Longitudinal control for guided transport

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LONGITUDINAL CONTROL FOR GUIDED TRANSPORT

A THESIS SUBMITTED IN PART FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF DOCTOR OF PHILOSOPHY OF LOUTHBROUGH UNIVERSITY OF TECHNOLOGY.

BY

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AUGUST 1980

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SYNOPSIS

The thesis describes a study of automatic driving in a guided transport system. Full scale practical experiments have been carried out with the co-operation of British Railways Research & Development Division.

Considerable attention is paid to the problem of line capacity with a rigorous safety constraint and operational and engineering limitations. An understanding of vehicle interactions under discontinuous and continuous signalling systems is demonstrated, leading to an explanation of why the theoretical steady state plain line capacities are not realisable. This is extended to show the importance of the vehicle trajectory and how shaping the trajectory can minimise journey time, headway, energy consumption and other performance criteria, bearing in mind the inconsistency of these aims and demonstrating the trade-offs.

Some theoretical work on generalised control systems is described and this demonstrates the need for a greater understanding of practical engineering constraints. Consequently, available literature on train performance has been studied and experiments carried out with an instrumented train. The results indicate an inadequate understanding of train behaviour in much that has previously been published. A mathematical model of the test train has been formulated and with the help of the Mathematics Applications Section of British Rail, this has been simulated on the computer. It is evident that railway braking systems, particularly those employing cast iron friction blocks, introduce significant control problems. The control system of the train is demonstrated to be non-linear and subject to severe stochastic disturbances of both environmental and system parameters. Instrumentation of the system is difficult and the report goes to some length to identify the fundamental limitations
of measurement of the principal state variables.

A complete single vehicle control system has been realised on the British Rail Test Line at Mickleover. It is anticipated that an engineered system would be microprocessor based and experience has been gained with Intel devices in the communications system, whilst a mini-computer system was considered more appropriate as a test bed for control principle development. The results of the performance evaluation and control tests at Mickleover give significant insight into the likelihood of realisation of some of the theoretical ideals developed in the earlier study. The report includes details of some of the authors more recent work with British Rail on a project to implement pilot scheme automatic train operation. The experimental work for this project has included the implementation of a simple automatic driver on a Motorola Microprocessor.
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I also wish to thank my family for their tolerance over a somewhat protracted period of thesis preparation. Finally, thanks to Davina Jamieson who has typed the script.
LIST OF SYMBOLS.

a  Nominal acceleration.  \((m/s^2)\)

A  Acceleration indicated by accelerometer.  \((m/s^2)\)

b  Instantaneous retardation.  \((m/s^2)\)

B  Emergency braking rate.  \((m/s^2)\)

\(B_1\)  Emergency braking rate of leading vehicle.  \((m/s^2)\)

\(B_2\)  Emergency braking rate of following vehicle.  \((m/s^2)\)

\(B^1\)  Jerk limited maximum brake level.  \((m/s^2)\)

c  Lateral jerk.  \((m/s^3)\)

C  Line capacity.

F  Propulsive force, (net).  \((N)\)

\(F_w\)  Wind drag force.  \((N)\)

\(F_m\)  Mechanical drag force.  \((N)\)

g  Gravitational acceleration.  \((m/s^2)\)

h  Line separation following turn-out.  \((m)\)

H  Headway.  \((s)\)

\(H(t)\)  Step function.

K  Longitudinal jerk.

\(K_p\)  Perceived lateral jerk.  \((m/s^3)\)

\(K_1, K_2, K_3\)  (App. R) constants.
K_1  Lateral acceleration (App. C, only). (m/s^2)

K_2  Nominal Headway. (s)

K_3  Constant of proportionality (s^-2)

K_4  Constant of proportionality (N/s)

K_5  Aerodynamic drag coefficient. (NS/m^2)

K_6  Rolling resistance coefficient. (N/kg)

K_7  Constant of proportionality. (s^2/m)

L_4  Length of transition curve. (m)

L  Vehicle length (m)

M  Vehicle mass. (kg)

R  Braking rate divisor.

r  Radius of curvature. (m)

S  Laplace operator.

S  Intervehicle separation. (m)

S_{a}  Additional distance travelled by initially accelerating vehicle. (m)

S_{b}  Additional distance travelled during brake release. (m)

S_{t}  Distance for speed transition. (m)

S_{x}  Excess distance travelled. (m)

t  Detection and reaction time. (s)

T  Time to reach critical point. (s)
\[ T_r \quad \text{Station replacement time. (s)} \]
\[ T_c \quad \text{Station clearance time (s)} \]
\[ T_b \quad \text{Station braking time. (s)} \]
\[ T_L \quad \text{Time lost. (s)} \]
\[ T_s \quad \text{Stopping time. (s)} \]
\[ U(t) \quad \text{Ramp function.} \]

\[ v_1, \dot{x}_1 \quad \text{Speed of leading vehicle. (m/s)} \]
\[ v_2, \dot{x}_2 \quad \text{Speed of following vehicle. (m/s)} \]
\[ v \quad \text{Instantaneous speed. (m/s)} \]
\[ v_m \quad \text{Maximum speed. (m/s)} \]
\[ \dot{x} \quad \text{Acceleration. (m/s}^2) \]
\[ \dot{x} \quad \text{Velocity. (m/s)} \]
\[ x_1 \quad \text{Leader position. (m)} \]
\[ x_2 \quad \text{Position of following vehicle (m)} \]
\[ \gamma \quad \text{Lateral displacement of divergent guideway. (m)} \]
1. INTRODUCTION.

1.1 Background.

Transport systems throughout the world are becoming aware of the rapidly advancing technologies of vehicle design and automatic control. Public transport systems have always been handicapped in terms of standard of service that they are able to offer, because staff costs are a high proportion of operating costs so that in order to compete on economic terms, large vehicles are dictated. Consequently, route coverage is poor and frequency of service low. However the convenience of private transport and road haulage at origin and destination points within urban areas is being eroded as congestion increases and traffic and parking schemes are introduced. Necessity frequently brings about the adoption of new technology and in many areas of the public transport system staff shortages are a real problem. It is now being realised that adoption of automation in the driving function of transport systems can reduce the need for staff training and also lead to greater efficiency of driving and energy savings. Already it is difficult to get staff to work the unsocial hours necessary to provide the transport system required by the public and in the long term crewless operation may be a way around this problem.

The broader issues of the transport requirement are beyond the scope of this study but the comments above serve as an indication of the requirement. British Rail and other Railway Administrations have been slow to adopt new
technology. This has in part been for technical reasons as the environmental and operational conditions dictate a very high specification, which is difficult to meet, but more importantly most functions which might be replaced by advanced technology are currently performed by highly developed conventional techniques. The economics of development of advanced technology to meet the specification and retraining of staff to cope with the new equipment means that the case for its development must be strongly supported with demonstration of both technical feasibility and acceptability to engineering and operating departments.

If new technology is applied directly to systems of conventional design, substantial improvements in performance may be achieved. The Victoria Line underground railway in London (Ref. 1) is a successful example of an early application of automation to the driving function. The Bay Area Rapid Transit Scheme is a more recent attempt to incorporate more new technology in a transport system (Ref. 2). Unfortunately in this application considerable difficulties have occurred through the transfer of technology from aerospace and other industries, and the system is not yet achieving its full potential. In this country and abroad computers and automation have been successfully applied to other aspects of railway operation. Modern Railway signalling and train describer systems employ computers and advanced data communications systems, (Ref. 3). For road traffic systems city centre traffic signals are co-ordinated by computer aided control systems,
(Ref. 4), and motorways have complex computer assisted monitoring and signalling systems (Ref. 5).

Automation may thus improve on the deficiencies of the manual systems but full advantage is not taken of the technology incorporated. The labour intensive public transport system requires the use of large units of transport, but proponents of automated systems claim that total automation of the transportation system removes this fundamental constraint without serious economic penalty and further, the rigid network dictated for the large vehicles is no longer necessary. A personalised or tailored transport system is then possible, where the system will serve economically the needs of individuals and factories within it. Cabtrack (Ref. 6), proposed in this country several years ago, was the first of many systems to be proposed for city centres travelling at modest speed with 2 to 4 persons per cab. More recently, Transport and Road Research Laboratory who sponsored some early Cabtrack work, have proposed another system, Minitram (Ref. 7), and studies have been undertaken to assess the technical feasibility of this system which though incorporating many of the features of Cabtrack, uses larger vehicles and can operate in a scheduled manner. British Rail at one time proposed a national system of self-propelled wagons, Autowagon (Ref. 8), which would have been container carrying flat wagons automatically controlled and running within the existing railway system without degradation of safety.
In the early 1970's, with the needs of Channel Tunnel and a possible new railway link to London's proposed third airport in mind, British Rail developed a new signalling and control system TACT (Total Automatic Control of Trains) with the aim of making full economic use of technology rather than developing a highly technological and possibly uneconomic implementation of standard signalling procedures. The practical work on vehicle control which forms the latter part of this thesis is based on the author's involvement with this project.

1.2 Evolution of Automated Systems.

There are clearly many factors which influence the development of transport systems and it is not the purpose of the present thesis to analyse them in detail. It is however appropriate to point out what the author believes to be the more important factors justifying the development of the technology described in this thesis.

The Victoria Line of London Transport was a big step forward and now some 10 years from its commissioning the arguments in favour of automation are stronger. In some respects London's railways are a special case, but they do serve as an indicator of developing needs of railways more generally. For some years now London Transport and British Rail in the London Area have suffered staff shortages which have made it difficult to run an effective service. The introduction of automatic operation has eased the problem by reducing the need for staff training and the use of television has
permitted one-man operation. There remains however the requirement for staff to work unsocial hours in order to provide the service demanded by the public. The way forward for such authorities as London Transport must be to crewless train operation. Such a step will only be possible when the train driving equipment can be shown to be adequately safe and reliable. Whereas some would argue that the man in the cab inspires public confidence, the author would contend that the majority of passengers are ignorant of present methods of working and would be unaware of a change to crewless operation.

Automation on a larger railway network may be justified as in the London Transport case as a means of perpetuating the existing service in the face of changing social values. It is the author's view however that greater benefits to the operator and society will accrue from exploitation of the potential of automation rather than replacement of existing functions with high technology. For high density passenger flows it is unlikely that a new mode of transport will appear in the foreseeable future, but automation of conventional systems can lead to improvements. The first feature of an automated system which may be exploited is the consistent running.

The time-table planning for railways recognises the difference in performance of trains and drivers and a large amount of spare capacity has to be built into the system in order to ensure smooth running. Indeed, Pearson (Ref. 9) has
demonstrated the need with a discrete signalling system for trains to be operated at considerably less than the theoretical line capacity. In an automated system the deterministic behaviour of the trains, combined with centralised control and regulation make it possible to run a more intensive service with no improvement of the signalling system. In a real situation it is unlikely that a signalling appropriate for manual operation would be maintained for automatic operation and it would be appropriate to include a system which would be suited to the automatically controlled vehicles rather than their ill equipped manually driven counterparts, and consequently further improvement would be possible. If the traffic does not require operation to the limit of system performance or capacity, the potential for exploiting automation is equally great as it is clearly easier to direct the efficient driving of automated vehicles than their manually driven counterparts.

In some applications there may be a need for a relatively high capacity at certain times of the day with a much reduced demand at other times. This type of demand pattern is difficult to satisfy with manually driven trains as stock and manpower has to be provided for peak services. It is clearly not possible to reduce this peak stock requirement other than by changes in the service pattern and running speeds, these changes perhaps also including automation. Since the staff problem no longer exists in an automated system, it is possible outside the peak to provide the level of service which the demand justifies, and so keep vehicle mileage down whilst providing a useful service. It
then becomes reasonable to provide a service at unsocial hours and to intensify that service to follow peaks of demand.

In the limit where system capacity permits, demand activated scheduling may be envisaged. In a dense urban network this might mean that the number of vehicles in traffic at any time was constantly varying in response to system loading. In a less busy network or at off-peak times on an urban network, individual demand activation of each journey might become feasible. The philosophy for disposal and storage of empty vehicles would of course need to be designed in order to provide an acceptable response time for journey initiation.
1.3 Operational Requirements.

Throughout the world new transport systems based on various suspension and guidance technologies are being developed. Conventional wheel on rail technology has been developed to a high degree and has resulted in the production of the Advanced Passenger Train. Of the more novel systems, the magnetically levitated vehicle developed by British Rail is currently being assessed for possible installation at Birmingham Airport. Personal rapid transit has attracted considerable attention in recent years and a number of systems have been proposed.

A number of review articles have appeared recently and it is not intended to duplicate the effort expended to prepare these. Ref. 10 is one such concise summary of the principal features of most of the proposed PRT systems. Studies for the general control requirement of automated guided vehicles have been reported (Ref. 11). These studies concentrate on system differences (for example central computer direct control of vehicles or individual vehicle following) and the system responses derived are to vehicle following laws designed with little consideration for safety in failure situations.

The foregoing comments show that transport systems are evolving with the following properties:

1. Laterally guided short vehicles.

2. Automatically controlled vehicles.
3. Close headway operation on the running lines.

4. Possible Scheduled operation but demand activated in the long term.

5. Closely spaced stops.

P.J. Walker has analysed the traffic requirement for urban travel in terms of journey speed, frequency of stops and other parameters (Ref. 12). It may be concluded from his study that a Minitram type system would satisfy the demand. Maund (Ref. 13) has analysed the problem in a slightly more mathematical manner in relation to "Activity Centre Transportation Systems", and he gives some statistical constraints for the control system design. British Rail in conjunction with ICL have carried out an extensive study (Ref. 14) of the feasibility of an automatic wagon system within the existing railway. No insurmountable problems exist, but in and around conurbations and on some main lines, a mode of operation capable of giving higher throughput than conventional track based fixed block signalling is required (Ref. 15 and 16). Appendix A describes the general features of both the Minitram and Autowagon systems.

Clearly the overall requirement of all systems is to provide a safe, reliable transit for each vehicle between a number of nodes in a network, with high utilisation of available track capacity. There is then no fundamental difference in the control requirement for the evolving new systems and those of a modern conventional railway.
1.4 Safety Requirement.

Traditional track transport systems have an enviable record for safety (Ref. 25). This is not an inherent feature of the system, but rather the result of pressure over a long period by the users of transport systems operated by public bodies. By way of comparison the user of a motor car is prepared to expose himself to risks which are considered unacceptable by the operating authorities for railway systems.

Public pressure for safety on the railways is crystalised in the Government Ministry Regulations (Ref. 24), whilst the minimal requirements of road vehicles are covered by the regulations contained in Ref. 26. These documents demonstrate the difference between individual responsibility in the case of the motorist and public responsibility in the case of the railway operator.

Guided transport systems do not have collision avoidance potential of steered vehicles and in determining the failure-performance this is of great significance. With manually controlled steered rubber tyred vehicles, little signalling is required as adhesion and brake forces available make stopping within sighting distance generally possible. It is only under conditions of extremely poor visibility or low adhesion that the need for signalling is felt. With steel wheeled vehicles decelerations and adhesion are much lower. Many workers suggest that a worst case failure (i.e. highest acceleration) might occur due to wheel locking of a vehicle, but it must be noted that a controlled maximum brake application
can result in higher deceleration. From railway experience it is evident that other failures occur, often as a result of suspension or guidance failure, when track damage may result in an effective instantaneous stop. The use of passive tracks with vehicle mounted switching cannot avoid this problem. The possibility of head on collision cannot be dismissed and with the inherently smaller mass of vehicles on automatic systems, the consequence of any obstruction of the track is more serious.

The safety constraint is therefore defined that if at any point on the network a vehicle shall fail, in the worst case coming to an abrupt halt, then the vehicle following strategy and the controller design shall ensure that no collision is likely to occur. Such a constraint may appear unduly restrictive in terms of system capacity, but Hinman (Ref. 28) and others have demonstrated the system capacity gains accruing from a less vigorous safety constraint may be small and Hinman also points out the related operational difficulties of maintaining close headways. It is felt that the foregoing argument justifies intensive study of operation under the proposed constraint, and it is further suggested that until the reliability of all system components can be proven in service no relaxation of the constraint should be contemplated.

The proposed control scheme for Minitram (Ref. 29) envisages headways approaching the main line steady state headway. Such headway will inevitably result in dangerous transition conditions (Ref. 30) if steps are not taken to
avoid them. The Autowagon system originating from within British Rail naturally incorporated consideration of the safety requirement from its inception and in most cases it does not appear to be a limitation on operational capacity, since sufficient spare capacity exists on the railway system. This is not so for Minitram and other personalised rapid transit systems.

Broadly the control requirement for the proposed schemes is for a headway control system which will keep vehicles spaced to a defined level of safety. There is a secondary requirement to provide the necessary central control and system management functions. These requirements have always been those of main line railway signalling (see Appendix B) and the control schemes must be considered as a development into the executive field of such signalling. For main line railways such a policy is being followed (Ref. 31). In the foreseeable future until the reliability of all control system components has been proven and the control requirement and data input more rigorously defined, it is most unlikely that systems incorporating an element of danger in normal failure situations will be permitted in this country. That is to say, if the potential for a crash exists even if the control system fails to safety, then for the present such systems must be ruled out. As railway signalling has proven over many years, guaranteed failure to safety is an extremely demanding engineering requirement even when the operational modes and control strategy are determined beforehand.
On the above premise, it is necessary to obtain a thorough understanding of the mechanisms of the vehicle interactions in a guided transport system, in so far as these affect safety, capacity and system performance. The latter parameter is taken to include time penalties and stability considerations.

1.5 Payload Constraints.

The basic safety constraint has been described; the other fundamental constraint which interacts with safety is that of passenger comfort, or for freight the ride index. This means that there are limits of maximum longitudinal and lateral acceleration, and jerk, which may be applied to the vehicle. Unfortunately, the effects are subjective and therefore difficult to quantify, particularly as observations depend upon the degree of restraint provided and the attitude of the observer.

Gebhard (Ref. 23) has produced a survey of a number of experiments undertaken with conventional transport systems and points out that what is very acceptable in a high performance car is considered uncomfortable by a railway passenger. Hoberock (Ref. 27) has updated Gebhard's work with a survey of more recent work.

With automated transport systems which utilise small vehicles, it is an economic necessity to provide high peak capacity, and if the system is not to be selective on its patronage, performance to suit the range of potential customers must be provided. In general this
PERMISSIBLE CURVING SPEED

LATERAL ACCELERATION

\[ = 1.2 \text{ m/s}^2 \]

FIGURE 1.5.1
means that standing passengers must be accommodated and since restraint of such passengers is not compatible with rapid loading and unloading, limitations are placed on the vehicle performance.

Reduction of speed at certain points on the main line will be necessary, particularly for the negotiation of curves where the lateral acceleration limit would otherwise be exceeded. The speed around a curve is limited primarily by passenger comfort limitations or cant deficiency. In many circumstances it will be physically impossible to cant the track and for typical PRT parameters maximum speeds around curves will be as shown by the solid lines of Fig. 1.5.1. If a high degree of banking can be provided, with allowance for unscheduled halt on the curves, permissible speeds rise to those indicated by the dash lines of Fig. 1.5.1. The design of the transition curves in this case is complicated (Ref. 32), particularly if vehicles have windows, by the tilt rate perceived by the passengers.

Operational procedures may dictate other speed transitions. Many workers assume that if off-line stations on a PRT system are provided, then it is possible to maintain a constant main line cruising speed over the whole network. Dias (Ref. 18) in his paper on PRT Geometry has shown that under this assumption, depending upon the severity of the jerk constraint, the length of a typical turnout may be between 75 and 200 m. With the density of network in urban areas, features such as stations and inter-changes
would be of unacceptable size and hence some reduction of speed will be necessary.

1.6 Engineering Limitations.

Engineering features both of the vehicle and track place limitations on system performance. Generally in the construction of a guided transport system, the cost of civil engineering works is a dominant factor. However, a minimum cost civil engineering job may be unacceptable if excessive gradient and curvature or inherent speed restrictions are included; there is therefore an assessment to be made in overall commercial terms to produce a cost effective solution. Maximum speeds may thus be dictated by the stability of the track base at different points along the track and speed may be further restricted through complex point work, in addition to reductions in speed necessary for reasons outlined in Section 1.3.

Vehicle design will also be a compromise. It would for example be difficult to justify installation of sufficient power to provide a uniform rate of acceleration, regardless of prevailing gradient. For the braking system there will be power dissipation limits at high speed and non-linearities arising from the physical properties of the braking system. All power systems will include significant lags and control may be further constrained by the type of prime mover contained in the vehicle.

Most features of the system are thus determined with little regard to the control implications and it is generally expected that a control system can be designed which
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<td>14.5 m/s</td>
<td>25.0 m/s</td>
<td>35.0 m/s</td>
</tr>
<tr>
<td>Maximum Longitudinal Accel.</td>
<td>1.2 m/s²</td>
<td>1.2 m/s²</td>
<td>1.0 m/s²</td>
</tr>
<tr>
<td>Maximum Lateral Acceleration</td>
<td>0.6 m/s</td>
<td>0.6 m/s</td>
<td>- m/s²</td>
</tr>
<tr>
<td>Maximum Jerk in all cases.</td>
<td>1.2 m/s³</td>
<td>1.2 m/s³</td>
<td>1.0 m/s³</td>
</tr>
<tr>
<td>Gradients.</td>
<td>10 %</td>
<td>10 %</td>
<td>2.5 %</td>
</tr>
<tr>
<td>Steady Wind.</td>
<td>25 m/s</td>
<td>25 m/s</td>
<td>- m/s</td>
</tr>
<tr>
<td>Minimum Curves.</td>
<td>8 m</td>
<td>8 m</td>
<td>- m</td>
</tr>
<tr>
<td>Vehicle Length</td>
<td>3(9) m</td>
<td>3(9) m</td>
<td>10-15 m</td>
</tr>
</tbody>
</table>
will cope with the constraints and provide the required overall system performance.

1.7 Control Possibilities.

The preceding sections have indicated the influence of control system design on operational efficiency of the system. To arrive at an effective control strategy, it is necessary to determine the scope for control. Furthermore any performance index of the control systems must be based primarily on the "external" system parameters, system capacity and journey times achieved. Other factors such as degree of safety and frequency of service are important but maximum speeds and instantaneous headways, though inseparable from the above have little significance of themselves.

Fortunately many of the variables are defined on other grounds than control considerations, and it is possible to accept many of the figures from specifications, such as those given in Table 1, as fixed or at least defining a limited range. Traditionally, control considerations have been brought in at a late stage in the system design, as this minimises the design constraints on other engineering areas, and generally adequate control systems have been possible at reasonable cost. The author contends however, that with intensely worked networks of small vehicles as proposed, this is not the case and the effect of the control scheme on the success or overall efficiency of the system may be very significant.
The sensitivity of system performance to design parameters outside the range of control but interactive with it, must be determined at an early stage. Obviously parameters which affect system capacity are vehicle length, maximum speed and braking rate. Optimisation in purely economic terms of traffic carried (Ref. 33) on a simple model based on these parameters and requiring absolute safety, dictates an infinitely long train moving at zero speed. Such a service would not attract much custom. In a general theoretical study, it is difficult to quantify a quality of service, but it is related to the frequency of service possible and the reduction in journey speed due to interaction with other vehicles. Clearly if the headway between two vehicles is made to depend linearly on their velocity, as is the case with simple pure moving block system, an increase in the frequency of service can be made at the expense of journey speed. However, as is well known when operating to this simple law, at low speeds the effect of vehicle length is more significant than the separation and the maximum capacity or frequency of service is obtained at some intermediate speed. The implications of this will be expanded in a detailed explanation of the vehicle following laws in Section 2.3.

Once the system is defined; the scope for control of a vehicle with one basic degree of freedom is limited. Essentially, the speed profile of the individual vehicle must be controlled, either directly or indirectly to ensure stopping at appropriate points, and running at permissible speeds through any necessary speed restrictions consistent with avoidance of collision or potential collision with other vehicles.
The control systems proposed for Autowagon and Minitram illustrate the difference of approach possible, although the requirement is similar. Autowagon places great emphasis on the safety aspect and aims to use this as a primary control with a track velocity profile back-up (Ref. 16). Early British Rail studies demonstrated this to be desirable and perhaps practicable.

Control for Minitram takes account of the fact that the system is a relatively small self-contained network of homogeneous vehicles (Ref. 34). A slot controlled system is proposed whereby each vehicle is allocated to a slot in the system network and its velocity is determined by the distance it lags behind that slot. The system is known as Position Lag Slot Control (PLSC). Time constants of the vehicle and the spacing of the slots are arranged so that if the slot allocated is incremented at a normal rate, the vehicle moves smoothly through the system with a steady lag behind the slot to which it is allocated. The spacing of slots is reduced at curves and other points where is is necessary to change the speed of all vehicles. The resultant control amounts to a track based velocity profile control, with the vehicles initialised at a time headway sufficient to ensure safety at all points in the network. In some respects the system may be likened to a two aspect fixed block signalling system with cab signalling and very short blocks. The individual control of the vehicles is open loop, rather than any equivalent of automatic track circuit block working, which might be employed in the equivalent railway. In the steady stage on a plain line it is relatively easy to assess
the safety of such a system, and so to determine permissible headways, but in the transient situation no objective study has been made. The mode of operation appears wasteful of line capacity in some circumstances, if the absolute safety criterion of this report is applied. If however, headways are determined by traffic requirements, dangerous transients may occur even though headways at steady speed may be more than adequate. Detailed analysis of station design and operating procedures with the dynamic consideration of Chapter 3 should clarify the situation.

Since most of the control systems may be considered as an extension of the established principles of railway signalling, to complete the background, an appendix is included describing the basis of conventional railway signalling (Appendix B).
2. AUTOMATIC DRIVING.

2.1 Interpretation of the Requirements.

From the preceding discussion it emerges that a class of transportation systems are evolving which rely fundamentally on the provision of automatic driving. The system will be controlled by public bodies and because automatic driving is involved, public accountability for the safety of the system will dictate extremely high standards. Therefore although advanced schemes have been proposed for very close headway control, it is likely that they will evolve from the proven safety techniques of conventional railway operation, (Ref. McNaughton, 19).

This study approaches the problem from both ends; initially a study of theoretical ideals of control of strings of vehicles, establishes which features of a system contribute significantly to its operational capacity; secondly an attempt to automate the driving of a conventional railway train provides considerable insight into the engineering problems which must be overcome if the theoretical ideals are to be realised. The remainder of this chapter will be concerned with the theoretical aspects of vehicle control.

In the previous chapter the requirements of automatic control have been stated as being to provide a safe reliable transit for each vehicle between a number of nodes in a network, with a high utilisation or track capacity; though in absence of sufficient potential traffic, the last constraint would of course be reduced and the specification could be simplified. Fig. 2.1 illustrates a journey
Figure 2.1 Automatic Driving Journey Profile.
profile which includes all the simple elements of a journey which will be required to move a vehicle through a network, with the constraints defined in Chapter 1. In the simplest case, this profile could be fixed and programmed into the track. The British Rail Wigley wire system (Ref. 20) and the normal operation of the position lag slot control of Minitram are examples of simple implementations. For operation of anything other than a simple shuttle, with fixed station stopping patterns, the shortcomings of this method of control are obvious.

In order to control several vehicles on the same line safely, it is necessary to communicate the presence of a vehicle to its follower. In a manually driven car, this link is normally purely visual, supplemented by advisory signs; for a manual railway (see Appendix B) a means of detection of the presence of the train, either manual or automatic is provided and the information is conveyed by lineside signals to following trains. The principles of railway signalling could readily be transferred to the simple automatic system, by the provision of switched alternative track profiles. Systems have been proposed to do this (Ref. 21). However, if the performance of all vehicles on the system is not required to be the same, and if all vehicles are not similar then the problems of detecting which vehicle is present and which profile it should use are considerable and lead to an excessive amount of hardware at the trackside. An alternative approach is to provide a two-way data link between the trains and the trackside equipment making it possible
to implement control schemes based on switched track profiles with a minimum of hardware at the lineside. The British Rail TACT system works on these lines.

It will be immediately apparent to the reader that operation to a fixed programme of switched track profiles means that the vehicles are very loosely controlled and their driving mechanisms are independent. This can be a disadvantage as the system then suffers from the major shortcomings of the basic signalling system, that of system instability when working close to capacity. Pearson (Ref. 9) has demonstrated theoretically, that under conventional railway signalling systems, operation at headways of less than 3 times signalled headway results in the onset of instability and this is often the case on the intensely worked suburban railways where under conditions of perturbation it may be necessary to cancel the running of certain trains in order to restore control of the line.

