THE DESIGN OF CONTROL SYSTEMS
FOR AUTOMATED TRANSPORT

BY

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Abstract

The design of control systems for automated transport has been discussed in two parts. Part one covers the influence of system structure on the properties of the system.

In it, the relative merits of centralised and decentralised controllers are discussed. It is concluded that decentralised, probably hierarchical structures, are most appropriate for transport control. Particular attention has been paid to the design of complex systems to ensure a good service dependability. A 'fail-soft' design is required, that is, one in which there is a planned, gradual degradation of a system following a failure. The design features necessary for such a characteristic are discussed in detail. Also discussed are the particular measurement and communication requirements for automated transport.

Part two of the thesis examines in detail three of the necessary control functions, namely the longitudinal control of vehicles, emergency control and junction control. There are two broad categories of automated control, synchronous and asynchronous. The former has been the subject of considerable research, the latter has been completely ignored. It is shown that, contrary to the stated views of many researchers, asynchronous control can achieve better
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Part two of the thesis examines in detail three of the necessary control functions, namely the longitudinal control of vehicles, emergency control and junction control. There are two broad categories of automated control, synchronous and asynchronous. The former has been the subject of considerable research, the latter has been completely ignored. It is shown that, contrary to the stated views of many researchers, asynchronous control can achieve better
performance levels than synchronous controllers, for example, the capacity of junctions can be almost doubled by using asynchronous control. Asynchronous systems have other important advantages over synchronous systems, for example, stations and junctions can be made more compact, thus minimising track costs (which comprise a major fraction of system costs), and failures are much less likely to cause major disruption.

Asynchronous control is usually associated with vehicle-follower systems. However a novel form of asynchronous controller has been devised and is presented in this thesis. This scheme, the asynchronous marker-follower control combines the advantages of synchronous controllers (simple processing and low communication requirements) with the advantages of a synchronous controller (an efficient use of track and a good response to failures). The normal performance of this scheme is as good as for vehicle-follower control. It does not have as good fault characteristics but offers much lower communication costs and simpler control.
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In this thesis, the design of control systems for automated transport is approached from a systems point of view. The first section discusses general aspects of control system design, namely, system structure, design for reliability and communication requirements. The treatment of the subject is novel and in particular, Chapter 2 - 'The Design of 'Fail-Soft' Systems', is completely original. The second section of the thesis discusses in detail, the longitudinal control of vehicles, emergency control and junction control. In all a novel viewpoint is adopted.

There are two broad categories of transport control, synchronous and asynchronous. The former has been the subject of considerable research, the latter has been completely ignored. This thesis concentrates on asynchronous control. Contrary to the views stated by many researchers, it is shown that asynchronous control can achieve a very much better performance than synchronous controllers. In addition, a completely new form of asynchronous control has been devised, and is presented in this thesis. This scheme, the asynchronous marker-follower control, combines the advantages of synchronous controllers (simple processing and low communication requirements) with the advantages of asynchronous
controllers (an efficient use of track and a good response to failures).

In the last section of the thesis, the computer simulation models, used to examine the control schemes, are described. The interactions between automated vehicles are particularly complex, consequently clear presentation is important. To this end a number of graph plotting routines were written and a moving picture display technique developed.

Each Chapter is supported by a bibliography of references particularly relevant to the chapter. In addition a comprehensive bibliography is contained in the Appendices.

It is appropriate at this point to acknowledge the many people who have helped me in this work. Foremost is my tutor Dr T H Thomas without whose criticism and insight little would have been achieved. Also Alan Hume who helped with the many tricky computing problems, my sister who typed the work, and the Science Research Council who financed the work.
Introduction

The continuously rising social and economic costs of current transport systems have stimulated considerable interest in alternative transport methods.

Automated transport systems are the particular interest of this thesis. These are characterised by small unmanned automatic vehicles operating along a fixed reserved track. These vehicles may carry from two to a hundred passengers at speeds ranging from 15 km/hr to 70 km/hr. Vehicles may ply a single route, stopping at each station, or operate in a network and offer an origin-to-destination, no-stops service. Vehicles may run with time headways (time separations) varying from \( \frac{1}{2} \) a second up to 2 minutes.

Such systems potentially offer the speed and comfort of private vehicles combined with the economy and freedom from stress of public transport. The faster, more predictable, response of automatic controllers, compared with the human operator, may also give increased capacity and better safety.

Much of the early work in automated transport was directed at establishing the particular role and qualities such systems could offer. Many hypothetical schemes were propounded most of which are now considered to be unrealistic, both economically and technically.\(^1\text{-}6\) More recent work has concentrated on less demanding projects, for example, thirty
vehicles to control rather than two thousand, five kilo-
metres of track rather than several hundred, vehicle headways
of $\frac{1}{4}$-1 minute rather than one second and shuttle-loop services
instead of dedicated origin to destination services.

There has been considerable interest in the optimal
control of particular operations in automated transport, for
example, longitudinal controllers, merging controllers,
vehicle dispatching. However few researchers have taken
account of the difficulty of implementing algorithms, the
costs of measurement and communications, the constraints
imposed by the rest of the system, all of which inevitably
reduce the effectiveness of their schemes.\(^{(7-10)}\)

There is little operational experience of automated
transport. Only a few systems have been built, notably at
Morgantown, West Virginia, AIRTRANS at Dallas/Fort Worth
airport and BART at San Francisco. None have been running
sufficiently long for much useful data to emerge. However
recent analyses of automated transit have been produced by
the United States' Office of Technology assessment. These
publications have emphasised the need for substantial further
research in a number of fields,\(^{(11-12)}\) namely

- System reliability - all the systems so far built have
  suffered from poor reliability.

- System integration - the increasing complexity of auto-
  mated systems requires that the entire system design is care-
  fully controlled, with specific design goals and a clear
  understanding of the interactions between subsystems.
Longitudinal control - automated systems need to operate at close headways. Better normal and emergency controllers and strategies have to be developed to allow these close headways to be achieved safely.

The Layout of the Thesis

The discussions which follow are divided into three main parts.

Part one covers the influence that the system structure has on the properties of the system. Thus chapter one considers likely structures for automated transport controllers; chapter two discusses in detail the design of 'fail soft' systems; chapter three identifies the particular measurement and communication requirements of an automated transport control network. These particular features have been chosen because they are fundamental factors in all transport control schemes, and must figure in any cost function related to the 'whole' system.

In part two (chapters four to six) are examined in detail three of the necessary control functions in automated transport. These are:

Chapter Four - The Longitudinal Control of the Vehicle - The amount of information transfer required for track/vehicle communication is an important parameter. To communicate less is cheaper but requires substantial onboard computation. To communicate more may allow a better overall control to be achieved but reduces the autonomy of the vehicle and possibly
reduces the resistance of the system to faults. The design of control algorithms with limited information transfer is discussed in detail and related to control schemes already in existence.

Chapter Five - The Emergency Backup to the Longitudinal Controller - In addition to the normal control another is required, the independent safety control. This oversees the normal controller. It is generally a very simple, reliable system monitoring only the vehicle separation, capable of issuing only one command (typically to brake at an emergency rate to zero velocity). Autonomy from the normal control system is essential to ensure that failures in the normal control system are independent of failures in the safety system. This reduces the likelihood of a joint and possibly catastrophic failure. The normal and emergency control systems will interact, particularly when the track is being operated near maximum capacity. There are costs associated with both unnecessary emergency manoeuvres and undetected unsafe situations. The satisfactory balance of these two costs will be an important design consideration.

Chapter Six - The Junction Controller - Junctions are usually the capacity limiting elements of a transport system. Control policies must be developed that allow high flows through the intersections, yet limit delays and the distances required for preparatory manoeuvres. A number of algorithms for ordering vehicles through the junction are presented. Their performance is analysed and compared.
Finally in part three of the thesis the modelling techniques, used to examine the control algorithms devised, are explained.

Automation of Transport

An automated transport system is a highly complex organisation involving many interacting operations. People have to be informed; vehicles have to be manoeuvred, directed and dispatched; failures must be identified and rectified; safety must be ensured.

Automation commits to hardware functions previously carried out by humans. The designer encodes the functions into a system as repetitive, preprogrammed, routine strategies which govern the response of the system to its environment. However flexibility is reduced since automation cannot build in responses to novel unforeseen events. When these occur the automated controller must refer control back to a human operator. A totally unmanned transport system is consequently unlikely ever to be achieved. Staff will still be required at stations, for maintenance, and for ensuring the safety and security of passengers.

Automation has been applied to the vehicle, to many station functions and to the centralised strategic control of vehicle movements. The value of such automation has yet to be conclusively established. Many aspects of it have been
extensively studied, often with optimisation in mind, yet those systems that have been built have not performed well. They have been costly to build and operate, have not achieved significant reductions in staffing and have not provided the quality of service that had been expected of them.

Control schemes are required which will enable the system to operate well under all foreseeable conditions. Their design is challenging. A system has to be created that has few precedents and where the scale of capital outlay precludes iterative (evolutionary) design methods. In these complex systems, governed by cost functions embracing economic, social and technical factors, design policies must find the best operating regions. Design is an optimisation procedure. Its purpose is to select, from the group of all the possible systems, the one which most effectively satisfies the problem specification.

This thesis discusses some aspects of the design of the control system for an automated transport network. A 'systems' approach has been used. This approach is particularly applicable to complex systems (systems which require substantial effort and time for their appreciation and understanding). In a complex system, future states cannot be easily predicted, particularly when the system is subject to random events. There are two main reasons for this.

- The complexity of phenomena for which a complete analysis is very costly.
- The limited ability of humans to cope with analysis.

As a result the successful design of large scale systems has
invariably been done by decomposing the system into a number of simpler sub-systems, each with its own goals and constraints.

The systems viewpoint assumes that it is both feasible and useful to breakdown the original design problem into a number of independent sub-problems (or sub-systems). Only the outputs of each sub-system are considered as relevant to the analysis of overall system behaviour. The functioning of each sub-system is only dependent on its inputs. Of central importance is whether an arrangement of sub-systems can be designed to act in an overall system optimal manner and how all the units, acting according to their own goals, can be made to achieve the overall goal. To optimise a single sub-system contained within a large system without regard to the effects of interactions can lead to such a degraded performance elsewhere in the system, that the overall performance is worse than without any optimisation. Coordination is required, that is, a suitable balancing factor from the rest of the system must be made visible to the designer of a particular sub-system. Then he, in minimising his own cost function, will be able to approximate the total system optimisation.

The process of design comprises the following activities.

1. Definition of objectives
2. Formulation of measures of effectiveness
3. Generation of alternatives
4. Evaluation of alternatives
Finalising

The design specification is a fundamental stage. All the influences, ranging from variations in physical variables to political conditions, that will act upon the system and its constituent sub-systems, must be detailed. The designer works to this specification; the inaccurate definition, or the designer's incorrect interpretation of it, will eventually result in faulty operation.

In his search for the optimum solution the designer needs measures of effectiveness, both for the system and the individual sub-systems comprising it. All the features of the proposed solution are evaluated in terms of these common measures. Possible system configurations will compare differently according to the measures chosen, consequently their definition will determine the final choice of design.

All optimal searches take time. To optimise or improve a design requires that understanding be increased. To obtain the knowledge necessary for that understanding takes time. Large scale systems change as processes change and as technology advances. If these changes take place faster than the control system can be designed and implemented, then the 'optimal' designs produced will no longer be optimal. There is a dilemma between needing to act without delay and understanding the situation better. Also the depth of analysis chosen, should depend on the likely benefits to be reaped. In complex design situations the dilemma is resolved by decomposing each major problem into several simpler problems.
Finalising

(5. Selection

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In complex design situations the dilemma is resolved by decomposing each major problem into several simpler problems.
Local optima are then sought and combined to form an overall 'good' system. This speeds up the design process at the cost of some loss of potential system performance.

The evaluation of design alternatives requires models as it is only rarely that designs can be built, tested and rebuilt during the course of a design. Models are abstractions (hypotheses, theories, simulations) about the system under consideration. They have to be sufficiently simple to be comprehensible, yet complex enough to yield useful information when extrapolated into unknown regions. Models are necessarily distortions of the real world. They must be tested and validated with known data to establish their significance and region of use. Measurements are then made on them in the hope that the results may be used to predict the reactions of the real-world system. However any extrapolation from a model is prone to unforeseeable error. Optimal decisions in the approximated world may not necessarily even be good decisions in the real world. Models say nothing about the effects of what is excluded and prevent the recognition that what is excluded may have some effect. A variety of models may be required each illuminating different aspects of the subject, so that understanding of the subject is increased.

In the design process, selection follows analysis. Selection is the art of balancing all the features of the various candidate solutions. It is not primarily a technical problem, the analyst removes as many of the technical uncertainties as possible. He defines the issues and
alternatives so that the decision maker may assess and choose a final design according to his value system.
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1. The Structure of Complex Control Systems

1.1 The Importance of System Structure

The designer of an automated transport network must choose which functions are to be automated and select an appropriate control structure. He must determine how the various control tasks will be distributed between the vehicle, the trackside, and any central controller. His design should minimise cost, ensure reliability, localise breakdowns, and facilitate maintenance and repair.

The choice of structure will determine the communications that will be required (communication links contribute substantially to both the cost and unreliability of a system). A suitable structure will allow the system to have a 'fail soft' character, that is, the system degrades gently as non-essential but useful information is lost.

The benefits which accrue from a judicious design of the control structure far outweigh those that can be achieved by optimisation at a detailed level. Yet system structure is rarely explicitly considered. (1)

The first stage of system design should be the specification of the subsystems and the structure of interconnections. The choice of a structure for a system is not amenable to formal techniques of analysis. Although some
work has been done concerning the theory of structure, the choice of an appropriate structure is usually made on the basis of a comparison with other systems exhibiting desirable properties.\(^{(1-2)}\)

1.2 Types of System Structure

Two distinct structures can be identified in a system.

* The physical or hardware structure: The distribution of system hardware around the geographical region and the communication links supplied to interconnect them.

* The information or software structure: The definition of functions required to perform the necessary control decisions and the information flows that must pass between them.

Since communication links allow information to be transmitted anywhere in the system, a functional unit in the system informational structure need not correspond to one discrete module of equipment. The degree to which communication links are used to transmit information from one locality to another for further processing depends on the relative costs of providing processing and communication equipment. Advances in the large scale integration of electronic circuits have tended to reduce the fixed costs of processor modules, also processing power is becoming
cheaper relative to communications. These trends favour the use of local autonomous dedicated processors having low communication requirements. \(^{(3)}\)

1.3 Possible Control Structures for Automated Transport

The most common control structures that are proposed for automated transport systems are:-

- Centralised
- Distributed network
- Distributed hierarchical

Centralised Structures - In centralised control structures, all measurement data is supplied to a central controller, and all control actions emanate from the central controller. All information about the state of the system is freely available for use anywhere in the system so maximising the potential performance the system can offer. \(^{(3)}\)

Centralised control systems use a large digital computer, time shared between a large number of functions. The use of a single resource (the central processor) shared by many users is governed by queuing type phenomena. Delays rise non-linearly with demand; near to saturation (about 80% capacity of the machine) delays rise rapidly and are highly variable. This sharing causes strong interactions between users which have therefore to be carefully organised.
and controlled to ensure satisfactory operation. The performance of centralised systems is limited by the speed of response of the central processor.\(^4\)

In situations where the speed of response is not critical, well understood centralised control structures may be able to offer a high level of performance. This is because all the system information can be used, even where its benefit is marginal.

