An allowance must be made, however, for the ATO system to request service-braking, for the braking force to be built up, and for the control system tolerances. This total ATO response time must therefore be reflected when determining instantaneous headways between trains as shown in figure 2. Here the Total Safety Distance TSD(v) corresponds to the worst-case emergency braking distance predicted by the ATP for the instantaneous running speed v. The Limit-of-Movement Authority (LMA) corresponds to the limit of safe movement for the following train. This is arranged to correspond to the rear of the leading train offset by a safety margin (SM). The ATO Driving Margin DM(v), which is related to the running speed, effectively acts as a buffer between the ATP Tripping Point (TP) and the LMA. The instantaneous headway corresponds to the time taken for the following train to travel the distance HD(v).

2.4 Headway Components

Two main design features of the WTCS are:

(i) dynamic on-board prediction of required emergency braking distance; and
(ii) frequent reporting of accurate train-location.

These individually give rise to an improvement in headway when compared with FBSS systems. The dynamic prediction of braking distance enables a train to continue at line speed up to a self-determined service-brake application point. This has two benefits. Firstly a train does not receive signalling checks as soon as it would with FBSS, and secondly there is an improvement in journey time. Although on a single inter-station run this improvement may be small, when cumulated over a complete round-trip it can become significant. This is in addition to the potentially large improvements due to the train following the absolute speed restrictions more exactly.

The second headway-component is that due to the improved resolution with which train locations are reported. With FBSS this resolution is dictated by the layout of track circuits. In headway-critical areas such as station departure tracks, the resolution is limited by the minimum operational length of track circuits. Figure 3 shows the interval between the clearing of successive track circuits as a train accelerates from a station stop at 1 m/s^2. This assumes minimum length track circuits of 40 metres. The minimum headway is usually set when the rear of the outgoing train has reached the end of the platform or beyond.

Figures 5 and 6 indicate the improvement in headway due to the two design features described above, in relation to the minimum headway for a typical 4-aspect FBSS layout shown in figure 4. These diagrams were produced using a multi-train simulator developed by Westinghouse Signals. Figures 5 and 6 show the time versus distance curves for two trains following at minimum headway into a station. The black area represents the paths of the two trains, whilst the shaded area represents the combined path of the required emergency braking distance and the ATO Driving Margin. Weir[6] refers to this combined path as the 'braking shadow'. The braking shadow is related to the instantaneous running speed by a very non-linear relationship. A dominant component is the braking distance itself which varies as the square of speed. This is evident at point A where the train commences a service brake-application for the station.

In figure 5, the occupancy-state of the track circuits is conveyed to the following train. The Limit-of-Movement Authority (LMA) steps to successive track circuit boundaries as the rear of the leading train accelerates from the station. Westinghouse Signals refer to this arrangement as Fixed-Block, Brake-Assured (FBBA). The occupancy states are transmitted to trains using track codes. This arrangement enables an existing FBSS system to be upgraded to full TBS in stages.

Figure 6 illustrates the additional improvement in headway that occurs when track circuit train-detection is replaced with a high-resolution TBS communications system. The LMA now follows the rear of the train with accuracy, allowing for both a safety margin and the processing delays.

Figure 4 shows the headway achievable with a conventional 4-aspect FBSS system. Here the shaded areas represent the periods of time that the track circuits convey restrictive track codes. In this example a minimum headway of about 108 seconds is indicated. With FBBA, this is reduced to just over 95 seconds as shown in figure 5. With the full implementation of TBS, the headway is improved by an additional 10 seconds. It should be noted that these figures are valid for a particular station on plain track. Further simulations would be necessary to verify that these improved headways could be achieved within the physical constraints associated with both intermediate turn-backs and terminal stations.