With automatic driving and a link providing information regarding line occupancy ahead of the train, the potential exists to reduce the quantisation of information to the train and thus to make more efficient use of available capacity, without degradation of the safety factor, which is such an important developed feature of the railway signalling system. For the purpose of this report,
systems employing continuous rather than discrete information are described as moving block systems, and the laws by which the vehicles are controlled are described as following laws.

The vehicle following laws discussed in this report are all based on the safety constraint described in Chapter 1. The definitions are not new, having been used by Pearson (Ref. 9) and the author in previous work, but for completeness they are included in Appendix D.

2.2 Comparison with Manual Driving.

It is clear that the aims of automated or manually driven systems are the same. The chief difference lies in the information paths, both in quality and quantity of available data. Branton (Ref. 35) has analysed the skill of the train driver and it is evident from his work that the driver receives his input data from a wide variety of sources. Branton separates out the data in order of ascending predictability ranging from that affected by momentary variations in climatic or traffic conditions, to that known with certainty at the commencement of the journey.

The manual driver makes use of fragmentary data from many sources to predict the likelihood of poor prevailing adhesion. For example, a driver on a normally intensely trafficked line, will know that under cold damp conditions,
following a break in traffic, he can expect very low adhesion. Under dry warm conditions, during normal running, he would expect to be able to use a higher braking rate. However, there are conditions under which a driver is not a very good predictor. Examination of the driving behaviour of a number of drivers (Ref. 35) indicates a tendency to make a brake application earlier than necessary, in order to gain confidence that the expected brake force is available. This may well be the result of experience of transient variations in adhesion and braking performance. Such short term changes, perhaps resulting from the onset of rain, can result in marked increases in stopping distance for some types of brake (Ref. 47).

The automatic controller is systematic in the production of its output demands, and although some measure of adaption to slowly varying time inputs may be possible, in general anticipation of circumstances is precluded. In general then, by design an automatic system will probably tend to use lower maximum braking rates, as it will have to be able to contend with worst case conditions. However, the manual driver whilst using the full braking capability of the train, may in fact take longer to stop due to the tendency to make an early application followed by a release.

The traction control exerted by a manual driver depends
Figure 2.2 Energy Saving Speed Profile

N.B. Journey time is equal for the two profiles, i.e. may be much less for high acceleration and retardation case.
upon a number of factors. Of these the late running of the train and the skill of the driver predominate. A less skilled driver may well make inefficient use of the traction and braking forces available to him, resulting in late running and high energy consumption. For many years it has been appreciated that efficient running to a time-table requires brisk acceleration and rapid braking so that the intermediate speed and hence the kinetic energy dissipated in braking can be reduced to a minimum. This is illustrated in Fig. 2.2. Clearly there are upper limits of the acceleration and braking rates that may be used in order to preserve passenger comfort, and there are of course physical limitations such as available adhesion. It is found on short station to station journeys that manual drivers frequently maintain power for longer than necessary and also that the same driving technique is used regardless of whether the train is late or early. On suburban services this manner of driving may reduce journey time by a few seconds and incur an energy consumption increase in the region of 30%. In an automated system it is practicable to monitor the progress of a train in relation to the operational requirements and enforce coasting or regulation of speed below that permitted for the line, leading to significant energy saving and greater consistency of running. Enforcement of coasting in this manner offers greater potential for energy savings than that obtained by fixed coasting boards used for manual driving.

It is clear then that a different approach is used in
automatic driving compared to manual driving and that energy and time-keeping advantages may ensue from careful choice of driving technique.
2.3 Vehicle Following.

Within the scope of this study, it is not possible to examine all the theoretical modes of operation of an automated guided system and to determine their effect on the design of the control system. It has been necessary to concentrate on the fundamental features. Primarily this means that limitations of control system design are to be determined with respect to passenger comfort and safety. System delays, time constants and controller characteristics of the vehicles are not considered fundamental, but consideration is given to the degradation of the theoretical optimum when engineering limitations are observed.

It is appropriate initially to consider the steady state capacity of a line under different following laws. Hinman (Ref. 39) has shown that if a high capacity, greater than that determined by absolute safety is required, then if the safety criterion is derived from the impact velocity under failure conditions, that capacity may be achieved by keeping the vehicles close together and not allowing large gaps to develop. This is clearly only practicable at low speeds, and the merging of fundamentally unsafe vehicle strings has been the subject of a considerable amount of work. It is generally recognised that increasing the emergency brake rate can increase the maximum capacity due to the reduction in braking distance. However, the significance of vehicle length, brake rate and jerk limitations, when related to the comfort constraints referred to in the previous Chapter, is not appreciated. A public transport system with high acceleration and corresponding jerk rates
would require sophisticated passenger restraint which would increase loading and unloading times to nullify the advantages of potential headway reduction. Furthermore British Rail have found it advantageous to use the available brake performance in normal running thus making the emergency and normal deceleration rates approximately equal. From the figures given by Gebhard (Ref. 23) and also Hoberock (Ref. 27), there exists a range of acceleration and jerk rates covering the Mini-tram and Autowagon requirements and these have been used.

As was explained in Chapter 1, a major difference between control system proposals for various guided vehicle systems is whether or not vehicle following is used to control the longitudinal separation of the vehicles. Under vehicle following control, each vehicle is aware of the position of the vehicle in advance of it, and is able to control its own speed and position so as to ensure its own safety. Much of the early work reported in the literature on vehicle following concentrated heavily on the stability of a string of vehicles and little regard was paid to the safety of the vehicles.

A considerable amount of work has been done on the simple vehicle following situation, but much of this has involved approximation for effects such as jerk limited braking, where a reduced constant deceleration is substituted. In some cases results obtained are extrapolated into areas in which their validity must be questioned (Ref. 36). Hajdu et al (Ref. 37) several
years ago wrote an extensive paper on control considerations for short vehicles, but neglected the dynamic safety requirement. Such a requirement was first recognised by the author in Autowagon studies (Ref. 16) of mandatory speed restrictions and in that specific case has been expanded upon by Calderbank (Ref. 38). Within fixed block and moving block systems, which some advanced German tramway systems operate (Ref. 40) the problem of station stopping is of great importance and has been analysed by Lagerhausen (Ref. 41 & 42). There is scope for further development of his ideas since the Tramway system is rather more rigidly constrained than the PRT systems under consideration here. Recent papers from the United States show road longitudinal control requirements for automatic highway operation (Ref. 43 and 44) to be very similar to the guided vehicle requirements and the conclusions of such studies are thus relevant.

The fixed block signalling principles described in Appendix B may be considered the simplest implementation of a vehicle following strategy. In this case at discrete points along the track the vehicle receives sufficient information to be sure the line ahead is clear for a greater distance than its own braking distance. Work has been carried out to assess the benefit of increasing the number of aspects within the block system (Ref. 45). For the purpose of this report only continuous signalling systems are considered, although it is realised that some of the techniques developed might equally be applied to fixed block
signalling systems.

2.4 Hierarchical Control.

Within any transport system, control must be exercised at a number of levels. Gelbstein (Ref. 50) has investigated this aspect of system operation and his representation of a typical system is shown in Fig. 2.4.1. The diagram has a hierarchical form and it will be noted that the vehicle control upon which this report concentrates forms the innermost and tightest control loop.
3. DYNAMIC CHARACTERISTICS OF VEHICLE FOLLOWING.

3.1 System Capacity.

Many system proposals have been based on a limited appreciation of the steady state characteristics of the vehicle following laws as described in Appendix E. Unfortunately these steady state characteristics only partially describe the system behaviour and great care must be exercised in their interpretation, to avoid the expectation of smaller headways than are physically realisable.

Consider the pure moving block characteristic illustrated in Fig. 3.1.1, which is typical for an Autowagon type system. It would appear that capacity of over 200 vehicles per hour might be achieved on plain line subject to a line limit of 30 m/sec. Speed restrictions would appear to be no problem as adequate capacity exists at the lower speeds. Unfortunately speed restrictions are a problem and, as is shown in this section of the report, if mandatory speed restrictions are to be observed, at best it is only possible to approach the high speed limiting capacity. This capacity can then only be achieved at some expense of journey time and if this is not allowable the capacity of the line is shown to be much reduced.

3.2 Disturbance from Steady State.

The need for a transition in velocity in order comfortably to negotiate the curves to be expected on a guided transport system was described in the previous Chapter, but other situations occur that disturb the system
FIGURE 3.1.1 AUTOWAGON CAPACITY PMB
operation:

1. The need to start and stop vehicles for stations or Depots, where they may be on the running lines.

2. Failure conditions where the system must be able to restart vehicles once the cause of the failure has been eliminated.

3. Junctions where there is a need to control flows.

Initially, in order to establish theoretical limits, it is necessary to consider an ideal vehicle. Such a vehicle will not be subject to limits of power, brake force, adhesion and non-linear resistance of a real vehicle. The results obtained from such a model show what performance may be achieved by strict adherence to the following laws. However, in many cases unrealistic demands will be made of the vehicle. In the later part of this study, the vehicle model is therefore developed to show the further performance limitations introduced. Further, it is necessary, when vehicle mass is brought in, to exercise some control over the braking and accelerating forces. For the purpose of this part of the report, simple controllers have been assumed. The difference in theoretical performance and that achieved with such controllers indicates the scope for controller design. This could become the subject of an extensive further study, and of course must take into account the full implications of
engineering limitations.

The transition into a speed restriction has been examined using simple first order vehicle models, which exactly obey the following laws. The models used are described in Appendix K, and have been implemented both in analogue and digital form on machines at Loughborough University. The choice of driving function for assessment of these models is important, as assessment with unrealistic inputs will result in misleading results.

As stated earlier, the dynamic safety requirement recognised in Autowagon studies has received little attention. The general approach (Ref. 19) has been to space vehicles so that during the velocity transition they do not interact in a potentially dangerous manner. However, as is shown in the later part of this report, this may be very wasteful of line capacity and a development of the Autowagon proposal for vehicle following is considered to give a much greater potential line capacity with no degradation of the safety requirement.

In consideration of design of vehicle controllers, due to the possible sizes of power units, it is appropriate to use multi-point or continuous controller characteristics rather than bang-bang or bang-coast-bang characteristics. Any controller will have saturation levels determined by available traction power and brake force, and when accelerating at very low speeds adhesion limits must be considered. Furthermore, if a prime mover is involved
there may be limitations as to how the control demand may be varied in order to provide reasonably efficient running. Initially, for the purpose of the study, time constants of the power and brake systems and jerk limitations will be ignored. This is equivalent to assuming an ideal power unit and including all the imperfections in the controller law. Detailed design for a specific system may then modify the controller to match the available hardware and so produce the specified characteristic. In the later part of the report, consideration is given to the design of an automatic driving system for a railway train operating on British Rail.

3.3 Derivation of the Vehicle Following Laws.

The laws to be considered here are defined by the safety requirement that in the event of the leader abruptly coming to a halt the potential for a crash shall not occur. Some workers have dismissed such safe headways out of hand on the grounds that they are unnecessarily restrictive of system capacity. However, operation at further reduced headways introduces operational difficulties if dangerous failure situations are to be avoided, as described by Hinman (Ref. 39). This together with the contention that by careful design useful capacities can be obtained safely, is the justification for detailed consideration of safe following laws.

The safety requirement dictates that the vehicle separation must at all times exceed stopping distance of the vehicle.
The stopping distance is determined principally by the retarding force available and the speed, but application time of the brakes and jerk limitations imposed for passenger comfort or load stability extend this distance. It is not sufficient to substitute a lower constant deceleration rate to take account of these factors in modelling dynamic situations.

In the preliminary study (Ref. 46) a number of safe following laws were identified; these are listed in the Appendix D with the derivation. The two potentially most useful laws are the pure moving block (PMB) and moving time block (MTB) laws, corresponding to instantaneous braking distance separation (headway proportional to speed) and constant headway (equal to that required at line speed), respectively. The steady state characteristics had been appreciated for some time now (Ref. 46) and are summarised in Appendix E.

3.4 Mandatory Speed Restriction.

Consider a plain line over which for part of its length a reduction in speed must be enforced. Initially, it is convenient to ignore the effects of jerk. The speed transition must occur in the higher speed region and thus has a corresponding journey time penalty. It is therefore generally assumed that the leading vehicle in a stream should reduce its speed using the maximum service braking rate. The velocity distance profile in this case is a segment of a parabola. If, as is necessary for a steady state to exist, the vehicles follow similar velocity distance profiles, Pearson (Ref. 9) has shown that under PMB control a critical instant occurs when if the separation is sufficient at that instant then it will
**Figure 3.4.1** Safety Margin during Maximum Effort Speed Change.

(distances are appropriate for Autowagon parameters)
**Figure 3.4.2 Potential Capacity of a Speed Restriction**
Fig. 3.4.3
be necessarily sufficient at all other times. If the initial speed is the line speed this is equally true for MTB. The critical instant occurs when the second train is about to brake for the restriction.

It is convenient to define the safety margin during the transient as the positive excess of vehicle separation over the braking distance of the following vehicle. With this definition it is possible to plot the safety margin as a continuous function through the speed transition. Fig. 3.4.1 illustrates the profile for a maximum service braking rate approach and the critical instant recognised by Pearson and others is clearly seen. It is thus seen that whereas an adequate safety margin may exist before and after the transition, an unsafe period may occur during braking.

Considering only the following laws with no allowance for quantisation or safety margins, Fig. 3.4.2 shows the line capacity as a function of the fractional value of the speed restriction. Comparison of this with Fig. 3.4.3 illustrating a plain line capacity as a function of fractional speed, shows how although considerably higher capacity is available at the lower speed, the safety requirements of the transition dictate a larger headway than that required at line speed. Advantage in terms of capacity is achieved with a lower speed of approach, in the limit running vehicles at the lower speed for the length of the line. This has obvious journey time disadvantages.
required headway

SPEED TRANSITIONS

MINIMUM JOURNEY TIME

moving time block

pure moving block

restricted speed

Figure 3.4.4 Headway required for a speed transition.
It is more convenient to represent the headway rather than the capacity on a diagram showing the effect of a speed restriction. On such a plot, Fig. 3.4.4, the normal pure moving block capacity curve for zero length vehicles becomes a straight line passing through the origin, and the corresponding moving time block capacity curve is a horizontal line intersecting the pure moving block characteristic at line speed. Analysis in Appendix G shows that the capacity limitation of the transition for a speed restriction results in a headway requirement for the maximum service braking case given by the third line in the diagram of Fig. 3.4.4. For severe speed restrictions, realisable headways are shown to be much greater than those of the steady state pure moving block curves. Inclusion of the vehicle length in the analysis distorts the lines to curves but the principle remains.

The reasons for the capacity shortcomings of the above method of control are the abrupt changes in the velocity profiles of the vehicles resulting in the critical instant referred to. At other times the continuous signalling system is redundant apart from its secondary benefit of increasing stability in the event of a further disturbance.

It is appropriate to consider the approach of a string of vehicles to a speed restriction when they are running at minimum headway at the higher speed, under the influence of the vehicle following laws. This leads to an alternative form of approach to the speed transition
Figure 3.5.1 Velocity Profiles PMB
3.5 Speed Restriction Entry Under Pure Moving Block Control.

The leading vehicle will follow the velocity profile described above. The first follower will, as soon as the leader commences deceleration, also brake but at a lesser and increasing rate. With the assumption of infinite resolution and no delays, subsequent vehicles will thus commence braking simultaneously. The braking rates along the stream will be progressively smaller. The velocity profiles for the first two vehicles of a string are illustrated in Fig. 3.5.1. When the leading vehicle enters the restriction, the first and all the subsequent followers will start to release their brakes in order to asymptotically approach the lower speed of the leader with the corresponding ideal separation. However, this implies travelling at all times at a higher speed than the leader and thus violating the speed restriction. It is then necessary at some point in time for the following vehicles to cease to obey the following law and brake for the speed restriction. It must be remembered that this is not a steady state and unconstrained by the restriction the following vehicles would enter the restriction at progressively higher speeds due to the natural damping characteristic of the following law.

To illustrate the severity of this problem, Fig. 3.5.2 shows the speed of entry of the first follower to a speed restriction plotted against the fractional value of that speed restriction. Since the speed of
Figure 3.5.2 Overspeed on entry to a restriction - PMB.
**Figure 3.5.3** Irregular separation of vehicles after entering speed restriction - PMB.

*NB. Lines joining points have no significance.*
subsequent vehicles will be higher it is clear that vehicles must be constrained to follow the restrictions.

If the vehicles are allowed to approach the speed restriction as above, but at the appropriate time made to apply their brakes at the maximum service rate to enter the restriction, all the vehicles will be in the restriction at the appropriate speed but with separations considerably greater than the following law requires. The string is effectively broken up and due to the different profiles followed by successive vehicles the headways in the restriction are irregular with a mean equal to the approach headway. This is demonstrated by example in Fig. 3.5.3.

3.6 Speed Restriction Entry Under Moving Time Block Control.

The separation of the vehicles under MTB is defined by:

\[ S = \frac{V_m \times V}{2B} \]

This linear relationship of the gap to the speed results in a slight difference from the PMB approach to a speed restriction. The brakes of the following vehicles are applied at a faster rate than in the PMB case but again they do not exceed the rate of the leader. Typical velocity profiles for a string of vehicles entering a speed restriction are given in Fig. 3.6.1 where the followers are not constrained to obey the restriction. There is a similar overspeed problem to that for PMB but it is not as severe. If the vehicles are constrained to follow the restricted speed in the MTB
FIGURE 3.6.1 VELOCITY PROFILES MTB
FIGURE 3.6.2 MTB FIRST FOLLOWER
Figure 3.6.3 Moving Time Block
Separations after speed restriction entry.
case, Fig. 3.6.2 shows how the separation achieved by the first follower varies as a function of the restricted speed. Fig. 3.6.3 shows how a string of vehicles is affected and it should be compared with Fig. 3.5.3. In this case as the number of vehicles is increased so the headway tends asymptotically to the desirable headway for the speed of the restriction.

3.7 Observations.

The most significant feature to note from a comparison of the previous two sections is that stable headways achieved in the restriction under PMB and MTB are not very different. If the speed restriction is to be obeyed, Figs. 3.5.3 and 3.6.3 show that if the leading vehicle obeys a minimum journey time speed profile then it is not possible to operate even to an approximation of PMB headway within the speed restriction. The headways of MTB for the first follower are greater than those of PMB but are considerably closer to the desired headways for that law. This apparent disadvantage of PMB might be counteracted to some extent by the increased tolerance to perturbation which it gives.

For a long string of vehicles under MTB, the difference in the velocity distance profiles of the NTH and the (N + 1) vehicle is small and the resultant headway between these vehicles in the restriction is close to the ideal. This suggests that there might be advantage in operating vehicles to a velocity profile similar to that of the 10th vehicle, say. The journey time costs and the advantage achieved is considered in the next Section.
FIGURE 3.8.1  EQUIVALENT EXTENSION OF SR
10TH VEHICLE PROFILE
EQUIVALENT EXTENSION OF SPEED RESTRICTION

FIGURE 3.8.2 JERK BRAKING
3.8 Velocity Profile Control.

It has been shown that there is a compromise between journey speed and line capacity if the safety constraint is to be applied in the speed transition on entry to a speed restriction. This observation forms the basis of a proposed method of control, whereby the shape of the velocity distance profile is adjusted in order to minimise headway for a given journey time sacrifice.

In Section 3.6, Figure 3.6.3 shows that the velocity profile of the 10th vehicle can give a significant improvement in steady state headway within the restriction. The journey time loss due to the shaping process may be expressed as an equivalent extension of the speed restriction by multiplying the time by the value of the restriction. Observation of the shape of the velocity profile suggests that it may be approximated by a jerk limited profile (see Appendix H). Figures 3.8.1 and 3.8.2 compare the journey costs of profiles based on the 10th vehicle profile and jerk regulation. It is unfortunate that the curves are quite different in character indicating that a different jerk limit is appropriate for each speed restriction value. The capacity advantage of a profile derived from that 10th vehicle is a function of the speed restriction value.

An alternative simple strategy for shaping the profile of vehicles entering a speed restriction is for the vehicles to be constrained to use a braking rate which is constant for all vehicles and less than the maximum or emergency rate used in determination of the safe
JOURNEY TIME
COST % headway

VELOCITY PROFILING
TRADE-OFFS

$V_s = V_m / 2$

Figure 3.8.3
Figure 3.8.4 Flattening of safety margin curve with jerk limitation.
following law. For a typical speed restriction, from maximum to half maximum speed, Fig. 3.8.3 compares the trade off of jerk limited and brake limited velocity profile shaping. It is apparent that the brake limited approach has an advantage over the jerk limited case and it is probable that an optimum profile could be derived having yet greater advantage. However, such a profile would be unlikely to have the simple mathematical form of the two proposals. Appendix H contains the analysis of the jerk limited and brake limited velocity profiles.

It is apparent from the above discussion that scope exists for considerable improvement in the capacity of a speed transition from the minimum time approach if velocity profile shaping techniques are employed. With shaped velocity profiles, the curves depicting the safety margin during the transition are much flatter, see Fig. 3.8.4. The implication of this is that for full advantage to be taken of the available capacity benefits a continuous signalling system must be used in order to provide continuous protection during the protracted hump of the safety margin curve. The capacity benefits could only be realised under a fixed block signalling system if sufficiently precise control of the profiles of the individual vehicles could be maintained and if the signals were accurately sited.

3.9 Exit From a Speed Restriction.

The study of speed restrictions has concentrated on the problems of speed restriction entry as previous studies
showed that these might well be the limiting factor in determining capacity of a line. The previous Sections have shown however that this is not necessarily the case and it is possible in a finite string of vehicles for headways less than line speed headway to occur in a speed restriction, even if the vehicles have not started from rest in the restriction. In the case of moving time block, since the desirable headway at all speeds is independent of speed it follows that if the headway is sufficient within the speed restriction then it will be sufficient through the exit transition and when line speed is regained.

With pure moving block this is not the case since the desired headway is linearly dependent upon the speed. It has been shown that for a steady state to exist, the velocity profiles of all the vehicles must be the same and thus the headway within a speed restriction cannot be less than that at line speed. In this case the situation is the same as for moving time block and exit of all vehicles from the speed restriction with maximum acceleration is permitted. In the case of an unscheduled disturbance it is possible for the vehicle profiles to differ and the following vehicles may be able to achieve smaller headways. These will of course be compensated for by correspondingly longer headways for some vehicles in a long string. Dependent upon the disturbances which occur within the restriction it is possible for the vehicles to have any headway down to the minimum permitted pure moving block headway.

For maintenance of safety in the exit transition it is
necessary for those followers which have reduced headways to restrict their performance so as to lose an amount of time equivalent to the difference between the actual headway in the speed restriction and the desirable line speed headway. Thus any gain of PMB over MTB on entry to a speed restriction is counteracted by a loss on exit. It is important to remember that average headways in the speed restriction cannot be less than the line speed headway in any case and the above comments apply only to the unscheduled disturbance of a finite string.

3.10 Station or Depot Stopping.

Stations or load transfer Depots need not be off the main running lines, unless it is a serious capacity limitation for them to be otherwise. For this reason stopping of vehicles on the main running lines may be required and the interactions of vehicles must be examined. One of the essential features of the automated vehicle systems, is rapid loading and unloading. Stop times of less than \( \frac{1}{2} \) minute appear quite reasonable and times down to 10 seconds may be practicable with suitable passenger controls. The stop time is of similar magnitude to the plain line headway for the safety criterion outlined in the previous Sections. If all the vehicles attempt to approach the station following a minimum journey time profile, it has been recognised that this is restrictive of capacity. Lagerhausen (Ref. 42) has shown this and he also demonstrates how continuous signalling can minimise the propagation of small delays. As with the
FIGURE 3.10.1 CAPACITY OF A SINGLE PLATFORM
speed restriction approach, described by Pearson (Ref. 9), in the case of a station stop the preceding train must clear the stopping berth before the following train may pass a critical point. Slow (Ref. 49), appreciating this, has proposed a two stage approach with a speed restriction in the station area. For Mini-trams this is convenient since the station geometry may well include sharp curves at the approach. There is naturally the journey time penalty associated with the gain in capacity which Slow demonstrates. Unfortunately if the approach is developed for multi-platform stations the speed restriction due to line curvature becomes the dominant capacity limitation and Slow does not recognise this. His results are however valid if station stopping times are large.

It is difficult to generalise the study of the station stop, but it is necessary to obtain some understanding of how operating procedures in the station area may affect capacity. Initially, a single platform on a uni-directional single line will be assumed. For purposes of comparison the capacity of such a platform with a single berth has been evaluated for the minimum journey time approach and the characteristics of a typical Mini-tram. Fig. 3.10.1 illustrates the capacity as a function of stopping time. The headway through a station is composed of two basic components, the station stop time and the replacement time. This is the terminology used by Slow.

The stop time is derived from external parameters,
FIGURE 3.10.2 STATION APPROACH
principally the characteristics of the passengers and the size of the vehicles. The replacement time, that is the time from the instant of departure of one vehicle to the arrival of the next, is dependent upon the approach velocity profile. PRT systems generally seem to favour detection of clearance of a preceding vehicle rather than vehicle following into the stop position. The main reason for this of course is that the technology of track circuit block working is well developed and proven in service (Ref. 17). If the constraint of track circuit block working is applied, the velocity profile of the following vehicle must permit stopping of that vehicle in rear of the platform berth, until clearance of the berth has been proved. If minimum journey time is also to be achieved this means that the front of the following vehicle must be at full line speed braking distance from the stop point when the first vehicle clears. The replacement time itself consists of two parts:

\[ T_r = T_c + T_b \]

The times for clearance of the leader and braking of the follower are represented by \( T_c \) and \( T_b \) respectively. Since stop time is comparable to the line speed minimum headway, the minimum headway through the station might be expected to be at least twice the minimum main-line steady state headway. Using the procedure advocated by Slow the replacement time may be significantly reduced since the following vehicle will be approaching at a lesser speed with a correspondingly smaller braking distance. Fig. 3.10.2 shows how the replacement time
may be reduced as a function of speed in the station area. It is assumed that station stops are long enough to permit such headways as may result. The difference between these curves and those of Slow are due to the change of parameter values for consistency in this report. From the results given in Appendix C, the station approach curves may dictate speeds as low as 2 m/sec and thus considerable headway reductions are possible.

If the curvature requirement is not as severe as the curved side of the Mini-tram D loop then the advantages are not as great and the artificial introduction of a more severe speed restriction in the station area causes an undesirable journey time penalty. A solution in this case is to extend the velocity profile design for speed restrictions to cope with the station stop. It is necessary for the following vehicle to be able to stop in rear of the platform berth in the event of the leading vehicle failing to clear. Thus it is permissible for the follower to be braking distance from this point at the instant the leader should depart. Should the leader fail to clear, safe stopping distance of the following vehicle is assured, as in normal circumstances the leader will clear and the follower by a slight modification of its brake application will be able to stop at the platform berth. The headway using this approach will always exceed the sum of the stopping time and the line speed minimum headway.

Higher capacities can in some circumstances be achieved
FIGURE 3.10.3 MULTIPLATFORM STATIONS
by the use of multi-platform stations. As indicated earlier the advantage of multiple platforms increases as the stopping time increases. This is because large stopping times increase the average headway and permit advantage to be taken of the small individual platform replacement times without a line speed approach capacity limitation. If there is any speed transition on the main guideway before divergence for the platforms, then the capacity will be less than the steady state capacity of the guideway at line speed. This sets an upper limit to the capacity of any station design on a single guideway. The actual limit will be determined by the speed of turnout and any clearance allowance. Fig. 3.10.3 shows for typical Mini-tram divergence constraints how the advantage in capacity for multiple platforms is achieved with larger station stopping times. Consideration of this might result in sophisticated controls to ensure rapid loading and unloading bringing considerable environmental and operational if not economic benefits, by the use of fewer platforms.

3.11 Diverging Junction.

Generally any speed restriction at a diverging junction will be determined by the curvature of the two routes. This means that different speed restrictions may apply to the two routes. Many PRT systems favour the use of vehicle borne switching equipment to avoid adding switching and proving times to the headway. However, there is advantage in track based switching and it is not clear which system will emerge. It is reasonable to assume that the switching will not contribute
significantly to the headway.