Several features of centralised systems militate against their use, especially the following.

* Communication costs are high as wide bandwidth channels to the processor are required. This effect is particularly marked if long distance channels are used to link all parts of an extended network to the central processor, as, for example, would be the case in an automated transport network.

* The concentration of control activity into one closely connected area makes the system very vulnerable to faults. A single fault can easily affect many functions simultaneously. Isolation of a fault is difficult because of the high connectivity between functions, via the memory and CPU of the computer.

* The complexity of interactions between subsystems makes the system operation difficult to understand. As a result it becomes more prone to software faults. An incomplete knowledge of the possible system states is more likely and may lead to undesirable and possibly unsafe conditions.
The greater number of system states makes fault monitoring and rectification difficult and costly.

There is an increased possibility of unforeseen feedback loops occurring which may lead to unstable behaviour.

**Distributed Networks** - An array of locally sited dedicated processors, each performing particular tasks are connected together. The characteristics of such systems depend on the style of system organisation chosen. The most common arrangement is the 'bus-bar' type in which all the system units are multiplexed onto a high-capacity communication link (the bus-bar). (Dia 2)

Bus-bar control structures are particularly suited to digital systems. Indeed they closely resemble centralised computing systems but with the increased speed and flexibility that distributed parallel processing allows. The capacity of the bus-bar limits system performance as it is governed by queuing phenomena similar to those experienced by centralised computing systems.

Bus-bar systems have a number of useful features. (5)

- Interconnections between functions are created by message addressing, consequently the system organisation is totally controlled by software. This can give great flexibility.

- Costs are reduced as there is only one communication link, although a higher bandwidth will be required of it.
* The simplicity of the bus-bar permits standardisation of the communications hardware. This reduces the costs of fault diagnosis, repair and maintenance, and facilitates the use of fail-safe circuitry and high reliability design.

* As duplicate standby equipment can easily be connected to the bus, redundancy can be very flexibly incorporated, particularly if one standby unit may be used to replace any of several similar ones.

* Bus-bar systems can be easily reconfigured. This allows the system to change easily as requirements change, so reducing the costs of obsolescence.

Bus-bar systems suffer from one major disadvantage. The multiplexed communication link is very vulnerable to both hardware and software failures. Both can easily cause a rapid system shutdown. There is no inbuilt protection against faults causing incorrect addressing equivalent to a random connection between subsystems. To locate and diagnose such a fault is likely to be very difficult, particularly if it were an intermittent fault. Some protection can be provided against hardware faults by the use of redundant communication links. However this substantially increases installation and material costs particularly if each cable is housed in a separate conduit.

Hierarchical Distributed Systems. - A hierarchy is a multi-layer control organisation. It can be considered as a filter,
each processing layer being associated with a range of frequencies or band of time scales. Together the layers cater for the entire range of frequencies apparent in the system. Only at the first layer are found the actual physical measurement and control variables. Data is progressively condensed as it moves up the structure. Decision times become longer, control action is more general and information has a more global context. Each unit in a hierarchy operates semi-autonomously in a specialised role. It receives limited strategic commands from its superior node. It passes on delegated commands to its subordinate units. In the absence of new commands the unit has a regulating function that it can execute using stored earlier commands. Feedback loops are closed locally, thus minimising the difficulty of controlling complex functions and compensating for long time lags.

Information is only selectively directed up a hierarchy. Consequently not all the system information is available everywhere in the network. Information of marginal value from elsewhere in the system cannot be used. This has several consequences.

- Hierarchies may use more equipment than similar centralised systems since individual functions are not shared. However this also allows functions to run in parallel and simplifies their design.
- The ultimate performance of a hierarchical system may be less than an equivalent centralised system.
DIA. 1 Centralised network

DIA. 2 Decentralised busbar network

DIA. 3 Decentralised hierarchical network

Greater generality
Longer timescales

Greater detail
Shorter timescales
As only essential information is transmitted around the system, communication costs are minimised.

The system can expand or contract locally without strongly affecting the rest of the system.

The most important characteristic of hierarchies is the autonomy of the subsystems within the structure. The decoupling and isolation of subsystems simplifies their design. As a result their operation can be more confidently predicted and fewer design faults result.

The strong control of communication provision minimises the likelihood that faults will create informal information paths along which to propagate. This simplifies fault isolation, diagnosis and repair. It also increases the resistance of the system to disturbances, changes in the operating environment and failures.

The three important features of hierarchical systems, their intrinsic resistance to faults, their relative ease of design, and their flexibility, all favour their use in large scale systems where reliability is important.

Bus-bar systems probably offer greater flexibility than the hierarchical equivalent. However their vulnerability to faults constrains their use except in very predictable environments and for systems requiring only moderate amounts of communication.

Centralised systems offer an efficient use of equipment. However against this must be set their complexity, vulnerability to faults and high communication costs.
1.4 The Choice of Subsystems

There are many ways of partitioning a system into a set of interconnected subsystems. The decomposition depends not only on the choice of system structure but also on a number of other factors. Of these the most important is the need to partition the system into sections of manageable complexity. A unit too large to be understood is likely to be inadequately specified, to perform badly and when it fails to be time consuming to repair or expensive to replace. A unit that is too small will incur unnecessary design overheads and will increase the problem of interconnection and coordination between units.

A simple measure of complexity could be - the number of significant states a device can adopt. However this takes no account of the evolution of the device (previous generations of a device give operational experience which allows the new generation to be more readily understood) or of the skill of the designer (his training and previous experience accelerate his understanding of a new device). Such factors alter the way in which complexity is perceived. A better understanding of how complexity is perceived and of the human approach to problem solving would allow design effort to be more effectively deployed. (10-15)

Subsystems should correspond to local concentrations of activity in the system. These are areas in which cheap local information is available and to and from which relatively little communication is required. This limitation
on the number of inputs and outputs is also a limitation on the number of states a subsystem can adopt, and hence on its complexity.

The new design effort can be minimised by choosing subsystems that correspond closely to already developed systems. This is an evolutionary design process. However where system requirements have changed and substantial modifications are required, it is often better to incorporate the design experience into a new custom-made device.

Timescales - A property of major importance is the timescale of a subsystem. Any system will respond to a range of timescales or band of signal frequencies. The measurement transducers at the systems interface with its environment will generate raw signals containing all these system frequencies. A system comprises function subsystems which process input information and generate outputs accordingly. Associated with these processors is the property of 'decision time' or 'processor speed'. This is related to the maximum bandwidth the processor can handle (analogue processes) or to the computing time required to process a sample of input information (digital processes). Each function in a system thus has a minimum time or maximum frequency it can respond to. Only information changing slower than the processor limit can be accepted from the input or transmitted from the output. Furthermore there will be a time delay before a change at an input can affect an output. This delay will be at least a decision time (or the bandwidth limit equivalent).
This 'time-scale' feature has several effects:

- The longer the time delays inherent in a system loop, the more autonomous a subsystem must become. The degree of autonomy of a subsystem is related to the time interval over which the subsystem must function independently and satisfactorily.

- Upper level units concerned with the optimisation of lower level processes must have a longer time scale than those lower level processes, since to collect the necessary information to reduce uncertainty several decision periods of the process must be observed. To evaluate the effect of an input to the lower level process, the upper level unit cannot work faster than the lower unit it is optimising.\(^{(1-2)}\)

1.5 Structure and Subsystems for Automated Transport Control

The control system for an automated transport network has to perform the following activities.

- Supervisory control: - Dispatching, scheduling and routing of both full and empty vehicles, start-up and shut down and possibly long term optimisation.

- Longitudinal track-side control: - Transmitting commands to vehicles (The control commands allow the vehicle to be manoeuvred at stations, through junctions and along the open track).

- Vehicle control: - Regulating vehicle speed, position and acceleration according to information from the trackside.
* Emergency control: - Ensuring the safety of the system, particularly the safe spacing of vehicles.
* Passenger control: - Providing route information, ticket dispensing, and checking, and marshalling.

A transport network will be physically distributed over a large area. The computing power required to carry out the necessary control will demand the use of several inter-connected computers carrying out specific tasks. The additional considerations of designability and reliability encourage the use of maximum autonomy, with low capacity communications linking the local centres of activity.

A number of layouts are possible of which the most common are: -

* Two tier localised control:- Local controllers, attached to the junctions and stations, supervise their adjacent track sectors. Vehicles are handed on from one sector to the next. Information about the vehicle (e.g., destination and status) may be carried by the vehicle (which is then interrogated by each local controller, or may be transferred from controller to controller by lateral linking. (Dia 4)

* Three tier localised control:- The local controllers are coordinated by a higher-level controller. This is usually concerned with system management (e.g., dispatching and routing, optimisation). (Dia 5)

* Two tier centralised control: - All control is located at one place from which commands are dispatched to
DIA. 4 Two tier localised control

DIA. 5 Three tier localised control

DIA. 6 Two tier centralised control

(from ref.16)
all the system. This arrangement incurs very heavy
communication costs. (Dia 6)

Whichever organisation is adopted, the controller
must take account of the changing physical structure of
the system, as vehicles move along the track and cross the
boundaries between track sectors. There will always be
some difficulty at the change over: Either the vehicle will
be controlled by both controllers simultaneously, or by
neither, both options involve some hazard. (16)
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2. The Design of 'Fail-Soft' Systems

2.1 Introduction

Reliability is an important parameter in the design of all systems. The larger and more complex the system, the higher is its potential benefit but so also is the cost of faulty running. Faults inevitably occur and more complex systems have correspondingly more faults. The use of extra complexity in a system may allow potentially higher performance levels. It may also prevent them being attained if the greater complexity leads to a reduction in system reliability. To maximise the operational effectiveness of a system the balancing of system performance against system cost must take account of the effects of unreliability. (1)

Any system can be characterised by its performance before failure, its performance after failure, and its probability of surviving without a failure. Within a particular cost budget, the system designer manipulates these three characteristics to achieve an acceptable operational performance.

There are three approaches to this manipulation.

The Perfectionist Approach - Components and operating procedures are chosen so that the probability of a failure
in service is reduced to a negligible level. Design techniques of this type include; the use of higher quality components, 'burn in', derating and planned replacement to reduce in-service failures, and the avoidance of novel, unproven technology. Typical of this approach is the no-repair design of consumer items, such as refrigerators, and large vehicle components. A failure, when it occurs, is total, the only redress is replacement.

The perfectionist approach is inapplicable to complex systems for two reasons. Firstly, the complex systems have a large number of components, all of which are 'vital' (that is the failure of any one causes a total system failure). Thus, for an adequate system life, impossibly high reliabilities are required for individual components. Secondly, the design of complex systems is difficult. The designer being human, will be unable to anticipate all the modes of use and consequently the likelihood of failure due to misuse increases. (7)

The Fail-operational Approach - Levels of redundancy and repair strategies are chosen to give a very low probability of in-service system failure. Commonly known as duplication or triplication, the fail-operational technique incorporates spare equipment into the system at strategic points. As faults occur, this is progressively substituted for the failed equipment. The original system performance is maintained until, at some point in the structure, the spare capacity is exhausted, whereupon the system fails completely.
Fail-operational design is appropriate where any significant loss in performance is costly and immediate repair is difficult or impossible, e.g., in aircraft control equipment.

For systems where loss of performance is not critical, the fail-operational design philosophy usually results in unnecessarily expensive schemes.

The Fail-soft Approach - A 'fail-soft' system is a system where the degree of degradation following some failure has been consciously planned. Systems, so designed, attenuate the consequences of a failure, not necessarily by preventing a fault affecting system performance, but by choosing a compromise between the degradation of system performance and the cost of extra fault proofing equipment. A common, though simple example of a 'fail-soft' system is a vehicle with power steering, power brakes, or active suspension. These are usually designed so that in the event of a failure in the servo mechanism some steering, braking or suspension is retained albeit with a poorer performance.

'Fail-soft' should be the normal design philosophy, since the perfectionist cannot be used with complex systems and the fail-operational is too expensive. However it is rarely explicitly employed, and has never featured in the published literature.

The discussion that follows presents some techniques by which a fail soft system may be achieved.
Fail-soft Systems - A system is a profitable enterprise created and run by an operator and providing a service to the user. Its performance can be defined thus:

\[ \text{PERFORMANCE} = (\text{VALUE OF SYSTEM}) - (\text{COST OF SYSTEM}) \]

or

\[ \text{SURPLUS} = \text{BENEFIT} - \text{COST} \]

The way the surplus, value and cost are distributed between the user and the operator is not important to the arguments which follow. The units of each term are money/unit time. Effective design and operation of the system maximises the surplus; ie, maximises the system performance.

\[ S = \sum_{\text{all states}} S_i P_i \]

where

- \( S \) - expected value of surplus
- \( S_i \) - mean value of surplus when in state \( i \)
- \( P_i \) - probability of being in state \( i \)

Alternatively, equation 1 can be stated:

\[ S = S_0 - \sum_{\text{all incidents}} R_k C_k \]

\[ S = S_0 - C \]

where

- \( S_0 \) - the 'perfect operation' surplus
- \( C_k \) - the cost of the \( K^{th} \) incident (ie, the change in surplus resulting from an incident)
- \( R_k \) - frequency of \( K^{th} \) incident
The fail-soft approach is to maximise $S$ for a given budget, either by increasing the potential performance $S_0$ at the expense of a larger loss term $\zeta$ or vice versa. The frequency term $R_k$ is influenced only by the reliabilities of the components that might produce the particular incident. The prediction of $R_k$ is well covered in a copious literature spanning many years. By contrast, the incident cost $C_k$ has rarely been considered, nor have methods of controlling it been developed (although some related topics have been studied in isolation). (2-8)

**Disruption** - The incident cost $C_k$ will be termed the 'disruption'. It comprises any increase in costs and any decrease in benefit resulting from an incident. (Dia 7)

**Degree** - The 'degree' of a fault is a measure of the importance of the failed component to the system. It is the loss in performance as a function of time. Consequently

$$\text{DISRUPTION} = \int (\text{DEGREE}) \, dt$$

over the incident duration

Degree is therefore $(\Delta \text{cost} + \Delta \text{benefit})$ per unit time.

The $\Delta \text{cost}$ term is the cost of the incident incurred by the operator for repair and replacement.

The $\Delta \text{benefit}$ term is the loss of service resulting from the incident. It is assumed to be much bigger than $\Delta \text{cost}$ and therefore more important. In the discussions which follow only the $\Delta \text{benefit}$ term is considered.
DIA.7  System performance following a fault

DIA.8  Effect of complexity on repair time

DIA.9  Fault performance of low speed and high speed functions

DIA.10 Fault performance of fast and slow functions with fixed repair time
A component anywhere in the system contributes in some degree to the performance of the system. During normal running this contribution is a maximum. Failure reduces the value of the contribution. The worst-case failure will give the lowest possible system performance, usually lower than would have been achieved had the system been designed without the component at all. The maximum degree of fault corresponds to this worst case.

Lessening the degree of a fault implies a reduction in the importance of some function and hence its associated worst-case error. This reduction might be achieved by simplification of the system, (with a corresponding reduction in its normal performance $S_0$) or by partitioning the system into smaller sections whose individual importance is thus reduced.