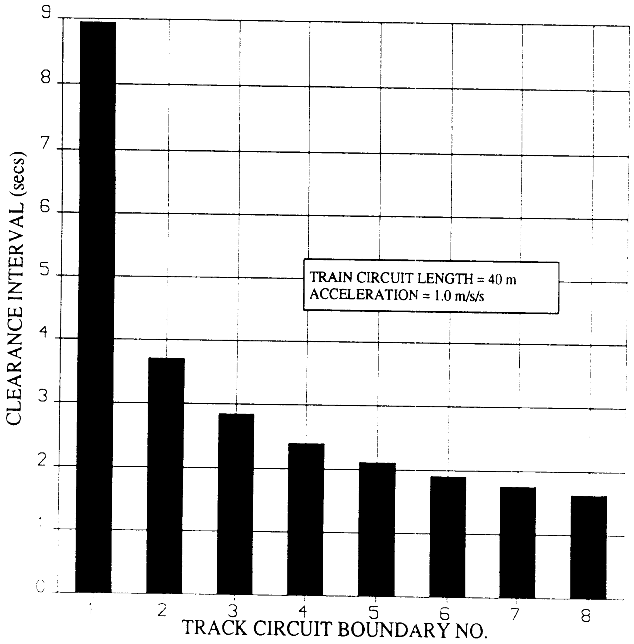

Figure 3 - Clearance interval for successive track circuits

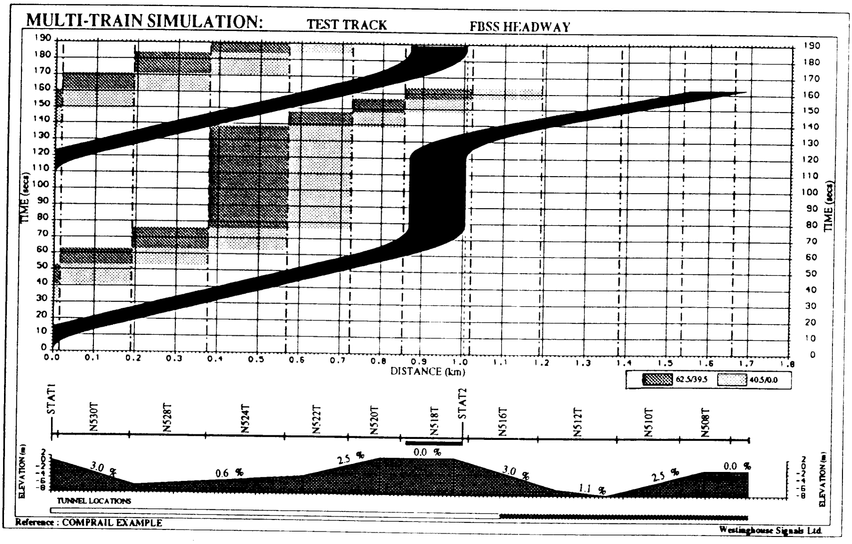

Figure 4 - Example of simulated FBSS headway

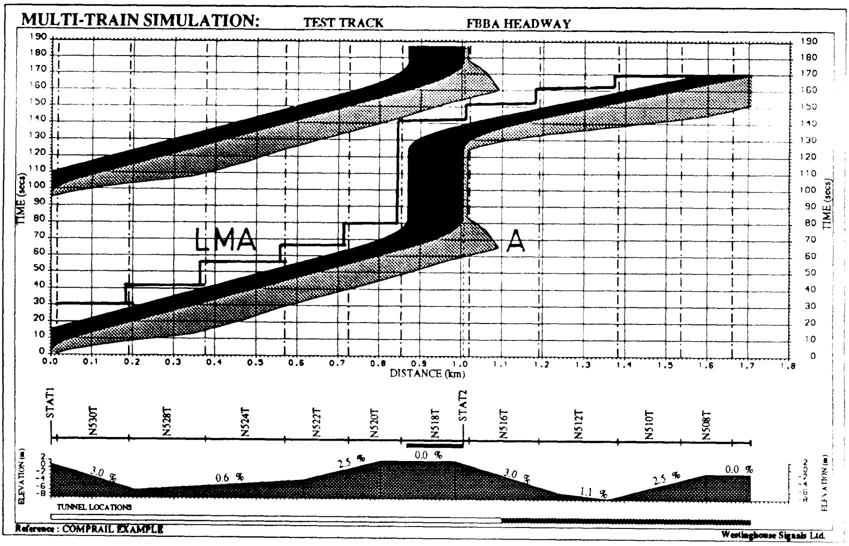

Figure 5 - Example of Simulated FBBA headway

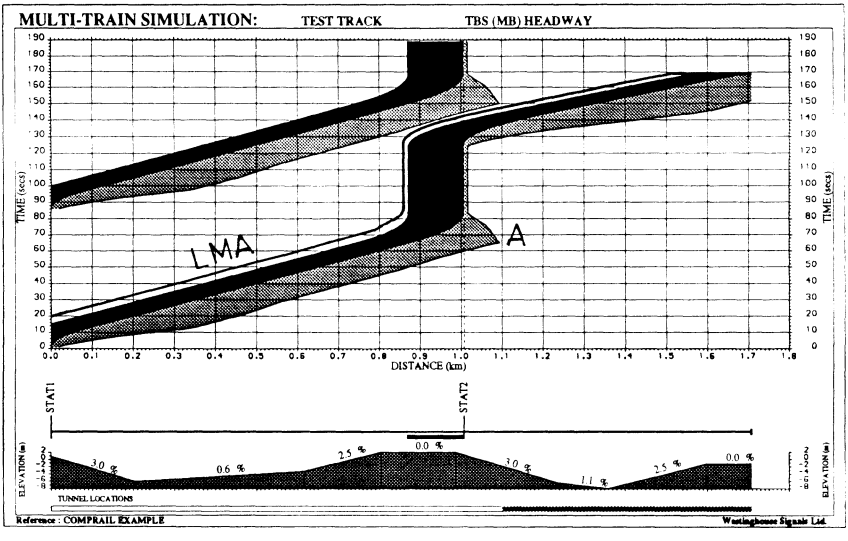

Figure 6 - Example of Simulated TBS (Moving Block) headway

2.5 Headway Flexibility

2.5.1 coasting control With FBSS, the introduction of energy-saving coasting generally degrades the achievable headway by up to several seconds. This is due to the extra time that a coasting train takes to clear block sections. Where coasting is implemented routinely during off-peak periods, this is not restrictive because the headway requirement is less onerous. However, where energy-costs or traffic-regulation strategies dictate routine peak-period coasting, this degradation in headway can become more significant.

With TBS, the introduction of coasting serves to improve the achievable headway rather than degrade it. This is because a train adjusts its required braking-distance dynamically in response to changes in running speed. A coasting train generally approaches a station with less speed, and therefore requires less braking distance. It can proceed further towards the train ahead before being checked by an ATO service brake request within the ATP protection envelope.

2.5.2 controlled-speed approach (CSA) As discussed in section 2.2.1., for a given train length and braking capability, a unique speed exists at which the line capacity is maximised. This characteristic is exploited by forcing trains to brake prematurely and enter stations at a controlled speed which is equal or close to the optimum value. This improves the headway significantly compared with that achieved from a full speed approach. Using the expressions developed by Bergmann[5], an improvement in headway of about 30% results when the station approach speed is reduced from 90 km/hr to an optimum value of 32 km/hr, for typical rolling stock parameters. The resulting degradation in journey time is small when compared with the improvement in headway. TBS permits CSA to be implemented selectively.

3. Steady-State Headway Performance

3.1 Intermediate Stations

The signal headway corresponds to the minimum steady-state headway that a train service can theoretically be operated at, assuming that every train has an identical speed versus distance trajectory. This headway is usually set at key stations which, because of excessive dwell times and/or local geography, form 'bottle necks'. Alternatively it might be a particular turn-back station that constrains the headway.