A string of vehicles may thus approach a diverging junction at close headway and some members of the string will be required to observe a speed restriction over the junction. Other than in normal route selection, this situation would also occur at the entrance to a Mini-tram D loop station when operating its flexible mode with express and stopping trains. Since it is undesirable for the following fast vehicle to be delayed by the stopping vehicles or diverging slow vehicles, a mode of control other than that derived for the mandatory speed restriction is required.

If the vehicles approach at line speed minimum headway, then of course some perturbation of the velocity profile of the follower is inevitable. It was shown in Sections 3.5 and 3.6, that the two continuous following laws described, when unconstrained, exhibit a damped response to a velocity variation of the leader. This is of course desirable here, and there is no steady state constraint of entry to a restriction for all vehicles. PMB was shown to give considerably more damping for the conditions examined. Thus a mode of control through the divergent junction might be operation of the slow vehicles to a velocity profile control designed to satisfy the speed constraint of the junction and cause minimum perturbation to following fast vehicles, which would follow under PMB control. If the slow vehicle velocity profile is designed as the approach to a mandatory speed restriction, no problems of mixes
of traffic will be encountered, but if this is undesirable consideration must be given to the need for sequencing of the traffic.

Clearly no firm conclusions can be drawn on this point without rigidly defining the system and modelling the specific circumstances with a realistic random traffic sequence. As in other dynamic situations there is a trade off between the capacity and journey time.

3.12 Merging Junction.

Similar considerations apply to the merging junction speed restriction as to the diverging junction. This means that streams of vehicles on the merging tracks may be travelling at different speeds as the flows coalesce. A simple system has been proposed for low speed PRT systems, whereby gaps are generated in the flow on the main line and the speed of merging traffic is adjusted on approach to the junction. This is ideal if speed constraints over the junction are not restrictive and some form of centralised slot control is in operation. However, if the speeds prior to the merge must be significantly different, then the step response of the vehicle becomes important. There may also be difficulties of synchronisation which will be clarified by system modelling.
4. BASIC VEHICLE CONTROLLERS.

4.1 Simple Vehicle Models.

Railway traction vehicles are complex non-linear systems and it is not possible to develop a representative general model. However, before going into the detail of design of a control system for a specific vehicle it is appropriate to consider the response of grossly simplified models to the basic control principles. The theory in the preceding chapter has assumed ideal vehicles capable of following the control laws precisely. From a performance point of view this is not unreasonable since appropriate constraints were brought in from the outset. However, power demand and hence the installed power requirements for such vehicles might well be excessive and the required precision of the measurement techniques might be unrealisable.

Any practical power or braking system will have time constants associated with its actuation, but more importantly the total mass of the vehicle and the available force determines the time constant of the vehicle response to any perturbation. Perturbations in normal running of strings of vehicles can be minimised by the appropriate choice of following law, but the perturbations arising in a failure situation or at a merging junction cannot be so treated. The consequent discontinuity in the velocity or deceleration profile with a vehicle of finite non-zero mass precludes operation to the following law. A vehicle control system is therefore required which will ensure safety and rapid recovery to following law control. It is important to
note that previous published work on the subject has separated out the design of the vehicle control from the following law control.  

The mass of the vehicle will be determined by the vehicle structure, the payload and the installed power. Braking and traction performance depend upon the mass, the installed power/force and the method of actuation. For PRT systems electric propulsion is favoured on environmental grounds with vehicles probably picking up current from the trackside. Automatic wagons would be more likely to carry their own power generation equipment and have electric final drive, to take advantage of the control potential and the available technology. In some circumstances battery traction might be considered but operational and technological factors limit its potential. The prime movers for Autowagon vehicles would be either diesel or gas turbine engines with the size dictated by the maximum power requirement. If regenerative braking is to be employed then the size of the traction motors will be determined by the braking requirement. This has the important effect that cruising at maximum speed may not be at the power limit so that controlled acceleration at all running speeds may be possible.

It is therefore reasonable to consider initially a vehicle model capable of uniform acceleration and retardation throughout the speed range. Such a linear model requires an increase in power proportional to any increase in speed when accelerating and increased power is also required to overcome velocity dependent
resistance. The simple model to be used initially will thus assume that sufficient power/brake force is available and controllable such that at all speeds the maximum acceleration or braking rate of the vehicle may be achieved.

4.2 Incorporation of the "Following Laws" in the Feedback Controller.

A considerable amount of work has been published on the design of controllers for strings of vehicles, using both classical and modern control theory (Refs. 56, 57 and 58). Most of this work has been directed at strings of vehicles operating at or near a cruise velocity on the main line, and the equations used, because they have been linearised, are only valid for small deviations about the cruise velocity. A typical equation is:

\[ M \ddot{x} = F - Mgsin \theta - F_w (\dot{x}, V) - F_m (\dot{x}) \]

where: \( F \) is the propulsive force, \( F_w \) is the wind drag force, \( F_m \) is the mechanical drag force and \( \theta \) is the slope of the guideway.

By linearisation about the nominal cruise velocity this is reduced to:

\[ \ddot{x} = -av + f - F_D \]

where: \( a \) and \( F_D \) are constants and \( v \) is the velocity error. The equations are taken from reference 58, but are reasonably representative. The corresponding
FIGURE 4.2.2
system block diagram is shown in Fig. 4.2.1.

Many control proposals for PRT and other guided transport systems acknowledge the need for a separate (and usually unspecified) safety control (Ref. 59 and 60). Because the design headways are close to, indeed within the safety definition of this report sometimes less than, the minimum safe headway, it follows that the normal mode of operation might be continuous operation of the safety control. As the information requirement for safety control may exceed that required for normal running, it follows that one control system capable of doing both jobs might be devised. Such a scheme is illustrated in block diagram form in Fig. 4.2.2.

Using the form of Fig. 4.2.2, a simple proportional controller with moving time block vehicle control may be represented by the following equation:

\[
\frac{\ddot{x}_2}{K_2} + K_1 \dot{x}_2 + x_2 = x_1.
\]

This equation clearly neglects power saturation and adhesion limits but it is useful to consider its response. The characteristic equation of the system is a simple second order differential equation. Examination of the coefficients shows the damping factor, \(\zeta\) to be:

\[
\zeta = \frac{K_1 \sqrt{K_2}}{2}
\]

For typical Autowagon parameters the damping ratio has the value unity and the system is thus critically damped. Clearly, increasing either \(K_1\) or \(K_2\), the
nominal headway and proportional gain respectively, increases the amount of damping. Position overshoot is obviously not permissible on safety grounds, so it is not possible for this linear system to be given a more rapid response.

In practice, tractive effort and brake force are limited; in the saturation regions the effective value of $K_2$ is altered giving an error dependent damping ratio, which is always less than the value pertaining in the proportional band. This means that for small perturbations the system is highly damped, whereas a rapid response is exhibited for large perturbations.

Other non-linearities will be introduced if tractive power rather than force is controlled, and if a representation of the aerodynamic drag is included. Inclusion of these features gives the distinctly non-linear equations:

\[
\frac{(M\ddot{x}_2 + K_4\dot{x}_2^2 + K_5M)\dot{x}_2 + K_6\dot{x}_2 + x_2 = x_1}{K_3}
\]

for acceleration when \((x_1 - x_2 - K_6\dot{x}_2) > 0\)

and

\[
\frac{(M\ddot{x}_2 + K_4\dot{x}_2^2 + K_5M) + K_6\dot{x}_2 + x_2 = x_1}{K_2M}
\]

for braking when \((x_1 - x_2 - K_6\dot{x}_2) < 0\)

These equations are for the moving time block following law defined in Appendix D; the pure moving block law also defined in Appendix D is inherently non-linear and precludes analytical treatment even in the simple
unconstrained case of the proportional controller;

\[
\frac{(M \ddot{x}_a + K_a \dot{x}_a + K_m M) \ddot{x}_a + K_b \dot{x}_a^2 + x_a}{K_s} = x_a \quad \text{(accel)}
\]

\[
\frac{(M \ddot{x}_b + K_b \dot{x}_b + K_m M) + K_b \dot{x}_b^2 + x_b}{K_b M} = x_1 \quad \text{(brake)}
\]

Other non-linearities may be included in the pure moving block control system equation as in the moving time block equation.

4.3 Response of Simple Theoretical Model to Normal Driving Functions.

The response of the system equations developed in the previous Section to normal driving functions can conveniently be investigated by computer simulation. Numerical techniques enable investigation of the non-linear variants as well as the linear forms. In the early stage of this study, simulation models were constructed in analogue and digital form on the Membrain MBD24 and the ICL1905 computers, respectively. The models are described in Appendix K. A control system is frequently characterised by its response to a step or impulse, as these driving functions have convenient mathematical form and facilitate system identification. However, such input functions do not give clear insight into the likely behaviour of a system of vehicles subject to normal driving functions. Accordingly, in the simulation work it was considered appropriate to model a system of vehicles rather than a single vehicle and to represent the system performance in a phase plane diagram. A typical simulation result is illustrated in Fig. 4.3 This figure shows the
AUTOWAGON
SYSTEM RESPONSE
WITH SIMPLE
PROPORTIONAL
CONTROL

Figure 4.3
situation which might occur, perhaps in a merging situation, where the two vehicles are initially running at the correct speed but with an inappropriate separation. The simulated vehicles are automatic wagons and the proportional power and brake force bands have been chosen to be 100 m. The full structure of the model is described in Appendix K. The significant conclusion is that with what appeared to be reasonable assumptions of vehicle characteristics, it is possible to produce a vehicle control system which can give acceptable transient response. Furthermore, the proportional bands have been chosen to be a fairly large proportion of the line speed headway and it is thus likely that such a scheme could be realised without an impossible instrumentation requirement.

Clearly the introduction of the proportional bands means that the basic headway must be increased from the minimum safe value. Autowagon work undertaken by the author and reported in Ref. 16 has shown that this increase in headway is small compared to the safe headway.

4.4 Limitations of the Modelling Technique.

The modelling techniques described in the previous paragraphs give useful insight into the likely system performance, but the results obtained are only as good as the input data used to specify the models. Unfortunately, neither Autowagon nor Mini-tram vehicles exist and it is therefore not possible to check the
validity of the models. It is however reasonable to consider how velocity profile following techniques might be applied to conventional railway vehicles. This potentially provides information on engineering problems and the likelihood of realisation of the more complicated proposals.
5. RAILWAY VEHICLE CHARACTERISTICS.

The purpose of this section of the report is to give the reader some appreciation of the basic characteristics of the wide variety of traction and braking equipment in use on British Railways. Railway vehicle traction and braking systems have developed over a large number of years and as the equipment is generally designed for a life in the region of 20 to 30 years it is not surprising that a large number of variations exist. Overriding constraints in the design of railway vehicles have been reliability, safety and durability. The following sub-sections describe traction systems, braking systems and the control interfaces provided.

5.1 Traction Systems.

Many forms of prime mover have been employed for railway traction, and these have been combined with an even greater number of transmission systems. For many years steam traction satisfied the requirements of the operational railway, but, during the last 25 years we have seen the development and adoption of diesel powered locomotives. Also within this period there have been considerable advances in main line railway electrification. There are now two main types of locomotive operational in Britain; diesel-electric locomotives in which an electrical transmission system is powered by a generator driven by a diesel engine, and electric locomotives in which a similar transmission system is supplied with power from the
lineside. Alternative forms of mechanical and hydraulic transmission have been employed with diesel locomotives, but experience obtained has caused the British Railways Board to standardise on electric transmission. There are however still in service many diesel mechanical multiple units.

The fundamental feature of most electric traction systems is the series wound d.c. machine, or traction motor. For many years the design of such motors has changed little and it is a tribute to the early designers that their principles have remained unchallenged. The basic characteristic of the series wound d.c. machine is well suited to traction applications. Such motors provide high starting tractive effort and are easily controlled by variation of their applied voltage. It is normal practice to regulate the current through the motors at low speeds in order to obtain highest possible starting tractive effort until a speed is reached where either in the case of a diesel the horsepower limit is reached or in the case of an electric train the maximum voltage is reached.

The methods used to control the traction motors in different types of locomotive vary a great deal and clearly the time constants of a pneumatically controlled diesel electric will differ greatly from those of an electric locomotive or multiple unit with electronic control. In the case of electric trains the supply
may vary from less than 1000 V d.c. in the Southern Region to 25 000 V a.c. single phase for main line electrified areas. The current may be picked up through a third rail, or fourth rail for the lower voltages where currents are very high (perhaps 3000 A for a train) and overhead lines are used for higher voltages (1500 V d.c. and above). The choice of supply includes many factors other than historical accident, but it is inappropriate to discuss them here, see Ref. 64.

For d.c. traction systems the supply voltage is usually equal to the maximum motor voltage (in some cases motors may be permanently connected in series). On starting it is necessary to restrict the current through the traction motor in order to keep the tractive effort developed within the adhesion limit and also the prevent motor damage due to excessive current. In conventional d.c. locomotives this is normally achieved by inclusion of resistance in the circuit. Thyristor chopper circuits appear to offer great potential savings of energy and maintenance but they are not yet widely accepted and concern is expressed regarding the generation of interference to signalling circuits.

Starting resistors are normally switched by means of a camshaft switch driven by a motor. The supply to the camshaft motor is controlled by a measure of the instantaneous traction current. In its simplest form this
may be a current sensitive relay controlling the camshaft motor. In more sophisticated control systems, such as the Siemens Siematic system (Ref. 48), a continuous measure of the traction current is used to influence the progression of the camshaft motor.

In order to improve efficiency where several motors are controlled, it is usual that the same camshaft switch is used to configure the motors in a series or parallel mode according to the speed. Problems of power sharing and particularly wheelspin detection are separately treated, see Ref. 54. If the speed range of a tractive unit is wide it may be necessary to incorporate several stages of field weakening in order to extend the speed range over which useful tractive effort can be developed. Field weakening in d.c. traction systems is usually accomplished by the main camshaft using the starting resistors as field current divert resistors. Since only a part of the total motor current flows through the field, the magnetic flux and hence the back e.m.f. is reduced and the armature current and hence the tractive effort is maintained.

A conventional a.c. electric tractive unit employs a transformer and rectifiers to provide a d.c. supply to the traction motors. Variation in the motor voltage for starting control is provided by camshaft driven voltage tap changers on the secondary of the main transformer. Clearly this method of control does not suffer the inefficiencies the resistance control. Field weakening, if provided, is achieved by the use
divert resistors. Thyristor control of a.c. traction is further developed than d.c. traction, as it is inherently easier and prototypes have been in service for some time. Certain overseas railways have progressed to series production of thyristor locomotives and multiple units.

The use of electronic control and thyristors in locomotives opens up new possibilities both for traction motors and control systems. Induction motors offer certain advantages in terms of reduced maintenance compared to commutator motors, but they have been precluded in the past because a variable frequency power supply was required. Such power supplies are now practicable and experimental work is well advanced. With d.c. traction, the use of separately excited motors with electronic control systems makes it possible to more effectively control the motor characteristic and to provide individual motor control and protection.

In a diesel locomotive a large diesel engine is used to drive a generator whose output is connected to the traction motors. In the past d.c. generators have been used extensively, but modern locomotives usually employ an alternator and rectifier. Power control is effected by control of the speed of the diesel engine and the excitation of the generator. A control system is provided such that the driver can demand a particular power output and the control system will attempt to match the load to the diesel engine output. Conventional locomotives employ a pneumatically controlled governor,
Figure 5.1.1 Diesel Electric Locomotive Control System.
and an electro mechanical system for control of the excitation of the generator. The principal element of this latter system, is the load regulator. A simplified diagram of the function of a diesel engine control system is given in Fig. 5.1.1. It will be seen that there are two main control loops. The first loop is that of the governor controlling the fuel rack in order to control the diesel engine speed. The high inertia of the diesel engine means the time constants of this loop are long compared to the second loop, that of the load regulator electrically controlling the excitation of the generator. Clearly the transient behaviour of such a system is complex. The basic principles of control were described early this century (Ref. 55) and methods of control have not changed very much, the main change having been in the implementation rather than principles.

5.2 Braking Systems.

As with traction systems, braking systems too have a long history of development and from early times the importance of safety has been appreciated. Following some unfortunate disasters with simple braking systems in the last century (Ref. 61) the need for a continuous failsafe braking system on passenger trains was established. Freight trains particularly where they run on non-passenger lines are not so restricted and even now trains run with brakes on the locomotive and the brakevan only.

Direct mechanical actuation of brakes is only feasible within a vehicle and from the early days of railways train brakes have been operated by air pressure, either
from a supply of compressed air on the locomotive or from atmospheric pressure on vacuum brake systems. For many years British Railways standardised on vacuum braking considering that this offered greater safety. This decision was reversed in the 1960's when the two pipe air brake was adopted as the standard for new main line stock construction. The two pipe system had numerous advantages compared to the various single pipe systems which preceded it, but the most important were the consistent brake pressure achieved throughout the train and the more rapid response times.

The complete history of brake development particularly that of triple valves and distributors is complex and further information may be found in Ref. 61. High performance electric suburban trains require a fast acting brake and since the propagation of air signals down a train could not provide a fast enough response, non-failsafe overlay braking systems were introduced and became popular from the 1930's. These systems employ electrical signals down the train to actuate air cylinders and are known as electro-pneumatic or EP brakes. The chief drawback of these brakes is the variability of brake force throughout the train where there is no regulation of pressure and reliance is placed upon the matching of performance of individual control units.

Braking systems introduced in the later part of this decade overcome this problem, with some increase in complexity, by the use of binary control of brake cylinder
pressure. The signals down the train are electrical and commonly use 3 wires for a binary representation of the required pressure. The actuators on the vehicles may be electro-mechanical as in the case of the Westcode system (Ref. 62) or they may incorporate electronics and local EP control as in the Davies & Metcalfe system (Ref. 63). The electronic method makes possible simpler drivers controllers and a reduced number of train lines if pulse width modulation rather than binary control is used.

The method of applying the brake force to the train is important from a control point of view as the various systems have very different characteristics. The earliest railway brakes relied on mechanical friction between wooden blocks and the wheel treads and were usually directly operated mechanically. For many years now the most popular material for friction braking on wheel treads has been cast iron. Cast iron is very consistent in performance compared to other materials, but its characteristics are highly non-linear and the force developed by a brake depends heavily on the work done by the block. A lot of work has been done to try to describe the behaviour of conventional cast iron brakes and even now it is not possible to get good correlation between observations on laboratory brake test rigs and the performance of train braking systems. Ref. 67 describes the results of extensive tests carried out by British Rail Engineers from Swindon and they have produced empirical formulae for the behaviour of brakes. A significant disadvantage of cast iron brakes is the
rapid block wear and for many years metallurgists have experimented with various alloys to try to improve wear rates without introducing undesirable effects such as block cracking. An alternative has been the use of composition materials developed by companies such as Ferodo and Trist Draper. Both these companies have developed treadbrake systems which are used extensively on London Transport, but they have not found popularity on British Rail. The main reason for this is that although the wear rates of the blocks are considerably less than the rates for cast iron on the same duty, the brakes exhibit considerable variability of performance particularly in wet weather. This leads to generally worse braking than cast iron and under some circumstances tyre damage which reduces the advantage of reduced block wear.

As has been the case in the motor industry, with increasing speeds of running, dissipation of power in the blocks has led to poor high speed braking and led to the development of disc brakes. Disc brakes invariably use composition pads and because the disc is not in contact with the wet rail, as is the tread of the wheel, the variability of composition treadbrakes is not found with discs. However, there are problems with the use of inboard brakes due to the build up of deposits on the wheel treads which lead to lower wheel rail friction. With treadbrakes, particularly cast iron, these deposits are scrubbed away by the rubbing of the block on the abrasive dust which it produces. On some trains equipped with composition treadbrakes London Transport find it necessary to fit
cast iron blocks on leading axles to assist this cleaning process.

Other forms of braking are used particularly on motored axles where electrical braking may be found. Due to the traction motor characteristics such braking can normally only be used at higher speeds. For the Advanced Passenger Train (APT) a novel form of braking in the hydro-kinetic brake has been developed, see Ref. 69 for this and other APT braking systems. In Germany and other countries where signalling distances are short for higher speed operation, track brakes are popular, although their use is limited to that of a safety brake as the resultant decelerations are not within the normal comfort limit. It is clear that braking systems have gone through many stages of development both for control and actuation and the present systems are not ideal. It is therefore to be expected that there will be continuing development in this field to provide braking systems with a fast response, consistent performance and adequate controllability to satisfy the operational requirements and minimise the maintenance.

5.3 Control Interfaces.

The control interfaces in traction units are almost as diverse as the traction and braking systems described in the previous Sections. Many traction units are designed for multiple operation and these units must be compatible with units of different design with which they work. Interfaces for multiple operation usually involve a combination of air and electrical signals
and there have been a large number of incompatible systems in use. There are also many units not capable of operating in multiple and these vehicles have their own internal control systems.

Generally brake controls are more compatible than traction controls and it may be possible for a unit to haul another unit dead. In some cases though, even when brake systems are functionally compatible it may not be possible to multiple the control if the arrangement of jumpers on the buffer beam is not appropriate. The problems of compatibility of control extends to rolling stock, particularly passenger stock where combinations of steam and electric heating, air conditioning, different lighting controls, public address as well as vacuum and air braking may limit what can properly run together and with what motive power.

For automatic control it must be assumed that trains of compatible stock can be made up and the problem is reduced to that of compatibility of the automatic equipment and the basic controls of the traction unit. It is not desirable for automatic control of a traction unit to preclude operation in multiple with the existing control interfaces, and this must be taken into account at the design stage of automatic systems to avoid operational difficulties. Generally, an automatic control system will drive a train in a different manner to the manual driver, because the driving commands are derived from different source data.
It is particularly important to consider the performance of a close control feedback system which might be required. The manual driver makes adjustments to his commands relatively infrequently on the basis of observed deviations from his target performance. The resolution of the driver's control is relatively coarse, but his facility for adapting to large changes in system performance is good and he soon learns to accommodate large time lags of the system. The resultant control is highly non-linear but stable. It is not easy to imitate such performance by an automatic system, but it is more convenient to apply simple linear feedback control to the variables which can be measured well. For such control to work efficiently a clear knowledge of the system dynamics is required, as without the driver's power of accommodation, it would be easy to induce instability.

If the unit is electrically controlled the interface to an automatic controller is considerably simplified compared to that required if the control is pneumatic. Modern main line trains (such as the High Speed Train) whilst employing pneumatic train pipe signals for brake control on individual vehicles, have electrical control inputs from the drivers controllers to electro pneumatic converters in each traction unit. Clearly, the interface to an automatic control unit in this case is simple, although the constraints of propagation down the train remain. Electro pneumatic controlled suburban stock braking systems also present a simple interface with the fast response characteristics of the electro pneumatic brake.
Traction control on some new stock presents an electrical interface, but more usually if a diesel engine is involved, a pneumatic signal is required. Electric multiple unit stock is normally electrically controlled, even though air operated contactors may be included in the system. The techniques of electro-pneumatic conversion developed for brake control, are conveniently extended to diesel engine control.

A new development in locomotive interfaces has been the production, for push-pull working, of a traction interface for a Class 47 diesel-electric locomotive, which is operated electrically from the remote end of the train using the train lighting control wires.
6. DESIGN OF A CONTROLLER FOR AN EXPERIMENTAL TRAIN.

6.1 Performance Specification.

The automatic driving experiments described in the following Sections were performed as part of a much larger project in the Train Control Group of the British Rail Research & Development Division. The project known as TACT, the Total Automatic Control of Trains, envisaged a hierarchical computer control system capable of operating trains over a wide area. By its nature the system was to be more suitable for application to proposed new railways rather than retrospective fitment to existing lines. At the time the project started, this was appropriate as such projects as Maplin Airport Link (Maplink) and the Channel Tunnel railway were expected to proceed. However, for demonstration purposes it was necessary for the system to operate on a conventional railway, with a mix of fitted and unfitted trains. The auto-drive module of the system, developed by the author, was designed to be of more general applicability as the need was foreseen for an automatic driving system to operate within the constraints of the 'existing railway or under some different system.

The performance specification for the TACT Auto-driver was developed in conjunction with the other British Rail staff within particular constraints of the developed communication link and the lineside processing equipment. The communication system was the outcome of several years of research and development effort at Derby and
by means of track conductor loops laid between the running lines enabled a central control computer to communicate with a large number of trains over a wide area using a single low power transmitter. In order to preserve the integrity of the link, coded messages were directed to each train addressed by a unique identifier and a rigorous handshake procedure was adopted before any data became executable. The format of the various messages and the polling time made it appropriate for the central control to issue to the vehicle relatively infrequent commands describing changes in the permitted speed and stopping co-ordinate. The central control rationalised the sequence of various driving commands, so that the auto-driver was presented with a single command at each point in the journey. It was the responsibility of the trainborne intelligence to drive to the constraints of the data transmitted from the central control.

The full specification of the TACT system is described in References 65 and 66, the TACT Operational Specification and TACT Engineering Specification, respectively. Extracts from these are included in Appendix Q. A major problem during the formulation of these specifications, was a lack of clearly defined operational requirement. Potential applications for a TACT system ranged from underground railways in London, to new high speed Inter-City railways. This inevitably meant that the performance requirements of the auto-driver were somewhat
Figure 6.1
PRINCIPAL DRIVING MODES
arbitrary although we hoped realistic.

The auto-driver performance specification is summarised in Fig. 6.1. This figure illustrates a velocity profile that it is considered contains all the elements of a normal journey and should provide the basis of an adequate demonstration of the capability of an auto-driver.

For this project there was no advantage in specifying the acceleration of the train, as little scope was available for traction control. For the experimental work only one automatically controlled vehicle was to be available and efficient running of a single vehicle requires acceleration at as high a rate as is practicable having due regard for the power equipment of the vehicle and the prevailing conditions of adhesion. In a large automated system global energy savings may be made under some circumstances by the control of acceleration of vehicles.

The deceleration rate to be used in the construction of braking curves was specified in order that some allowance could be made by the auto-driver for the effects of gradient on stopping distance. The deceleration so specified was constant as the stopping distance and was based on an off-line computation of the average gradient to the stop. Where adverse changes of gradient occurred on the approach to a stop, a conservative average was employed. To provide complete gradient specification to the vehicle would have required a much greater
information flow from the central control.

The tracking accuracy following the braking curve is of little importance in itself, but it does of course affect the entry to a speed restriction and the stopping accuracy. It is clearly desirable for the braking to be smooth and to avoid excessive deceleration which might result in wheel pick-up. Furthermore if a supervisory safety system is used, it must be possible to discriminate between normal operation and the initiation of emergency procedures. This discrimination is facilitated if the auto-driver follows a well defined constant deceleration curve.

The specification of permitted speed recognises that this is a constraint imposed by safety considerations and a one sided tolerance is therefore imposed. It may be necessary to closely track the permitted speed if travelling time is at a premium, although in general this is not the most energy efficient driving strategy.

6.2 System Characterisation.

It is important in the design of any control system to obtain an adequate understanding of the behaviour of the system to be controlled. The necessary information may be derived from manufacturers specification of components or from tests performed on the system. With larger systems such as railway vehicles, full scale testing is an expensive and time consuming exercise.
Unfortunately, the designers and manufacturers of traction control equipment do not anticipate retrospective fitment of automatic control equipment and consequently the specification whilst adequate for normal installation and maintenance work does not give much essential data for control system design.

The vehicle chosen by British Rail for their first experiments of automatic train driving was Test Unit Gemini. This unit is a two car multiple unit, originally built to the Derby Lightweight DMU design but converted when new to battery operation with Siemens traction equipment. The vehicle ran experimentally in the Scottish Region for some time and was later acquired by the Research Department. Although a unique vehicle it is convenient as a test vehicle in that whilst its operation is constrained to a recognised test line at Mickleover, suitably qualified research staff may drive it and automatic driving is permitted. The biggest drawback to its use, is that compared to most other British Rail traction units it is very poorly documented.

At the commencement of the TACT Auto-drive Project no power supply was available on the train for instruments and there were staff limitations. A simple programme of tests was defined which led to an understanding of the functioning of the control
equipment and quantified the performance of the train under test conditions. The test results are described fully in Ref. 51, and summarised in Appendix N.

The results obtained from the tests generally substantiated the limited traction documentation, but significant difficulty was experienced in trying to reconcile braking test results with generally accepted theory.