For many extensive systems, degree can be conveniently divided into 'intensity' and 'extent'.

The 'intensity' is the value of the function to each of its users. The 'extent' is the number of users. Thus:

$$\text{DISRUPTION} = \int f_a(\text{INTENSITY}, \text{EXTENT}) \, dt$$

For example, a typical structure for a transport control system has a local area controller dispatching regular commands to the individual vehicles within its zone. The degree of a failure in this area controller is strongly dependent on the number of vehicles being controlled (ie, its extent) as well as the loss in value of the information put out to each vehicle (ie, its intensity).
Duration - Systems intended to have a useful life that is long with respect to the mean time between failures, must be repaired. The disruption caused by a fault is dependent on its 'duration'. However any change on the system output cannot be faster than the signal producing that change. Consequently the information output by a rate-limited function, even if it is faulty, will not change the system faster than that limit will allow. This suggests that it is not only the absolute duration of the fault which is important, but also its duration in units of the failed processor's decision time. A fault in a high speed processor will become noticeable more rapidly than if the processor were low speed. (Dia 9)

Repair times however depend on the complexity of the function involved. (Dia 8) For functions of a similar complexity, repairs will take a similar time. As a result, a failed high speed function of similar complexity to a failed low speed function will cause a proportionately greater disruption, unless particular measures are taken to reduce its repair time. (Dia 10) (3)

2.3 Potential Performance, Disruption and Operational Performance

To achieve the highest potential performance of a system, each item of information should be used to its maximum value i.e., the information should be accepted as valid, used as fast as possible and everywhere possible.
However, if the information is in error, the resultant disruption will also be a maximum. The operational performance then achieved may well be lower than if the information had not been used. Thus increased system complexity, aimed at extracting the maximum value from information will increase the potential system performance but may decrease the actual operational performance.

If, as an alternative, the increased complexity is used to improve reliability, the potential performance will not be improved, but the actual performance may.

THE CONTROL OF DISRUPTION FOLLOWING A FAULT

2.4 The Control of Unanticipated Faults

A designer can only explicitly design for faults that he has anticipated. His ability to foresee and evaluate their consequences depends on the complexity of the system. He will not be able to forecast all faults and consequently will not devise a comprehensive set of contingency plans.

Action taken to compensate for unexpected faults can only be taken at the time of failure. The action is the sequence of 'on-line' design decisions made by the system operator involved with the fault. He is a part of the system and can be considered as a flexible, unspecialised, decision maker. In many systems he is the most important control of disruption resulting from a system failure.

Methods for dealing with anticipated faults are intro-
duced into the system design from the outset. Each strategy can be considered as the optimal use of a new system, (the new system being the original system changed by having a faulty component).

Three running states can be identified:

* Normal - the system is operating along its most profitable, maximum performance, trajectory through system state-space; a path previously anticipated by the designer.

* Faulty - the system is operating below its maximum performance trajectory but on a trajectory optimal for the system with a failed component. Again the path is one anticipated by the designer.

* Extraordinary - the system is being guided along a path in its state-space by the real-time design decisions of an operator. He covers for all unanticipated situations. His success depends on his ability, knowledge (training) and whatever system functions are accessible. He takes direct control of these functions via man-machine interfaces. Effective operator control depends on the good design of these interfaces.

2.5 The Control of Anticipated Faults

Action taken to control a fault is directed against the disruption caused by the fault. This control action will moderate the degree of the fault as a function of time and/or duration. More control will reduce disruption but at greater expense. A balance has to be sought.
2.5 Types of Fault

A failure is an event, after whose occurrence the output state of a device shifts outside permissible limits. It is sometimes exceedingly difficult to formulate the specification of a failure, where for example, there are subjective characteristics involved.

Failures may be:

- Instantaneous - There is a sudden loss of function.
- Gradual - A prolonged deterioration of equipment leads finally to a failure.
- Permanent - Failed equipment is inoperative until repaired.
- Intermittent - Failures last for a short time. The system is momentarily disturbed. The faulty equipment then resumes normal running possibly leaving observable transient consequences in the system. Where a component is wearing out, final failure is often preceded by a series of intermittent faults.
- Independent - Each failure occurs independently of any other. Failures are usually assumed to be independent events even though a fault in one component varies the operating conditions of other components and consequently the probability of their failure.
- Dependent - The failure is caused by the failure of another component.
- Common mode - Faults in different pieces of equipment, which all result from a common source failure. The prevention of common-mode failures is particularly important where independence is assumed or required. (6,7)
2.7 Sources of Faults

There are two phases in the life of a system. They are the design phase, in which all actions prior to running take place. (The design and specification of the system hardware, system software and forecasted operating environment, including maintenance and operating procedures), and the operational phase, in which the system runs in its actual environment, is subject to inputs and produces outputs. Faults can arise in either phase but their consequences will be observed only during the operation phase.

Faults in the design phase result if equipment, algorithms and the system environment differ from those intended or forecast. Design faults are likely to be systematic, that is, similar faults arise in related equipment; the same equipment always fails under the same conditions. Design faults are frequently the source of common-mode failures. As design faults are necessarily unanticipated, all systems are vulnerable to them. Techniques such as standardisation, simplification and evolution may reduce incidence of design faults. The use of independent designers reduces the risk of common failures in separate devices.

Faults arising from incorrect data supplied as input to the system, or from a component failure, are amenable to systematic fault control techniques.

2.8 The Propagation of Faults

Erroneous information will propagate along any available path through a system. Most paths will be the formal
channels comprising the information structure of the system. The remainder will be informal routes, resulting from a causal-chain interaction of system components that has no part in normal running. For the predictable operation of systems these informal routes must be identified: Often, for successful fault control they must be eliminated. These informal links are often created by the fault itself. For example, in a computer, an incorrect processor operation can easily destroy data totally unconnected with the failed function.

The speed at which faults propagate is limited by the delays that are introduced by operations along the path followed by the fault. Increasing the time delays caused by these operations will reduce the rate at which a fault can affect the system output. Operations should therefore be designed to work at the lowest speed consistent with their fulfilling their roles satisfactorily during normal running.

2.9 Classes of Fault Control

Fault control systems can be either open-loop or closed-loop.

Open-loop - Open loop fault control is sometimes called 'built-in' redundancy. Equipment is used which is more elaborate than the minimum necessary to achieve the desired function. Every component is active all the time, but the configuration is such that when one fails, the function as a whole does not fail. The construction and effectiveness of these systems relies upon the fault modes of a device being known.
Two approaches are possible. The first aims to make any failed unit transparent to the rest of the system, i.e., the transfer function $G_{-}$ with $m$ components is the same as the transfer function with one component.

$$G_m(s) = G_{m-1}(s) = G_1(s)$$

This approach can be used with relays or diodes with which the likely faults are either open-circuit or short-circuit.

Under the second approach, failures are permitted to cause some change in the transfer function of a unit, but the redundancy is used to place a limit on this change. Queuing systems are of this type. (7)

Closed-loop - Closed-loop fault control is more important. Although greater expense is involved, in principle any fault can be controlled.

A monitor measures the actual system state and compares it with a prediction generated from a model. The detection of a discrepancy initiates action designed to counteract or remedy the failure. The output of the monitor may be continuous or discrete. The design of fault controllers having continuous error signals can make use of the well developed theory of feed-back control. Usually, however, fault protection is carried out using discrete fault monitoring; the detection of a fault causing a specific strategy to be selected from a small number of alternatives. (Dia 11) (7)
DIA.11 Schematic of system and fault controller
2.10 Monitoring

A system has a set of realisable states. The states that correspond to normal operation are defined by the system specification. All other states correspond to faulty operation.

In practice, often only the intended running states of a device are closely defined, as the complete definition of all failure states would be very time consuming and costly. Four techniques are in common use.

- Equipment is designed to have only a few conceivable failure states, for example, fail-safe equipment. (This is only feasible for very simple, usually mechanical, devices).
- Only important failure states of a device are detailed. (Unfortunately the importance of a device state may depend on the application of the device. In some situations, a particular failed state might be unimportant, in others it might be very important).
- Only the most unreliable parts of a device are considered in an analysis.
- Dependent and simultaneous faults are not analysed.

2.11 The Requirements of a Monitor

A failure generates errors which propagate away from the failure site. These errors are detected by the monitor. There are thus three sets of function states.

- The states which correspond to the function specification and are therefore the correct states.
• The actual states generated by the function
  (including its error states).
• The states interpreted by the monitor as correct
  ones.

In a perfect system these states are all the same; in prac-
tice, limitations in both the function and the monitor
ensure that they are not. As a measure of this, two para-
 meters may be defined.

The 'coverage' of the monitor is the fraction of errors
that the monitor detects. The 'restrictiveness' is the
fraction of normal states classified as faulty. Inadequate
coverage is expensive as many faults are not detected.
Excessive restrictiveness is expensive because there are
many false alarms. Usually a trade-off can be made between
the two.

Only a limited number of monitors can be deployed in
a system. These will test the most important variables,
those which, if faulty, would cause maximum disruption. The
information yielded by the monitors is the only information
available for locating and controlling failures. Thus more
monitors allow a more comprehensive check on system operation,
a better identification of the failure site and a more
appropriate selection of control strategies. However extra
expense is involved and as the error detecting transducer is
in series with the processor being checked, the system
reliability may be reduced and the system response slowed.
2.12 Fault Location

Most fault analysis and control assumes that faults occur randomly, each fault is independent of any other and there is a negligible probability of simultaneous faults.

However monitors detect the errors resulting from a failure, not the failure itself. Although the failures may be random, the errors detected frequently will not be, for the following reasons.

* Monitor coverage of the system states is not complete. Consequently multiple dependent errors may be recorded some distance from the failure site, possibly at several different parts of the structure and not necessarily at the same time.

* Systematic design faults may cause a similar fault to occur simultaneously in a number of functions or monitors.

* There is a delay between the occurrence of a fault and its detection. The longer this time delay is, the higher is the probability of more faults occurring, all of which would have to be considered as arising simultaneously.

For effective fault location, monitors must detect all important faults. Each monitor must have a high coverage and low restrictiveness. Monitors must be closely spaced, thus partitioning the system into areas of low complexity (and high reliability).

If these conditions are satisfied, then the unambiguous logical location of some faults may be feasible. (For
example, by using cause-consequence analysis to identify the signature of monitor outputs resulting from a particular fault). If not, automatic fault location is not possible, and fault control measures must attack errors rather than identify and isolate the originating failure.

2.13 Error-Detection Techniques

Redundant Parallel Processors - Operating on the same input data, two or more independent processors can be used to carry out a function. If corresponding results disagree, at least one computation is faulty. The use of more than two resources enables voting to identify the faulty unit.

Independent processes can be interpreted as:

* The same process on the same hardware at different times (time redundancy to detect intermittent faults).
* The same process on different hardware at the same time (hardware redundancy to detect hardware faults).
* The same process based on different algorithms in the same hardware (software redundancy to detect software faults).
* Combinations of the above (these offer protection against all faults including design faults).

Common-mode failures render redundancy monitoring ineffective. Important common-modes are the input data, systematic design faults and environment changes.
Redundancy is the only means of simultaneously achieving high coverage and minimum restrictiveness. Redundancy is expensive and because of the necessary comparison operation, speed of operation is limited to that of the slowest processor.

Other Error-Detection Techniques - Non-redundant monitoring is a check on the reasonableness of the information at the monitored point. Coverage is lower, restrictiveness is higher, but costs are much reduced. Monitors may check for particular vital states (either normal or faulty) to whose absence or presence a high system cost is attached. The boundary between normal and faulty running corresponds to the point at which system running costs are deemed unacceptable. (Dia 12)

Error Detection Using Information Redundancy - Using coding, redundancy can be incorporated into data signals. Many sophisticated error detection and correction codes have been devised which are effective for a wide range of possible fault situations. They are used in communication links and data storage/retrieval systems. It may be extendable to other functions, for example by incorporating into the input data a condition that is unaffected by the function and can be verified from the output data. (9-12, 16)
2.14 Fault Recovery

The objective of the fault recovery phase is to restore normal system operation with the minimum of disruption, following a failure. This requires the location and repair of the failed unit and the use of standby control to limit the disruption incurred in the interim.

Repair Times - The overall time to restore the original service depends on the repair arrangements. Plug-in replacement modules restore service rapidly at a high cost. Remove, repair and replace strategies give a high system downtime but are cheaper to operate. The exact balance chosen between the two depends on the time scale of the failed function, faster functions will generally have to be repaired faster.

The provision of on-line monitoring allows a faster response to failures. Off-line monitoring by maintenance men improves system reliability and makes better use of test equipment, so reducing costs that way.

Standby Control of System Disruption - In place of the failed function, standby equipment provides an alternative that has the best possible system value given available resources.

Standby measures are selected by switching, that is, the system structure is reorganised. The rearrangement may maintain the original system performance or provide a reduced performance. The more closely the original
performance is to be maintained, the more expensive is the provision of substitute standby processors.

There are several techniques of standby control:-

* The failed unit can be replaced by another similar unit. For fast acting important functions, the switching must be on-line and automatic.

  Direct function replacement depends for its effectiveness upon the failure being located in the replaced function. Otherwise faulty information will be input to the replacement function and system disruption will not be controlled.

  Direct function replacement, an example of the fail-operational technique, is expensive.

* The failed function can be isolated and the downstream structure modified so that the information lost is no longer required by the remainder of the system. This feed-forward type of control necessarily entails some loss of system performance. It is much less expensive, as precise fault location is no longer necessary.

In some cases it is possible to substitute standardised information for the signal that has failed. The standardised signal is chosen to minimise subsequent disruption, and could be

  - an average value command
  - the last correct command
  - a predetermined value
  - a human operator input.
2.15 Vital Functions

Although a hierarchy of fault protection strategies can be incorporated into a system to attenuate the consequences of most faults, some vital functions will remain unprotected. It is at these points that a perfectionist approach should be applied, that is, components with a high intrinsic reliability should be used.

2.16 Safety

Reliability and safety are closely connected. A correctly functioning system is never unsafe (provided the system is correctly designed). The cost of unsafe operations is very high, consequently any failure, which may lead to an unsafe mode, is attributed a quasi-infinite system cost. In these situations system realisations are required which minimise the probability of these failures. Very often this requires the use of perfectionist or fail-operational techniques.
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3. Measurement and Communication in Automated Transport

3.1 Introduction

Communication in automated transport is characterised by the regular transfer of information between moving vehicles and fixed control centres distributed over a wide area. Bidirectional communications between vehicle and vehicle, vehicle and control centre, control centre and control centre may all be necessary.

The control system engineer would like to have independent communication channels for each information flow. Such provision would however be wasteful, being excessively expensive and under-utilised, although a more precise control might be achieved. Communication facilities have to be chosen in balance with the rest of the system, enabling adequate information flows to take place whilst minimising capital and running costs. As with all communication systems, time delay information rate and error rate are important parameters. All can be improved by supplying additional bandwidth, signal power or less noisy channels at an increased cost.