In verifying the signal headway, it is necessary to examine the minimum achievable headway at each station. This is carried out with consideration of the following:

- the relationship between tractive effort and speed
- the local track gradients
- the length of the trains
- the ATP emergency braking model
- the TBS processing delays
- the ATO Driving Margin
- the service braking rate
- the nominal emergency braking rate
- the maximum permitted jerk level

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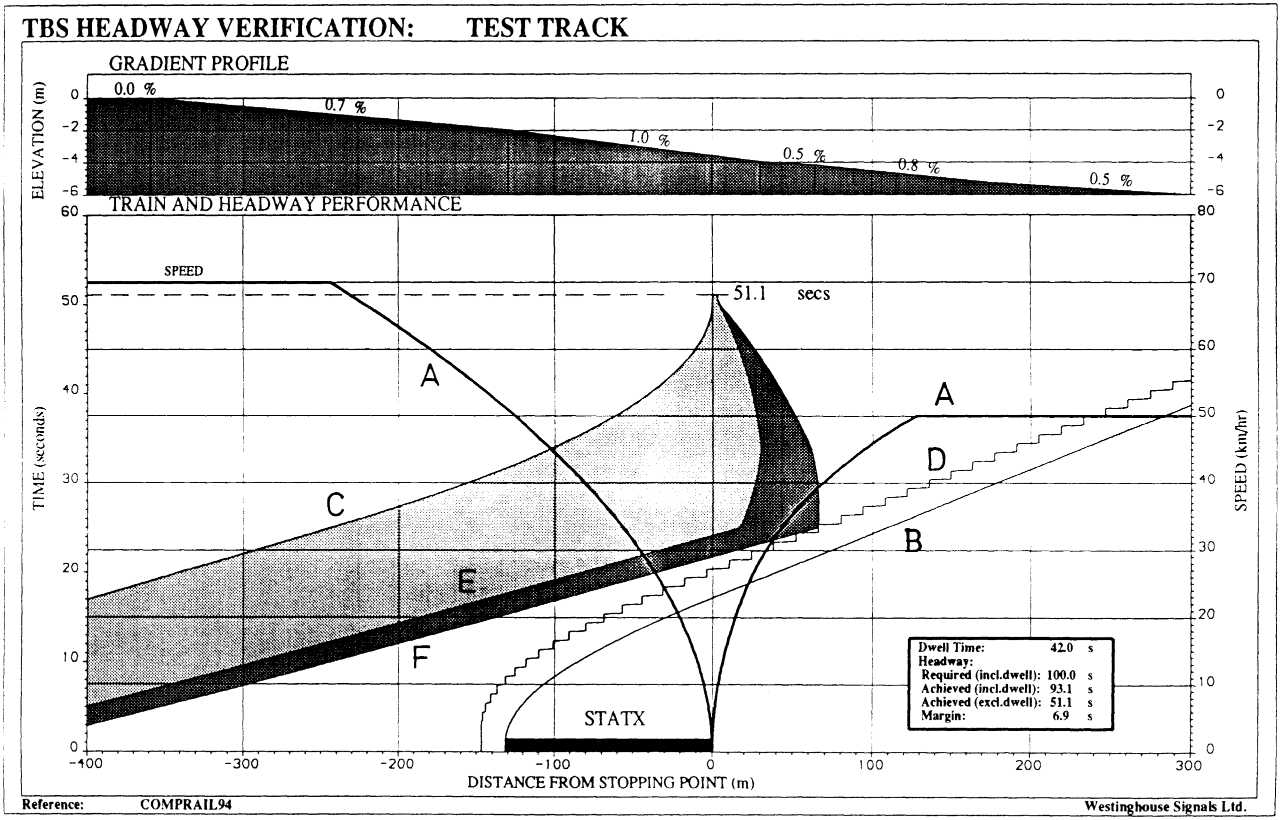