6.3 Modelling of the Braking System.
At an early stage in the project it was recognised that control of the braking system was to be the most demanding of the control functions. The characterisation tests described in the previous Section gave considerable insight into the behaviour of the braking system. Unfortunately, the tests had to be carried out prior to the installation of an electro-pneumatic interface and it was therefore not possible to derive any measure of the transient performance of the braking system from measurements on the train. The manufacturers of the electro-pneumatic interface, Davies & Metcalfe Limited, were most co-operative and arranged a test rig with similar volumes of pipework to those of Gemini, and this was used during the pre-delivery commissioning to obtain records on an ultra violet chart recorder of the dynamic performance.
Fig 6.2 Simplified brake schematic for battery railcar.
Figure 6.3 Deviation of Brake Performance from Empirical Formula.
A simplified diagram of the braking system is shown in Fig. 6.2 and it is clear that this is a complex non-linear system. In order to facilitate the design of a suitable control system, a computer model of the system was developed. The computer program for this purpose was developed by the Mathematics Application Section of the Train Control Group. This model incorporated the measured performance of the train combined with estimates of the dynamic performance of the electro pneumatic interface. The experience of development and use of the model is described in Ref. 53 and summarised in Appendix M.

A significant point which came to light during the development of the simulation model was the lack of correlation between the test data obtained from Gemini and the accepted empirical formulae describing the behaviour of cast iron treadbrakes. Fig. 6.3 shows the difference between a typical Gemini test and the empirical "Swindon" formula. The test data from which the Swindon formula is derived is described in Ref. 67. The Gemini test data is much flatter over the main part of the speed range and some difficulty was experienced in trying to fit a formula of similar analytical form to the Swindon formula. It was found necessary to segment the speed range and apply different formulae.

The electro pneumatic brake controller is a four bit binary input device, based upon the design developed for the three bit binary controllers fitted to the High Speed Train. At the design stage there was some doubt as to whether the distributors fitted to Gemini
would be capable of resolving the small train pipe pressure changes associated with control of the least significant bit, and there was uncertainty about hysteresis in the two stages of the pneumatic control. In the event these fears were unfounded, but the simulation was structured to allow their inclusion if necessary.

6.4 Instrumentation for Control.

The specification for control described in Section 6.1, requires close control of train speed and position, and specifies that fluctuations in acceleration should be kept to a minimum. For traction control, the railcar is fitted with a semi-automatic camshaft control, incorporating current feedback, see Ref. 48. A single electrical line, the "R" light, provides an adequate monitor of the state of the automatic gear and no measure of traction current or other traction variables is explicitly required.

For speed and distance measurement, a simple and robust optical tachometer system was developed within the Train Control Group. The transducer consists of two slotted discs attached to the end of the axle with a peg-in-slot drive and optical reading heads to sense the disc positions. The discs are arranged so that their pulse outputs are nominally square waves, electrically in quadrature. The quadrature output enables determination of direction of motion from an edge transition. In this application the discs have 12 poles and with the dimension of the Gemini wheel this gives a distance resolution of
0.288 m. A microprocessor is associated with the reading heads to determine the direction, position and velocity. The microprocessor is also used as a communications processor to control the train end of the track to train communication link. The speed is determined by counting the number of tachometer pulses received in a gating period. For TACT the gating period was chosen to be equal to the cycle time of the control processor which was one second. This provided a speed signal of adequate resolution and accuracy to satisfy the TACT specification.

To design a brake control system with a reasonable response, considering the large and variable time constants of the braking system, it was considered that derivative feedback would be required. It was clear that the tachometer processing system could not provide a useful measure of the train acceleration due to the fundamental limitation of distance resolution. The best that could be obtained would be a long term average which would be of little value for control. The most attractive alternative means of determining acceleration at the time, was to employ a direct analogue transducer of the type being evaluated for use on the APT tilt system. With hindsight the choice of this Electro-level, whilst adequate for the experimental use, has severe drawbacks for inclusion in engineered systems. The principles of operation and the basic weaknesses of the Electro-level are described in Appendix P. Alternative transducers were considered and the reason for their rejection is also given.
6.5 Development of Control Algorithms.

It was the intention in the early stages of the TACT programme, that the control processor should be implemented on a microprocessor of similar type to that used for message handling. The limited power of such a processor together with the restrictions of the pre-determined message formats of the system, influenced the design of control algorithms considerably. At an early stage in the development, there was considered to be a strong case for the use of a mini-computer in the place of the microprocessor during the development phase, in order to provide more flexible program development and editing facilities, and for this reason an HP21MX mini-computer was purchased.

The algorithms were designed from the information acquired during the characterisation tests described previously. These tests provided an understanding of the behaviour of the traction and braking systems, and a measure of the train resistance over the operational speed range.

In the early paragraphs of the present Chapter, the operational requirements for the system were described. The velocity profile illustrated in Fig. 6.1 consists of a number of segments, which correspond to different modes of control. The primary modes are clearly: acceleration to target speed; regulation of speed at permitted speed; and braking to target speed and position. To achieve a smooth transition between each of the primary modes, secondary modes are required and Fig. 6.1 illustrates the profile with all the control mode changes indicated.
Fig 6.4 Decision Thresholds
The form of control in each of the above modes is quite different. During the acceleration phase, control is primarily sequence control, based on feedback of certain performance parameters. Speed regulation is achieved by a non-linear regulator. Braking to target requires a profile tracking controller. The following paragraphs consider the design requirements of each of these controllers.

6.5.1 Acceleration Control.

As has been explained earlier, the railcar is equipped with a semi-automatic camshaft controller giving some 81 steps of control, 6 of which may be held by the driver's control. During normal acceleration, the current regulation of the camshaft controller governs the train acceleration. If the adhesion is poor, careful progression through the notches is necessary to avoid wheelslip. An additional facility to assist in these circumstances is the Reduced Tractive Effort (RTE) control which significantly reduces the set-point of the current regulator. Under some conditions, it is possible to overload the resistance control gear by attempting to engage too high a traction notch with a heavy load, so that the camshaft stalls or runs slowly resulting in overheating of the motor and starting resistance grids. The manual driver has instructions to avoid this and the automatic driver must use similar techniques to avoid damage.

Fig. 6.4 illustrates diagrammatically the arrangement for traction control and Fig. 6.5 is a flow chart of the
Figure 6.5 Flow chart of principal routines for acceleration.
BATTERY RAILCAR

SPEED - TRACTIVE EFFORT DIAGRAM

--- GROSS T.E. DERIVED FROM TEST DATA
--- SIEMENS DATA CORRECTED FOR WHEEL WEAR AND CURRENT LIMIT

NOTE: FIELD WEAKENING PERCENTAGES ARE NOMINAL VALUE
acceleration algorithms (simplified), to illustrate how control demands to satisfy the requirement of the above paragraphs are generated. From the flow chart it will be apparent that the major part of the software is concerned with checking and correcting wheelslip. Normal progression through the traction notches requires that a critical speed for each driver selectable notch be achieved before the next traction notch is demanded. This enables the auto-driver to keep track of the position of the camshaft and facilitates the detection of wheelslip.

6.5.2 Speed Regulation.

Speed regulation requires the use of the traction and the braking systems together to constrain the speed of the train within acceptable limits. The railcar is equipped with a discrete form of power control, so that even when working against a hypothetical constant train resistance, it would be unlikely that one of the available traction notches would provide balancing power and thus constant speed. If the traction characteristic, shown in Fig. 6.6, is examined it will be seen that for a given speed, typically two or three traction demands of the total six give a significantly different power at the rail. It will also be noticed that on the natural part of each characteristic (i.e. beyond the current regulation region), the tractive effort varies significantly with speed.

To design a speed regulator with the above constraints,
capable of operating throughout the speed range, requires a speed dependent interpretation of the notch requirement for a given speed error. The mechanism of the camshaft control, as well as the comfort of passengers, makes it undesirable to repeatedly apply traction for short periods. It is therefore necessary that the traction demands should result in an appropriate acceleration through the control band taking account of the track gradient. The very coarse nature of the power control necessitates this last feature, otherwise an integral term could be added to proportional power control to eliminate the steady state error which would develop.

Specification of unnecessarily close control of speed, would result in the frequent application of tractive power followed by braking, and it is necessary to define reasonable tolerances, such that this does not happen, as energy wastage and wear would negate any advantages of control. However, typical main line gradients are such as to cause a train to significantly increase speed when coasting downhill, and so brake control must be included for speed regulation. Since the electrical brake interface is itself a closed loop pressure control on the braking systems, it was considered that a small fixed level overspeed brake should be sufficient.

Fig. 6.4 shows the decision diagram used to determine the output demand to the train in the speed regulation mode. It will be noted that hysteresis has been included on each of the decision boundaries on this
FIGURE 6.7
TARGET DATA
General Braking Target
This is necessary to overcome the tendency to chatter between modes which will occur due to quantisation noise on the tachometer with relatively slow rates of change of speed. The names of each of the phases on the diagram are self-explanatory with the exception of drive and accelerate. Accelerate refers to the previous mode, in which acceleration at the maximum rate is demanded. Drive refers to the traction mode within speed regulation where traction notch demands are derived as described above.

6.5.3 Brake Control.

Brake control is required for two types of target, speed restrictions and stopping targets, respectively. The chief difference between the treatment of the two types is the mechanism for brake release at the target. As was explained in Section 6.3, the time constants of the braking system, particularly for release, are very long. Fig. 6.7 shows the data supplied to the train in the automatic braking mode. From the target data the trainborne intelligence computes the braking curve shown on the figure. The application time constant of the braking system means that the train is incapable of following the discontinuity of gradient at the top of the braking curve and a secondary mode of control, the initial brake mode, is introduced to smooth the entry to the braking curve and avoid a large transient.

The initial brake mode is an open loop mode of control, as the duration of the mode is comparable to the system
time constant and direct control is not possible. The brake application is initiated at a time approximately equal to the dominant time constant before the train is expected to reach the intersection of the permitted speed with the braking curve. As inadequate data on the behaviour of non-linear features such as the brake rigging and return springs was available, some flexibility was built into the algorithm for development purposes. The normal mechanism for exit from the initial brake to follow the braking curve is the expiration of a fixed time from the initiation of the brake application. Optionally, the transition may take place when the speed error is sufficiently small.

On leaving the initial brake mode, the train will have a fairly small error with respect to the braking curve, and the brakes will be partially applied. This is a reasonable initial condition for the main braking algorithm for following the braking curve. Whereas it might be possible to design a non-linear controller capable of stopping the train in the right place, the design would probably be more complicated than a comparable linear controller, and problems might be encountered with passenger comfort and safety supervision. We therefore chose to try to design a simple controller using the error with respect to the braking curve as the controlled variable. Clearly, it is possible to define either a speed error or a distance error between the train state and the specified braking curve. Consideration of the shape of the braking curve, (a parabola) shows that its
gradient is inversely proportional to speed. This means that if a speed error term is used, the sensitivity of this error term to positional error increases as speed reduces. This feature is exploited to advantage in the design of brake control algorithms to give a progressive tightening of control as the target is approached. This enables high accuracy of position control to be achieved without difficulty in controlling the transient which would otherwise occur at the top of the braking curve with a fixed gain controller.

The controller output consists of a pressure estimate corrected for the known non-linear speed characteristic of the braking system, a proportional speed error term and a derivative term derived from an analogue accelerometer input. The complete controller with the braking curve error generator closely resembles a conventional 3-term controller for small deviations from the set point at constant speed. However, as it is a braking controller, it is not a constant speed system and a non-linearity is introduced by the inter-relation of the speed and distance terms. It is therefore not possible to apply standard tuning techniques for adjustment of the gain terms and the special techniques used are described in the Appendix R.
Note: The stop at Mickleover Victoria is optional.
6.6 The Experimental Installation.

The testing of the system described in the previous paragraphs was carried out on the Research & Development Divisions Test Line, located at Mickleover, near Derby. The test line forms part of what was once the Great Northern Line from Nottingham to Derby, and it joins the present Derby to Stoke on Trent line at Eggington Junction.

As has been mentioned earlier, the development of the auto-driver formed part of a much larger project, TACT (Total Automatic Control of Trains). Important features of the TACT system were the central control computers, and the continuous track to train communication link. The communication facilities and central control of TACT were evaluated under realistic conditions in the Manchester area, but at that time automatic driving was not possible on a route open to service traffic. A stretch of line at Mickleover about 2.2 km in length was equipped with the TACT communication system, and the central control computers were located in the laboratory at Mickleover.

The test line although originally double track, is now operated as a single track line with a train staff. The line is subject to a maximum speed restriction of 45 mile/h throughout its length, except under special conditions. In order to demonstrate the ability of an auto-driver to work in conjunction with central control, an imaginary profile including speed restrictions, stations and signals was developed. Fig. 6.6.1 illustrates
FIG.6.2 WILMSLOW TACT CONTROL CENTRE
the profile chosen, and it will be noted that speed restrictions are different for the two directions of running.

The central control computer system consisted of two mini computers and a colour video display system together with disc storage, see Fig. 6.6.2. The development of the central control equipment was carried out in the early 1970's, and at that time intelligent video terminals were not available hence the need for one of the mini computers to be dedicated to driving the video display. The larger mini computer in the central control system received inputs from the trackside indicating the position of all trains including those not equipped for automatic running, and the state of the signals. From this data the computer was able to generate driving demands in the form of targets for the train to achieve. A rigorous handshake protocol was adopted for security reasons as all trains were addressed through the same communication medium. Initially on entry trains were addressed by location, thereafter they were addressed by identity. For automatic running with central control, it was necessary for the train to be driven manually into the equipped area and halted. Subject to satisfactory communication being established with central control, automatic operation would be offered to the manual driver, who would have the option to accept this facility or to continue driving manually.

Recognising the constraints of operation with the central control, and the need for a research staff to operate
Figure 6.6.3
central control, a moving test facility was provided in the trainborne equipment such that operation quite independent of the central control could be achieved.

The trainborne equipment consisted of two computers, a microprocessor whose function it was to control the line protocol for communication with central control, and a mini computer acting as the control processor for driving the train. The general arrangement of the hardware is shown in the diagram of Fig. 6.6.3. The teletype was used to initially start the program running in the control processor, and also when in the moving test mode to input the target data. The magnetic tape unit was used to log in some detail the performance of the automatic driver during a run. Limited facilities were provided on the train for listing of the magnetic tape log and also in the later stages of development online graph plotting facilities were available. However, graph plotting hardware on the train was not found to be entirely satisfactory and British Rail facilities at Derby were used to plot graphs examples of which are included in this report.
7. THE PERFORMANCE OF THE AUTO-DRIVER.

7.1 Evaluation of the Auto-Driver.

It will be appreciated that the total software in the auto-driver control processor represents a complex system. In order that the problems of software de-bugging might be divorced from the problems of real time control in as far as this is possible, the initial implementation on the train was a simplified sub-set of the system described in the previous Chapter. All the main features of the auto-driver were present, but the algorithms were simplified.

Serious problems of electrical noise were experienced in the commissioning of the auto-drive equipment prior to the train running. The principal weakness of the hardware in this respect was the link between the microprocessor and the mini computer, and as this was functionally connected with the operation of the analogue accelerometer, for the initial test running no measurement of acceleration was possible.

On the first test run, the train was driven automatically, but some problems were experienced due to arithmetic errors in the software. Elimination of these errors produced a system capable of driving the train but there was scope for improvement both in the stopping accuracy and the regulation of acceleration during braking.

With the commissioning of the accelerometer, it was then possible to test the complete system as designed. By
Figure 7.2.1 Normal Starting.
this stage it had been possible to complete the implementation of the software for the basic system. The gain values used in the controller had been chosen from simulation and significant improvements were made by adjustment of the control parameters. By design the software system was structured so as to facilitate the alteration of such control gains and other control variables. It was thus possible at the commencement of any particular run to choose a set of control parameters for that run and the parameter set would be logged together with the performance log on the magnetic tape for further analysis.

7.2 Acceleration of the Train.

As was mentioned in the specification for the automatic driver, the principal function of the acceleration algorithms was to provide sequential control for the train notching controls and to provide protection for the automatic camshaft gear. The techniques of selection of traction notches in a simple progression with the increase of train speed, was shown to work well; see Fig. 7.2.1. This figure illustrates a normal start with no adhesion problem, and it will be seen that the traction demand increases in steps as the train speed increases. The acceleration profile shown on the same figure approximates to the shape of the tractive effort characteristic and it is possible to interpret the state of the traction control gear from the shape of this characteristic. The labels inserted on this characteristic show the operation of the automatic camshaft gear to be in step with the output demands of the auto-driver.
Figure 7.2.2 Overload during Acceleration.
Figure 7.2.4 A difficult start with slip at higher speeds.
Under conditions of heavy load, the progression of the camshaft is rather slower than normal, and it was found on a steep uphill grade (1 in 110), the specified overload time limit could elapse within a notch, causing the software to declare an overload and act accordingly. Fig. 7.2.2 illustrates this. It will be seen that during the later stages of acceleration traction notch 5 is selected and held for a period and then reduced to traction notch 4. This is the point at which overload is declared and after a recovery period, the traction notch is restored to notch 5. And in this case the acceleration is then satisfactorily completed. Another feature which will be noted on this graph and on the previous example is the reduction in traction demand prior to notching off on achieving the required speed. This is a design feature with the object of reducing the jerk and also minimising the current switched by the motor contactors.

Under conditions of extremely poor adhesion, normal starting as indicated in the previous two examples is not possible. In such circumstances slip may occur either immediately on starting or during the reconfiguration from series to parallel after momentarily losing tractive effort. Figs. 7.2.3 and 7.2.4 illustrate clearly this effect. Fig. 7.2.4 is for the starting case, and the algorithm is seen to be working properly first attempting to start the train by two attempts with normal tractive effort and then after attempting to start the train with reduced tractive effort finally resorting to use of notch 1, the shunting
Figure 7.2.5

Autodriver unable to achieve target speed (Run 2L424).
notch in order to get the train rolling. Fig. 7.2.4 is for the case of loss of adhesion during reconfiguration at about 15 mile/h. In this case the algorithm correctly removes power and after a recovery period to allow the wheelset to regain adhesion with the track and also to allow the camshaft to return to the home position, traction is progressively reapplied. The time spent in the lower series notch with a reduced tractive effort tends to increase the train speed slightly and so reduces the risk of further slip on re-selection of notch 3. It was found however that under extreme conditions it would be possible for the auto-driver to hunt continuously between notch 2 and 3 trying to attain notch 3 but never quite succeeding. Fig. 7.2.5 is an example of this occurrence and it was interesting to observe that under such conditions the manual driver was unable to do any better than the auto-driver.
Figure 7.3.1: Speed Regulation 50 Hz Uphill.
Figure 7.3.2 Speed Regulation 78p/s Downhill.
Figure 7.3.3. Speed Regulation 70 p/s Downhill.
Figure 7.3.4 Speed regulation to follow on-line computed time-keeping curve.
Figure 7.3.6 Speed Regulation Downhill (1%o).
7.3 Regulation of the Train Speed.

The algorithm for this mode of driving, is a non-linear regulator, see Section 6.5.2. The performance in this mode is limited primarily by the quantisation of the speed determined from the tachometer. The basic resolution of the disc, combined with the simple processing results in a resolution of approximately 0.5 mile/h. The processor cycle time was chosen to be 1 second and under normal circumstances the train speed would take several seconds to change by one unit of speed resolution.

The performance of the algorithm was as expected from the design work. The only problem experienced was that of specification of the decision thresholds which were initially implemented as greater than, rather than greater than or equal to. The result of this oversight was slight degradation of the speed regulation.

Figs. 7.3.1 to 7.3.4 illustrate the performance of the algorithm over a range of speeds, and it will be seen that the regulation is substantially independent of speed.

A slight drawback of the control is its sensitivity to gradient; Figs. 7.3.5 and 7.3.6 illustrate for the same regulated speed the effect of an uphill and a downhill gradient, respectively. From a study of a number of test runs it has been shown that, the sensitivity is approximately 1 mile/h per 1% gradient.

The performance of the speed regulation algorithm was considered quite adequate, the sensitivity to gradient was not apparent from the driver's speed indicator.
The total period of automatic running was about 14 months and with very nominal mileages being covered purely for experimental purposes, very little maintenance to the railcar was necessary. One result of this was that starting with the unit fresh from Works overhaul at the beginning of the testing period, by the end of the testing period the braking system required considerable adjustment and the blocks were badly worn. This progressive change in the trains characteristics, affected the control system operation in two ways, firstly the overspeed brake was affected, and secondly the fixed level initial brake. The initial brake will be dealt with in the next Section. The effect on the overspeed brake was sufficiently marked that a brake cylinder pressure which had been quite adequate for speed regulation in the early tests was quite inadequate in the later tests. The lesson to be learned here is that the fixed level brake proposed for the TACT overspeed brake must be replaced by a brake increasing in severity with increasing speed error and possibly including integral control.

7.4 Brake Control for Station and Signal Stopping.

The auto-drive software, within the TACT system, makes no distinction between station and signal stopping. A feature of the TACT system is the inclusion of safety monitoring in the central control, and the only failsafe device on the train has to be the emergency brake. If any distinction between signal and station stops is required this can be accommodated by use of the retardation control character in the message sent from
central control to the vehicle.

Braking algorithm design has been covered in Section 6.5.3. In general, the performance of the braking system corresponded quite well with the simulation work carried out earlier. Unfortunately, the pneumatic delay estimated by the brake equipment manufacturer proved to be significantly in error, and it was necessary to retune the simulation and trainborne algorithms.

The initial brake algorithms functioned as intended to provide a reasonable initial condition for the braking curve following algorithm. The simple fixed time algorithm was generally more satisfactory than the algorithm which changed mode when the speed error was sufficiently small. This was particularly so when the brakeblocks were worn and a heavier initial brake pressure was demanded. In some circumstances, it could be possible despite an initially slower response for the initial brake to cause the train to brake to a stand without intersecting the braking curve. The simple elapsed time initial brake was subject to the same uncertainties as the alternative, but it did guarantee transfer to the braking curve following mode.

In addition to the physical uncertainty of the behaviour of the braking system, the asynchronous operation of the control cycle contributed to the uncertain state of the brake application at the end of the initial brake phase.

The braking curve following algorithm was tested extensively, a total of approximately 1000 runs being made. As had been
Figure 7.4.1 The need for derivative feedback.
Figure 7.4.2 Damping effect of derivative feedback.
Figure F 7.4.3 Histogram of Stopping Accuracy (TACT).

- All tests
- Down test only (design direction)
mentioned earlier the need for the accelerometer was demonstrated when this facility was not available for the early test runs. Under these conditions stopping accuracy was reasonable, but excursions of train acceleration were larger than desired. Inclusion of the derivative feedback from the accelerometer reduced the fluctuations in train acceleration, and improved stopping accuracy. Figs. 7.4.1 and 7.4.2 contrast the performance with and without the accelerometer feedback. In both cases the controller gain values have been adjusted for good performance. Appendix R describes in detail the methods used to evaluate the control algorithm and determine appropriate gain settings. With the method adopted, and a knowledge of the simulation behaviour, it took little time to establish working values for the gain settings.

Having once established a good set of control parameters, throughout the development period, at intervals tests were repeated using the same settings. Under these conditions despite changes in the train characteristics, due to block wear as explained earlier and weather conditions, the stopping accuracy and other measures of the goodness of control remained consistently good. Fig. 7.4.3 shows a histogram of the stopping accuracy of the control algorithm for the same control parameter settings and this is constructed from all tests carried out with these control settings. It will be noted that the standard deviation of stopping accuracy is little greater than the resolution of distance measurement. The design aim of biasing the stopping to the safe side of the target
Figure 7.4.4 Inherent brake release
has been achieved, and no overshoot of the target has been observed. It must be remembered that the stopping accuracy referred to here is that perceived by the train with reference to its last observed beacon. This measurement is vulnerable to errors incurred by wheelslide and errors of calibration. This point will be enlarged in a later Section.

In order to ensure passenger comfort it had been intended to include a brake release phase immediately prior to stopping. Reduction of brake cylinder pressure at low speeds is an inherent feature of the design of the control system, since the increased coefficient of friction between the cast iron blocks and the wheel treads causes the train trajectory to diverge from the braking curve, the negative velocity error so formed driving the control algorithm to reduce the brake cylinder pressure. Fig. 7.4.4 illustrates a typical occurrence of this action where it will be seen that following the period of acceleration regulation, the brake demand is reduced prior to the stop.

Cast iron blocks are well known for their non-linear friction properties resulting in very high friction at low speeds. Unfortunately the rate of increase of the coefficient of friction with reducing speed at low speeds, is such that with the brake release time constants of Gemini, it is not possible to release the brakes sufficiently fast to avoid a noticeable jerk. In fact it was found after several tests that it was not possible to improve upon the brake release characteristics inherent in the curve following algorithm.
7.5 Brake Control for Speed Restrictions.

The approach to a speed restriction is similar to the approach to a stop target. The difference is that the brakes must be fully released when the target speed is achieved. Failure to release the brakes sufficiently early will result in a significant underspeed and a waste of kinetic energy.

The braking system of Gemini has a release time from full application in the region of 20 seconds. Clearly, a significant speed will be lost during the brake release when the train speed is diverging from the braking curve. It is necessary therefore to move the braking curve followed when braking to a speed restriction target in order to accommodate the brake release phase without exceeding the speed restriction at the point of entry. This is accomplished by the auto-driver software.

Fig. 7.5.1 is a graph of a typical speed restriction entry and the brake release phase is clearly shown. As the train speed approaches the permitted speed within the restriction, the brake demand is progressively reduced so as to ensure entry to the speed restriction at the required speed.

With faster acting braking systems, as are found on modern multiple unit stock, a simpler brake release algorithm could be employed and a smaller shift of the braking curve would be necessary.

Curve following during brake release would be an added complication and is unlikely to be justified. From
observations in the cab of a railway train, it is difficult to tell the exact point in distance when the brakes have been fully released. Traction instruments are heavily slugged, and so long as the train speed is reduced to approximately the value of the speed restriction as the leading end of the train passes the board indicating the commencement of the speed restriction, this is adequate.
Fig. 8.1  B.R.A.T.O. Trainborne Equipment.
8. BRITISH RAIL AUTOMATIC TRAIN OPERATION.

8.1 The BRATO Project.

Many lessons were learned from the TACT programme of work, and after much consideration, with influence from the Railway Engineering Departments, it was decided that the way ahead for automatic train control on the British Rail, was in the form of a less ambitious scheme than the TACT system. During the TACT work, a parallel programme of work had been undertaken within the Train Control Group, to develop a safety supervisory system capable of monitoring the driver's speed and ensuring that at all times it remained within safe limits. The system was based on coded safety information transmitted from signal locations through track conductor loops, the data transmitted being appropriate for the aspects displayed. The BRATO system proposal embodies this feature of distributed safety and the safety supervisory module is combined with an auto-driver derived from the TACT experience.

Fig. 8.1 illustrates the structure of the BRATO trainborne equipment. Equipment at the lineside, coupled to inductive loops extending from the location of the fixed signals, will transmit safety and driving data to the trains. The potential benefits of automatic train operation (ATO) have been evaluated, see Ref. 50 and Table II.

A major area of potential savings is that of energy consumption. Simulation studies have shown that by exploiting the ability of an automatic driving system significant energy savings may be made. In the first stage of the BRATO work
it is proposed that off-line generated energy saving speed distance profiles will be followed by the train.

The facility to alter performance data in real time will be provided in the pilot scheme implementation, but the full realisation of the benefits in Table II is a long way off.

8.2 Tachometer Studies.

A major shortcoming of the TACT system, was the performance of the distance and speed measurement system. The system produced an average speed estimate with an averaging period of 1 second and an update frequency of once per second. The distance measurement system provided for calibration to 0.5% and a distance resolution of 0.228 m. It was not possible to obtain a useful measure of train acceleration from the tachometer heads, and for this reason an analogue transducer was employed to supplement the tachometer output.

On a track over which the gradient may vary, the output of a seismic accelerometer and that derived from the motion of the wheelset will be different. Appendix T presents the analysis of this. For control purposes both measurements have their virtues, the seismic measure is closely related to the longitudinal force between the wheel and the rail, the motion of the wheelset is naturally associated with the progression along the track and includes the effects of gradient.

It has been shown that the use of an acceleration signal
BENEFITS OF A.T.O.

GREATER FLEXIBILITY IN OPERATING PERIODS (night service) LOWER COSTS.

ENERGY SAVING BY OPTIMISED RUNNING.

IMPROVE PUNCTUALITY & RELIABILITY OF SERVICE.

ALLEVIATION OF POSSIBLE RECRUITMENT PROBLEMS (unsocial hours).

LESS DRIVER TRAINING TIME.

MAINTAIN EXISTING SAFETY RECORD WITH INCREASED SPEEDS & SERVICE FREQUENCY.