In automated transport, certain tasks of the human operator have been replaced. Extensive measurement and monitoring is required, both to relay information enabling controllers and algorithms to work effectively, and to provide checks designed to ensure the safety of the system.
The state variables of most interest are position and its time derivatives of velocity, acceleration and jerk. The ability of a vehicle controller to minimise absolute position errors directly influences the maximum vehicle flow a system can achieve. Precise operations at merges and stations depend upon both position and speed control. Accurate speed control is required to satisfy safety constraints, for example speed limits on bends and headway constraints when approaching other vehicles. Passenger comfort is determined by the quality of acceleration and jerk control. Precise acceleration control is difficult to achieve. Closed loop jerk control may not even be attempted, although vehicle response characteristics can be designed to ensure that jerk stays within acceptable limits.

The coordinated operation of a complete transport network requires the systemwide generation of time. Clocks can be easily manufactured to high accuracy but methods have to be incorporated to ensure that all are synchronised. This creates additional communication requirements. (1)

3.2 SYSTEM FEATURES

In this section are discussed the general features of transport communications which determine the overall behaviour and capabilities of the transport scheme.
3.3 The Degree of Automation Sought

The ability of a human operator to make fast overall assessments of unusual situations ensures that the total automation of systems as complex as transport networks is most unlikely. At some stage it becomes a more effective solution to employ somebody rather than attempt to devise appropriate equipment and strategies. The creation of schedules, maintenance and recovery from severe failures, are examples of activities not yet amenable to full automation.

Of paramount importance is the provision of an effective interface between the automatic equipment and the operator. Humans are particularly effective at identifying patterns of behaviour but are easily overloaded with data. Communication techniques have to be devised which display primary information in easily recognised forms. Safeguards have to be incorporated to reject unsafe or incorrect operator decisions yet allow him adequate flexibility.\(^2\)

3.4 Communications Involved in Open-Loop, Closed-Loop and Fault Control

The system structure chosen for the controller will have the most profound impact on the amount of communication required in the system. (See Chapter 1)

Within the control structure, pairs of interconnecting subsystems can be analysed in terms of 'controller' and a 'plant'. The role adopted by each subsystem depends on the
primary direction of information flow: the 'controller' is the upstream element and supplies appropriate inputs to the 'plant' which responds with an output. (Dia 13)

The relationship between the controller and the plant can be either open-loop or closed-loop.

Open-loop - Conceptually the controller holds a model of the plant. Using this model and knowing the desired system output, the controller generates the necessary plant inputs. The accuracy of the system output is totally dependent on the fidelity of the model. As no measure of the actual plant output is used by the controller, random disturbances and unforeseen incidents cannot be compensated. Incorrect operations resulting from equipment or strategy failures will go undetected.

Open-loop systems require only one-way communication links. They may be appropriate where the system is predictable, that is, it is reliable, well known and subject only to minor random disturbances, or where the cost of two-way communications is excessive. (Dia 14)

Closed-loop - In a closed-loop system, the controller has access to measures of the actual plant performance. This feedback information allows compensation for minor disturbances such as noise, hardware and environmental variations. More sophisticated controllers may use the feedback information to track the optimal operating point of the system. (adaptive control)
In closed-loop systems the controller may not necessarily hold a conceptual plant model. However the use of a plant model by the controller improves its ability to compensate for disturbances and enables optimum seeking methods to proceed faster. Such an arrangement is commonly called feed-forward control or model-reference control.

Closed-loop control schemes require substantial investment in two-way communications, measurement transducers and control equipment. They are essential for good performance in poorly defined, noisy environments with many random disturbances. (Dia 15)

**Fault-Control** - Fault-control systems are usually closed-loop. Measures of actual system states are compared with predicted values of the states. The detection of abnormal discrepancies initiates standby strategies designed to counteract the effects of the failure. (See Chapter 2)

Extra transducers, circuitry and communications are required for fault-control.

Within a closed-loop system, elements may be operating locally in an open-loop manner. (Dia 16) If measurement activities are moved further downstream, they will monitor a wider range of system states. A single transducer will tap information output by several preceding elements. However the information yielded is more general and its interpretation becomes more difficult: Feedback control
DIA.15  Closed loop system

DIA.16
B is part of a closed loop but is itself operating open loop. C is part of the system and operating open loop.
DIA.15  Closed loop system

DIA.16
B is part of a closed loop but is itself operating open loop. C is part of the system and operating open loop.
becomes more complex to design and delicate to adjust. Fault detection becomes less precise and corresponding strategies more clumsy. A balance must be struck between the ineffectiveness of monitoring too few activities and the high cost of monitoring all. This balance fundamentally influences the measurement and communication equipment provided.

3.6 METHODS OF DIRECTING INFORMATION TO THE CONRECT RECIPIENT

There are two classes of information routing. The 'many to one' where several units may wish, possibly simultaneously to communicate with one unit. The 'one to many' where a single unit may wish to communicate selectively with any one of a number of units. The former requires the organised multiple use of a single channel. The latter is concerned with addressing techniques. These classes arise in all communication systems and have been extensively studied particularly for telephone and computer networks. Consequently only specific situations associated with transport networks are discussed here.

4.5 Multiple Use of a Single Channel

The large number of links required and the physical separation of network elements dictates the use of control structures and strategies requiring limited information flows.
In many situations a single channel has to be shared between several users. The added requirement for moving point to fixed point communication introduces further complexity, as messages must intercept the desired recipient in time and position.

With an uncontrolled channel serving several independent users, there is a finite probability of two or more simultaneous transmissions. Although errors caused by such a collision can be identified using coding techniques, strategies to ensure that the correct message is retrieved are hard to devise.

The use of the channel must be organised so that transmissions from independent users cannot take place simultaneously, that is, the channel is exclusively dedicated to one user for the duration of its transmission, it then becomes available to other users.

Interrupt type systems offer a method of channel synchronisation. However they require the use of parallel lines, one from each user, to a priority resolving unit controlling the message channel. In most situations arising in transport systems this arrangement is not possible. A variety of arrangements are feasible:-

The channel can be captured by a user in two ways; either directly, (requiring each user to listen to the channel), or indirectly, (via a central controller). With direct channel organisation either, a demand-responsive or fixed-sequence service can be operated.
Direct-Channel Organisation with a Demand-Responsive Service
- A user, wishing to send a message, transmits immediately if it finds the line clear. If a busy line is encountered, the user continues to test the line at fixed intervals until an idle state is found. It then transmits. (If the user transmits immediately a previous transmission finishes, there is an increased probability that two or more users, all delayed by the same previous user, will transmit simultaneously).

Direct-Channel Organisation with a Fixed-Sequence Strategy
- For a fixed-sequence type of operation, each user is allocated the channel in sequence. The rota must be pre-arranged and therefore cannot respond to local variations in demanded information flows. Each user must know and be able to identify its position in the sequence. Complications arise where the potential users of the channel can change (e.g., where vehicles enter a new communication zone, the appropriate new signalling schedule must be loaded into them).

Synchronisation of individual users to the message stream can be achieved in two ways. If messages are fixed length - that is, all users are allocated the channel for a fixed time slot even if they have no information to transmit - then 'flywheel' type synchronisation is possible. Each vehicle takes its timing information from the received message stream. The failure of any individual user does not halt the message stream.
The use of stop-start codes to define the message boundaries allows vehicles, with no information to output, to use the channel less. The start of each transmission relies upon the end of the previous one. If one user fails to transmit, backup procedures are required to restart transmission.

**Characteristics of Direct-Channel Organisation** - Direct-channel organisation needs little equipment. Demand-responsive schemes give no indication of failed users, a check which is possible in a fixed sequence scheme. The demand-responsive service is however the more effective where information flows are highly irregular and unpredictable.

In the demand-responsive mode users experience a mean delay which rises steeply when the demand rate exceeds 75% of the channel capacity. Below this demand rate the mean delay is substantially less than for fixed-sequence systems. If vehicles have only limited storage for messages pending transmission, both schemes show significant reject rates, that for the demand-responsive system being lower than that for a fixed sequence system. (Dia 17 - 19)

Fixed sequence systems offer the advantage that delays are bounded, although this is only significant near channel saturation.

**Notes** - A survey of the literature did not reveal much information such as has been presented above. Reference 3
Characteristics of a single shared communication link operated cyclically or asynchronously

KEY:
- Asynchronous
- Cyclic

(1), (2) The number of buffers the transmitter has to save messages pending transmission.

NOTES:
- Time is in units of the message length.
- 99% delay is that delay below which 99% of delays lie.
does however contain a wide ranging discussion of the state-of-the-art in distributed computer networks.

* The direct-channel demand-responsive scheme described above would appear to be a novel suggestion.

* The results presented above were produced by simulation. A description of the program is given in Appendix 1. The results are only valid for systems where the demands to transmit can be modelled by a Poisson process. If the times that the user will want to transmit can be predicted, then a carefully designed fixed-sequence system may give better service.

Indirect Channel Organisation (Using a Central Controller)
- A control unit can be used to organise a communication channel. If only one channel is available between controller and users, the only policy that can be operated is for the controller to poll each user in turn. A demand-responsive service cannot be operated (as any user initiated message would be independent and therefore uncontrolled).

A link organised by means of a central controller might employ two communication channels between the controller and users. If both channels are of identical design and have the same characteristics then a variety of strategies can be operated. (NB, this is a simplifying assumption, not a requirement) - One channel can be designated an addressing line, the other the message line. These channels could be interchangeable, enabling some degree of standby service to
be operated in the event of a failure. Any mix of fixed-
sequence and demand-responsive policies can be operated
enabling the advantages of both to be incorporated.

Against these benefits must be balanced the alternative gains that would have been achieved by operating
each of the two channels independently for the same link.
This provides lower delays and reject rates as a consequence
of the lower usage of each channel.

3.7 Addressing

The successful transmission of information from one
place to another in a system requires routing to the correct
location, and timing to ensure that it will be received.

In transport networks a channel may serve a number of
physically separated users, which may be fixed or moving.
If the addressee is moving the channel routing system must
be organised to direct the message to the track segment
adjacent to the vehicle. Should the segment be able to
encompass more than one vehicle at a time, then messages
must include vehicle identity in their code. Advance
messages can be sent if track segments have storage buffers
from which the information will eventually be relayed to
the vehicle. (Dia 20)

Communication systems linking fixed points have been
extensively studied, particularly with respect to distributed
computing systems, telephones etc. The extra refinement
necessary to communicate correctly and efficiently with
moving vehicles is the main concern of this paper.
DIA. 20 Types of transmission to a vehicle

DIA. 21a A message is received everywhere all the time

DIA. 21b A message is displayed everywhere at a particular time
The Geographical Addressing Problem - Information must be directed to intercept the desired vehicle, that is, it must be available at an appropriate track-side position and time.

A message can be displayed over the whole track, a track segment, or a fixed point. If the vehicle does not act immediately on the received information its storage on the vehicle is required. If the track does not immediately relay the information to the vehicle then track storage is required. (If the track/vehicle link is available over an extended distance, the vehicle and the track can share the same store).

Reference to the position-time trajectories of the vehicles yields the following possibilities.

• A message is available over the whole track for an extended time; all vehicles receive the same message. The information changes infrequently and the transmitter may be effectively the track store. (Dia 21)

An example is the system-wide transmission of system status, signals such as, normal or emergency, service option, fare scale, etc.

• A message is available over the whole track at a particular time; all vehicles are contacted. Vehicles store the message if necessary. (Dia 22)

• A message is available over a portion of track for an extended time; not all vehicles are contacted, only those passing that portion of track. (Dia 23)
DIA. 21c Message displayed over a portion of track for an extended time

DIA. 21d Message displayed over a track zone at a fixed time

DIA. 21e Message displayed at a fixed position for an extended time

DIA. 21f Message displayed at fixed position and time
DIA. 2lc  Message displayed over a portion of track for an extended time

DIA. 2ld  Message displayed over a track zone at a fixed time

DIA. 2le  Message displayed at a fixed position for an extended time

DIA. 2lf  Message displayed at fixed position and time
* A message is available over a portion of track at a particular time; only vehicles within the zone recieve the information. Information can be made vehicle specific if their trajectories are known. The number of vehicles to be contacted and the tolerance on vehicle position determine the length of the zone. (Dia 24)

* A message is available at a point on the track for an extended time; information is position dependent and reaches all vehicles passing by. Information can be made vehicle specific by controlling the display time according to the number of vehicles to be contacted and the tolerance on the scheduled time of arrival. (Dia 25)

* A message is available at a point on the track at a particular time; vehicles are uniquely contacted but the exact vehicle location is required. (Dia 26)

Geographical Addressing by a Centralised Unit - The central unit requires accurate knowledge of vehicle position. This can be derived either by measurement or from predetermined schedules. Successful communications depend totally on the correct working of the controller and the system. Disordered, misplaced or undetected vehicles will cause faults as messages become misdirected or lost.

Geographical Addressing Operated by the Vehicle - Some degree of protection against communication failures, caused by local running anomalies, is provided by using the actual
vehicle movements to control both the position and duration of message display.

Occasionally even the message contents are generated by the vehicles, in which case, no intervention is required from a central controller.

**Message Addressing** - Coding added to a message enables labelled recipients to recognise messages intended for them. Message addressing allows the easy addition or removal of communication units from the network. The security and reliability of message addressing are strongly dependent on the coding techniques used. \(^{(4)}\)

Geographical and message addressing can be provided simultaneously. The duplication of addressing information will enable some faults to be detected. The effectiveness of the fault detection depends on the independence of the two systems.

If the recipient of a message acknowledges it with its own identity (and/or a copy of the message), a closed-loop communication results, enabling the message transfer to be checked and errors corrected. \(^{(5)}\)

\[3.0 \text{ MEASUREMENT}\]

**The Influence of Measurement on Communications** - To control and operate numbers of vehicles, the control centres must have information from all the vehicles in the system.
Essential signals are measurements of position, velocity acceleration and vehicle status (identity, destination, etc). Some or all of this information will be required by both the control centre and the vehicle. Information needed at the trackside and measured or stored on the vehicle, or vice versa, therefore requires communication from one to the other. If this is not economic, then the information must be duplicated on the vehicle and at the trackside. For example, information about own velocity or acceleration is readily available on-board a vehicle, but is difficult to measure from the trackside. Conversely position is more easily determined from the trackside. Track speed limits are fixed and easily stored at the trackside, whereas their storage on-board vehicle requires a complex interpretation according to vehicle position.

Measurement techniques can be associated with the particular form of communication used across the vehicle-track interface. Often a physical property of the signal is modified, for example, its phase or its amplitude, in a way that does not interfere with the message already being carried by the signal.

Measurements can be made either discreetly or continuously in time; the output information may be presented either as a digital or analogue signal. Usually, but not necessarily, discrete measurement techniques generate digital signals and continuous measures generate analogue signals. The falling cost of digital processing increasingly favours
digital signal forms, particularly in harsh environments (ie, noisy channels, and low signal strengths) provided adequate bandwidth is available. However, continuous signals are usually cheaper to generate and simpler to use. For example, analogue transducer signals are directly usable in control loops, whereas in digital systems both analogue to digital and digital to analogue conversions are generally required.

The information in digital signals is not affected by signal attenuation over distance (unless the signal strength falls below a certain threshold). Digital signals do not drift, an important consideration where measurements are made over a long period of time.

Position Measurements - Vehicle positions are measured along the track relative to some fixed point. They must be known sufficiently accurately to allow both successful communications and safe manoeuvres.