Figure 7 - Example of TBS headway verification

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Figure 7 shows the results of a computed headway-verification in graphical form. Here curve A represents the speed of a train approaching the station at 70 km/h, braking to a stand-still and then accelerating up to a restricted speed of 50 km/h. Curve B indicates the time path for the rear of the train accelerating out of the platform. Curve C indicates the time path for the leading edge of the train approaching the station and coming to rest. Curve D represents the LMA issued to the approaching train. This corresponds to the worst-case location of the rear of the leading train, reported, in this example, once a second, and offset both in time by the system time delay and in distance by an additional offset.

Curve E represents the time path of the emergency stopping-location predicted by the ATP. The ATO Driving Margin is added to this distance to form Curve F. The minimum headway is satisfied when curve F just comes into contact with curve D, the two trains being on the verge of interaction.

It will be noted that curve E extends beyond the station stopping point. This is due to the assumption that even as a train brakes normally into a station, there is the possibility that the ATO could request full tractive effort erroneously. Whilst this would ultimately be detected by the ATP as an LMA violation, the time required for the EB force to be applied would mean that, in the worst case, the train would come to rest with its leading edge beyond the normal stopping point.

3.2 Terminal Stations

The timing constraints associated with turning trains back at terminal stations often dictate the signal headway. This is more likely to be the case for end-to-end services where all trains travel to the extremities of a line. Where certain trains turn back at intermediate stations, the headway requirements at termini become less onerous, leaving sufficient margins for the extra time associated with turn-back moves.

Given a physical track layout, the turn-back headway depends on the time required for trains to move either into turn-back sidings or through crossovers, and to be detected clear of points. Additional time is required for new routes to be set up and for points to be moved. The detection of trains at junctions is normally performed using track circuits. For FBSS systems, the track circuit layout and allocation of track codes has to be a compromise to safisfy the headway and speed requirements of all associated routes. TBS, by contrast, is self-optimising, thereby allowing the headway and speed performance to be optimised for each route involved in a turn-back movement.

In practice it is difficult to generalise on the headway performance at turn-backs because of the variety of physical layouts possible and the parameters involve. For these reasons a detailed headway model is necessary for each case. This permits the constraining features to be identified and for recommendations to be made for improvements.

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4. Disturbed Running Performance

4.1 General Considerations

Theoretical studies of MB systems rarely consider the dynamics of train movements that arise when the instantaneous headway between trains falls below the minimum sustainable steady-state value. Under these conditions trains 'interact' through the MB control system and their behaviour becomes subject to the non-linearities and time delays involved. For this reason, predicting the behaviour analytically is difficult, and the most effective solution is to build up simulation models of the system components.

Studying the dynamics of train movements under these conditions is essential because, during peak-periods, intensive metros rarely sustain an ideal steady-state headway. Even the most effective on-line traffic-regulation algorithms require a finite time to re-stabilise a service following a disruption. During this time considerable signalling interaction could occur.

Relatively small delays at stations lead quickly to interaction. This is because peak-period service headways are typically no more than 10 to 15 seconds greater than signal headways. With 'free-running' MB-based systems, once interaction occurs, the ATO demands varying levels of motoring and braking in response to the LMA location which may be stationary, accelerating, decelerating or advancing step-wise at constant speed.

4.2 Disturbance Mechanisms

An extended dwell-time is the most common disturbance due usually to platform overcrowding. Other disturbances can occur such as a partial traction failure which reduces the available tractive effort of a train thereby reducing its speed. A train may be brought to a stand-still by an ATP EB application resulting either from an ATO failure or from a manual driver over-speeding.

4.3 Fundamental TBS Control Requirements

4.3.1 requesting service braking for a stationary LMA The ATO has to reduce the service braking deceleration in order to bring the train to rest acceptably close to the LMA. However, it is necessary to form a target point that falls short of the LMA by a sufficient margin. This is because, even at low speed, the ATP assumes a certain 'run-away' acceleration.