Table II
can improve the performance of a brake control system. The measurement of acceleration is also useful for assessment of the performance of such a system and can help in the design of simple traction control systems requiring minimum feedback. There are disadvantages in the use of analogue transducers; they are difficult to engineer in a rugged form and are susceptible to problems of mechanical noise.

The above considerations lead the author to recommend the development of an improved tachometer system capable of providing an estimate of the train acceleration from the measurement of rotation of the wheelset. The author developed some simple theory to show how a fine resolution optical shaft encoder mounted on the axle end might be used to produce estimates of speed and acceleration. This work was extended considerably by Mr. I.P. Milroy and Mr. W. Forsythe at Loughborough University. This work resulted in the joint paper Ref. 72. This theoretical work was supplemented by tests carried out at the author's direction on the British Rail Research & Development Divisions Test Line at Mickleover (Ref. 74).

For the purpose of these tests a train was fitted with an axle mounted shaft encoder giving 1000 pulses per wheel revolution. The encoder was driven through a conventional peg in slot drive. For experimental purposes, data was collected by a mini computer and punched out on paper tape, for off line analysis with simulation of varying sampling period and effective number of poles. Unfortunately, at this stage the
practical interpretation of the newly developed theory was incomplete and attempts were made to sample the output of the tachometer too fast. The result of this was that small errors of eccentricity in the alignment of the shaft of the encoder and the axle bearings produced unacceptably large sinusoidal oscillations of the speed and acceleration estimates.

Initially these problems were considered fundamental, and methods were sought whereby the mechanical drive from the axle end to the encoder might be improved. This was achieved by the use of flexible bellows couplings. These couplings consisting of a concertina shaped brass tube have the ability to accommodate end float, axial misalignment and angular misalignment, whilst still transmitting true circular motion. Whereas test experience with these couplings has been good, they are difficult to assemble to the end of a railway axle, and from fatigue considerations their lifetime is unlikely to be sufficient.

The improved practical interpretation of the tachometer theory, developed by the author (see Ref. 72), now means that eccentricity of the drive is not a significant problem and the processing algorithms can accommodate the imperfections of a reasonably engineered housing (see Appendix U).

Concurrent with the tests for the suitability of shaft encoders for speed and acceleration measurement, tests were carried out of the suitability of the combination of the same shaft encoders and track mounted beacons.
for distance measurement, (Ref. 74). The track mounted beacons used for these tests were end-of-section beacons as used for position location in the supervisory safety system. Their original design did not require a precision distance reference as distance resolution was in 20 m units, but the basic unit appeared as though it might give an adequate position reference for the more demanding needs of the automatic driver. The initial test at Mickleover showed great repeatability of distance measurement and implied exceedingly good repeatability of the marker position. The total spread of the results was better than 0.1% of the mean, with a standard deviation of .015%. Furthermore, a systematic trend in the data corresponding to the amount of work done by the braking system, or heat put into the wheelset, showed the wheels to be expanding noticeably over the duration of each test.

Recognising the importance of the wheel heating effect, tests were organised under service conditions using a train in the Manchester area. These tests showed that over a 6 month period under various weather conditions and including the use of emergency brake applications the total spread of the distance measurements was no worse than that measured at the Mickleover Test Site. It was very significant that out of over 500 measurements made including heavy brake applications on wet rails, no instances of wheelslide were experienced. This was not compatible with the experience gained with Gemini at Mickleover, where creep of perhaps 1/2 to 1 m could be experienced on a single stop under dry conditions. The
Figure 8.2.1 BRATO Tachometer Performance.
The key here may lie in the friction material used for the tread brakes, in that the Class 304 Multiple Unit used for the Manchester tests was fitted with composition brakeblocks, whereas Gemini is fitted with cast iron blocks. It is not felt that the traffic density was a major factor.

The understanding of trainborne distance measurement by measurement of the rotation of the wheelset has now been developed to the extent that it is possible to specify a tachometer system for BRATO application, giving an adequate estimate of both velocity and acceleration. The performance of such a tachometer is illustrated in Fig. 8.2.1 and for comparison, the output of an analogue transducer recorded at the same time as the digital measurements were made, is included. Appendix U describes the application of the above mentioned theory and the analysis of test data to produce the BRATO tachometer specification.

The method of operation of end of section beacons and transponders (as used for TACT work) are explained and compared in Appendix V.

The conclusion from the work to date on axle mounted tachometers must be that these devices are capable of much better performance than was hitherto believed. If combined with a suitable position reference, (the British Rail end-of-section beacons have proved suitable), axle mounted shaft encoders can provide the basis of a high precision distance measurement system. Calibration
is difficult as there is no better alternative measurement facility. Calibration of track distances can be carried out by making repeated measurements with a train, fitted with a precision tachometer, and comparing the mean value of the measurements with a similarly measured mean value of a known distance. Automatic calibration of trainborne processing equipment is more difficult, but if the track is calibrated in the above manner, it is possible to digitally filter measurements of successive track distances in order to obtain a calibration factor for the system.
8.3 Control for an Electric Multiple Unit.

The trains to be controlled within the BRATO pilot scheme are Class 304 Electric Multiple Units. These trains operate from a 25 kV single phase electrical supply and are equipped with electrically operated pneumatic air brakes, (EP brakes). The characteristics of the units had been obtained in a similar manner to the tests carried out on Test Unit Gemini and are reported in Ref. 70.

The present programme of work is for fitment of a fleet of vehicles with automatic driving equipment for service operation. With this in mind it is important that the control system design work be carried out thoroughly to avoid problems when the trains enter service.

Although considerably more powerful than Gemini, the Class 304 traction system is controlled in a similar manner. A camshaft operated tap changer operates on the secondary of the main transformer in a similar manner to the camshaft operated resistance controller of Gemini. The camshaft drive motors are quite different, and Gemini has considerably more steps of control than the Class 304. This latter feature means that smooth control of acceleration is not possible, and some lurching on starting is almost inevitable. The brake control is considerably different to Gemini, the e.p. control system providing a much quicker response and the use of composition brakeblocks giving a quite different characteristic of the variation of coefficient of friction with speed.
Figure 8.3.1 (part I) Demonstration Autodriver Performance.
Figure 8.3.1 (part 2) Demonstration Autodriver Performance.
Work is currently being undertaken in conjunction with Sheffield University in order to identify the system characteristics for brake control, using a system identification package SPAID (Ref. 71).

A simple control system has been designed and tested on a train in the Manchester area. The controller described in Appendix W was implemented on a microprocessor (Motorola 6800), and advantage was taken of the opportunity to include some features seen to be lacking in the TACT auto-driver. The performance of this experimental auto-driver is illustrated in Fig. 8.3.1. It must be noted that timescale and resource limitations as well as processing power limitations dictated that the algorithm used in this application should be as simple as possible consistent with providing a reasonable demonstration of automatic driving. No traction protection facilities were provided, and as the simple tachometer processing used could not provide an estimate of the train acceleration, braking curve following was performed using a $P + I$ control based on speed error with respect to the braking curve.

8.4 Hardware Developments.

Over the last few years very significant changes have taken place in terms of hardware available for communication and control purposes. This has affected both the processing power which might reasonably be made available on a train and the cost. Early automatic wagon work envisaged the use of analogue controllers with a very minimum of digital electronics onboard the
vehicles. Indeed automatic wagon demonstration work was carried out using significant numbers of relays combined with analogue control equipment.

Microprocessors became available in the early stages of the TACT work, and it was intended that two 4 bit processors should be used on the train, one as a communications processor, and the other as a control processor. In the event as mentioned earlier in the report, a mini computer was used to replace the control processor as it offered better development facilities. However the algorithms used in the TACT auto-driver were designed such that they could be implemented on the simple microprocessor.

With the advent of more powerful microprocessors such as the Motorola 6800 processor, and the significant reduction in memory cost, it becomes less important to try to design algorithms for the processor. The current BRATO development work is being carried out using a DEC LSI-11 microcomputer. This machine is the smallest of the DEC range of mini computers, and has the great advantage of software compatibility with the manufacturers larger machines. This makes possible development of software on a larger system, and the software can then be down loaded to the smaller machine for execution.

It is anticipated that the hardware trends observed will continue, and quite soon we may see a single chip implementation of the DEC machine. This could lead to more compact, considerably less complex and hence probably more reliable hardware, which would be functionally similar
to the equipment currently under development.
9. CONCLUSIONS.

9.1 Vehicle Following.

The work described in Chapters 1 to 4, has indicated the practicability of use of the vehicle following technique as the basis of a system of control for a guided vehicle system. It has been shown that it may be quite unsatisfactory to base the design of such a control system on an understanding of the steady state capacity characteristics.

An understanding of the dynamic interactions of vehicles operating under various control laws has been developed. From this work a technique has emerged for the shaping of the velocity distance profiles executed by each vehicle. The use of shaped profiles provides significant increases in system capacity at a minimal cost in terms of journey time.

The techniques developed can only be fully exploited in an automated system with continuous signalling. However, even in a simple system with manual driving and fixed block signalling, advantage may be gained by the use of the techniques.

A significant difference between this work on vehicle following, and much of that contained in the literature, is that safety and vehicle control are treated as an integral part of the control problem for vehicle following. Separation of these functions can lead to operational difficulties, particularly if vehicle following is attempted at headways close to the minimum safe headway. This
has lead many workers to abandon the safety criteria used in this report.

It is the author's belief, that abandonment of the safety criterion does not result in significant improvements in system performance, particularly if the techniques developed in this report are employed.

9.2 Control of Railway Vehicles.

In order to assess the engineering problems, and hence the likelihood of realisation of the techniques referred to above, with the co-operation of his employers, British Rail, the author has been responsible for the design and development of automatic vehicle controllers for full scale application to railway vehicles. This work had lead to an understanding of problems of control and instrumentation of which many workers in the field are clearly unaware.

The vehicles to be controlled represent highly non-linear systems with very long time constants. Nevertheless it has been possible to design control systems capable of performing as well or better than the manual driver.

The development of these systems has been carried out in the context of British Rail projects for the development of automatic driving techniques for use on British Railways. This has naturally limited the scope of the work, but it is convenient that systems requirements for automatic driving with a safety supervisory system necessitates the close following of a braking curve. Generally the curves
used are characterised by constant deceleration. This
is not the natural characteristic of the braking system
and therefore control action is necessary to follow the
curve.

Braking curve following is therefore closely analogous
to following the shaped profiles referred to in the
previous section. Since it has been shown to be
possible with railway trains of conventional design
to follow braking curves within very close limits
it is likely that the velocity profile shaping techniques
proposed in this report could be realised.

Were new stock designed with automatic control in mind,
there would be no difficulty in providing an adequately
fast response. Conventional railway braking systems
are normally slugged in order to provide a reasonable
jerk performance. In the case of Gemini for which one
of the controllers described was designed, the distributers
being of an old design are slugged a great deal more than
their modern counterparts.

9.3 Instrumentation and Communications.

The performance of any control system can only be as good
as the input data. In the case of a railway vehicle it
is very difficult to provide precise state measurement
with respect to the track.

In this report it has been shown that axle mounted shaft
encoders can provide the precise distance measurement
required for automatic control. It has further been shown
that by the use of suitable processing techniques, adequate estimates of speed and acceleration, for use in control algorithms, may be obtained.

Position marker beacons of an existing design, have been shown to be ideal for use as position reference points.

In an automated system, it is necessary for distance measurement to be continuous and for all trackside features to be specified with respect to a common origin. Work carried out by British Rail has shown that where several engineering departments may be involved, each working to their own site plans, it may be very difficult to achieve the consistent specification required. For small scale system implementations a site survey may be practicable, but for a large system a great deal of work is required no matter what method is chosen.

The choice of communication link from track to train will have a great bearing on the scope for control and hence the likely success of a scheme. Modern communications technology potentially provides many solutions, but few have been tested in the railway environment. If distributed safety is to be a feature of the system, a communication link such as the British Rail Inductive Loop or the London Transport Coded Track Circuit is appropriate. Where centralised safety can be accepted, a broadcast communication system may be employed. The TACT variation of the British Rail Inductive Loop, or radiating cable are possible solutions. Free space radio may be used if Home Office licensing regulations permit. The potential advantage of free space radio is
that it may give two way communication between track and vehicles with a relatively high band width.

9.4 The Potential For Automatic Driving.

This report whilst concentrating on the technical problems of automatic driving has covered a wide range of potential applications. Systems which might employ automatic driving range from the novel PRT systems, employing new forms of guidance and suspension, to conventional passenger railway trains.

For PRT systems automatic driving is an essential feature. Whereas in most cases the economics for introduction of such transportation facilities is questionable, it is likely that in the next few years we will see the introduction, at least on a small scale, of such systems. Likely sites for these systems include large international airports and major exhibition sites. Since the systems cannot compete in capacity terms with conventional rapid transit systems, it is unlikely that the PRT proponent's dream of city centre networks offering a rapid door to door service, will be realised in the foreseeable future.

The application of automatic driving to conventional railway systems is optional. Arguments in favour of automation have been raised on numerous grounds. Of these the least controversial are energy saving and consistency of running. Much greater savings are possible, by fully exploiting the potential for automatic driving, but this requires the co-operation of engineering departments and trade unions. In the long term,
introduction of automatic driving will be inevitable if certain services are to continue. It is to be hoped however, that transport administrations together with their workers will be able to adopt a constructive approach, which may lead to the adoption of new technology to provide improved services for their customers, together with improved opportunities for their staff.
APPENDIX A. PRINCIPAL FEATURES OF AUTOWAGON AND MINITRAM SYSTEM.

A1 INTRODUCTION.
Most of the proposed systems of guided vehicles and dual mode vehicles fall into the category of short automated guided vehicles. Since this study is intended to consider the general theoretical aspects of safety interactions and vehicle controllers it is not appropriate to review the systems here. Ref. 10 gives a reasonably up to date summary of the principal features of most systems of personal rapid transit. For freight the British Rail Autowagon system is the only system of its kind.

For general conclusions to be drawn from the theoretical treatment, it is necessary to select typical system parameters to interpret the results. Autowagon and Minitram proposals with their flexibility of operation and differing applications are reasonably representative of the range and information concerning them is fairly readily obtainable.

A2 PRINCIPAL FEATURES OF MINITRAM.
The minitrain concept is essentially a system of small automated individually powered passenger carrying vehicles operated on a segregated guideway. For a detailed description of the system, the reader is referred to Ref. 7 and to the appropriate specification, (Ref. 22). A typical Minitram vehicle would be about 3 m long with accommodation for up to 6 seated and perhaps 8 standing passengers. The vehicles are capable of coupling into trains of up to 3 vehicles, thus giving a capacity of 42 places per train. The vehicles are electrically powered, operating generally on a lightweight
overhead guideway, at plain line headways as low as 10 seconds.

The tracks are normally uni-directional so that double track is required for a two directional flow. A typical Minitram station form is the "D loop" illustrated in Fig. A2.1. This form has been recommended recognising the capacity limitation of stopping and starting on a single line. Larger stations would of course comprise as many platforms as was necessary to cope with the traffic demand. The relatively small size of the vehicles and the coupling capability provides a degree of flexibility in operation, so that out of peak periods, single vehicles might operate and in the peak or on busy routes, up to 3 vehicle trains might be employed.

In the early stages of implementation, and during peak periods, scheduled operation is envisaged, but the station design has potential for "on demand" operation and mixed express and stopping train services, albeit at reduced system capacities.

The overall capacity of the system is somewhat less than of an exclusive bus lane with an intensive service, but environmental intrusion is considered less and quality of service should be higher. Clearly, Minitram is not a serious competitor in the rapid transit area so adequately served by modern automated high capacity conventional railway systems, but rather an intermediate system offering great flexibility in operation and thus much of the attraction of the private motor car.
A brief summary of the technical performance is given in Table 1.

A3 PRINCIPAL FEATURES OF AUTOWAGON.

Although extensive studies were carried out by the British Rail Research Department, concerning the Autowagon concept, for obvious commercial reasons little was published. An outline of the system was published in Railway Gazette International (Ref. 8), but the summary below is extracted from the British Rail Project Description.

The essence of the concept is a fleet of 10 000 to 20 000 self-powered driverless container carrying vehicles moving up to 100 million tonnes of freight annually, much of which would be won from the roads. The movement pattern for these vehicles would be planned in real time by a national computer hierarchy which could grow out of TOPS (the British Rail Total Operations Processing System, monitoring vehicle movement and providing management and customer services). Actual control over vehicle movement would be maintained by existing signalling systems, either automatically or signalman operated according to local circumstances. There would of course be some capacity problems, but since Autowagon would not require un-interrupted green signalled timetabled paths, they would be able to exploit the considerable amount of random spare capacity that is denied to the planners of timetables. In conurbations and other areas of high density flows, a moving time block convoy control system would be employed. The relationship between the head and tail of such a convoy and other trains would be in accordance with the standard fixed block arrangements. Within
the convoy moving time block control (or such other control as might be devised) would be employed, with consequential increases in train line capacity as the signalling system would not have been designed with Autowagon in mind. Further possibly more significant advantages would be obtained in the various transition situations which arise, including starting, stopping, negotiating mandatory speed restrictions, merging and diverging. Since the convoy control system is used to overcome some of the very obvious deficiencies of the fixed block signalling system, for high capacity purposes it is very important that the system performance should be predictable and result in high utilisation of available track capacity.

The technical performance is summarised with the Minitram characteristics in Table 1.

<table>
<thead>
<tr>
<th>TABLE 1.</th>
<th></th>
<th>Minitram</th>
<th>Autowagon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>slow</td>
<td>fast</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>14.5</td>
<td>25.0</td>
<td></td>
</tr>
<tr>
<td>Maximum Longitudinal Acceleration</td>
<td>1.2</td>
<td>1.2</td>
<td>1.0 m/s²</td>
</tr>
<tr>
<td>Maximum Lateral Acceleration</td>
<td>0.6</td>
<td>0.6</td>
<td>- m/s²</td>
</tr>
<tr>
<td>Maximum Jerk in all cases</td>
<td>1.2</td>
<td>1.2</td>
<td>1.0 m/s³</td>
</tr>
<tr>
<td>Gradients</td>
<td>10</td>
<td>10</td>
<td>2.5 %</td>
</tr>
<tr>
<td>Steady Wind</td>
<td>25</td>
<td>25</td>
<td>- m/s</td>
</tr>
<tr>
<td>Minimum Curves</td>
<td>8</td>
<td>8</td>
<td>- m</td>
</tr>
<tr>
<td>Vehicle Length</td>
<td>3(9)</td>
<td>3(9)</td>
<td>10-15 m</td>
</tr>
</tbody>
</table>
FIGURE A.2.1  D LOOP STATION
FIGURE B1  BLOCK SIGNALLING

FIGURE B2  3-ASPECT SIGNALLING

FIGURE B3  4-ASPECT SIGNALLING
APPENDIX B. RAILWAY SIGNALLING.

The purpose of the signalling system is to keep trains a safe distance apart at all times, but other than such specialised applications as approach control at junctions, no direct control is included. Normal control is exercised by the driver of the train with regard to the timetable and geographical constraints. The signalling system is therefore part of but not the complete safety system.

Earliest railway systems despatched trains along a line at intervals of time which, including a safety margin, should have allowed preceding trains to clear. However, the "open loop" problems of such control were evident and fairly rapid development of the railway resulted in the block system, which has survived with little modification over large areas of the network to this day (Ref. 3). Basically, the line to be signalled is divided into block sections with associated protecting signals. The entrance to a block is protected by a home signal or stop signal and a distant or warning signal is placed braking distance in rear of this signal. The arrangement is shown in Fig. B1. The block length may vary considerably depending upon the traffic requirement, a minimum being the braking distance of hundreds of yards, and large block sections being several tens of miles long.

A communication system with mechanical and electrical interlocking prevents the signalman from admitting more than one train into each block. The headway attainable on a given line is clearly related to the block length. Where traffic is heavy, block lengths are correspondingly shorter, and distant signals may extend back to the preceding home signal.
and be physically mounted on the same post. This leads to a uniform system of blocks with signals separated by the line speed braking distance. Each signal is capable of displaying three aspects, and even if two or more men are required to operate each signal this is the fore-runner of the three aspect colour light signalling system illustrated in Fig. B2. The signal separation is basically the braking distance of the worst braked train on the line, defined according to the braking curves (Ref. 67), which take account of gradient and train performance.

The system involves very coarse quantisation of distance, but for the defined speed and braking performance for which the line is signalled, no improvement in steady state capacity can be achieved by sophistication without relaxing the safety requirement. This is an academic observation, since in practice we do not have consistent train performance or a steady state. In the real situation, advantage is obtained by finer quantisation of distance measurement. The British Rail standard four aspect colour light signalling system provides finer quantisation of distance information by the introduction of a second warning signal half way between the warning signal and the stop signal. With this system, slower trains operating on a line signalled for high speed need only react to the second warning signal. For trains of comparable performance following one another there is less tendency for propagation of disturbances to running. Fig. B3 illustrates the standard four aspect system.

In some areas of the Southern Region of British Railways, where very high density flows are encountered, a pseudo fifth aspect
is introduced at terminal approaches to minimise the interaction of trains approaching platforms.
APPENDIX C. MAXIMUM SPEEDS AROUND CURVES.

The maximum permissible speed around a curve is determined in general by the comfort of passengers or load stability under applied lateral acceleration forces. The maximum permissible values of lateral acceleration are not clearly defined, but in the case of passengers, experiments have been carried out with existing modes of transport to determine passenger tolerance to different rates of acceleration. Gebhard (Ref. 23) and Hoberock (Ref. 27) have summarised a number of these experiments both for lateral and longitudinal acceleration. Their conclusions together with current practice form the basis for definition of acceptable limits of comfort.

The lateral jerk, or rate of build up of the acceleration, is important for both passengers and freight. This is not so easily measured as the steady state acceleration, since it is a function of the rate of change of curvature, the velocity and the rate of change of velocity, since in general the speed will not be constant over the transition curve. Several proposals have been made for transition curve designs, but generally it is assumed that it is possible to traverse the curve at cruising speed so the analysis is based on steady speed.

In his paper on PRT Geometry Dais (Ref. 18) recommends the clothoid curve. This is a curve of constant jerk which for small angles of deviation approximates to:

\[ Y = \frac{5}{3} x^3 \]
FIGURE C1 UNBANKED CURVES
A typical turnout for a loop or off-line station would be composed of four sections taken from such a curve, in appropriate orientations to provide constant jerk of changing sign. The jerk is defined by the equation:

\[ C = 16 \frac{h}{L_4^3} \]

where \( h \) is the ultimate line separation and \( L_4 \) is the length of the turnout. He shows for typical PRT parameters how the length of such a turnout would need to be between about 250 and 600 feet depending upon the severity of the jerk constraint imposed.

Curves of such proportions would not easily fit into the urban fabric of British cities, so some reduction of speed must be accepted to reduce the size of curves and turnouts where necessary.

The lateral acceleration experienced by a body moving in a uniform curved path of radius \( r \), when travelling at a velocity \( v \), is defined by the following equation:

\[ K_1 = \frac{v^2}{r} \]

so if the maximum lateral acceleration is specified, then the maximum permissible speed around the curve is defined by the equation:

\[ V = \sqrt{K_1 \times r} \]

This is illustrated in Figure C1.
FIGURE C2. BANKED CURVES
If the curve is banked to an angle $\alpha$, toward the centre of the curve, then a resolved component of the gravitational acceleration acts so as to reduce the perceived lateral acceleration of the passenger. In this case, the maximum speed is increased and defined by the equation:

$$V = \sqrt{(K_p + g \sin \alpha) \times r}$$

where $K_p$ is the perceived lateral acceleration and:

$$K_1 = \frac{K_p + g \sin \alpha}{\cos \alpha}$$

Fig. C1 shows the typical steady state cruising speed around uniform curves, for different lateral acceleration limits. Fig. C2 shows the permissible speed around severely banked curves. It must be appreciated that it is not always possible to apply such banking, and the design of transition curves will become very complicated if constraints of cant gradient are included. No banking whatsoever may be permissible in the region of switches and reverse curves and in these cases the more severe speed restrictions of Fig. C1 must be employed.
APPENDIX D. DEFINITION OF FOLLOWING LAWS.

The basic safety constraint may be expressed as a minimum separation of vehicles and we refer to the "Following Laws" so derived as moving block systems, because of their derivation from railway block principles. There is much confusion in the literature concerning the definition of moving block signalling, and it is necessary within this report to rigorously define different forms of moving block.

Pure Moving Block is defined where the minimum inter-vehicle distance is equal to the stopping distance of the following vehicle at all speeds. This is clearly the limit of safety according to our definition. Neglecting jerk and vehicle length the system may be expressed:

\[ S = \frac{V^2}{2 \times B} \quad \text{D1} \]

Moving Time Block is a following law which may be considered as a linearisation of pure moving block. The vehicles are constrained to keep a constant time headway exceeding the safe line speed headway at all times. The following law is defined by the equation:

\[ S = \frac{V \times V_m}{2 \times B} \quad \text{D2} \]

Moving Space Block is a system of operation where the separation between vehicles at all times exceeds the line speed stopping distance. Neglecting jerk and vehicle length this may be expressed mathematically as:

\[ S = \frac{V_m^2}{2 \times B} \quad \text{D3} \]
Systems which do not satisfy our criterion of safety have been proposed, one such being Differential Moving Block, requiring a separation equal to the difference in braking distance of the two vehicles.
FIGURE E.1  SEPARATION, MTB & PMB
APPENDIX E. STEADY STATE PROPERTIES OF THE FOLLOWING LAWS.

The steady state characteristics of the following laws are fairly well appreciated and have been adequately reported previously (Ref. 46). This appendix summarises the principal characteristics of the moving time block and pure moving block laws.

E1  PURE MOVING BLOCK.

Using the definition from Appendix D, the capacity in Vehicles per hour derived from this is:

\[ C = \frac{3600}{V/2B} \]  

E1

This is a hyperbola tending asymptotically to infinite capacity at zero speed and zero capacity at infinite speed. Thus it would appear that if a steady state can exist, the capacity will be determined by the highest speed of operation and not the lowest, though this is contrary to general intuitive feelings. Expressed differently, the steady state capacity of a line cannot exceed the capacity of the highest speed section of the line.

E2  MOVING TIME BLOCK.

Using the following law definition from Appendix D, the capacity may be expressed as:

\[ C = \frac{3600}{Vm/2B} \]  

E2

This is a constant value independent of speed, but is determined by the maximum speed. Fig. E1 illustrates the required vehicle separation as a function of speed.
Steady State Capacity

Fig. E2
FIGURE E3  PMB EFFECT OF VEHICLE LENGTH ON SPEED FOR PEAK CAPACITY
THE SIGNIFICANCE OF VEHICLE LENGTH.

At low speeds, where the vehicle length exceeds the braking distance, the sharply rising characteristic of the pure moving block law is modified to fall with a reduction in speed. This results in the familiar pure moving block capacity characteristic with a peak capacity at some intermediate speed. For a main line railway, with typical braking performance and 10 coach trains, the peak capacity occurs at about 40 mile/h (18 m per second). Braking rates for automated systems as proposed are not very different to those of the railway, but due to the shorter vehicle length, the peak capacity for Autowagon occurs at a speed of only 4.5 m per second, and that for Minitram around 5 m per second.

The shape of the moving time block characteristic is also modified by the effect of vehicle length, the general shape of the capacity curves for both laws is illustrated in Fig. E2. The figure is constructed for typical automatic wagon parameters, and the laws for vehicle separation excluding vehicle length are indicated by dashed lines.

For given braking performance, the speed at which maximum capacity might be available under the pure moving block characteristic depends upon the vehicle length. The curve of Fig. E3 shows how the speed at which maximum capacity
CAPACITY

\[
\begin{array}{cccc}
1 & 0 & 0 & 0 \\
2 & 0.95 & 1.3 & 5.12m \\
3 & 3.54 & 5.2 & 20.50m \\
4 & 17.70 & 26.0 & 102.50m \\
\end{array}
\]

FIGURE E4 PMB VEHICLE LENGTH
FIGURE E6 PMB BRAKE RATE
capacity is obtained varies with vehicle length expressed as a fraction of the line speed braking distance. A better picture of the overall effect on steady state capacity is given by Fig. E4, showing the capacity variation with speed for several vehicle lengths. Fig. E5 shows the corresponding capacity variation with length with the moving time block law. Since the vehicle length has been normalised to the braking distance, a table is inset in Fig. E4 to interpret the vehicle length in terms of typical Autowagon and Minitram performance.