Trackside position measurement systems will locate a vehicle to the fixed resolution of the transducers. They are expensive unless precise measurements are required only at a few key points, for example, at junctions or station approaches.

On-vehicle position measurement requires instrumentation in each vehicle. The resultant measures must be periodically updated to the track standard to remove any accumulated errors. The frequency of this updating depends on
Position measurement techniques are either absolute or incremental. With the former the full precision of the device is used all the time. No memory is required but the signals are wide bandwidth. With the latter, in which position increments are counted, memory is required, signals are of narrow bandwidth, and the measurement is subject to accumulated error, similar to drift in analogue systems. Incremental devices tend to be used for measurements made over long distances.

Velocity Measurements - Analogue signals proportional to speed are given by Doppler shift methods or devices relying on electromagnetic induction. Both are ineffective at slow speeds. The differential of a position measurement can also be used as a velocity signal but it is likely to be noisy and restricted in bandwidth.

Position based speed measurements are made by timing the transit time of a vehicle between two markers. This yields a discrete measure. Alternatively the rate at which markers are passed can be measured, yielding a continuous (though lagging) measure.

Correlation methods can also be used to measure speed, this also yields a continuous lagging measure.

The first scheme is more appropriate where markers are widely spaced, the second where they are closely spaced. The third method does not require markers but requires
the transducer accuracy and the maximum error allowable.

Position measurement techniques are either absolute or incremental. With the former the full precision of the device is used all the time. No memory is required but the signals are wide bandwidth. With the latter, in which position increments are counted, memory is required, signals are of narrow bandwidth, and the measurement is subject to accumulated error, similar to drift in analogue systems. Incremental devices tend to be used for measurements made over long distances.

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Correlation methods can also be used to measure speed, this also yields a continuous lagging measure.

The first scheme is more appropriate where markers are widely spaced, the second where they are closely spaced. The third method does not require markers but requires
distinctive track irregularities in order to produce a signal suitable for correlation. All three are ineffective at zero or low speeds.

**Acceleration Measurements** - A signal proportional to acceleration can be generated using the relationship

\[ \text{Force} = \text{Mass} \times \text{Acceleration}. \]

Any component of lateral acceleration can be removed by constraining the instrument to respond only to accelerations in a vertical plane aligned along the vehicle axis. On slopes however, it is difficult to dissociate the vertical gravitational component. Fortunately this is not usually necessary as the acceleration perceived by passengers is the measured acceleration.

Rate of change of acceleration (jerk), although an important measure of passenger comfort is not usually measured. \(^{(6)}\)

**Time** - To ensure synchronism throughout a system, all users must have access to the same time standard. Either local clocks have to be periodically updated from a master clock, or continuous system-wide transmission of time is required.

A comprehensive catalogue of techniques for measuring position, velocity, and acceleration, and techniques of communication is given in Appendix 2.
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4. Longitudinal Control

DESIGN CRITERIA FOR LONGITUDINAL CONTROL

4.1 Introduction

The accurate and reliable control of vehicle speeds and spacings is critical to the success of any automated transport system. The choice of longitudinal control technique will determine the system structure, most of the communications required and the operational performance that can be achieved. The longitudinal controller chosen will essentially determine the quality of service that can be offered and the cost of providing that service.

The objectives of the longitudinal control system are easily summarised; people should be moved to their destination quickly, safely and dependably at reasonable cost. A particular combination of service type, vehicle size, vehicle performance, running frequency and station spacing must be established that most favourably balances the value of the service provided and the cost of its provision. A wide spectrum of solutions have been proposed. One extreme is the auto taxi: small high performance vehicles carrying individual parties of 1 - 6 people, running at very small time separations (1/8 - 10 seconds) provide a service akin to
the conventional taxi. A fine mesh of track covers the whole city and stations are frequent, so that accessibility and convenience of travel are high. Major technical difficulties with such systems still remain to be solved. It is certain that the heavy costs of auto-taxi, both capital and environmental, will severely limit its application for the foreseeable future. A less ambitious proposal is the auto-tram; vehicles are larger than auto-taxis holding 10 - 100 passengers and run at time separations of greater than 10 seconds. A service similar to the bus or tram is offered and is less convenient for the traveller than that of auto taxi, however the control requirements are much less demanding. At the other end of the spectrum, the automation of metro systems is well advanced with examples in many parts of the world. In such systems a minimum headway of 90 seconds is typical.

Much of the early interest in automated transport was directed at auto taxi. Recently though, there has been a growing interest in auto tram systems reflecting their simpler control problems and lower costs.  

4.2 Fundamental Performance Measures

Potential travellers will only choose a particular mode of transport if the performance it provides is sufficiently good. This performance can be gauged by the factors:—

- Ride comfort
- Journey time
Journey dependability

Safety

Cost

Ride Comfort - The ride comfort experienced by a passenger depends primarily on two factors - the noise and vibration transmitted within the vehicle, and the levels of acceleration and jerk (rate of change of acceleration) used during vehicle manoeuvres.

Vertical vibration depends on the suspension chosen for the vehicle and the quality of the track. Suspension, propulsion and braking apparatus are usually interdependent and consequently a choice of suspension method may also determine the braking and accelerating characteristics of the vehicle, thus indirectly influencing the control of the vehicle.

Lateral vibration depends on the choice of steering mechanism. This choice will also influence longitudinal control by determining the time to switch a vehicle and by setting the minimum radius a vehicle can negotiate.

Noise levels are controlled primarily by the detail design of the vehicle, they have no significant effect on longitudinal control. \(^{(2 - 4)}\)

Studies of subjective reactions of passengers have established approximate values for acceleration that should not be exceeded for a comfortable ride. Furthermore, to avoid discomfort the level of acceleration should not fluctuate
continuously (thus requiring an overdamped vehicle response to changing inputs or disturbances).

Limiting values for jerk have not been reliably established although there is some evidence to suggest that, if only low levels of jerk are used, limits on acceleration can be raised. A commonly proposed rule is that any change in acceleration should take at least one second. In practice, jerk is unlikely to be controlled explicitly but will be limited to acceptable levels by the dynamics of the vehicle. (4 - 7) Typical values of acceleration and jerk considered for automated transport are:

- Limit with seated passengers - acceleration $2 \text{m/s}^2$ jerk $2 \text{m/s}^3$
- Limit with standing passengers - " $1.2 \text{m/s}^2$ " $1.2 \text{m/s}^3$

with emergency deceleration rates of twice the normal rate.

This compares with

- Normal acceleration $1 - 2 \text{ m/s}^2$ - lifts
- $1 - 1.6 \text{ m/s}^2$ - metros
- Emergency $2.5 - 3 \text{ m/s}^2$ - lifts
- Decelerations $1.4 - 3.5 \text{ m/s}^2$ - metros
- Jerk $0.5 - 0.7 \text{ m/s}^3$ - lifts and metros.

Acceleration and jerk limits directly affect system performance. Higher limits allow the vehicle to achieve higher average speeds and carry out manoeuvres in shorter distances. This, for example, will then allow a shorter spacing between stations.

The geometry of curved track and the speed at which it is negotiated is determined by acceleration/jerk comfort.
levels. Thus for example, to effect a sidestep of 2 m at a speed of 12 m/s with a jerk constraint of $1.2 \text{ m/s}^3$ requires 45 m of track. A bend taken at the same speed must have an approximate radius of 130 m.\(^{(22-23)}\)

It will only be possible to fit complex structures such as junctions or stations into the existing city streets if most curves are negotiated at reduced speeds. This in turn reduces track capacity and increases control costs.

Acceleration/jerk comfort levels also influence the design of the track in the vertical plane, when the track changes level.

**Journey Time** - The total journey time ($T_j$) for a passenger to go from origin to destination is the principle parameter measuring the quality of service provided by a transport system. It is made up of a number of components.

$$T_j = T_w + T_s + T_v$$

where

- $T_w$ - walk time to and from the station
- $T_s$ - station wait time
- $T_v$ - in-vehicle time.

Each of these components is a random quantity, that is, it will have a mean value and a distribution.

Decreasing station spacing reduces the average passenger walk time. However, if vehicles stop at every station, in-vehicle time increases as vehicles stop more often. Skip-stop or non-stop services counteract this at the expense of initial station wait time.

- 57 -
DIA.22 Typical dimensions for full speed curve or turnout

DIA.23 Maximum bend radius when subject to a lateral accn. limit of 1.2 m/s² (from ref. 4)
For a given service pattern and passenger demand, smaller vehicles running at shorter time headways reduce the mean passenger wait time at the expense of more complex control and higher costs per passenger. (6)

In-vehicle time has three components:

\[
Tv = T_b + T_c + T_d
\]

where

- \(T_b\) - base trip time
- \(T_c\) - speed change delay
- \(T_d\) - queuing delay.

The base trip time is the time a journey would take if the vehicle travelled its whole journey as fast as speed restrictions allow. All the while a vehicle is travelling at a speed lower than the track limit it is accumulating delay. The speed-change delay is the time, extra to the base time, taken to travel a section of track. It depends on acceleration/jerk limits and the vehicle manoeuvres required by the control policy. Queuing delays occur in any system where vehicle movements are not completely determined before a vehicle starts its journey. Queues form at junctions when individual vehicles are delayed to resolve a conflict. Delays due to queuing are very dependent on controller design and tend to rise rapidly when the system is being operated near to its maximum capacity.

The weighting of each component of journey time so as to reflect its relative importance to the passenger is the
subject of some debate. The final choice of system operating point is very dependent on this weighting.

However, a general rule operates; for a given travel demand, higher service frequencies (implying smaller vehicles) and higher performance vehicles give a better quality of service at a corresponding increase in equipment costs, running costs and control complexity.

Service Dependability - Service dependability is a measure of how close the service quality of the actual system approaches the design service. Low dependability means erratic, poor service to travellers and will not attract patrons. Good dependability implies a 'fail-soft' system characteristic as discussed in Chapter 2. In the event of a failure the system should continue to run, albeit at a lower performance.

Safety - The level of safety required of an automated transit system must be at least as high as the best conventional transport systems. Morgantown is designed such that the probability of two vehicles colliding is less than once in 26 years. Safety, reliability and service are strongly linked. Inadequate component reliability gives poor service and may reduce safety. High levels of safety can be achieved at the expense of service or at the expense of dependability.
Costs - The costs of an automated transport system are dominated by the civil engineering costs of station and track (approx 60%); the control systems contribute 10 - 20% of total costs. Of the control costs approximately half are for development of software, the remainder for the measurement, communication, processing and actuation equipment.

Junction and station costs can be substantially reduced by simplifying their layouts, for example, by the use of on-line stations, low speed turns and the elimination of grade separation at junctions. However such designs reduce system capacity, a loss that can be only partially recouped by the use of sophisticated control algorithms. (1, 12-15)

4.3 Intermediate Performance Measures and Desirable Control System Attributes

In the analysis presented below, three intermediate performance measures are used to describe the performance of a longitudinal control system. These measures reflect in a condensed form the fundamental performance measures discussed above. They are - the minimum time separation at which vehicles can run (which determines the track's capacity to carry people), the delays imparted to vehicles during a journey, and the distances required to effect necessary manoeuvres (which will influence the geometry of the system and hence its cost). Two constraints are taken to apply, one is safety, the other is the comfort limits on acceleration and jerk.
In addition to the quantitative evaluation of performance yielded by the measures listed above, a number of desirable system attributes are considered. Only a qualitative treatment of these attributes is feasible, however their inclusion in a control scheme will allow better system performance to be achieved. These attributes reflect trade-offs made elsewhere in the system design.

Thus:

- There is a big incentive to develop longitudinal controllers that allow the use of simple compact civil engineering structures. This primarily affects junctions and stations (since straight track costs are fairly insensitive to vehicle control). Thus control strategies should be able to operate successfully with tight radii curves, at-grade crossovers and on-line stations.

- Good longitudinal control performance is necessary both when operating normally and when faults have occurred. This requires firstly that safety is ensured and secondly that adequate flexibility and a suitable structure are built into the controller to enable the system to cope with failures in a fail soft manner. The principle requirements for a fail-soft system can be summarised from Chapter 2.

- The structure should be decentralised and preferably hierarchical.

- Control should be divided into function modules.

- Each function module should be located near the subject of control and require only local information for minute to minute running.
Coordination with the rest of the system, to ensure smooth running and optimisation, should be on a 'parameter adjustment' principle so that intervention from the higher level improves the performance of, but is not essential to, the lower level. The local module should thus be semi-autonomous.

- Module complexity should be limited, for example, where a process is required in several places, it is preferable to duplicate equipment rather than share it, algorithms should be chosen for understandability, rather than optimal performance.

- System management algorithms must be flexible and able to respond easily to local anomalies in running.

- Failure states should be chosen to maximise system performance whilst in the failed state.

- Communication requirements should be minimised and safety status information confined to very reliable links.

DESIGN FOR SAFETY

4.4 'Worst-Case' versus Probabilistic Criteria

Safety can be assured by one of two design approaches. In the first or 'worst-case' approach, safety is ensured by a combination of; engineering to much higher standards than normal, any component whose failure might conceivably
lead to an accident; so designing the system that the failure of a component leads directly to a safe (usually low performance) state, that is, fail-safe design; using redundancy where the first technique is not possible and the second does not achieve adequately high reliabilities.

The design specification is determined by considering the 'worst-case' combination of events (even if it is anticipated that the probability of the worst case combination arising is very low).

Traditionally the very high standards of safety on the railways have been ensured by the use of fail-safe design. Fail-safe design relies, for its effectiveness, upon using systems and components whose modes of failure are few and well-known. This is only possible because, long operating experience has revealed a catalogue of failure modes, the simplicity of key components allows them to be overdesigned to make failure improbable, and a safe system-state is available. However, even train control is not intrinsically safe, for safe running is heavily dependent on the driver correctly remembering and interpreting his rule book.

A completely fail-safe system probably cannot be designed, particularly if the control equipment is in any way complex. Note for example, that it was the unsafe failure of a vital 'fail-safe' speed-control component on a BART train which caused it to leave the track at Fremont. (17)

The alternative to fail-safe design is redundant design, in which continuing system operation is assured in the event
lead to an accident; so designing the system that the failure of a component leads directly to a safe (usually low performance) state, that is, fail-safe design; using redundancy where the first technique is not possible and the second does not achieve adequately high reliabilities.

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The alternative to fail-safe design is redundant design, in which continuing system operation is assured in the event
of a single failure. In addition to the extra equipment required, extensive maintenance and repair facilities are needed to ensure that the redundancy is maintained. Redundancy is used particularly on aircraft where safe system states are not available. Again not all unsafe failures can be eliminated by redundant design.\(^1,6,16\)

The probabilistic (or fail-soft) design process yields the second and more controversial approach to safety. Referring to Chapter 2, section 2.2, equation 2, the cost term \(C\) is chosen to maximise \(S\) for a given budget. This means choosing an optimal balance between the frequency term \(R_k\) (which depends on the reliabilities of components) and the incident cost \(C_k\) (which depends on system design). For unsafe failures (that is, failures that cause human injury or death), the incident cost \(C_k\) is so high that the designer can reduce the frequency of such events to extremely low levels before cost of the measures approaches the expected incident cost. An extensive reliability analysis is required to identify all possible faults, and associate with each its probability of occurring and an expected cost. Such an analysis leads then to the 'best' system specification. However, in practice a number of difficulties arise.