4.3.2 regulating speed for a non-stationary LMA Potentially, TBS permits a train to regulate its speed in order to follow a non-stationary LMA ahead. Due to the processing and communication delays, an LMA advances in steps. The ATP system must hold the LMA at a fixed location until it is proved safely that the 'obstacle' has advanced to a new location.

The rate at which the LMA advances depends on the rate at which the location of the obstructing train is reported. For example, if the train travels at a constant 50 km/h, then a reporting interval of one second would give rise to a step-distance of about 15 metres. The ATO control system for a following train which is forced to interact, would be required to regulate the speed smoothly in response to this stepping LMA. A more typical situation is when the LMA accelerates step-wise behind a train leaving a platform.

4.3.3 **restarting stationary trains held at restrictive LMA's** A major disturbance could result in several trains being forced to a stand-still in close proximity behind stationary LMA's. In its unregulated state, TBS could permit these trains to re-start in quick succession, once the source of the disruption clears. This would result in maximum starting current being drawn by several trains simultaneously over a localised area. With conventional dc rectifying substations, this would result in a large power surge involving a significant reduction in line voltage. This problem is identified by McCormick and McKenna[7].

FBSS systems, by contrast, impose more 'natural' sequencing on the re-starting of trains. Each train has to clear a full overlap before the restrictive track codes behind permit the following train to re-start. Furthermore, the spacing between the trains is greater, giving more scope for better load-sharing between adjacent substations.

TBS therefore requires regulation that ensures that successive trains do not re-start simultaneously. In any case, the benefits of re-starting trains simultaneously, from a consideration of overall traffic regulation, is minimal. This is because bunching would probably re-occur at another station.

4.4 Multi-Train Simulation

4.4.1. **basic TBS model** To investigate the multi-train performance of TBS, a simplified model has been developed which is illustrated in figure 8. This reflects the general performance of a TBS system and does not necessarily reflect the exact design of the WTCS.

The ATO model produces a per-unit traction demand or a per-unit service braking demand depending on the difference between a desired profile speed and the current speed. In the absence of a restrictive LMA, the desired speed is derived from the track geography, subject to externally-imposed coasting commands. In the presence of a restrictive LMA, the ATO generates a modified profile with a target point close to the LMA.

Given a demand from the ATO, the traction/brake control model produces a jerk-limited application of tractive effort or braking effort. This is applied to a model of the train dynamics which produces a net acceleration. This is integrated successively to derive speed and location, both of which are fed back to the ATO controller.

The ATP model monitors the speed and location continually, and raises a 'trip' condition when a violation of the envelope of safe performance is detected, thereby aborting the simulation.

The model assumes a constant line voltage, and is based on an integration update time of 0.1 seconds. The latter is short enough to capture the jerk-limit transients and system time delays.

4.4.2 **free-running speed-regulation against a non-stationary LMA** Figure 9 shows the simulated speed-performance of a free-running ATO controller which regulates solely against the location of the LMA, once interaction has commenced. It shows the performance of four trains that enter the inter-station section with an initial headway that is 12 seconds lower than the minimum steady-state value. Train 1 completes the run unimpeded, but trains 2, 3 and 4 experience increasing interaction. A typical jerk-limit of 0.5 m/s^3 is imposed on changes of both tractive effort and braking effort.

The ATO Interception Point (IP) corresponds to the end-location of the ATO Driving Margin, projected ahead of the ATP total safety distance. When the IP comes into contact with an LMA, the ATO requests service braking. In figure 9 this occurs at location 'X'. The braking force, applied under jerk limiting, begins to reduce the train speed. As the speed falls the IP stops advancing and may even reverse direction. This fundamental characteristic is due to the progress of the IP being governed by the predicted emergency braking distance which is related non-linearly to the train speed.