**E4 THE SIGNIFICANCE OF BRAKING RATE.**

From the capacity definitions at the beginning of this appendix, it is clear that the capacity is strongly dependent upon the braking rate. For pure moving block this is illustrated in Fig. E6 this apparently large increase in capacity related to an increase in emergency braking rate has lead many to suggest the use of high braking rate in order to increase line capacity. However, dynamic considerations described in Section 3 and Appendix H show the problem to be more involved.

**E5 JERK LIMITED BRAKING.**

If a jerk limit is applied to the brake application, the effect is similar to that of a first order lag up to full braking. This means that time is taken to apply the brakes and thus the stopping distance is extended. If the stopping distance is calculated to determine the desirable separation of vehicles, then account must be
FIGURE E7  JERK BRAKING
FIGURE E8  JERK SIGNIFICANCE
taken of any initial braking or accelerating. The stopping distance of an accelerating vehicle is much greater than that of a coasting or braking vehicle, due to the jerk limit on removal of accelerating forces. When stopping with a jerk constraint, the integral of the acceleration with respect to time must be the same as in the simple braking case. The stopping time is thus given by the equation:

$$T_s = \frac{V}{B} + \frac{B}{K}$$  \hspace{1cm} E3

where in this equation $K$ is the jerk limit and the equation is valid only if the initial speed is sufficient to permit build-up and removal of maximum acceleration. The stopping distance derived from this equation is:

$$S = \frac{V^2}{2B} + \frac{BV}{2K}$$  \hspace{1cm} E4

Fig. E7 shows the acceleration and velocity time profiles corresponding to the above formulae and the principal effect is demonstrated to be rounding of the sharp discontinuities of gradient in the velocity profile. Fig. E8 shows the effect on capacity both for pure moving block and moving time block systems. For a given braking rate, the effect of jerk increases with a reduction in speed. This is because at lower speeds the time taken to apply and remove the brake force is a more significant proportion of the total stopping time.
It was stated above that the allowance to be made for jerk depends on the initial conditions and Pitts (Ref. 69) has formed a general equation for the stopping distance of the following vehicle at speed $V$. Translated to the notation of this report, Pitts equation becomes:

$$S(V) = tV + \frac{V^2}{2B} + \frac{Vb}{K} + \frac{Vb^2}{2Bk} + \frac{tVb}{B} + \frac{tb^3}{2BK} + \frac{b^4}{8BK^2} + \frac{t^2b^2}{2B} + \frac{Bb^2}{4K^2} + \frac{tBb}{2K} + \frac{bt^2}{2} + \frac{b^3}{3K^2} + \frac{b^2t}{K}$$  \hspace{1cm} E5

The detection and reaction time, $t$, may be neglected in considering the ideal performance, and the expression simplifies to:

$$S(V) = v^2 + \frac{VB}{2B} + \frac{Vb}{K} + \frac{Vb^2}{2Bk} + \frac{b^4}{8BK^2} + \frac{Bb^2}{4K^2} + \frac{b^3}{3K^2}$$  \hspace{1cm} E6

even this expression is cumbersome and in order to appreciate the significance, it is appropriate to consider the extreme values of acceleration which may be present at the instant of failure. Equation E4 defines the stopping distance with no initial acceleration. It can be shown by integration of the velocity over the appropriate time interval but the additional distance travelled by a vehicle with an initial maximum acceleration is given by:

$$Sa = \frac{2VB}{K} + \frac{2B^3}{3K^2}$$  \hspace{1cm} E7

Similarly the additional distance travelled during
The removal of the brake application on coming to rest is given by:

\[ S_b = \frac{B^3}{24K^2} \quad \text{E8} \]

Thus, if maximum braking is applied before the instant of failure, the stopping distance becomes:

\[ S = \frac{v^2}{2B} + \frac{B^3}{24K^2} \quad \text{E9} \]

If maximum acceleration is applied before failure the corresponding stopping distance becomes:

\[ S = \frac{v^2}{2B} + \frac{2vB}{K} + \frac{17B^3}{3K^2} \quad \text{E10} \]

Whereas the distance given by equation E9 may not differ much from the distance from equation E4, the distance defined by equation E10 is clearly much greater than that of equation E4.

Thus it must be concluded that if allowance is to be made for the jerk limitation in braking distance calculations, allowance must also be made for the initial conditions of the vehicle. Equation E5 shows that in general this may involve a complex calculation.
APPENDIX F. ELECTRICAL NOISE ON TRACTION VEHICLES.

F1 INTRODUCTION.

It has been recognised for some considerable time that the electrical noise environment within traction vehicles, either electrically propelled or employing electrically operated control gear, is very severe. Although the TACT (Total Automatic Control of Trains) Autodrive equipment was designed to operate in the environment, problems occurred during commissioning in Spring 1976, which highlighted the need for greater attention to noise immunity considerations in some aspects of system design.

As a development test bed for ATO principles, the equipment comprised a number of modules interlinked by numerous screened cables. Opto-isolator/couplers (OIC) were employed to eliminate ground loops and improve noise immunity. Care was taken in the system design to provide adequate earthing and power supply de-coupling and low pass filters were included in the mains supplies.

F2 NOISE SOURCES.

This Section shows the magnitude of the noise immunity design problem by describing the noise sources and potential difficulties of suppression. The test vehicle for TACT work was Test Unit Gemini, a two car battery railcar. Although its traction system is unique on British Rail, the general control gear on Gemini has some features in common with a conventional system. The control voltage is 110 V derived from tappings on
Figure F1
Operation of compressor contactor, solenoid coil voltage
500 V/cm vert.
0.5 mS/cm horiz.

Figure F3
As above, but measuring supply voltage at main isolating switch
100 V/cm vert.
0.2 mS/cm horiz.

Figure F4
Operation of D.S.D. solenoid, supply voltage measured in Autodrive traction interface
200 V/cm vert.
1 mS/cm horiz.
Figure F2 Contactor Coil Supply Arrangement.
the 440 V traction battery and solenoid operated contactors are used extensively. Some of the coils of these contactors have been identified as possessing significant inductance and with the capacitance of the associated line, switching of the inductors results in unstable arcing and very large noise voltages. Fig. F1 illustrates the supply arrangement for a typical contactor coil. The unstable arc of the governor switch on the compressor contactor results in the coil voltage illustrated in Fig. F2 which was taken at Point "a" of the diagram, Fig. F1. The restriking of the arc and subsequent recharging of the line is shown clearly; the behaviour is analogous to that of a relaxation oscillator. The envelope voltage rise is determined by the current in the inductor and the capacitance of the line; the mechanism is explained in some detail in Ref. 1. The restriking of the arc discharges the energy stored in the line capacitance into the supply with the result that supply side spikes are generated, Fig. F3. The photograph, Fig. F3, was taken on the main battery feed at the isolating switch (Point "b" on the diagram) and shows spikes of comparable magnitude to the control voltage which are developed across the battery. The photograph, Fig. F4, was taken further from the battery, at the point where the TACT 110 V feed for relay operation is tapped off. The amplitude of the spikes of Fig. F4 is in excess of 300 V. These measurements are wholly consistent with the observations of control gear on diesel electric locomotives referred to in Ref. 76.

In general, suppression techniques can be applied to troublesome contactor coils, particularly if this is done
at the design stage. However such techniques usually introduce a slowing down of the drop-out of contactors and introduce additional potential failure modes. For example, a very effective way to suppress a coil is by the addition of a free-wheeling diode, but the circulating current will delay the release of the relay armature. This delay may, as in the case of the compressor contact on Gemini, be unimportant, but such a suppression diode will behave as a free-wheeling diode for any other inductive load connected on the same side of any isolating switch. Care must therefore be exercised so that the operation of the system is not adversely affected.

The above paragraph is intended to indicate the nature and complexity of the problem. For a more detailed treatment of suppression techniques the reader should consult Ref. 76. From our own and other work in this area, and from the consideration that it may be impossible to suppress all noise sources, a clear principle emerges, namely that when designing electronic equipment for use in a traction environment, it is desirable that the equipment should be capable of functioning without modification to the traction gear. New traction systems may of course be designed with electronic equipment noise limitations in mind, in which case the designer of the electronic equipment will have a somewhat easier task.

THE TACT EQUIPMENT.

The TACT equipment is described in Appendix Q and from the diagram contained in that Appendix is will be seen
that the system consists of a number of modules surrounding a central control computer. Opto-isolator/couplers are provided on all inter-modular links and on the train lines where they enter the equipment. All input/output and inter-connection cables are multi-core overall screened cables, in most cases being R.S. Components 19-way cables terminating in unscreened plugs with a screen brought through to a pin connection. The screens were originally all earthed at the interface module. Most signals within the system are transferred between modules as TTL logical signals. The train line signals emanate from 24 V relay contacts and use has been made of changeover contacts wherever possible, thus providing a low impedance source in either state.

Most signals are electrically relatively slow and permit the use of slow opto-isolator couplers. However, the micro-processor data flag and the accelerometer busy and strobe pulses are all comparatively fast signals; the speed of response of the control computer to these signals requires that they and their associated data bits are driven through fast opto-isolator couplers. The most critical signal for noise immunity is the micro-processor data flag. In normal operation this provides a burst of 26 800 nanosecond pulses, at a rate of 1 every 0.5 micro seconds, in each one second period. On the leading edges of these pulses the data bits change and they are read by the control computer on the trailing edge. Corruption of these data flag pulses therefore results in additional or missed data, either of which will be detected as an error
by the software.

**F4 USE OF OPTO-ISOLATOR/COUPLERS.**

Opto-isolator couplers were used extensively in the design of the TACT equipment in order to eliminate the possibility of ground loops on inter-module links. It was also appreciated that significant relative earth potentials could exist in a traction vehicle. Differential measurements made during the course of electrical noise investigation of the TACT equipment, have shown that relative noise voltages on exposed metalwork of modules less than 2 m apart may exceed 50 V, thus tending to justify the use of OIC's rather than line driver/receivers. It was assumed that common mode coupling through the OIC would be negligible but our tests have shown that this is not always so; Section F5 describes the effect.

The preferred location of the OIC is at the receiving end of the line, as illustrated in Fig. F5 and F6, this arrangement permitting simple RC filtering. The distribution of the OIC current limiting resistance as shown in Fig. F6, provides a measure of balance to the signal. Earthing the centre of the capacitance reduces the capacitive common mode coupling at the receiver. The filter should of course be made at the entry to the module and the enhancement of Fig. F6 may not be used if several data line share a common return. Note that the total resistance of the circuit provides current limiting to the opto-isolator. The RC must be chosen so as not to significantly degrade the signal.
A non-preferred location for the OIC is at the sending end, but it is sometimes necessary to place the device here as in Fig. F7. This arrangement makes the provision of RC filtering difficult as the maximum series resistance is dictated by logic low constraints and the maximum capacitance is determined by ringing on the line and energy dissipation in the OIC transistor on turn on. A good general principle if this arrangement must be employed is to use the shortest cable length possible, with slow RC filtering at the sending end (on the diode side of the OIC), to reduce the common mode coupling, and fast filtering at the receiving end to remove high frequency noise, as illustrated in Fig. F8.

**OPTO-ISOLATORS INTENDED FOR HIGHER SPEED OPERATION.**

Opto-isolator/couplers used for fast data signals are internally constructed as shown in Fig. F8. The base of the second transistor of the Darlington pair is brought out in order to enable a resistor to be connected between Points A and B; this resistor has the effect of reducing the gain and increasing the speed of the device. Initially resistors used in the equipment were selected so as to give adequate speed of operation and the conditions of available drag. The wide spread of individual device characteristics means that since worst case design methods were employed, the actual operation conditions of any OIC were not well defined.

At first sight it appears that operation of the OIC's in a fast mode would give a large signal band width and correspondingly a large noise band width. It was therefore postulated that
Figure F9 Internal construction of high speed O.I.C.
operation of the OIC's in their slower mode should provide
a measure of filtering as long as no timing problems of
the data transfer occurred. However in practice it was
found that the noise performance of the OIC's in the slower
mode was significantly worst than during fast mode operation.
We believe this apparent anomaly can be explained as follows.
The most sensitive state for noise is the off state in which
the LED is extinguished and the transistors turned off. The
primary coupling mechanism in this state is the capacitive
coupling between the LED and the photo-diode in the base
of the Darlington pair. Since the gain of the OIC in the
slow mode is high, it follows that the common mode
transmission will also be high. We have therefore found it
appropriate to run the OIC's in their fast mode with
separate RC filtering preceding the OIC to give the
required speed of operation and hence noise band width.

In the case of the micro-processor flag pulses, this was
still insufficient and the 800 nanosecond pulses had to
be stretched to 35 micro seconds before sufficient filtering
could be applied to solve the problem.

Opto-isolator couplers are generally capable of providing
a very high degree of common mode voltage isolation.
However, the internal diode and transistors are very
sensitive to abnormal drive. In particular in the off state
of the LED the reverse voltage must not exceed a threshold
which could produce breakdown of the LED and, more importantly,
the pull up supply in the receiver side must not exceed a
very small reverse voltage. Normally this latter constraint
is unlikely to be violated, but if sufficient lead length
FIGURE F10
is attached to the device or if additional capacitance is added to perform a filtering function, failure may occur.

F6 EARTHING.

Fig. F10 shows a simple equivalent circuit of 2 inter-connected earth modules. Each module is assumed to have capacitance to ground and to have lossy inductive connection to ground. It is thus possible in a noisy environment for the two systems to possess earth potentials of \( V_{cm1} \) and \( V_{cm2} \) respectively. Clearly any direct inter-connection of the modules incurs an earth loop and could produce a significant common mode voltage. However the effective isolation of this common mode voltage by the use of OIC's with small forward capacitance reduces the need for solid earth bonding, as there is no closed path for induced earth current.

F7 SCREENING.

Extensive use has been made of screened cables in the TACT system. Since most signals terminate in unbalanced sources or loads it is not practical to use balanced feeds or twisted pairs. It is believed that the major source of interference is capacitive from the electric fields of the cables running in close proximity, rather than from mutual inductance of the cables. It was expected therefore that good quality screened cables suitably earthed would provide adequate noise immunity. Earlier work by the author, Ref. 77, indicates the significance of the choice of the appropriate cable for best effectiveness in a given frequency band. Since the troublesome noise spikes have a band width in excess of 10 MHz it is desirable that the
ORIGINAL ARRANGEMENT

MODIFIED ARRANGEMENT

SCREEN CONNECTIONS TO OBTAIN CAPACITIVE BYPASS OF OTC

FIGURE F11
screens of the cables be properly terminated in screened plugs, Ref. 78. Unfortunately the plugs used in the TACT equipment did not provide for proper termination of the screens. The problem was not severe in the case of the shorter cables (up to 3 m) so long as the earth connection was at the opposite end to the OIC to avoid capacitive by-pass. This is illustrated in Fig. F11. Longer cables (up to 20 m) proved troublesome, presumably due to the distributed impedance of the cable and core impedences with the unbalanced nature of the signal.

Satisfactory performance was obtained with the arrangement described in Section F4.

F8 POWER SUPPLIES AND CROSS-COUPLING.

All TACT modules, with the exception of 110 V traction relays, are supplied with 240 V 50 Hz from a motor generator run from the traction batteries. All modules incorporate small LC filters. In addition it was found necessary to include a radio frequency filter in the supply to the HP computer as this would not operate satisfactorily without it. Cross-coupling within the modules, generally via the power supplies has been a major problem, and considerable time was expended to differentiate between causes and effects. Normal decoupling techniques have been employed at the power supplies resulting in significant reduction of the noise voltage; however noise voltages of comparable peak magnitude to the supply voltage persist.

The power supply to the relay driver transistors is particularly important as the relays are remote from the electronics. The voltage ratings of the transistors \( V_{ce0} \)
Figure F12
Operation of driver's brake controller, voltage impressed on 24 volt supply
10 v/cm vert.
0.5 mS/cm horiz.

Figure F13
Sporadic traction noise during acceleration, voltage impressed on 24 volt supply
10 v/cm vert.
0.5 mS/cm horiz.
must provide an adequate margin for the power supply voltage plus any expected noise voltage. In the TACT equipment a 24 V supply has been used with 50 V transistors. This margin is inadequate in the application as noise voltages exceeding 30 V, albeit for extremely short periods, have been observed on top of the supply voltage and two failures have occurred. Fig. F12 shows the noise experienced on the 24 V supply before the application of suppression techniques, due to operation of the drivers safety device solenoid. Fig. F13 shows the noise generated by an unidentified contactor in normal running at about 30 mile/h.

CONCLUSION.

Experimental observation of the electrical environment of traction vehicles, and consideration of the practical problems of suppression of an existing traction system lead us to believe that suppression of all noise sources to an acceptable level for transmission of low level base band logic signals is probably an impossible task. Accordingly we believe equipment must be designed to work in the presence of the noise.

To avoid ground loops and hence overcome some noise problems the TACT equipment made use of opto-isolator couplers extensively. A study of the behaviour of the-system has shown that caution must be exercised in the use of such couplers, but it is questionable whether line drivers and line receivers providing a pseudo balanced signal path would be an improvement since they would introduce a significant common mode signal due to the inherent earth coupling. The TACT equipment functioned satisfactorily
for a period of some 14 months on an experimental train and we believe validated the approach of making the equipment tolerant of the severe environment in which it exists rather than attempting to undertake what may be an impossible task of improving the environment sufficiently.

The experience gained in the design and use of the TACT equipment has been employed in the design of BRATO equipment. Experimental equipment has been made to operate satisfactorily on an overhead electric 25 kV multiple unit and engineered equipment is currently being developed. In this equipment which is rather more compact than the TACT equipment a combination of line drivers/receivers and opto-isolator couplers is employed.
APPENDIX G. CRITICAL POINT ANALYSIS.

It has been shown, Ref. 9, that for a succession of trains approaching a speed restriction, there exists a point at which if they are then safe, they will be safe at all times during the speed transition. For the simple case of maximum effort braking, with no jerk limitation, this critical point occurs when the first vehicle is the full line speed braking distance from the point of brake initiation of the following vehicle. Ignoring vehicle length (as is reasonable with Autowagon parameters and moderate speed restrictions), the time taken for the first vehicle to reach the critical point is given by:

\[ T = \frac{V_m - V_s}{B} + \frac{V_s^2}{2B} \]  

The two terms of this equation correspond to the time taken braking to the restricted speed and that travelling the remainder of the braking distance at restricted speed, respectively. If the vehicle length is included in the formulation, the time taken to reach the critical point becomes:

\[ T = \frac{V_m - V_s}{B} + \frac{V_s^2}{2B} + \frac{L}{V_s} \]  

Clearly if maximum effort braking is being used and the vehicles are identical then the profiles followed by the vehicles will also be identical. Thus for the specified conditions, equations G1 and G2 define the minimum safe headway. If these headways are compared with the steady state requirements of pure moving block and moving time block, we find them to be considerably in excess of either. Neglecting vehicle length the moving time block headway is given by:

\[ H (mtb) = \frac{V_m}{2B} \]  

For pure moving block, again neglecting vehicle length the
FIGURE G1 HEADWAY LIMITS FOR MAXIMUM EFFORT BRAKING.
headway is given by:

\[ H(pmb) = \frac{V}{2B} \] \hspace{1cm} G4

The headway represented by equations G1, G3 and G4 are plotted in the Fig. G1.

It is clear that the potential headways suggested by equation G4 are unrealisable in a steady state transition, since this would require following trains to gain time on their leaders, whilst still following the same velocity profile. It is shown in the main body of this report that if sufficiently close control can be exercised over the velocity profile followed by each vehicle, then performance approaching that suggested by equation G3 may be obtained. This improvement in headway can only be achieved at the expense of journey time and of course represents a departure from the maximum effort braking situation.
APPENDIX H. VELOCITY PROFILE SHAPING.

The passage of a string of closely spaced vehicles through a speed transition has been shown in Section 3 to be potentially restrictive of capacity, regardless of the signalling system employed. For a stable steady state to exist, with vehicles passing through the transition, all velocity profiles must be identical.

It has further been shown in Section 3, that with moving time block control and approach at line speed headway, the headway in the restriction tends to the ideal headway as the effect of the restriction propagates along the string. This suggests that it may be possible to maximise journey speed or capacity by shaping of the velocity profiles followed by the vehicles.

H1 MOVING TIME BLOCK SPEED RESTRICTION ENTRY.

Consider the case of a string of vehicles approaching a speed restriction under MTB control.

The initial conditions are:

\[ V_1(0) = V_m \]
\[ V_2(0) = V_m \]
\[ T(0) = \frac{V_m^2}{2B_2} \]
\[ X_1(0) = -\left(\frac{V_m^2 - V_s^2}{2B_1}\right) \]
\[ X_2(0) = X_1(0) - T(0) \]
The instantaneous velocity of the leader is given by:

\[ V_1 = \frac{V_m}{2B_2} - B_1 t + B_1 \frac{U(t - \tau)}{V_m} \]

Where \( U(t - \tau) \) is a delayed ramp.

When following the leader according to the MTB law:

\[ \frac{dT}{dt} = 0 \]

and

\[ \frac{dT}{dt} = V_1 - V_2 \]

Thus:

\[ \frac{d(T/V_2)}{dt} = V_2 (V_1 - V_2) - \frac{V_m}{2B_2} \cdot \frac{dV_2}{dt} = 0 \]

For \( V_2 \neq 0 \), which must be true for \( V_m > 0 \) and \( T \leq \frac{V_m}{B_2} \)

Thus

\[ V_1 - V_2 = \frac{V_m}{2B_2} \cdot \frac{dV_2}{dt} = 0 \]

Substituting for \( V_1 \) and taking Laplace transforms;

\[ \frac{V_m \cdot V_2(s)}{2B_2} \cdot s + \frac{V_2(s)}{s} - \frac{V_m}{s^2} + \frac{B_1}{s^2} - \frac{B_1 e^{-\tau s}}{s^2} = 0 \]

Rearranging and taking inverse transforms;

\[ V_2(t) = \frac{V_m}{2B_2} (1 - e^{-\frac{2B_2 t}{V_m}}) - B_1 t + \frac{V_m B_1 (1 - e^{-\frac{2B_2 t}{V_m}})}{2B_2} + B_1 (t - \tau) + \frac{V_m B_1}{2B_2} (e^{-\frac{2B_2 (t - \tau)}{V_m}} - H(t - \tau)) \]

It might be possible to similarly analyse the behaviour of successive vehicles in the string, but it is likely to be a time consuming exercise, and the expressions for the velocity profiles in the region of the tenth vehicle can be expected to be complicated.

An alternative approach is to try to approximate the tenth
Figure H1. Comparison of jerk limited profile with 10th vehicle profile.

- * 10th vehicle.
- Jerk limited.
- Reduced braking.
Figure H2 Definition of Excess Distance.
vehicle profile with a simple analytical form. Fig. H1 shows the tenth vehicle profile compared with a constant jerk profile and the correspondence is very good.

H2 JERK LIMITED SPEED TRANSITION.

Consider now the approach to a speed restriction with a profile defined by constant jerk but still subject to constraints of maximum braking.

Nominal time to brake \( t_{\text{nom}} = \frac{V_m - V_s}{m_B} \)

Average speed for any symmetrical (time) profile = \( \frac{V_m + V_s}{2} \)

Case (A). If full brakes achieved, time for transition:

\[
 t_1 = \frac{V_m - V_s}{m_B} + \frac{B}{K}
\]

Case (B). If full brakes not achieved, time for transition:

\[
 t_1 = \frac{2B^1}{K} \quad \text{where} \quad B^1 = \frac{2(V_m - V_s)}{m_B}
\]

\[
 = 2\left(\frac{K(V_m - V_s) \times 2}{K}\right)
\]

\[
 = \frac{8(V_m - V_s)}{K}
\]

Distance-for-transition (Case A): \( S_t = (V_m + V_s) - (V_m - V_s) \)

(since \( \frac{m_s}{m_B} \) and \( \frac{m_s}{K} \))

Distance-for-transition (Case B): \( S_t = \frac{8(V_m - V_s)}{K} \left(\frac{V_m + V_s}{2}\right) \)

Excess distance travelled at reduced speed during transition (see Fig. H2) given by:
Figure H3 Computer Simulation of varying Jerk Limit.
Figure H4: Journey time and headway trade-offs for jerk limitation.
\[
S_x = s_t - \frac{v_m^2 - v_s^2}{2B}
\]

Lost time \( t_x = t - \frac{v_m - v_s}{B} - \frac{S_x}{v_m} \)

As described in Section 3, there is a compromise between journey time lost and system capacity. The time loss for various conditions of speed limit and jerk constraint is easily established by substitution in the above equations. The necessary increase in headway is difficult to establish analytically because of the discontinuous nature of the velocity profiles and it has proved convenient to analyse numerically on the University ICL1905 computer. A computer program has been written and as well as evaluating numerically the headway requirement, it produces a graphical output showing the behaviour of the safety margin during the transition.

Fig. H3 is an example of the output of this computer program and in this case it is evident that the more restrictive jerk constraint result in flatter safety margin curves, which of course require less excess headway. The penalty of journey time cost is not evident. Fig. H4 clearly shows the trade-off of headway versus journey time cost for a jerk constrained approach to various speed restrictions.

**H3 BRAKE LIMITED PROFILE.**

Consider as an alternative to the jerk limited profile of Section H2 the restraint of braking to some fraction of that available. Let the braking rate employed be \( B/R \), where \( B \)
is the emergency braking rate and \( R \) is a constant greater than unity. The distance travelled braking at the reduced rate is given by:

\[
S_t = R \left( \frac{V_m^2 - V_s^2}{2B} \right)
\]

Corresponding time \( t_1 = R \left(\frac{V_m - V_s}{B}\right) \)

Normal braking distance:

\[
S_m = \left( \frac{V_m^2 - V_s^2}{2B} \right)
\]

with a corresponding time

\[
t_m = \frac{V_m - V_s}{B}
\]

Excess distance travelled is:

\[
S_x = (R - 1) \left( \frac{V_m^2 - V_s^2}{2B} \right)
\]

So that the excess time to complete the transition is:

\[
\frac{t_L}{t_m} = t_1 - t_m - \frac{S_x}{V_m} = (R - 1) \left( \frac{V_m - V_s - \frac{V_s^2 - V_s^2}{2BV_m}}{B} \right)
\]

So long as the gradient of the safety margin curve is less than the restricted speed at the point of minimum safety margin, the excess headway required may be determined by computation of the time taken to travel the normal braking distance and subtracting the minimum headway from this. The minimum headway is given by:

\[
H = \frac{V_m}{2B}
\]
Figure H5: Journey time and headway trade-offs for brake limitation.
VELOCITY PROFILING TRADE-OFFS

\[ v_s = \frac{v_m}{2} \]

Figure H6.
The time taken to travel the corresponding distance at reduced braking rate is given by solution of the quadratic:

\[- \frac{B t^2}{2R} + V_t - \frac{V_m^2}{2B} = 0\]

so

\[t_1 = \frac{V_m R + \sqrt{(V_m R)^2 - V_m^2 R}}{B}\]

and in this case, the negative square root is the required solution. For typical autowagon parameters, the journey time penalty and the excess headway have been evaluated and are plotted in Fig. H5.

**H4 COMPARATIVE ASSESSMENT.**

Figs. H4 and H5 show that there is benefit to be gained from shaping of the profile, but the difference in the shape of the curves suggests that the precise shape of the profile is important. Fig. H6 summarises a comparison of brake limited and jerk limited approach to a speed restriction of value 0.5 x line speed. This figure, surprisingly, shows a significant advantage of the simple brake limited approach over the jerk limited approach.

There is no reason to suppose that the brake limited approach itself is optimal and further study would be justified to try to identify the optimal profile.
FIGURE K2  MTB MODEL

FIGURE K1  PMB MODEL
APPENDIX K. SIMPLE VEHICLE MODELS.

K1 FIRST ORDER MODELS.

The transition into a speed restriction has been examined using simple first order models which exactly describe the following laws. It is inappropriate to use such a model for step response assessment where infinite acceleration would inevitably be called for.

In general the results presented here have been obtained using an MBD24 operational computer. This is an instrument bearing great similarity to an analogue computer externally, but operating digitally internally. The digital operation makes possible amongst other things precision multiplication. The flexibility of operation of the integrators and the total lack of drift results in an extremely powerful machine although digital operation does introduce some of its own problems. Scaling of the variables is necessary as with an analogue computer but the facility of setting integrator gains continuously aids the programmer. Where necessary the use of the MBD24 has been supplemented by the use of the University ICL1905. Programs for the 1905 have been written in 1900 Fortran.