- The high costs of the reliability analysis of complex systems will preclude a comprehensive identification
of all possible states, consequently there is no guarantee that all possible unsafe states will have been found.

- Both the low probabilities and the high cost of an unsafe system state are difficult to evaluate. Consequently in a system where safety considerations place a limit on system performance (such as in transport) an optimistic choice of system specification may have a very costly outcome if the choice proves incorrect. Thus the choice of specification must take account of the potential errors in the assessment process. As a result, it is unlikely that the 'fail-soft' approach will yield a substantially different result, when safety is at risk, than the conventional, conservative 'worst-case' analysis. However it is interesting to note that reference 19 advocates an approach to transport safety similar to the fail-soft one outlined above. (Dia 24)

With automated transport systems, it is likely that the complexity of equipment, the use of electronics in safety systems, and the lack of operating experience for much of the new technology required will force designers to use a combination of worst-case and fail-soft design.

In any system, however carefully designed, unsafe failures will eventually occur and result in a collision. The operating speeds of urban transport systems are likely to be modest, so reducing the likelihood of serious injury or death. However vehicles must still be designed to protect the passengers inside them. This aspect of safety
The choice lies in this region.

Probable cost

Operating point

Pessimistic choice lies in this region

Optimistic choice lies in this region

Net benefit

autotaxi

autotram

automatic train

Time headway

Delay

intolerable

high

satisfactory

low

Flow

Capacity

Flow

distance headway

- 97 -
can draw substantially on current design techniques for other modes of transport, particularly the motor car.\(^{(5,20,21)}\)

4.5 Safety, Headway and Capacity

**Safety** - Two conflicting factors influence the choice of minimum vehicle separation during normal running, the track capacity which increases as the minimum vehicle separation decreases, and the safety hazards which increase as the minimum separation decreases.

Two principle accidents can result from a failure in the longitudinal control system; collision with another vehicle or obstruction on open track and collision with track structure or another vehicle at a junction. In both cases, an effective protection can be provided by ensuring that there is always sufficient unoccupied track extending in front of each vehicle. Thus the vehicle may slow down safely if an abnormal situation is detected. The length of this zone, the variables that should be monitored and the strategies to be used when an emergency is detected, have been the subject of much debate. It is generally agreed that two types of controller are required - a longitudinal controller that normally has control of the vehicle, and an emergency controller whose function is to decide whether an emergency situation exists and to take appropriate action. A more detailed discussion of emergency procedures is contained in Chapter 5. However, invariably one function of
the emergency control is to emergency brake the vehicle to zero speed should the distance between the vehicle and another vehicle (or obstacle) fall below the specified free zone. It is the length of the safety zone which places an ultimate limit on the track capacity of a system. In the section which follows, the interaction between an emergency controller as outlined above and the normal controller is discussed and is used as an example to illustrate the two approaches to safety.

Capacity - The capacity of a system measures its ability to transport people. For a given passenger demand, shorter headways reduce waiting time and the associated smaller vehicles allow faster services to be operated. However costs per passenger increase, with the increase in the vehicle numbers, the required reliability of each (to maintain the same system dependability) and the complexity of control. Consequently the overall benefit of operating at a particular headway might look as in diagram 25. (Dia 25)

In an autotaxi system the curve is shifted towards low headways, with respect to autotram and automatic trains, reflecting the different weighting attached to performance measures in the system specification.

Capacity can be formally defined as the maximum flow of vehicles that can pass along the track. For constant-speed track this can be directly calculated from the safety criterion. Through speed changes capacity is very difficult
to calculate explicitly but can be found by simulation.

At junctions an alternative definition of capacity is sometimes required - it is that vehicle flow above which service becomes unacceptable. (That is, delays become too large, manoeuvres require too much room etc) (Dia 26)

Definitions

Flow - average number of vehicles passing a point on the track in unit time

Capacity - maximum flow of a section of track

Time headway - time interval between successive tails of vehicles measured at a point on the track

Mean time headway - \[ \frac{1}{\text{Flow}} \]

Minimum time headway - \[ \frac{1}{\text{Capacity}} \]

It should be noted that capacity is essentially a time quantity.

Headway - The 'distance headway' between two vehicles is the distance between the tails of two successive vehicles travelling along the track. It is this distance which is directly constrained by the safety criterion, since it must not fall below the specified safe minimum, if an emergency stop is to be avoided. (Dia 27) The specified minimum is termed the 'emergency headway'. It sets a switching boundary; vehicle spacings less than the boundary result in emergency
stops. The designer must choose a suitable value for this boundary and also decide the minimum headway at which vehicles normally run such that the emergency monitor does not interfere with the operation of the normal control.

4.5 Choice of Normal and Emergency Headway

'Worst-case' Approach - Any collision may result in injury or death and, under this approach, is attributed a quasi-infinite system cost. Thus the control system is designed to make the probability of a collision as small as can realistically be achieved.\(^{(22)}\)

The emergency headway is chosen so that even under the worst-case conditions the vehicle can stop without a collision. Consequently the braking distance is calculated with the minimum guaranteed value of braking rate. It is assumed that; the weather is bad; the vehicle is on a down grade; it is heavily loaded; there is a following wind; at the instant of the emergency the vehicle is travelling at the maximum speed allowed by the tolerance of the speed measurement; it is accelerating and the longest detection and actuation delays apply. The calculation of braking distance and its sensitivity to changes in parameters is well covered in the literature, see for example references 6, 22 and 24.
Probabilistic Approach - A number of costs have to be considered when choosing the size of the emergency headway.

- The cost of a collision. If the minimum vehicle headway is set at less than the emergency stopping distance, a vehicle encountering an obstacle will be unable to stop without a collision. The energy dissipated in the impact can be used as a measure of the severity of the collision.

In safety research on conventional motor vehicles, the equivalent brick-wall impact speed (EBIS) is used as a measure. This is the speed at which the vehicle would have to collide with a brickwall to dissipate the same energy. The EBIS depends on the circumstances of the collision.

For example:-

| Collision with an immovable object | EBIS = velocity of vehicle at impact |
| Collision with another free-moving vehicle | EBIS = \( \frac{1}{2} \times \) relative speed at impact |
| Collision with another vehicle with its brakes applied | EBIS = \( \frac{3}{2} \times \) relative speed at impact |

The EBIS can be related to the probability of death or injury via statistics collected for conventional transport. (A small automated transport vehicle may be assumed to provide a similar protection to passengers as conventional vehicles). \( \text{(6,25,26,27) (Dia 28)} \)

The cost of injury or death is not easy to establish, for example in a paper by Morag (28) in 1975, a figure is quoted of £64000 per death. The Road Research Lab (29) in 1971, suggest the cost of motorway death to be £25,000.
DIA.28 (from ref.6)

Equivalent brickwall impact speed [km/h]

DIA.29

DIA.30 Distribution of stopping distance about normal

brakes fail 'off' collision results

brakes fail 'on' excessive deceleration results
In neither case is it clear what is included, however it is likely that inflation and increasing compensation awards will have substantially increased these estimates by today.

The cost of equipment damage is much smaller than the cost of injury. The worst collision might destroy £30,000 of equipment (one vehicle and some track)\(^{(30)}\) the same accident could severely injure or kill many of the passengers, say £200,000 \(+\) at today's prices.

If damage and injury is proportional to the energy dissipated, that is \(E = B I^2 S\) a typical cost curve would look as in diagram 29. The maximum speed gives the maximum impact speed possible. The maximum assumed depends on whether vehicles can collide head-on or not.

* The cost of emergency braking. This cost is primarily a nuisance cost with components corresponding to passenger discomfort, energy wasted and resultant service disruption. It is probably nearly constant and very small compared with the collision cost.

* The cost of braking at too high a rate. If there is a fault in the emergency braking apparatus and the brakes are too effective, the vehicle stops too rapidly. There is no collision but passengers may fall and be injured, or hit by dislodged luggage. A cost must therefore be included to take this eventuality into account.
For each velocity, an average emergency stopping distance can be specified, this will be termed the nominal stopping distance. Consider a vehicle that starts emergency braking at a headway defined thus:

Headway = q \cdot \text{nominal stopping distance}

and define

\[ r = \frac{\text{actual stopping distance}}{\text{nominal stopping distance}} \]

Diagram 30 shows the distribution of stopping distance about the nominal.

Diagram 31 shows the cost of collision as a function of collision velocity.

For \[ r < q \quad \text{EBIS} = 0 \]

For \[ r \geq q \quad \text{EBIS} = f(r,q), \text{where } f(\ ) \]

is monotonically increasing and depends on initial velocity and the behaviour of the vehicle ahead.

Combining all these factors together for a given initial velocity gives the cost of stopping \( C(r,q) \) as a function of \( r \). This is shown in Diagram 32.

Thus, given that an emergency stop is required, a cost can be associated with a decision to make emergency headway equal to the nominal stopping distance \((q=1)\). The cost is reduced if the headway is made larger \((q > 1)\). For all possible choices of emergency headway a cost can be calculated

\[
\text{Cost} (q) = \int P(r) \cdot C(r,q) \, dr \\
\text{all } r
\]

This is shown in Diagram 33.
Cost of stopping as a function of $r$

Cost of using a headway $q$

Comparative operating costs of two sorts of brakes
DIA.31 Expected cost of collision

DIA.32 Cost of stopping as a function of r

DIA.33 Cost of using a headway q

DIA.34 Comparative operating costs of two sorts of brakes
The use of closed-loop emergency braking gives a better control of stopping distance so reducing the spread of the distribution $P(r)$. Consequently the cost $(q)$ as a function of $q$ will be sharper and enable a smaller value of $q$ to be used for a given operating cost. (Dia 34)

In practice emergency braking will not start exactly at the design switching boundary but will take place at some point randomly distributed about it. The distribution $P(q)$ will depend on factors such as measurement precision and decision and actuation time lags. The effect is to spread the distribution of stopping points (the stopping point distribution is a convolution of the switching and stopping distance distributions).

The actual vehicle state will lie in the vicinity of the normal operating point unless a failure occurs. The distributions are shown on diagram 35 where

$K = \frac{\text{actual headway under normal control during close following}}{\text{nominal stopping distance}}$

The convolution of the 'normal control' distribution $P(k)$ with the monitor distribution $P(q)$ gives the probability of emergency braking. The probability of false alarms is the convolution of the monitor distribution with that part of the normal running distribution corresponding to correct operation. The cost of these false alarms is the nuisance value of emergency braking.
The trapezoidal manoeuvre:
full accn. reached
4.7 CONTROL OF VEHICLE MOVEMENTS

Control of vehicle movements is a two stage process. Firstly a desirable trajectory (expressed as values of jerk, acceleration, velocity and position as functions of time) is determined. Then this trajectory is made the input to a vehicle controller designed to ensure that the actual vehicle state stays near the demanded state in the face of disturbances etc.

4.8 Network Management of Vehicle Fleet

Vehicle management is the most global level of vehicle control. Inputs such as passenger travel demands, the recycling of empty vehicles and fault status are put together to produce specific vehicle movements around the network.

Vehicle management techniques can be classified according to the amount of predetermined, synchronous vehicle movement in the system. Synchronous vehicle movement is movement whereby each vehicle follows the same velocity profile along the track, for example, vehicles run at a fixed time headway. Conversely through asynchronous track sections each vehicle follows a velocity-position profile that varies from one vehicle to the next.

Any system can be conveniently categorised into three areas, namely the stations, the open track and junctions. Each may be operated synchronously or asynchronously.
Table 1 summarises the style of operation for some commonly proposed fleet management techniques.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Station</th>
<th>Track</th>
<th>Junction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Neverstop</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>2 - Synchronous Slot</td>
<td>A</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>3 - Quasi-synchronous slot</td>
<td>A</td>
<td>S</td>
<td>A</td>
</tr>
<tr>
<td>4 - Asynchronous</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
</tbody>
</table>

S - synchronous
A - asynchronous

**Neverstop Control** - Neverstops are of little commercial importance but are included here for completeness. Each vehicle follows the same velocity-position profile along the whole track. The time headway is fixed, consequently, the slower vehicles travel, the closer they become. The minimum speed is set by the vehicles closing up completely (minimum speed = vehicle length/time headway).

Some mechanical neverstop systems have been built. In one design, vehicles are all coupled to a variable pitch screw driven by a stationary engine. In stations, the screw pitch becomes finer, vehicles close up together and travel slowly so enabling passengers to embark or disembark. Between stations the vehicles accelerate and travel at a higher speed. As all vehicles are mechanically coupled
together, it is not considered necessary to have an independent safety system. High mechanical efficiencies and an inherent energy regeneration keep running costs low.

Neverstop systems without mechanical coupling lose most of the advantages, as energy regeneration is complex, independent safety monitoring is essential and reliability is lower. However, vehicles can be arranged to actually stop in stations (although only for a rigidly specified time).

Neverstop systems are completely centralised. The service offered is inflexible. Any fault immobilising a vehicle, including a failure to load passengers in the specified time must halt the entire system. Consequently it is unlikely that such systems will be used in any network application. (31)

**Synchronous-Slot Control** - One of the earliest proposals for vehicle management in automated systems was the 'synchronous-slot' concept. On the main-line track and through junctions, conceptual pointers (or slots) are moved along the track, each following the same velocity-position profiles. At junctions, the pointers are in synchronism and merge together. At the start of its journey each vehicle is assigned to a pointer by a central control. This central control has previously projected forward the system state to identify the earliest path (pointer) through the system that does not conflict with other prearranged vehicle movements.
A passenger using the system experiences a random wait at the station of origin, but once on-board a vehicle, has a fixed journey time. Stations are operated asynchronously and, so that stopping vehicles do not interfere with vehicles that are not, stations are off-line. To enter the station, vehicles are diverted from the main-line. To leave the station, the vehicle is accelerated up to line speed and synchronised with its pointer before rejoining the main-line.

Synchronous-slot has the following characteristics.

- Stations are expensive, as long approach and departure lanes are required. If vehicles are queued at the station more track is required. Station size can be reduced by using low-speed turnouts from the main-line, however this reduces main-line capacity. \(^{(6,7,32,33)}\)

- Trackside control is relatively simple. In one implementation, the velocity profile is written onto the track using closely spaced track markers. The central control broadcasts a stream of pulses to every vehicle. Each pulse is interpreted as an instruction to advance one marker. The spacing of the markers defines the speed of the vehicle. 
  \[
  \text{(Speed} = \text{marker spacing} \times \text{pulse rate})
  \]

- Synchronous slot is highly centralised and has not the flexibility to react to abnormal running conditions. If a vehicle fails, other vehicles cannot be routed around the failure, as there is no guarantee that a conflict free alternative route will exist. Similarly, if for any reason, a station cannot accept a vehicle intending to enter, there
is no way of re-routing the vehicle elsewhere. Consequently any failure will cause an immediate shutdown of the entire system, with the attendant problems of sudden changes in power demand, alternative travel provision for travellers and restart.

The passenger is likewise limited by the inflexibility of the system. He cannot for example change his destination en route except by stopping at the next station he passes and rebooking his journey.

Safety monitoring can in principle be carried out relatively simply. As the vehicle paths are known, the monitor need only check that vehicles are attached to a pointer (that is, there should be no vehicle between pointers). However this does not check that the pointers are moving correctly. To do this requires the monitor to check intervehicle spacing.