Eventually the IP separates from the LMA, thereby permitting motoring to be re-applied. Jerk-limited tractive effort therefore builds up the speed again, and re-accelerates the IP back towards the progressing LMA. On interception the cycle repeats. As the speed of the advancing LMA increases, the duration of successive interceptions becomes less. The ATO therefore cycles between motoring and braking, but the jerk-limiting and time delays do not permit substantial tractive effort or braking effort to be achieved.

The simulations indicate that the dominant factor in these oscillations is the jerk-limiting rather than the discrete nature of the advancing LMA. The difference in performance between that due to a continuous-advancing LMA and a typical discrete-advancing one, is not significantly great.

Clearly the performance indicated in figure 9 is unacceptable from a control performance point of view even though, technically, it stays within the 'comfort' threshold set by jerk-limiting.

4.4.3 stabilizing algorithms ATO control algorithms have been investigated aimed at maintaining stability under conditions of inter-train interaction, without degrading the benefits in steady-state performance. The effectiveness of a given algorithm in eliminating oscillatory control demands, must be evaluated in terms of its impact on both steady-state headway, on which the performance of the signalling system is measured, and inter-station journey time. The main objective is to permit trains to maintain line speed for as long as possible before being checked by restrictive signalling commands. An algorithm that forces trains to service-brake prematurely thereby degrading the steady-state headway, may be unacceptable unless the benefits in control performance can be demonstrated.

The algorithm which gives the most consistent performance without any degradation in steady-state headway, is one based on minimum control action. On encountering a restrictive LMA, the ATO requests service braking continuously until the LMA has advanced by more than a certain distance. The result is to re-introduce some headway-margin thereby reducing the likelihood of subsequent interaction. An additional benefit is that queued, stationary trains re-start in a definite sequence rather than simultaneously. As discussed previously, this reduces the risk of excessive power surges.

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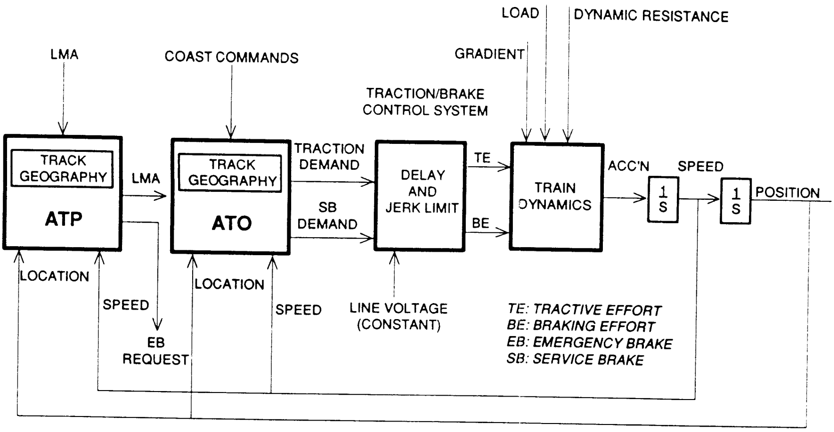