Figs. K1 and K2 illustrate the models which have been used to investigate PMB and MTB respectively. The equations which they model are:

\[ \text{PMB} \quad S = K_1 (V)^2 \]

\[ \text{MTB} \quad S = K_1 V \]
Figure K3. Driving circuit - Leading Vehicle.
Figure K4 Follower Model from ECVL.
The equations are suitably scaled and the control circuitry necessary to extract the results has been omitted. The mathematical functions available on the MBD24 minimise the amount of external processing of results but if analogue output is required the resolution of the digital to analogue converters places a limit on the small excursions which can be reproduced smoothly.

Fig. K3 shows the driving circuit used to generate the position and velocity co-ordinates of a leading vehicle. In the basic form illustrated the jerk constraint is neglected, since this masks the principal effects of the discontinuities in the acceleration profile.

The models described here were used to produce the results presented in Chapter 3.

K2 THEORETICAL MODEL FOR AUTOMATIC WAGON.

The principal features of automatic wagons have been described in Appendix A. In order to determine how such vehicles might behave under the influence of the various control laws, a comprehensive computer simulation was constructed. The simulation is written in Fortran and has been run both on the British Rail IBM370 and the University ICL1905 computers.

Although the simulation is for a hypothetical vehicle, features such as rotational inertia and traction and braking response times are realistically modelled. Fig. K4 is a flow chart describing the vehicle control sub-routine of the program ECVL. This program, the listing of which is attached, simulates the behaviour of two vehicles merging to form a convoy. Initial conditions of velocity or separation errors are simulated.
LISTING OF PROGRAM
ECVL
SUBROUTINE CLEAR
COMMON IPLOT(160,60),V1,V2,H,I,J,CLOC,COF1,COF2,MASS,HDE,FORM,IRCC,
I(10),K(15),L
DATA IBLANK/1H/,1D0/1H/.7
C CLEAR ARRAY
DO 202 IX = 1,160
DO 202 IY = 1,60
IPLOT(IX,IY) = IBLANK
202 CONTINUE
C PLOT AXES
IX = 91
DO 203 IY = 1,60
IPLOT(IX,IY) = IDOT
203 CONTINUE
IY = 31
DO 204 IX = 1,160
IPLOT(IX,IY) = IDOT
204 CONTINUE
C WRITE(2,210)
210 FORMAT(1H1,48H,V1,...,V2...HEADWAY HDE HOES)
212 L = 0
RETURN
END

SUBROUTINE PLOT
DIMENSION IAX(7)
COMMON IPLOT(160,60),V1,V2,H,I,J,CLOC,COF1,COF2,MASS,HDE,FORM,IRCC,
I(10),K(15),L,N,ER(100),TIME,ICL,GA,GB
510 DELAY = (N-1) * CLOC
HOES = 19. * V1
506 WRITE(2,560) V1,HOES,DELAY,GA,GB
503 FORMAT(1H1,2HINSTABILITY PLOT VI = ,TS,2,16H M/S HOES = ,
TS,.2,2H M,.22X,10H VELOCITY ERROR M/S,5X,BHDELA = ,TS,.3,5H SEC,3X,
15HGA = ,TS,.4,2X,SHGB = ,TS,.2)
IX = 82
M = 1
DO 501 IY = 1,59.4
IPLOT(IX,IY) = K(M)
501 M = M + 1
WRITE(2,502) ((IPLOT(IX,IY),IX=1,160),IY=1,32)
502 FORMAT(1H1,160A1)
SF = HOES/80.
J = 1
DO 505 IX = 21,141,20
IAX(J) = SF = (161. - IX) * 0.5
505 J = J + 1
WRITE(2,503) IAX(1),IAX(2),IAX(3),IAX(5),IAX(6),IAX(7),
503 FORMAT (1H1,17X,14,16X,14,16X,14,16X,14,16X,14,3X,
11HHEADWAY)
WRITE (2,504) ((IPLOT(IX,IY),IX=1,160),IY=33,60)
504 FORMAT(1H1,160A1)
WRITE(2,5042)
5042 FORMAT (1H1,2H DYNAMIC CONVOY FORMATION POWER CONSUMPTION KEV,
2H WATT SECONDS 2X,2HV1,5X,2HV2,4X,2HEADWAY)
C RETURN
END

PAGE 2/4
SUBROUTINE SYSTEM
COMMON I1PLOT (140, 60), V1, V2, H, HI, CLOC, C0F1, C0F2, MASS, HDE, F0RM, IROC, 1, 1((15)), L, N, ER(100), TIME, ILL, GA, GB, IRUN.

C
C STORE ERROR VALUES IN ER ARRAY TO CREATE NET FORCE ZERO FOR DELAY
C TIME, THUS COASTING.
C
305 CONTINUE
3051 ENERGY = 0.
3052 RETARD = 0.
306 IFR = 0.
311 DELV = V2 - V1
C
C FORM RESISTANCE
C
350 RES = C0F1 + C0F2*V2*V2
3501 RES = 0.
360 IFR = IFR + 1
H = DELV * CLOC + H
C
C FORM ERROR, CALC FORCE
C
ERROR = HDE - H
DO 315 J = 1, N
JJ = H + J
ER(JJ) = ER(JJ) + 1
C
316 CONTINUE
3161 ERROR(1) = ERROR
3162 ERROR = ERROR
320 IF(ERROR) 330, 3201, 350
3201 FORCE = 0.
GO TO 357
C
C VE. ERROR
C
C TIME 332 FIDUDED FOR POSSIBLE ZERO_V2
C
330 IF (ERROR = 100. * GA) 331, 331, 3361
3361 POWER = 200000. * ERROR/(100. * GA)
GO TO 332
331 POWER = 200000.
3321 POWER = POWER/(V2 = 00001)
3321 ENERGY = ENERGY - POWER/10000.
C
C ENERGY_INTEGRATOR KILOWATT SECONDS
C
334 IF (FORCE = MASS) 330, 330, 3341
3341 FORCE = MASS.
350 F0RM = FORCE - RES
C
C INCORPORATE ROTATIONAL MASS
ACCEL = FORM/(MASS + 7270.)
GO TO 330
C
C VE. ERROR
C
340 FORCE = -MASS * ERROR / (100. * GB)
3401 FORCE + MASS
350 RETARD = RETARD + FORCE * V2/10000.
C
C ENERGY_INTEGRATOR KILOWATT SECONDS
C
PAGE 2/4
**VAR IV**

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- FORM = FORC - RES
- ACCEL = FORC/MASS
- DV2 = ACCEL + GLOC
- V2 = V2 + DV2
- IF (V2 > 35.) 302, 302, 3050
- V2 = 35.
- IF (1F1R < 1ROC) 311, 3021, 3021
- CALL INTER
- TIME = TIME + 1ROC/1CL
- IF (TIME = TRUN) 300, 370, 370
- WRITE(2,370) ENERGY,RETARD,MASS
- WRITE(2,3704) V1, V2, H
- FORMAT(1H*,67X,5F8.2)
- FORMAT(IN, THEnergy = , FB.1,5X, 9HRETARD = , FB.1,5X, 6HMASS = , 16)
- CONTINUE
- RETURN
- END

**VAR IV**

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**BLOCK DATA**

- COMMON IPLT(160,60), V1, V2, H, HI, GLOC, COF1, COF2, MASS, HDE, FORM, IROC,
- r L(10), K(15)

**DATA**

- I(1), I(2), I(3), I(4), I(5), I(6), I(7), I(8), I(9)/H1, H2, H3
- L(10), L(15), L(16)

**END**

**VAR IV**

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**SUBROUTINE INTER**

- COMMON IPLT(160,60), V1, V2, H, HI, GLOC, COF1, COF2, MASS, HDE, FORM, IROC,
- r L(10), K(15), L

411 HDES = 19. * VI
412 HCS = (2*HDES - H)*60./HDES
413 DVS = (V1 - V2) * 4. * 30.
414 IX = HCS + 1.5
415 IY = DVS + 1.5
416 IF(IX) 400, 400, 417
417 IF(IX-160) 418, 419, 400
418 IF(IY) 400, 400, 419
419 IF(IY-60) 419, 419, 400
420 IPLY(IX,IY) = I(L)
420 IPLY(IY,IX) = I(L)
420 WRITE(2,501) V1, V2, H, HDE, HDES
421 FORMAT (5F8.2)

422 CONTINUE
423 RETURN
424 END

**PAGE 4/4**
Figure K5  Schematic for Class 304 Braking Simulation.
Figure K6  Response of Class 304 Braking Simulation.
output is presented in the form of a phase portrait on the line printer.

The vehicle model contained within the program ECVL has been used extensively in other programs to assess the likely performance of automatic wagons in various dynamic situations including failure conditions.

K3 MODELS OF REAL TRAINS.

In order to design controllers for automatic driving of trains it has been necessary to construct models of both the Research & Development Divisions test vehicle Gemini and the Class 304 EMU. The simulation of Gemini is more fully described in Appendix M.

The simulation for the Class 304, whilst based on the experience of Gemini simulation, was carried out on a much smaller scale. The simulation was carried out on the MBD24 computer and only the braking system of the train was simulated. It was clearly not possible to properly simulate a digital control system on an analogue machine, but sufficient insight was obtained to enable a satisfactory design of microprocessor controller to be produced. The block diagram of the analogue simulation is presented in Fig. K5. Fig. K6 is typical of the system response braking to a target.
APPENDIX M. SIMULATION EXPERIENCE.

M1 INTRODUCTION.

In the design of any real control system, it is necessary to assess the available description of the system to be controlled, design a controller based on sound principles and finally test and adjust that controller on the real system. Frequently, it is found that either the real system does not exist until the design process is complete, making complete characterisation difficult, or such measurements as are possible do not completely describe the system's behaviour. It may be that the cost of experiments with the real system is high but allied to all these situations the chance and consequence of controller design errors are considerable. In these circumstances it is desirable to find alternative means for testing control proposals before final installation and commissioning.

In the Auto-drive programme a combination of all the above factors was present and justified the development of a simulation model, in which control algorithms could be exercised prior to installation on the Test Vehicle Gemini.

M2 SIMULATION MODEL - REQUIREMENTS.

There were two principal requirements which the simulation model had to achieve in this application for it to be successful, both being typical of most simulation exercises investigating the performance of process controllers. The first requirement was accuracy of modelling the real system, whilst the second related to the ability of the model to test various control strategies; each requirement is considered in greater detail in
the following sections.

M2.1 Accuracy of Modelling.

In any application the model must represent with adequate realism the system to be controlled in order that the developed control algorithms, when applied to the model, satisfy the performance specification and require, at most, only minimal adjustment when transferred to the real system. This requirement implies a clear understanding of the system to be controlled, which in this case was acquired by a series of carefully controlled experiments, referred to as the characterisation tests, see Appendix N. Appendix N illustrates the difficulty in fully describing the behaviour of the train to be controlled, a problem aggravated by modifications made to the brake equipment following the characterisation tests. It is desirable that the variability of significant physical parameters be modelled. This will generally increase the complexity of the simulation considerably and unless it is easy to run the simulation many times under different conditions, a more rational approach is to obtain an understanding of the likely mechanisms of variability and to simulate only selected "worst case" conditions.

The stochastic variations in performance of railway friction braking systems are notorious and much effort has been extended on means of measurement and improvement of braking. Where cast iron treadbrakes are employed to provide a frictional torque to the axles, the variability is considerable. The battery railcar test data provided an incomplete description of this behaviour so that an imprecise model of the brake equipment
and its operation had to be accepted. Nevertheless, the accuracy of modelling was considered to be adequate for the value of the model to be realised. The difficulties with representing the high order and non-linear behaviour of the brake equipment are described in Ref. 75.

M2.2 Adaptability to Various Algorithms.

The model was regarded primarily as a development tool for the evaluation of train performance, when subject to one of various auto-drive algorithms. As such, it was necessary that it should be readily accessible to a control engineer for manipulation of the various coefficients and other variables necessary for on-line tuning and to monitor the response to various stimuli. In addition, certain constraints had to be designed into the model to represent those found in the real system. For example, the format and cyclic updating of information presented to the trainborne auto-drive equipment are two such constraints. The model had to be structured to accommodate these requirements and this feature is further described in Section M3.3.

M3 CONSTRUCTION OF THE MODEL.

Although the battery railcar model was unique, the construction technique is common to numerous computer based simulations. From an examination of previous work, Ref. 79, the pattern of a 7 stage process has been identified. These stages are:

1. Definition of the overall requirements which the simulation must achieve.
2. Data collection to characterise the nature of the system to be modelled.

3. Compilation of a mathematical model representing the real system by a set of equations containing measured parameters.

4. Translation of the mathematical model into a computer model (or program).

5. Testing the program using the mathematical model as a specification.

6. Validation of the model to establish that its behaviour resembles that of the real system under various conditions with acceptable accuracy.

7. Use of the model.

In working through the list of 7 stages the first has already been described in Section 2. However, the remaining stages, particularly 2 to 4 inclusive, are examined in the following paragraphs.

M3.1 System Characterisation.

The performance data from which the model was constructed was obtained from extensive testing of the railcar described in Appendix N. Instrumentation was limited but sufficient results were obtained to provide an adequate description of the behaviour of the traction and braking system of the vehicle. Since the data did not in general fit accepted empirical
formulae, it was necessary to structure the simulation specifically to suit the test data, thus losing some of the generality of the simulation. It was evident during this work that previous descriptions of the behaviour of friction braking system were inadequate for partial brake applications. This situation has arisen because brake studies have been predominantly directed towards full service applications.

Reference is made in the Swindon Report, Ref. 67, to the variation of coefficient of friction with speed and with work done in the blocks, but the shape of the characteristic curves given is significantly different to those observed in tests with railcar. The methods adopted to provide a simulation with similar performance to the tests are described in Ref. 75.

M3.2 Mathematical Modelling.

It is necessary to obtain a description of the system, ideally, in a simple linear mathematical form. Such a representation, perhaps as a set of linear differential equations linking the state variables of the system, is amenable to classical methods of design and stability analysis and modern methods such as optimal control. If such a description were possible there would be little justification for a simulation. Generally, real systems incorporate varying degrees of non-linearity. Even when it is possible to reasonably approximate the performance by a linear representation, if the cost of the experiment or non-availability of the plant dictate, it may be necessary to simulate the operation of the
system before applying control techniques to the real system. The validity of any linear analysis will be reduced further if the control system is to be implemented in a sampled digital form. It is of course possible to use a sufficiently large controller so as to sample the data at an adequate rate with sufficiently fine resolution to approximate closely to the continuous system. This approach will almost certainly involve the use of excessive on-line processing power. Analytical techniques are available to extend the linear analysis to sampled data system, the drawback is that such techniques involve very cumbersome mathematics and are generally incapable of dealing with non-linearities combined with the sampling.

From the railcar test data, and the framework within which the control algorithms must work, it is apparent that the system is highly non-linear. The sampling rate of once per second is large compared with some system time constants; the delays of instrumentation and actuation are large as are the stochastic variations in some important parameters.

The above general discussion shows that the problem is ideally suited to solution by the application of established control techniques and testing of the results by simulation. The large differences in brake application and release times and the non-linearities of the braking system performance makes representation in an analytical form very difficult and this precludes the use of normal analytical techniques. For the traction system the control requirement is less stringent and the need is for an algorithm to accelerate
the vehicle up to a required speed and maintain that speed, adopting a driving technique appropriate to the vehicle, its control actuators and the operational requirement which has been defined in Appendix Q.

As the main principles of such a traction algorithm are likely to be based on sequential control and logical decision making it is unlikely that simulation of the system would contribute to the system design. It was originally intended that a full simulation of the battery railcar with its braking and traction algorithms be constructed but it was appreciated that the braking simulation was of greater importance. Accordingly, the structure of the computer program provided for insertion of traction simulation data and control algorithms although it was possible to run the controlled braking simulation in the absence of the traction data. In the event, the effort necessary to provide an adequate braking model within the timescales precluded the development of the traction model.
M3.3 Simulation Structure.

In Section M2.2 reference was made to the constraints which were built into the model. These determined its structure and ensured that the behaviour of the model was representative of the railcar, its auto-drive hardware and software. Fig. M1 shows that the simulation was structured on a 3 level hierarchy: the upper level consisted of the Continuous Systems Modelling Package (CSMP), a generalised software unit designed to solve a set of equations relating to an event. In this application the CSMP package was used on a repetitive basis to simulate the time varying control variables and train performance. In addition to the run data on channel A the main program was associated with the intermediate level in the hierarchy through three further channels.

The model was designed to provide for braking, coasting and traction operations for which braking and traction input modules were specified. These modules were associated with channels B and C respectively and were responsible separately for the manipulation of the control level commands. The processes whilst being characteristic of the brake and traction equipment behaviour also fashioned the control variables in a manner which was acceptable to the CSMP main program. The third channel, D, was the output from the main program and linked through the TACT interface to the control program.

The final stage in the structure of the model was also the dominant one, this being the provision for the control program under evaluation. The TACT interface was introduced to provide
**Diagram:** Block Diagram of Simulation Model.

1. **RUN DATA**
   - A

2. **MAIN PROGRAMME**
   - B
   - C

3. **CONTROL PROGRAMME**
   - D

4. **BRAKING INPUT**
5. **OUTPUT**
6. **TRACTION INPUT**

---

**Figure:** BLOCK DIAGRAM OF SIMULATION MODEL.
quantisation of, and access at one second intervals to, the output data. This arrangement was representative of that envisaged for the trainborne auto-drive hardware and software.

M4 EXPERIENCE IN USE.

The simulation runs on the IBM 370 computer and is available either via the normal batch mode or through the VDU terminals. The use of the program is fairly straightforward and most difficulties arise from the size of the simulation and the flexibility of data input and output procedures. For example, it is only possible to run the program for the full execution of one or a series of targets and once the program is running no interactive facilities are available. This restriction can be inconvenient as the cost per job is high and investigation of a minor detail and a certain parameter variations may be very expensive and tedious if several runs have to be made. Basically the program provides its output as a list on the line printer but optionally graph plotting of the important variables is available.

M5. CONCLUSIONS.

The use of simulation in the development of control algorithms appears well justified. The benefits of large scale simulation are not as great as would be expected. This arises for two main reasons, associated with the development and use of the simulation. During development of a simulation, experience gained leads to such an understanding of parts of the system as to render simulation unnecessary. In use, particularly with a large simulation, it is difficult to communicate adequately
with the simulation and this results in the production of an amount of computer output which is either too great to be analysed or is excessive for the purpose.

The simulation of the battery electric multiple unit for development of control algorithms has been useful, although not as much as was expected. The accuracy of the characterisation data dictated the precision with which the system could be modelled, and there was no virtue in simulating features which could not be verified. A natural tendency to incorporate unnecessary detail of the ATO interface equipment compounded the complexity.

In future work it may be better to model on a small scale individual elements of the control problem, rather than try to specify and develop another large scale simulation.
Fig. N1  Battery Railcar Traction Current Characteristic.
Fig. 2 ON-OFF TRACTION TIMES
GROSS TRACTIVE EFFORT
VS SPEED CHARACTERISTICS

- Siemens Data (corrected)
- Test Data

Fig N3 TRACTIVE EFFORT (TONNES)
APPENDIX N. GEMINI CHARACTERISATION.

Design of an efficient control system requires a detailed knowledge of the system to be controlled. Prior to the TACT experiments, little information was available to describe the traction and braking systems of the battery electric multiple unit, Gemini. The train was built in 1958, generally to the design of the Derby Lightweight Diesel Multiple Unit, but it was adapted from new to be powered by lead acid batteries supported in cradles beneath the frame of each vehicle. The traction motors and control gear were supplied by the German Siemens Company.

Tests carried out by the Author in order to determine the characteristics of the test train are described in Ref. 51. Limitation of resources at this stage in the project precluded the use of sophisticated instrumentation and computer analysis. Speed, traction current, brake cylinder pressure and distance were recorded manually and ultra-violet recordings were made of train acceleration derived from an Electrolevel accelerometer. The response times of the traction and braking control systems were determined from a large number of stopwatch measurements.

The results of the tests were reduced by manual analysis to a number of diagrams which effectively describe the behaviour of the traction and braking systems. For traction the most significant results are the tractive effort diagram, derived from all the dynamic test data and the control gear timings from the static testing. The results are fully described in Ref. 51 but figures N1, N2 and N3, taken from that report describe the behaviour of the traction system and have proved sufficient for the design of traction control algorithms. From Fig. N3 it will be seen that for lower speeds there
FULL FIELD SERIES (NOTCHES 1-2)

FULL FIELD PARALLEL (NOTCH 3)

WEAK FIELD (NOTCHES 4,5,6)

FIG.N. GEMINI: CIRCUIT CONFIGURATIONS.
FIGNS. SIMPLIFIED BRAKE SCHEMATIC FOR BATTERY RAILCAR.
Fig. N6  SPEED (FEET / SECOND)
Fig. N7  NOMINAL RETARDATION vs DRIVER'S NOTCH
Fig. N9 

GRADIENT CORRECTED TRAIN RESISTANCE

SPEED MILE/h
is good correspondence between the Siemens design data and the experimental results. For higher speeds the lack of correspondence is probably attributable to the fact that in the past problems have occurred with the starting resistance grids. Some of these have been changed with the result that the degree of field weakening in drivers notches 5 and 6 do not correspond with the design values. The starting acceleration of the train is normally high, and this justifies the inclusion of wheelspin correction algorithms in the auto-driver as described in the main text. Figure N4 shows the circuit configurations for the various driving notches illustrated on Fig. N1, this figure is taken from Ref. 52.

The braking system of the railcar is shown diagrammatically in Figure N5, taken from Ref. 53. It is clearly a complex high order system. The coefficient of friction between the cast iron blocks and the wheels varies widely with speed and is also subject to severe stochastic influences. Fig. N6 shows the typical variation in deceleration through the speed range. Fig. N7 shows the correlation of nominal retardation with brake cylinder pressure. A diagram based on this figure was used for the design calculations for the braking algorithms. Fig. N9 shows how very slow the system is to respond to changes in brake demand.

The final design curve shows the train resistance plotted as a function of train speed, Fig. N9. There is surprisingly good correspondence between the experimental results and the curve plotted from the empirical formula used by the Testing & Performance Section.
Figure P1  Typical transfer characteristic of Electrolevel.
APPENDIX P. THE ELECTRO-LEVEL ACCELEROMETER.

The electro-level is a simple transducer working on the principal of a spirit level. The glass vial contains a conductive electrolyte and electrodes are provided at each end and in the centre at the bottom. It is thus possible to measure acceleration by sensing the potentiometric changes of a resistance between the electrodes caused by displacement of the bubble. In order to avoid electrolysis of the electrolyte it is necessary for the device to be energised from an alternating source. This complicates the design of a sense amplifier and a synchronous detector is necessary.

Unfortunately when used to measure acceleration the electro-level exhibits a number of shortcomings. Firstly, the linearity and the symmetry of the device are clearly determined by the shape of the glass vial. Fig. P1 illustrates a typical transfer function. Since the device is non-linear and asymmetric, it is difficult to define a general set-up procedure.

Further disadvantage is evident in the dynamic response. Fig. P2 illustrates the response to a fairly rapid change of acceleration, approximating to a step input. The short term response is that of a lightly damped second order system with a natural frequency in the region of 3 Hz, but it is noted that the final value achieved after 20 to 30 seconds is some 5% greater than the value after the initial transient. This very slow setting is attributable to wetting of the glass above the bubble during the transient and is an inherent feature of the device.

The electro-level is thus not an ideal device for the measurement of train acceleration, although it does exhibit certain important
Figure P2

Response of Electrolevel Accelerometer.
advantages compared with other alternatives. It is an inexpensive device and probably its greatest advantage is its durability in the railway environment. Experiments with expensive servo-nulling devices which potentially overcome the weaknesses of the electro-level have shown that they are not sufficiently robust for long term application on railway vehicles. The main cause of failure has been the pivot bearings used in the servo-nulling arrangement. A new device has recently been developed using the servo-nulling principle but avoiding the use of pivot bearings and results from some experimental tests with the Advanced Passenger Train are encouraging.

The electro-level is an analogue transducer and suffers the common shortcomings of such devices, namely; calibration must be carried out with each device, long term stability of the device and its electronics require periodic re-adjustment and finally for interface to digital control equipment an analogue to digital converter is necessary and such devices are inherently expensive. The particular disadvantages of the electro-level transducer combined with the general disadvantages of analogue transducers provide much of the justification for the development of digital instrumentation described in this thesis.
HP 2100 COMPUTER

TACT MODEM
Tx/Rx

TO TRAINS IN TACT AREA

HP 2100 CONTROLLER

V.D.U.

DISC

SYSTEM KEYBOARD

PRINTER

TELEMETRY CONTROLLER

TACT KEYBOARD

LONDON RD. SIGNALS

TREADLES, POINTS

WILMSLOW SIGNALS

FIG. Q1 WILMSLOW TACT CONTROL CENTRE
APPENDIX Q. THE DEVELOPMENT PROGRAMME FOR TACT.

Q1 INTRODUCTION.

A development programme commenced in June 1972, to investigate and demonstrate in a realistic railway environment a centralised form of train control. The development programme was split into two main phases, firstly the develop information processing and communication equipment and secondly to develop automatic driving equipment. The first phase was carried out in the Wilmslow Area on an operational line carrying freight and passenger traffic. The communication and central control facilities were demonstrated within an equipped area of 13 km. Automatic driving experiments were carried out on the Research & Development Division's experimental test line at Mickleover.

Q2 CONTROL CENTRE.

The basic elements of the control centre at Wilmslow are shown in Fig. Q1. Although lineside signals are not a necessary feature of TACT their inclusion in the data has been necessary at Wilmslow as the equipped train must observe the aspects of existing signals.

A telemetry system has been installed to monitor the aspects of running signals and shunting signals, and to relay these to the control centre. Additionally, the lie of certain point work and the state of the "train entering" treadles are monitored by the telemetry system.

Duplication of the processor within the control centre is
planned for a later development phase; initially a single processor is responsible for servicing the telemetry data and compiling train instructions which are despatched regularly every 5 seconds to the equipped train.

The second processor depicted in Fig. Q1 drives a colour visual display unit (VDU) showing line occupation, train descriptions and information on the speed and position of the test train. The VDU normally displays the line section containing the train and the facility also exists to display any section of the equipped area.

Q3 COMMUNICATION LINK.

Track conductors are used, laid in a continuous manner in the centre of the track. Line terminal equipment in lineside cabinets services the track conductor loop using a two channel omnibus link terminated in the control centre.

At a late stage in the Wilmslow experiments, radiating cable was installed for comparative assessment against track conductors. Radiating cable can handle the speech and data circuits, and one cable can give multi-track coverage.

It was intended that a free space radio system should also be installed for comparison against track conductors, but for the present such plans have been shelved.

Q4 TRAIN EQUIPMENT.

The basic elements of the train equipment are shown in Fig. Q2. The controller is responsible for message handling, servicing the
transponder interrogator and generating train control signals. Using the output of the controller the three modes of operation are technically feasible, namely, supervisory cab displays with manual driving, automatic driving with supervision by train attendant and finally full automation of all functions (ceewless operation). Fig. Q2 does not show the duplication of equipment which will be needed to give the high availability and integrity required.

The interrogator reads each transponder as it is passed over and stores the identity of the last one received for transmission to the control centre. This gives a precise and unique positional report of the train detection, refined for control purposes by a tachometer measuring distance from the last transponder.

The auto-driver is required to use the power and braking system of the test train to drive it as specified by data from central control. Target co-ordinates are derived with constraints of permitted speed and desired retardation. The basic movements made under manual driving have been examined and a sub-set selected for demonstration of auto-driving, recognising that this stage of the project is not expected to exploit the full potential of automatic control. The demonstration provides: acceleration to a required speed from a lower speed or from rest, maintenance of speed within specified limits, reduction of speed for permanent way restrictions and bringing the train to a halt with sufficient accuracy for either station or signal stops. The auto-drive system must be capable of responding to train reversal and other operational procedures demanded by central
control. The braking control system will also hold the train stationary on a gradient and provide controlled deceleration under emergency conditions.

Further details of the TACT system are contained in References 65, 66 and 73.
Figure R1: System Diagram.
APPENDIX R. TUNING TACT BRAKING ALGORITHMS.

R1 ALGORITHM STRUCTURE.