The high cost of stations, the large amount of communication to the central control and the impossibility of incorporating a graceful degradation of service after failures all combine to make synchronous slot an unattractive control scheme. (34)

Quasi-synchronous Control (QSC) - Quasi-synchronous control was developed to increase the flexibility of the basic synchronous-slot technique. Vehicles are dispatched from stations without the guarantee of a conflict-free journey.
On open track and through junctions, markers follow the same velocity-position profiles. However junctions are locally controlled, and impending conflicts are resolved by dynamically transferring vehicles from one marker to another. This point transfer manoeuvre is called slot-slipping. If the number of pointers that can be slipped is limited, then the appropriate speed profiles can be built into the vehicle control logic as stored manoeuvres. The necessary trackside control can then be limited to the control of the ordering of vehicles through the junction.

- Journey times under QSC are no longer deterministic, as random delays are introduced at each merge. However waiting time at the station is reduced as vehicle departures can take place immediately a spare pointer passes the station.

- QSC allows a decentralised control structure to be used. This reduces communication costs and allows the system to respond flexibly to fault conditions. As the vehicle route no longer needs to be predetermined, a network link, disabled for some reason, can be isolated and vehicles re-routed around the fault (provided that an alternative route exists).

- QSC has one principle disadvantage. When operating near capacity, occasionally it becomes impossible to resolve a merge conflict (because too many slots must be slipped). Special measures then have to be taken to ensure safe operation. Usually the vehicle is routed in the wrong
direction, or onto special reserved track. Similarly at stations, access may be denied occasionally as a consequence of congestion or fault and the vehicle must go to another station or return for another attempt.

- Vehicles under QSC are not necessarily close to a marker, consequently safety monitoring must check inter-vehicle spacing. (34, 35, 36)

**Asynchronous Control** - In asynchronous vehicle control no attempt is made to predetermine vehicle movements. Junctions, stations and open track can all be controlled locally with vehicles being handed on from one section to another. Detailed information about particular vehicles is not necessarily required. A central controller is not essential but one can be used to improve the performance of the system (for example by coordinating junction operations and modifying routing commands to contain the effects of a fault, or congestion). Some asynchronous systems allow a trade off to be made between line speed and capacity. To take advantage of this property the control system must communicate to vehicles, commands dependent on the individual situation of the vehicles. Synchronous schemes which simplify control requirements so that all vehicles have the same trajectories could not make use of this property.

Asynchronous vehicle management can be realised using two control techniques. In the first, the vehicle-follower method, an on-board vehicle controller maintains safe
vehicle-spacings by using vehicle-to-vehicle ranging.\(^{(37)}\)

The inter-vehicle spacing is made some function of vehicle own speed and speed and position relative to one or more preceding vehicles.

On open track where there is no preceding vehicle in range, the vehicle travels at the track speed limit or at a speed commanded from the trackside. The vehicle controller can be considered as having four constraints, safe following speed, track speed limit, control speed, and comfort limits. It chooses the most restrictive as its command input.

When vehicles are running in a group under headway control they form a platoon. A particular requirement of the headway controller is that such platoons are spatially stable, that is, disturbances to the leading vehicle are attenuated as they pass down the vehicle string. It has been shown that provided

\[
\frac{|V_{n+1}(jw)|}{|V_n(jw)|} \leq 1 \quad \text{for all } w
\]

this condition is satisfied,\(^{(38)}\) where

\(V_n\) — velocity of \(N^{th}\) vehicle
\(V_{n+1}\) — velocity of \((N+1)^{th}\) vehicle

If this condition is not satisfied any disturbances become multiplied by the cascaded control action of the following vehicles so that the last vehicle undergoes large fluctuations in speed etc.

In the second method of asynchronous control, marker-follower control, inter-vehicle ranging is removed. Instead, individual vehicle trajectories are designed to ensure that
safety constraints will not be violated (provided the system is working normally). Trajectories are then communicated to vehicles as a time-varying position set-point to the vehicle propulsion control. Such an arrangement decouples the motion of one vehicle from the next so removing the string-stability constraint. As no ranging is required measurement and communication requirements are reduced. However, accurate measurements of vehicle position and complex calculations must be made instead.

4.3 Performance Characteristics of Fleet Management Techniques

Trapezoidal Speed Change Profile - All vehicle trajectories can be viewed as a sequence of speed changes induced by commands from the trackside. The trackside calculates the desired trajectory using the fundamental equations of motion. It is usually desirable that the speed-change manoeuvre is completed in minimum time (and distance), that is, the vehicle realises its limits on jerk, acceleration and velocity where feasible. This minimum-time speed-change manoeuvre is effected using the trapezoidal acceleration profile.

Assuming that the same limiting values on jerk and acceleration are used for both acceleration and deceleration, the trapezoidal profile is described by the following equations in conjunction with diagrams 36 - 41.
The trapezoidal manoeuvre: full accn. not reached

DIA.42 Velocity profile of headway changing manoeuvre
If \((V_2 - V_1) > \Delta T_1\) ie, maximum acceleration is realised

then \(T_1 = \frac{A}{J}\)

and \((V_2 - V_1) = A(T_1 + T_2)\)

and \(D = \left(\frac{V_2 + V_1}{2}\right)(T_2 + 2T_1)\)

or \(D = \left(\frac{V_2^2 - V_1^2}{2A}\right) + \left(\frac{V_2 + V_1}{2}\right).A\)

If \((V_2 - V_1) \leq \Delta T_1\) ie, maximum acceleration is not reached

then \(A_L = T_1 J\)

and \((V_2 - V_1) = J\Delta T_1^2\)

and \(D = (V_2 + V_1)T_1\)

or \(D = (V_2 + V_1)(V_2 - V_1)^{1/3}\)

where

\(V_1\) - initial velocity
\(V_2\) - final velocity
\(A\) - maximum acceleration
\(A_L\) - acceleration limit reached
\(T_1\) - acceleration application time
\(T_2\) - period of constant acceleration
\(D\) - manoeuvre distance
\(J\) - jerk value
Headway Changing Manoeuvre - A second type of manoeuvre is frequently used, namely a manoeuvre to change the spacings between vehicles. This is achieved by using a three stage operation. Stage 1 changes the speed of the vehicle from the initial \( V_1 \) to an intermediate level \( V_i \), stage 2 is a constant speed section and stage 3 is another speed change from the intermediate speed \( V_i \) to the final speed \( V_2 \). (Dia 42)

If the manoeuvre must take a time \( T \) and use a distance \( X \) then it can be shown that the necessary intermediate speed is

\[
V_i = \frac{1}{(a_1 + a_2)} \left\{ a_1 v_1 - a_2 v_2 - \frac{a_1 a_2}{a_2 - a_1} \left[ \frac{Z}{(v_1 - v_2)^2 + (a_2 - a_1)(Y - 2X) + 2(v_1 a_2 - v_2 a_1)Z} \right] \right\}
\]

where

\[
Z = T - \left( \frac{a_1 + a_2}{J} \right)
\]

\[
Y = \frac{a_1 v_1 + a_2 v_2}{J}
\]

\[
a_1 = \frac{a}{J}
\]

\[
a_2 = \frac{a_2}{J}
\]

\( J \) = jerk limit used

\( a_1 \) = acceleration reached in stage 1

\( a_2 \) = acceleration limit reached in stage 3
A standard safety criterion has been adopted so that the performance of the fleet control techniques outlined above can be compared. This safety criterion can be summarised thus:

- There are negligible actuation and detection delays
- Jerk constraints during emergency braking are not applied
- A guaranteed rate of emergency braking is available \( (ae) \)
- Collisions at any speed are not allowed
- The minimum distance headway during normal running must not be less than \( K \times \text{emergency headway} \)

where \( K \) is a safety factor.

This specification yields an emergency distance headway

\[
H_e(v) = \frac{v^2}{2ae} + L
\]

where

\( V \) - vehicle speed
\( L \) - vehicle length
\( ae \) - emergency braking rate

and a minimum distance headway for normal running of \( H_D(v) \)

\[
H_D(v) = K \times H_e(v)
\]

(NB Each vehicle has a tolerance zone about its commanded position. With vehicle-follower systems only one such zone need be included in the headway, with marker-following two must be included. This consideration is reflected in the choice of \( K \)).
The Capacity of Open Track - The capacity of constant-speed open track, \( C(v) \) is limited by the minimum normal distance headway.

\[
C(v) = \frac{v}{H_d(v)} = \frac{1}{H_n(v)} = \left( \frac{v}{2ae + \frac{L}{v}} \right) K
\]

where

- \( H_n(v) \) - time headway between vehicles

Plotting \( C(v) \) against \( V \) yields the familiar hump shaped curve. (Dia 43) The speed at which capacity is a maximum is denoted by \( V_{sat} \). This maximum occurs when the emergency stopping distance \( x = K \cdot \text{vehicle length} \times K \)

\[
V_{sat} = \sqrt{2aeL}
\]

The capacity of constant-speed open-track cannot be exceeded. It is an upper limit on vehicle flows. Diagrams 44 and 45 show the distance headway and time headways respectively as functions of velocity.

4.10 Synchronous Control

The capacity of synchronous track is constant because the time headway is fixed. This means that the safety criterion will be violated both above a maximum speed and below a minimum speed. Consequently vehicles must travel between these speeds. (Dia 46)

If speed charges are required anywhere on synchronous track, for example because of small track radii at corners, or station turnouts, the time headway between vehicles must be increased from the constant speed minimum. The increased
headway is necessary because vehicles close up as they go through a speed reduction.

Consider the position-time trajectory of a vehicle and the locus of its associated minimum headway as shown in Diagram 47.

The closest that the vehicle may approach a previous vehicle is controlled by the locus of the minimum headway, since no other vehicle trajectory must pass through the shaded zone. (If it did the safety criteria would be violated). On synchronous track, the speed reduction always starts at the same point, therefore a sequence of vehicles looks as shown in Diagram 45, where $H(t)$ is the locus of headway, $S(t)$ is the trajectory of vehicle, and $t_{\text{critical}}$, $P_{\text{critical}}$ is the time, position coordinate of the critical point.

The minimum time headway on synchronous track is $T_c$, where $T_c$ is the maximum time separation of the vehicle trajectory $S(t)$ and its associated headway locus $H(t)$. Diagram 49 shows the plot of time separation $(T)$ between $H(t)$ and $S(t)$ against position through the manoeuvre.

An alternative approach is to consider the safety factor $K$ plotted through the manoeuvre as a function of time. At the critical time $K$ must not be less than the value specified for minimum normal running. The Diagrams 50 - 51 show the appropriate plot of $K$ against time through the manoeuvre. $D$ is the distance separation of two vehicles passing through the speed change manoeuvre, $D_c$ is the critical separation.
DIA 46  Showing safe and unsafe zones

DIA 47  Slowing down manoeuvre
DIA.48 Showing the critical time separation

DIA.49 Time separation for slowing down manoeuvre
Figure 5.50 Showing the critical spacing separation

Figure 5.51 K-Factor for slowing down manoeuvre

- 127 -
K = \frac{D}{H_e(t)} = \text{separation of vehicles/}
\text{emergency headway}

There is no simple way of specifying exactly where
during the speed-change manoeuvre the critical vehicle
separation will occur or what the value of the separation
will be.

A reasonably accurate assumption can be made, namely
that the critical separation occurs at a point whose position,
time coordinates are \( H_d, H_T \) from the start of the manoeuvre.
This allows an estimate of the critical separation to be
made. (Dia 52)

\[ T_c = -\left(\frac{V_1}{a}\right) - \frac{1}{a} V_1^2 + 2H_d a + \frac{a^4}{5J^2} \]

provided

\[ \left(\frac{V_1 a}{J} + \frac{a^3}{6J^2}\right) < H_d < S_m \]

where

\( T_c \) - critical headway
\( J \) - jerk used
\( a \) - acceleration
\( V_1 \) - start velocity
\( V_2 \) - end velocity
\( H_d \) - distance headway at velocity \( V_1 \)
\( H_T \) - time headway at velocity \( V_1 \)
\( S_m = \frac{V_1 a}{J} + \frac{1}{6} \frac{a^3}{J^2} + V_1 \left(\frac{V_2 - V_1}{a} - \frac{a}{J}\right) + \frac{1}{4} \left(\frac{V_2 - V_1}{a} - \frac{a}{J}\right)^2 \)
Notes

i. The estimate gives a slightly optimistic value for the critical headway and does not apply for final speeds that are either close to the initial speed or very low.

ii. The estimate depends only on the initial speed V.

iii. The use of lower jerk values increases the capacity through the manoeuvre but at the expense of a longer manoeuvre zone.

Diagram 53 shows the variation in the capacity of a speed change manoeuvre according to initial speed. (For a final speed satisfying Note i above)

Diagram 54 shows the variation in the capacity of a speed change manoeuvre according to final speed (with a constant initial speed). The region of constant capacity corresponds to the estimate proposed above.

Diagrams 55, 56 show the effect of limiting jerk on the time separation and safety factor curves plotted as functions of distance and time respectively.

Diagram 57 shows the plot of time separation against position through the manoeuvre for different speed changes (from constant initial speed \( V_1 \) to a variable final speed \( V_2 \)).

Diagram 58 shows the same curves but for a speed-up manoeuvre from a variable start speed \( V_1 \) to a fixed final speed \( V_2 \).
DIA.52 Showing point used to estimate the capacity of a speed change.

DIA.53 Capacity of a speed change - fixed end speed (4.0 m/s) variable start speed.

DIA.54 Capacity of a speed change - fixed start speed (12 m/s) variable end speed.
DIA 55 Effect of limiting jerk on time separation

DIA 56 Effect of limiting jerk on k factor
Diagrams 57 - 58

These diagrams show the variation of time separation through a manoeuvre as a function of position. Each picture is comprised of a set of speed changes.

Diagram 57 a, b, c

\[ n_1 \] Speed change from 12 m/s to 11.5 m/s
in steps of 0.25 m/s

\[ n_{44} \] Speed change from 12 m/s to 1 m/s

Diagram 58 a, b

\[ n_1 \] Speed change from 1 m/s to 12 m/s
in steps of 0.25 m/s

\[ n_{44} \] Speed change from 11.5 m/s to 12 m/s
DIA 57a Slowing down:

\( \text{jerk} = \infty \)

DIA 57b Slowing down

\( \text{jerk} = 12 \text{ m/s}^3 \)
DIA 57c Slowing down: jerk=1 m/s³

Distance thru. manoeuvre [m]

Time separation [s]
DIA.59 Time separation for speed-up manoeuvre

DIA.60 K Factor for speed-up manoeuvre
Speed-up manoeuvres are much simpler than slowing-down manoeuvres since the critical separation occurs always at one or other end of the manoeuvre and has a value equal to the steady-state time headway. (Dia 59,60)

4.11 Quasi-Synchronous Control

The performance of quasi-synchronous controllers differs from synchronous controllers because, at some points on the track, headway changing (slot-slipping) can take place. Headway changing is achieved by delaying a vehicle by an integer number of time headways. Vehicles could also be made to advance slots, but, as long distances and high speeds are required to complete the manoeuvre, it is rarely attempted.