Figure 8 - Basic TBS Simulation model

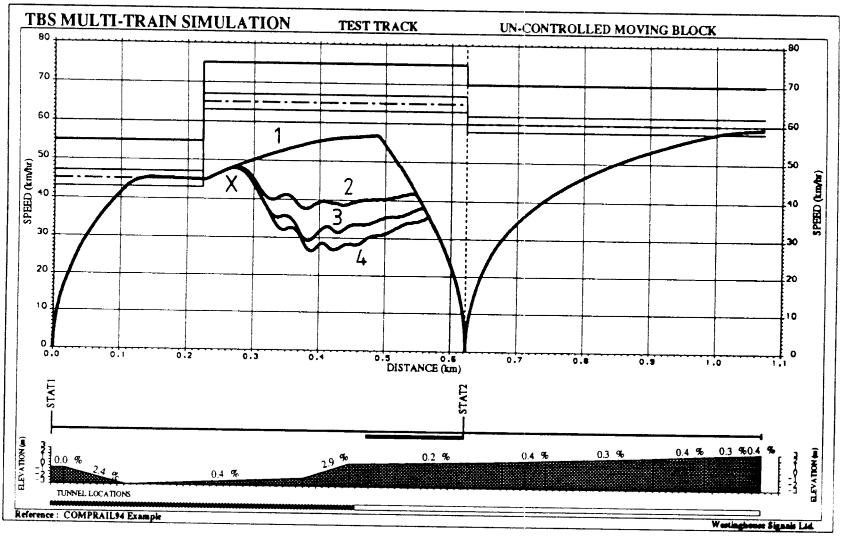

Figure 9 - 'Uncontrolled' Moving Block performance for initial delay of 12 seconds

The disadvantage of this algorithm is that it increases the likelihood of trains being forced to a complete stand-still instead of being permitted to speed-regulate. The effect of a major disturbance therefore spreads more quickly, affecting more trains. Compromise algorithms have therefore been investigated which sacrifice a small amount of steady-state headway in order to modify the train performance in advance of a full service-brake application for a restrictive LMA. This permits trains to proceed at a lower performance level instead of being forced to a stand-still.

4.5 Optimal Feedback Control

Optimal control techniques were widely researched during the 1970's for Automated Guideway Transit (AGT) and Personal Rapid Transit (PRT) systems. These systems, which failed to receive funding, were to be based on large numbers of small automated vehicles operating in complicated city networks, with headways of only a few seconds. It was expected that these systems would be in a frequent, if not continuous, state of inter-vehicle interaction. The propulsion and control systems were designed together, full use being made of the, then, recent advances in modern control theory.

Whilst, in theory, some of these control techniques could be utilised in an ATO controller, there are two reasons why they are not likely to be applicable in practice to conventional metro rolling stock:

(i) As highlighted by Snowdon[8], traction and braking systems are traditionally controlled on a 'macroscopic' basis with high levels of traction and braking, large speed variations and significant transitional time delays.

Optimal feedback methods involving 'tight' control loops, require much higher levels of performance that that for which the equipment is designed. These problems are compounded by the fact that, traditionally, the control, braking and traction systems are designed independently by separate contractors.

(ii) The operational objective of a metro service is to maintain a predictable steady-state headway. Whilst in practice disturbances are frequent, effective traffic-regulation ensures that the resulting interaction should only be short-term.

5. Conclusions

This paper has identified some of the control aspects associated with Moving Block based TBS, when trains are forced to interact. Simulations have shown that, without adequate consideration in design, the potential exists for the ATO performance to exhibit poor stability. A dominant factor in this performance is the effect of jerk-limiting.

ATO correcting algorithms have been developed aimed at producing stable performance without incurring penalties in either steady-state headway, inter-station journey time or energy-usage. An additional constraint has been identified as having to ensure that 'queued' trains do not re-start simultaneously, once a disruption ahead clears.

The simulations performed indicate that in order to permit trains to keep moving behind non-stationary LMA's, then for simple stabilising algorithms to be effective, a small degradation in steady-state headway may be necessary. Here, a following train is forced prematurely to a lower performance level.

An algorithm which gives consistent performance without sacrificing steady-state headway, is one which does not permit consecutive trains to speed-regulate at braking distance. Instead, a following train is forced to brake continuously until the LMA has advanced by a specified distance.

The application of more complicated techniques, based on optimal feedback control, have been investigated. However, it is considered that these techniques are only applicable to automated transit vehicles that interact continuously in a non-scheduled way. Conventional heavy metro and suburban railway operations seek to avoid signalling interaction, and maintain a predictable steady-state headway. More importantly, the traction and braking systems employed in conventional rolling stock, are not, at present, designed to the performance levels required for such control.

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