The algorithm structure is dictated by the vehicle characteristics and the available processing power. The system structure is illustrated in Fig. R1. It will be noted that the primary controlled variable is the train speed error calculated with respect to the braking curve. The nominal brake force is modulated in response to the velocity error using proportional plus integral control. Because of the inter-relation of speed error and distance error as the braking curve is followed, there is an inherent integral term in the control. This makes the controller appear as a conventional three term controller, but the coefficients are not constant. As mentioned in the main text this was a design feature causing the system gain for position error to increase as the target is approached.

R2 TUNING THE ALGORITHMS.

The system equation may be stated as:

\[ F = K_1 + K_2 x + K_3 \left( x - \frac{2a(x - x_0)}{\dot{x}} \right) + \frac{K_4 (\ddot{x} - \ddot{x})}{\text{prop. term}} + \frac{K_5 (\dddot{x} - \dddot{x})}{\text{deriv. term}} \]

clearly the equation is non-linear and not amenable to classical methods of tuning. However in order to get an approximate starting point for experimentation the equation may be linearised about an operating point. It is then necessary to carry out tests on the system to investigate changes in the system response corresponding to changes in the proportional and derivative gain terms. Since the high order characteristic of the braking system of the train has
Figure R2: Regulation of Acceleration.
Figure R3

Stopping Accuracy

- All tests overshoot
- All tests stop short
- Very poor stopping
- Area of very good stopping

Prediction time zero

35 tests

Uphill running

Numbers are overshoot/undershoot in pulses (± 0.228 m)

Derivative gain (DACE)

System gain (CACE x DACE)
Figure R4  Speed Regulation

Prediction Time Zero
35 Tests
Uphill Running

Area of Good Speed Control
Poorly Defined

Poor Velocity Following

Very Poor Velocity Following

Derivative Gain (Dace) vs. System Gain (DACE x DACE)
Figure R5: Composite Performance

Prediction Time Zero
35 Tests
Uphill Running
been represented by a first order system with a time delay, a further control variable is available that of the system prediction time. Prediction used in this way corresponds to the use of phase advance compensation in analogue controllers.

R3 PRESENTATION OF RESULTS.

It has been found convenient to present the results of the experimental running in summary form on a two dimensional parameter plane having axis of derivative term gain and system gain respectively. For a test run, performance has been quantified according to three classifications; these are stopping accuracy, close following of the braking curve and regulation of train deceleration. It is thus possible within the parameter plane to construct contours of goodness of control. Figs. R1 to 4 comprise a set of these curves; Figs. R1 to 3 being the individual contour diagrams for the three performance attributes and R4 being the composite diagram. These graphs included here by way of example are for zero prediction and running in the down direction. Similar curves were constructed for other prediction times and for up direction running.

A significant result was that the design values of proportional and derivative gain gave quite acceptable performance although a small improvement was obtained by increasing the system gain. The controller was shown to be stable and consistent in its performance for a wide variation of system parameters. Tests were carried out with a wagon attached to the two car railcar in order to simulate a significant change in load and this had no effect on the stopping accuracy. A more significant test
was made by isolation of more than 50% of the brakes of the railcar and again the stopping accuracy was acceptable.
APPENDIX T. MEASUREMENT OF ACCELERATION.

The acceleration of a train may be measured using a seismic accelerometer, such as the Electrolevel described in Appendix P. On level track, neglecting effects of mechanical noise, the output will be a true representation of the acceleration of the train.

On a gradient the accelerometer output will also be influenced by the resolved component of gravitational acceleration acting in the plane of the gradient. This means that at constant speed on a constant gradient the accelerometer output will be equal to the resolved gravitational component. For a train accelerating or braking on a gradient the output of the accelerometer will be given by:

\[ A = \ddot{x} + G \sin \phi \]

T1

Where \( A \) is the output of the accelerometer, \( \ddot{x} \) is the acceleration of the train along the gradient, \( G \) is the gravitational acceleration and \( \phi \) is the angle, positive for raising gradient. The corresponding force, \( F \) will be given by:

\[ F = M \ddot{x} + MG \sin \phi \]

T2

Where \( M \) is the vehicle mass. From the above, it is clear that the output of the accelerometer is linearly related to the force applied to the vehicle.

On a composite gradient the accelerometer output will consist of the train acceleration along the track plus the resolved gravitational acceleration at that point. A choice must then be made as to whether constant force or constant acceleration braking is required. Measurement of acceleration with a seismic accelerometer is particularly appropriate if braking forces close to the available
adhesive force are employed. The drawback of constant force control is the complication incurred in the construction of the velocity distance profile and consequent difficult in achieving good stopping accuracy. The alternative is to adopt constant acceleration control, along the line of the track. Clearly with this approach, a slightly more conservative braking rate must be employed. It is also evident that the gravitational component contained in the seismic accelerometer output is in this case an unwanted noise signal. The gravitational signal may be approximately cancelled by the subtraction of the known gradient, but this is a less than ideal solution and taking account of the other shortcomings of seismic accelerometer measurement as described in Appendix P, the derivation of train acceleration from an axle mounted tachometer is recommended, see Appendix U.
LIST OF SYMBOLS AND ABBREVIATIONS USED IN APPENDIX U.

$a_0, a_1, \ldots$ : Coefficients of the algorithm.

$f_b$ : Brake Frequency.

$f_s$ : Sampling frequency.

$h$ : Sampling interval.

$h_s$ : Sampling interval giving minimum error.

$J$ : Constant giving error due to truncation of the Taylor Series.

$k^m_m$ : $m$th element of the K-matrix (counting 0,1,2 \ldots m).

$k^n_n$ : $k_Q$ is the quantization error

$m$ : Number of points used in the algorithm.

$n$ : Order of the algorithm ($= m-1$).

$n_t$ : Number of poles on encoder.

$p$ : Order of the derivative.

$Q_y$ : Quantization level chosen for $y$.

$Q_{ya}$ : Quantization level required to meet the accuracy specification.

$Q_{yr}$ : Quantization level required to give the resolution specified.

$R$ : Resolution

$r$ : Equals $+p$, $0$, $-p$ in integration, prediction and differentiation algorithms respectively.

$y$ : Input variable, or current sample of it, $y_0$. 
\( y_e \) : Per-step, or local, error in estimating the required function of \( y \).

\( y_{eq} \) : Component of \( y_e \) due to quantization.

\( y_{et} \) : Component of \( y_e \) due to truncation of Taylor Series expansion.

\( y^{(m)} \) : \( m \)th derivative of \( y \).

\( y_r \) : Estimate of the desired function of \( y \).

\( y_s \) : \( a_0 y_0 + a_1 y_1 + a_2 y_2 + ... + a_n y_n \).

\( y_t \) : True value of the desired function of \( y \).

\( y_o \) : Latest sample of the input \( y \).

\( y_1, y_2, \ldots \) : Values of \( y \) at \( (t-h) \), \( (t-2h) \), etc.
APPENDIX U. BRATO TACHOMETER DESIGN.

In order fulfil the operational requirement for the automatic driver a performance specification was produced. Velocity estimates were required to an accuracy of ± 0.3 m/s with a resolution of 0.1 m/s, together with estimates of acceleration to an accuracy of 0.1 m/s² and 0.05 m/s² resolution.

It is required to choose:

(i) Sampling period \( h_s \)

(ii) Number of poles \( n_t \) required on the encoder (that is the value of \( Q_y \))

(iii) Which algorithm to employ in the estimation (that is the value of \( m \))

The development of the theory necessary for the design of the algorithms is given in Reference 72, a paper by the author together with Messrs. Milroy and Forsythe. For convenience the relevant equations are summarised below:

\[
h_b = \left\{ \frac{K_{n_y} Q_y M! l_y}{J y(m)} \right\}^{\sqrt{m}} = \frac{1}{f_b} \quad \text{(U1)}
\]

\[
h_s = h_b \left\{ \frac{p}{m-p} \right\}^{\sqrt{m}} = \frac{1}{f_s} \quad \text{(U2)}
\]

Setting \( h = h_s \) in equation 2.8 of Ref. 72 gives:

\[
y_e = \left\{ \frac{mK_{n_y} Q_y}{m-p} \right\}^{\frac{m-p}{m}} \left\{ \frac{y_y(m)}{n!p} \right\} \frac{p}{m} \quad \text{(U3)}
\]
The resolution $R$ can be interpreted as the minimum velocity for acceleration that the system can detect, therefore the series:

$$Y_s = a_0 y_0 + a_1 y_1 + a_2 y_2 + \ldots$$

must add up to at least 1 pulse count, which is equivalent to a distance that we will denote $Q_{yr}$. So

$$R = Q_{yr}/h^p$$  \hspace{1cm} U4$$

From equation U3 we can define the quantum size required to meet the accuracy specification as:

$$Q_{ya} = \frac{m-p}{mK_r} \left\{ \frac{n!p\rho_y e^{m_p}}{J_y(m)} \right\} \frac{P}{m-p}$$  \hspace{1cm} U5$$

while from equation U4, U2 and U1 we can define

$$Q_{yr} = R \frac{m}{m-p} \left\{ \frac{m! \rho_{Kn}}{J_y(m)(m-p)} \right\} \frac{P}{m-p}$$  \hspace{1cm} U6$$

The quantum size to be used is denoted $Q_y$ and is the smaller of $Q_{ya}$ and $Q_{yr}$.

We will now investigate the use of these formulae using 2, 3 and 4 point algorithms. To do this we need suitable estimates of $y(m)$ and from examination of typical records of $y$ these have been taken as:

$$y(2) = 1 \quad \text{m/s}^2$$
$$y(3) = 0.1 \quad \text{m/s}^3$$
$$y(4) = -0.05 \quad \text{m/s}^4$$

U1 ESTIMATES OF VELOCITY.

U1.1 The simplest algorithm that could be used is:

$$Yr = \frac{1}{h} (y_0 - y_1)$$
So from its structure \( m = 2, k_n = 1, p = 1, J = 1 \) (in fact, with algorithms for the first derivative it always turns out that \( J = n! \)), and from the specification above \( y^{(2)} = 1.0 \text{ m/s}^2, y_e = 0.3 \text{ m/s}, R = 0.1 \text{ m/s} \).

To satisfy the specification on accuracy we have, from equation U5:

\[
Q_{ya} = \frac{1}{2} \left\{ \frac{(0.3)^2}{1.0} \right\} = 0.045 \text{ m}
\]

while equation U6 tells us that to give the resolution we want

\[
Q_{yr} = 0.02 \text{ m}
\]

hence we take

\[
Q_y = 0.02 \text{ m}
\]

this yields a sampling frequency \( h_s \), from equations U1 and U2

\[
h_s = \left\{ \frac{0.02 \times 2}{1.0} \right\}^{\frac{1}{2}} = 0.25
\]

The wheel to which the encoder is fitted might typically have a diameter of 1 m, so the number of poles \( n_t \) is simply related to \( Q_y \) by

\[
n_t = \frac{\pi}{Q_y}
\]

Hence the number of poles required from the encoder is about 160.

U1.2 The 3 point velocity algorithms is

\[
Y_r = \frac{1}{2h} \left( 3y_0 - 4y_1 + y_2 \right)
\]

so \( m = 3, k_n = 2, p = 1, J = 2 \) and \( y^{(3)} = 0.1 \text{ m/s}^3 \),

\[
y_e = 0.3 \text{ m/s}, R = 0.1 \text{ m/s}
\]
Hence \( Q_{ya} = \frac{2}{6} \left\{ \left( \frac{0.3}{0.1} \right)^2 \right\}^{\frac{1}{2}} = 0.17 \) (from eqn U5)

\[ Q_{yr} = (0.1)^{\frac{3}{2}} \left\{ \left( \frac{3(2)}{0.1(2)} \right) \right\}^{\frac{1}{2}} = 0.17 \) (from eqn U6)

Obviously

\( Q_y = 0.17 \) m

and so

\( n_t = 20 \) poles

The associated sampling frequency is

\( h_s = 1.7 \) s

Which might in practice be rounded up to 2 s see Section 2.3.3 of Ref. 72).

U2 ESTIMATES OF ACCELERATION.

U2.1 The simplest algorithm is

\[ Y_r = \frac{1}{h^2} \left\{ y_0 - 2y_1 + y_2 \right\} \]

and therefore \( m = 3, n = 2, p = 2, k_n = 2, J = 6 \),

while

\[ Y^{(3)} = 0.1 \text{ m/s}^3, \quad Y_e = 0.1 \text{ m/s}^2, \quad R = 0.05 \text{ m/s}^2 \]

\( Q_{ya} = 0.007 \)

while \( Q_{yr} = 0.2 \)

Clearly the accuracy requirement is much the more stringent, so \( Q_y = 0.007 \), and \( n_t = 450 \) poles. The corresponding value of \( h_s \) is 0.7 seconds.

U2.2 A four point algorithm for acceleration is
\[ y_r = \frac{1}{h^2} \left\{ 2y_0 - 5y_1 + 4y_2 - y_3 \right\} \]

and therefore \( m = 4, \ n = 3, \ p = 2, \ K_n = 6, \ J = 22. \)

\[ Y^{(4)} = 0.05 \ m/s^4, \ Y_c = 0.1 \ m/s^2, \ R = 0.05 \ m/s^2 \]

yielding

\[ Q_{ya} = 0.009 \]
\[ Q_{yr} = 0.33 \]

\[ Q_y = 0.01 \] in round figures

Hence \( n_t = 350 \) poles

and \( h_s = 1 \) s.

An upper limit of 250 poles is regarded as desirable because of the high cost of exceeding this figure, so it is worth examining the effect of using a tacho with that number of poles. Equation U3 gives us the accuracy we can expect using a 4 point algorithm:

\[ y_e = 0.12 \ m/s^2 \]

although this is marginally higher than the target figure of \( 0.1 \ m/s^2 \) it may be satisfactory, especially considering the lack of precision in choosing \( y(m) \).

U3 THE CHOICE.

The possibilities examined above gave the following results, in summary:

<table>
<thead>
<tr>
<th>Velocity</th>
<th>( m )</th>
<th>( h_s )</th>
<th>( S )</th>
<th>( n_t )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>0.2</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>
The combined velocity and acceleration computations could be taken care of by the 250 pole encoder using the four point algorithm for acceleration and the two point algorithm for velocity. In the latter case the figures now read:

<table>
<thead>
<tr>
<th>m</th>
<th>$h_s$</th>
<th>$S$</th>
<th>$n_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration</td>
<td>3</td>
<td>0.7</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.0</td>
<td>250</td>
</tr>
</tbody>
</table>

so a sampling interval of 0.2 seconds could be employed with every fifth sample used in the acceleration computation.

However, there is obviously some computational advantage in a scheme that uses the same sampling interval for both velocity and acceleration, and if we use the three point algorithm with the 250 pole encoder and a sampling interval of 1 second it will be found that $y_e = 0.05 \text{ m/s}$ which is well within the specification, so this represents another alternative for the velocity computation.

**U4 THE UPDATE AND COMPUTATION INTERVALS.**

It is possible to update the output more frequently than the calculations of sampling interval carried out above would seem to allow.

For instance, to take a hypothetical case, if a two point algorithm for velocity is being used with $h_s = 1 \text{ second}$ but we wish to update the output every 0.5 seconds (the update interval) then the input is sampled every 0.5 seconds and the
Figure U1 Hypothetical velocity estimation

Figure U3 Datum for Measurement.
TEST RUN 38703 FROM BURRAGE TO MAULDETH ROAD
3-TERM VELOCITY 4-TERM ACCELERATION

FIGURE U2.
computation carried out using alternate samples rather than adjacent samples (see Fig. U1). On this basis h would be referred to as the computation interval and can in general be any (integer) number of times greater than the update interval.

In the case of the train velocity and acceleration measurement, the sampling and update interval was chosen as 0.1 seconds and the computation interval as one second for the calculation of both velocity and acceleration, using of course the 250 pole encoder, with m = 3 for velocity and m = 4 for acceleration. Fig. U2 illustrates the performance achieved with this arrangement on a test on a Class 304 Multiple Unit. The output of a seismic accelerometer is also shown for comparison with the derived acceleration, but it must be remembered that the accelerometer was body mounted and also subject to gradient effects.

U5 DISCUSSION

U5.1 The Datum for Measurement.

Because the coefficients in differentiation algorithms sum to zero, the datum for measurement of y may be taken at any convenient point, e.g. $y_0$ (see Fig. U3), so that the computation of

$$Y_s = a_0 y_0 + a_1 y_1 + a_2 y_2 +$$

becomes

$$Y_s = a_1 y_1 + a_2 y_2 +$$

This is not only convenient but, more importantly, it reduces the length of the data word, which need now be only long
enough to accommodate the difference between the smallest and the largest samples used in the algorithm.

U5.2 Noise.

An important factor that has not so far been mentioned is the effect of noise on the input $y$. It has been assumed that quantisation is the only noise present and therefore that the value of $Q_y$ is determined by this alone. If, however, there is an appreciable amount of other noise, which is quite likely of course, this will increase the degree of uncertainty beyond the value of $Q_y$. It would be possible, given the time and the effort, to characterise this additional noise and arrive eventually at a probability density function for the noise in total, but there must be some doubt as to whether, in the circumstances, the effort would be worth it. A simpler, though less rigorous approach is first to estimate very roughly an r.m.s. value for the noise, expressing it as $kQ_y$. Since this may be positive or negative, the maximum degree of uncertainty in the positive sense is $(k + 1)Q_y$ and in the negative sense, $kQ_y$. If, by $a_+$ we denote the sum of the positive coefficient in the algorithm and by $a_-$ the sum of the negative coefficient, then the worst possible quantisation error is given by $k_n$ where, now

$$k_n = (k + 1) a_+ + (K) a_-$$

and the theory explained above can be used as before. If $k$ is small then $k_n$ approximates to the value used earlier.

U5.3 Algorithm Length.

All the algorithms defined here and in Ref. 72 can be
described as digital filters and represented as such with the aid of the z-transform. This enables us to draw a frequency response for the filter (see any text book on z-transforms) and, if we are differentiating, that response must increase as the frequency increases, at least up to a certain point. That point will be fixed by the number of terms in the algorithm, the more terms the higher the frequency. It is possible therefore that by going to a large value of m (i.e. many terms) we may exceed the band with of the signal we wish to extract and begin to amplify noise. So it is prudent to make do with the smallest value of m that seems to meet the specification.

U6 CONCLUSIONS.

The advent of the microprocessor has greatly speeded up the computerisation of control systems and apparently left the books some way behind. We found it difficult to extract from existing literature on sampled data systems adequate guidance on such fundamental matters to the practicing engineer as the choice of sampling frequency and the quantisation levels necessary to achieve a given accuracy or resolution.

Consequently we have had to do it ourselves, with the results described in Ref. 72. They show that there exists, as one would expect, a complex relationship between accuracy of estimation and the choices the designer makes of sampling frequency, quantisation level, and the length of algorithm.

Using the theory contained in Ref. 72, a high performance tachometer has been designed, and its performance verified by tests carried out on the Class 304 Multiple Unit.
Figure VI  Transponder System.
APPENDIX V. TRANSPONDERS AND END OF SECTION BEACONS.

The provision of distance reference points is of fundamental importance in any train control application. During the past decade various devices have been used experimentally to provide these reference points. For British Rail use, two devices have emerged as being of practical value. The passive inductive transponder developed in conjunction with the Plessey Company is used in the drivers speed advisory system for the Advanced Passenger Train. The end of section beacon developed as part of the programme of work on inductive track loops has been used in numerous Research projects, and will be used in the British Rail Automatic Train Operation Pilot Scheme.

VI TRANSPONDERS.

The transponder system is illustrated diagrammatically in Fig. VI. The track mounted device is completely passive, all power is derived from the trainborne transmitter. Power from the train aerial couples into the loop aerials of the transponder and a large proportion of the received power is rectified to provide operating power for the internal logic and transmitter of the transponder. The transponder logic generates a code pattern which may contain up to 14 binary coded decimal digits of information. The code is programmed into the device before installation at the track side. The coded message is used to modulate the output of a low power transmitter which communicates the coded message to the train aerial.

It is necessary for the track and train transmitters
Figure V2 Systematic errors of location due to transponder reading time.
to operate on different frequencies in order that the information content of the transponder may be recovered by the train receiver. The train transmitter operates at a frequency in the region of 150 kHz, and the track transmitter at half this frequency conveniently derived by division of the received carrier.

Since the data contained in the transponder is regarded as safety data, extensive checking procedures must be carried out before it is accepted. The coded data is preceded by a synchronisation pattern and a parity code is appended to the end of the message. In the CAPT system only a limited amount of information is required from the transponder and redundant coding is used within the coded message to provide a very high degree of security. Computer simulation of likely error patterns and extensive testing on the Railway have resulted in the choice of a code which is acceptable to the Signal Engineer's Department.

With no data errors it may be necessary for the trainborne equipment to receive two virtually complete message sequencies before synchronisation is possible. With possible bit errors, three or more sequences may be necessary. Since the data rate is relatively slow, the delay incurred in identifying the transponder is translated into an uncertainty of its position.

Fig. V2 illustrates this. The upper part of the diagram shows the field pattern to be expected as the train passes over the transponder. The graph in the lower part of the diagram shows the position at which the
transponder would be perceived to be located as a function of train speed. It will be seen that there is a significant systematic error of location as a function of train speed and a smaller random component arising from the time synchronism of the coded messages and possible data errors.

V2 END OF SECTION BEACONS.

Track conductor loops as used by British Rail consist of two parallel conductors laid between the running rails and fed as a continuous loop from a lineside transmitter. Loops are normally end fed, the remote end of the loop being terminated resistively. For determination of direction the train aerial uses both electric and magnetic field components, but information may be received using only the magnetic component. The end of section beacon is a convenient device which may be connected in series with the loop and provides a positive distance reference.

The end of section beacon consists of two parts; the first part is a pair of wooden ramps used to raise the track conductor loop and positively establish the electric field, the second part is a coil approximately \( \frac{1}{2} \) m x 1 m consisting of approximately 6 turns of wire contained in a tube to provide electrical screening. This latter part of the beacon provides a considerable increase in magnetic field and a complete cut-off of the electric field.
VERTICAL MAGNETIC FIELD
ABOVE AN 8 TURN E.O.S.,
0.5 m x 1.06 m, RAISED 114 mm
ABOVE NOMINAL SLEEPER
LEVEL.

ANTENNA
HEIGHT
Z = 0.216 m

MINIMUM
DESIRED
LEVEL

MAXIMUM SIGNAL
FROM 0.5 m
TRACK LOOP

FIG. V3 E.O.S. MAGNETIC FIELD
The tolerances of the design of the track equipment and the train aerial are such that it is possible to define electric and magnetic signal thresholds and so identify the features of the track conductor loop and the end of section beacon. Fig. V3 illustrates the electric and magnetic signals which would be received on the approach to and when passing over an end of section beacon. Field sequence logic within the receiver provides a high integrity signal to indicate that the appropriate train of events has occurred and the final M2 transition is deemed to be the location of the end of section beacon. By design the slope of the magnetic field in the region of this final transition is very steep and it is thus possible to achieve a very high degree of repeatability of position location; this has been demonstrated by the experimental work referred to in the main text.
In early 1979, British Rail Management requested a demonstration of the feasibility of automatic driving. The train to be controlled was a 4-car Electric Multiple Unit, Unit No. 039 of Class 304. The time available before the required demonstration did not allow the development of a comprehensive hardware and software implementation, but building upon the experience of automatic braking tests carried out in 1978, a simple automatic driving system was produced for demonstration in April 1979.

PRINCIPLES OF OPERATION.

The structure of the control algorithms closely resembled that of those used in the earlier TACT experiments. In order to satisfy the timescales it was necessary for the software implementation to be as simple as possible, but the opportunity was taken to include changes of principle in order to overcome the recognised deficiencies of the TACT controller.

The demonstration was carried out on a stretch of line in the Manchester Division, between Wilmslow and Mauldeth Road Stations. The stretch of line is approximately 13 km long and includes 5 intermediate stations. Though part of the operational railway having a regular passenger service, the line is designated as a test site for automatic train control experiments. The signals along the route are equipped with transmitters and track conductor loops, and the end of section beacons associated with each track conductor loop provided convenient distance reference points for automatic driving. Equipment was not available
Figure W1.
Figure W2
to convey the automatic driving information from the trackside through the track conductor loop communication medium to the train and for this reason the automatic driving demonstration equipment used stored data contained within the control processor memory. The only function of the track conductor system was the provision of distance reference points.

Fig. W1 illustrates the structure of the hardware employed. It will be seen that at the heart of the system is a Motorola 6800 Microprocessor. Data regarding the progress of the train is provided by an axle mounted shaft encoder and the distance reference points referred to above.

A precise knowledge of the distance between the end of section beacons, obtained during previous experiments, enabled the expected distance for each section to be programmed into the microprocessor. Initial synchronisation was achieved by comparing the measured distance between the first two end of section beacons encountered with the stored values and looking for a close match. Once synchronisation had been achieved the next expected beacon would be known, and because the repeatability of distance measurement was so good, it was possible to put a very fine tolerance on the expected values and so maintain close synchronisation.

The route data for each stage of the journey was kept very simple. Fig. W2 illustrates the route and the profile followed by the auto-driver. It will be noted that a different form of driving has been used for each stage of the journey and in the route data this is characterised
by the mode to be employed when the specified speed has been reached. For the demonstration this mode was either to coast or to maintain speed uphill or downhill. If the mode were coasting, a coast point was also specified such that regardless of whether the specified speed had been reached at that point, coasting would be enforced.

Control was divided into 3 stages for each journey stage. The first stage was that of acceleration of the train to the permitted speed. This was implemented as a sequential increase in the demanded traction power as the train speed increased. The second stage was that of speed regulation or coasting. Clearly for coasting no control was necessary; for speed regulation a development of the TACT algorithm was used. The change involved the overspeed brake which had been shown to be inadequate with widely varying brake performances. For smaller overspeeds (of the order of \( \frac{1}{5} \) mile/h) a fixed pressure overspeed brake was applied, and for larger overspeeds, the brake pressure was made to depend upon the integral of time for which the overspeed persisted. Braking control for the stopping targets was again based on developments from the TACT algorithms. Within the software a braking curve was constructed and the velocity error of the train with respect to this curve was used as the controlled variable. Proportional plus integral control was used to form a desired brake cylinder pressure. No direct measure of brake cylinder pressure was used as this would have entailed considerable hardware complication, and as there are 4 independent brake control units on the train a single pressure measurement might not have been representative. A pressure estimate was derived from a software model.
Figure W3 Autodriver Performance (Part 1)
Figure W3 Autodriver Performance (part 2)
based on the nominal parameters of the braking system. The error of the demanded pressure with respect to the estimated pressure was passed through software histeresis and output sequence logic before being output to solid state drivers driving the e.p. train lines. To reduce the initial transient which would occur at the commencement of braking due to the time constant of brake application, a small initial brake application was made prior to engagement of the curve following algorithm.

W2 PERFORMANCE OF THE AUTO-DRIVER.

Equipment was installed in the train on 4 April 1979 and demonstrated on 20 April 1979. This was the first occasion on British Rail that micro-electronics had been directly interfaced to the power circuits of a traction vehicle. The hardware functioned correctly and automatic driving was achieved on the first run. However several small software errors were evident and a great deal of effort was necessary to overcome problems of disturbance of the operation of the microprocessor when passing through the neutral section on the approach to East Didsbury Station. On passing through such a neutral section, the 25 kV supply is interrupted for a few seconds and this generates considerable disturbance on the control supply voltages throughout the train. However the problems were satisfactorily overcome and a complete demonstration of automatic driving was provided.

Fig. W3 is a computer reconstruction of recorded data from a typical run. The general shape may be compared with that of Fig. W2 and it will be seen that the objective has been achieved. Fig. W3 also shows the acceleration of the
Data from automatic driving tests on Class 304 electric multiple unit 18/19th April 1979. 68 measurements.

Figure W4 Accuracy and Repeatability of Stopping
train as well as the speed plotted against time. From this it will be noticed that the start is not very smooth, this is a feature of the train and its simple control system and is common in manual driving. The effect could be significantly reduced by the use of a more complicated control algorithm.

No comment is necessary regarding the coasting phase where speed increases or decreases according to gradient and train resistance. Speed regulation is quite adequate in the maintain speed mode but the manner by which it was achieved made very large demands on the air supply. This demand for air could be reduced by accepting wider variations in train speed.

The braking control was generally adequate although the coarse quantisation of speed estimation caused some unnecessary chatter of the e.p. valves. The perceived stopping accuracy was extremely good; this is clearly shown in Fig. W4.
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