There are a number of schemes for slipping slots -

- The vehicle stores only a manoeuvre to slip one slot. This must be used repeatedly if a number of slots are to be slipped. (Dia 61)

Notes

i The vehicle motion is uncomfortable
ii The length of the manoeuvre zone depends on the number of slots slipped
iii Simple vehicle control
iv Allowance must be made in the headway for the speed change.

- The vehicle has a fixed intermediate speed. The manoeuvre is continued for differing lengths of time according to the number of slots to be slipped. (Dia 62)
DIA.61 Manoeuvre to slip single slots

DIA.62 Slot slipping with fixed intermediate speed
Notes

i Manoeuvre is more comfortable

ii The length of the manoeuvre zone depends on the number of slots slipped but is less than in the previous case.

iii Vehicle controller needs only one intermediate speed but must store the timings for each manoeuvre to slip a set number of slots.

iv Allowance must be made in the headway for the speed change.

* Vehicle has a fixed manoeuvre distance. The intermediate speeds are varied according to the number of slots to be slipped. (Dia 63)

Notes

i Manoeuvre length is fixed

ii Vehicle controller must store the speeds and probably the timings for each manoeuvre. If the manoeuvre distance can vary from location to location in the system, on-board or tracksise processing will be required.

iii Allowance must be made in the headway for the worst case speed change. (That is, minimum manoeuvre distance and maximum number of slots slipped).

* If the constraint that each manoeuvre must start at the same place is relaxed, then the minimum headway can be reduced, but at the expense of the manoeuvre backing up

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DIA.63 Slot slipping with fixed manoeuvre zone

DIA.64 Fixed time slot slipping

Notes: Manoeuvre start \((P_{1,P_2})\) propagates upstream within a platoon. An empty slot allows the start point \((P_3)\) to move downstream again.
the track. The achievable capacity of the track is not increased because gaps must be left in the traffic flow to prevent the manoeuvre backing up too far. However, short-term transient overloading can be tolerated. (Dia 64)

Notes

i The control of slot-slippering is made much more complex

ii Communication requirements are increased as there must be continuous communication in the control zone.

4.12 Asynchronous vehicle-Follower Control

The capacity of constant speed track under vehicle-follower control depends on the vehicle-following law used. There are three laws commonly used.

1 Fixed-Spacing - a fixed minimum inter-vehicle spacing is probably the easiest to instrument and control. Diagrams 65 to 68 show the headway, capacity and safety factor as a function of velocity.

2 Constant-Capacity - vehicle headway is proportional to velocity. (Dia 69 - 72)

3 Square Law - vehicle spacing is proportional to the stopping distance. It is only with a square law spacing that capacity can be traded for speed. (Dia 73 - 76)

Platoon-Controlled, Vehicle-Follower Systems

- The trackside controller divides the vehicle stream into groups of vehicles. The trajectory of the leading vehicle in each group is controlled from the trackside, the
DIAS. 65-68  The fixed spacing headway law

Distance headway [m]

DIA. 65

Time headway [s]

DIA. 66

Capacity [veh/s]

DIA. 67
DIA. 69-72 The constant capacity headway law

\( V_t \) vehicles touch \( V_{mn} \), lowest safe speed

\( V_{mx} \), highest safe speed
The stopping distance headway law
remaining vehicles in the group run behind the leader under vehicle-follower control. Each platoon resembles a loose-coupled train but, because individual vehicles are not mechanically coupled, it can be split and reformed without slowing down.

There are two styles of platoon control. In one, the group of vehicles follow very close together and for longitudinal control and safety purposes are considered as one long vehicle (individual vehicles are so close together that should one vehicle decelerate sharply, the following vehicles develop only a small relative velocity before the inevitable collision). At diverges, the vehicle group becomes split up as individual vehicles take their own routes. After the diverge the vehicles coalesce into new groups.

The advantage of such a control scheme is that the benefits of a small-vehicle type of service can be provided, whilst retaining some of the simplicity of control associated with long-headway systems. This apparent simplicity is however illusory, due to the severe safety and control problems associated with the making and braking of vehicle groups. For example - at the instant after a vehicle has left a group, the two remaining groups of vehicles will be separated by a gap which must either be closed up or expanded. During either transition there will be a period of high risk. This vulnerable state could only be tolerated if the vehicles were travelling slowly, or if both track and vehicles were engineered to very high standards and a probabilistic safety
criterion were used. Furthermore, as inter-vehicle spacings of any size can arise during normal operation, an independent safety monitor cannot use intervehicle spacing as a safety criterion. As a consequence a much more complex and expensive safety system must be used which checks for the faulty operation of each section of vehicle equipment.

Notwithstanding the difficulties, two organisations have proposed using this form of control, FLYDA, and MATRA in their ARAMIS system. MATRA built a test track but it seems likely that they have now abandoned the enterprise.

In the second style of platoon control, vehicles always travel a safe distance apart. Platoons can no longer be considered as one vehicle, as the effect of the follower control is to make each vehicle follow a different trajectory from the next. In particular, the further down the string a vehicle lies, the more gentle will its manoeuvre be. (Dia 77-79)

Consequently to change the speed of a platoon takes a long time and requires a considerable distance.

The time and distance can be reduced by making the lead vehicle execute a very exaggerated manoeuvre such as shown in Diagrams 80 - 82, where the front vehicle is slowed to a low-speed before accelerating to the final speed.

All vehicles in a platoon passing through a speed restriction and then returning to normal line speed experience the same delay as the front vehicle. However, the front vehicle must commence its manoeuvre some distance before the restriction in order that the last vehicle in the platoon
DIA.77 Acceleration profiles of vehicles in a platoon subject to a speed reduction
[1] etc. is position of vehicle in group
(1 is front)

DIA.78 Velocity profiles for the same manoeuvre as for dia.77
DIA.79
Position-time trajectories for vehicles in a platoon undergoing a speed reduction
(vertical lines represent working headway for vehicle)
DIA82 Position-time trajectories of vehicles in a platoon passing through a speed restriction
DIA.BI. Velocity profiles for the same manoeuvre as for dia.B0.

DIA.B0. Acceleration profiles of vehicles in a platoon undergoing a two-stage speed change.
DIA. 80 Acceleration profiles of vehicles in a platoon undergoing a two-stage speed change
also complies with the restriction. This results in extra average delay.

Models of the vehicle system carried in the trackside controller cannot easily be made to take account of the disturbances acting on the real vehicles. Consequently, the accurate prediction of the effect a demanded manoeuvre will have on a vehicle string, prior to its being executed, is difficult. This makes it impossible to use junctions and speed restrictions efficiently.

As a result platoon-controlled vehicle-follower systems are not attractive. Although they offer a highly decentralised control system with low track-to-vehicle communication requirements, the performance that can be achieved is severely limited.

Vehicle-Follower Systems with Supplementary Trackside Control of Individual Vehicles - Vehicles operate under vehicle-follower control, that is they select the most restrictive constraint in force at the time. However when specific manoeuvres are required, every vehicle receives trackside control commands (unlike the platoon-controlled scheme in which only the front vehicle of a group receives commands from the trackside).

There are two important types of manoeuvre - speed restrictions and the close-packing of vehicles.

For a speed restriction, vehicles are required to be travelling at a set low speed after a certain point on the
track has been passed. The front vehicle of a platoon can be commanded to follow the appropriate trapezoidal profile. Simultaneously the remaining vehicles in the platoon start to slow down according to following law characteristics. If left uncorrected, each vehicle would pass the start of the speed restriction at progressively higher speeds. Therefore at some point each vehicle must transfer from its vehicle-following trajectory to the trapezoidal trajectory. (That is, the demands of the trackside control become more restrictive than those of the vehicle-follower control). If vehicles are to be delayed only the minimum amount they must switch trajectories at a point which varies from vehicle to vehicle. To do this each vehicle carries a processor enabling it to calculate when to join the trapezoidal profile. Communication from the trackside is a fixed point message conveying the new speed limit and sited a suitable distance in front of the restriction. Alternatively, the processor can be placed at the trackside and transmits to the vehicle, using a continuous communication link, the command to switch.

In both cases good measures of vehicle position, velocity and acceleration are required if an accurate jerk limited transition is to be made.

A simpler but lower performance speed restriction can be achieved by commanding all vehicles to slow down at the same point on the track. The command post must be located so that the fastest vehicle can slow down before the start
DIA.83 Velocity profiles of a platoon of vehicles passing through an enforced speed restriction

DIA.84 Velocity profiles of a platoon of vehicles passing through a simple speed restriction
of the speed restriction, slower vehicles will consequently be delayed by more than is necessary. (Dia 64)

When a vehicle switches from a vehicle-follower trajectory to the trapezoidal trajectory the enforced slowing down introduces gaps into the vehicle platoon, that is, the platoon spreads out. The extent of this platoon elongation is of interest since it is related to the capacity that can be achieved through speed restrictions or junctions.

In the simplest form of speed restriction, all vehicles are commanded to change to the new speed at a fixed point on the track. A platoon encountering such a speed restriction becomes very spread out. Diagram 85 shows the time separation of vehicles before and after such a speed restriction. It can be seen that the worst case is inferior to what could have been achieved had a synchronous type speed change been carried out (that is, the incoming vehicle spacings have been increased to allow for the speed change. All vehicles carry out the same manoeuvre at the same point. See section 4.10)

At the other extreme a speed restriction could be operated by slowing down the front vehicle of a platoon sufficiently far in front of the restriction so that by the time the back vehicle of the group has reached the restriction, it too has reached the new speed. A long manoeuvre distance is required, the length of which depends on the platoon size. (Dia 86) (NB, A theoretical analysis, if it could be
DIA.85 Time spacing between vehicles of a platoon after passing through a simple speed reduction from 12 to 45 m/s. 
N is the time separation between the n-1 and the n-th vehicle, 
a is the synchronous headway appropriate to the speed change, 
b is the high-speed, close-packed headway, 
c is the low-speed, close-packed headway.

DIA.86 Manoeuvre distance as a function of platoon size for a speed change from 12 to 45 m/s.
carried out, may well show that an infinite manoeuvre distance is required. The data presented here have been produced by a simulation in which the manoeuvre is considered as finished when all the vehicles of a platoon are within 1% of their final speed). However, vehicles remain close packed at the end of the manoeuvre. A reduction in the manoeuvre distance can be traded for a decrease in the packing of the vehicle platoon by the following technique. With reference to Diagram 87, at point B there is a mandatory speed restriction, all vehicles must pass this point at the new low speed. At point A a speed reduction command is given to the front vehicle of the platoon. Distance $X$ is the manoeuvre zone. After the front vehicle has passed point A all vehicles start to slow down under vehicle follower control. As they come close to point B they are forced to slow down from whatever speed they have, to the final speed. Diagram 88 shows the trade-off between the length of the manoeuvre zone $X$ and the packing that can be achieved for a particular speed reduction.

Once past the speed reduction zone vehicles travel at the speed limit on a constant speed section of track. They maintain the spacings that were created at the start of the section. This is because to change the time spacings between vehicles requires vehicles to travel at different speeds, (in a practical system, inaccuracies in the vehicle speed measurement would tend to make vehicles move apart or close up slowly).
Speed command post for front vehicle of platoon

DIA.87

DIA.88 Time of vehicles in a platoon as a function of $X$ after a speed reduction from 12 to 4.5 m/s

- a is the high speed close packed headway
- b is the low speed close packed headway

[N] as for dia.85
Vehicles are released from the speed restriction at a fixed point on the track. Front vehicles in a platoon execute a trapezoidal transition to the new high speed. The behaviour of subsequent vehicles depends on the spacings between the vehicles on the low speed section.

Suppose the time spacing between two vehicles is greater than the minimum time headway at the new higher speed. Then, if the first vehicle accelerates on a trapezoidal profile, the second vehicle will do so also. The vehicle following controller will not be activated and the time spacing between the two vehicles will be the same at the high speed as it was at the low speed.

If the low speed time-spacing between the two vehicles is less than the minimum time headway at the higher speed then, under the same conditions for the front vehicle, the second vehicle will initially accelerate on a trapezoidal profile. At some point its vehicle-following control will be activated and delay the following vehicle. Finally when both vehicles are travelling at the high speed they will be separated by the minimum time headway for that speed.

A packing manoeuvre has the following specification - groups of vehicles travelling at one speed, not necessarily close packed are manoeuvred so that by the time they reach the end of the manoeuvre zone they are travelling as close-packed as possible at a second speed. Packing manoeuvres of this type are essential for the efficient use of junctions.
The manoeuvre is carried out in three stages. The first stage is a speed change to an intermediate speed. This intermediate speed is different for each vehicle. During the second stage, vehicles run at their intermediate speeds. In the third stage each vehicle changes speed to the final speed.

The intermediate speeds are calculated so that by the time vehicles have reached the end of the second stage they have closed up any gaps. The closer the intermediate speeds are to the final speed the better is the packing achieved on the output. With reference to Diagram 89, the intermediate speeds depend primarily on the delay time $T$ and the length of the manoeuvre zone $D$. Both increasing $T$ or decreasing $D$ will reduce them. Increasing $D$ reduces the spread of intermediate speeds between the front and back vehicles of a platoon and therefore helps improve packing, (but $T$ must be increased to compensate).

The effects of the vehicle-following constraint on the manoeuvre are two-fold. Firstly, the start of the manoeuvre backs upstream, to a degree dependent on the packing of the incoming stream of vehicles. Secondly near the end of the second stage of the manoeuvre the vehicle-following controller takes over control of vehicles in an unpredictable manner and delays vehicles by small amounts. This makes the packing less effective. This unpredictability makes the efficient operation of junctions difficult to achieve. (For a more detailed discussion of the packing manoeuvre and its effects
DIA.89 Schematic of packing manoeuvre showing principle parameters
on junction control refer to Chapter 6. Diagram 9c shows
the position-time curves of vehicles in a packing manoeuvre.

Asynchronous Point-Follower Control – The combination of
asynchronous vehicle management with point-follower control
has not been considered in the literature. The scheme offers
some of the simplicity of marker-following with the improved
performance allowed by asynchronous operation. Marker-
following uncouples vehicle movements, so removing some of
the unpredictability of vehicle-follower control. The design
of the vehicle controller is also simplified as the condition
for platoon stability is no longer relevant.

With asynchronous point-follower control a trackside
controller computes an individual trajectory for each vehicle.
This trajectory is chosen so that vehicles travel as close-
packed as safety criteria allow. Thus unlike vehicle-
 follower systems, in which the vehicle-follower controller
ensures the safe spacing of vehicles, in marker-follower
systems vehicles are always given safe trajectories. The
computational requirements are much increased, but actual
vehicle movements are more predictable.

In marker-follower control, the trackside computes the
desired trajectory and transmits it to the vehicle in a
convenient form. The vehicle decodes the transmissions into
a position-time profile, which is input to the vehicle
controller.

As for vehicle-follower control, there are two important
manoeuvres, speed changing and packing. There are two time
DIA.90a Packing manoeuvre in a vehicle follower system. Note the curvature of the trajectories that results from target 'slip'.
DIA.90b. Packing manoeuvre in an asynchronous marker-follower system. Note the backing up of the manoeuvre start.
spacings of importance; the minimum time spacing of vehicles travelling at constant speed $T_{\text{min}}$, and the minimum time spacing ($T_{\text{sp}}$) required for vehicles to travel safely through a fixed point speed change manoeuvre. $T_{\text{sp}}$ is greater than $T_{\text{min}}$ because it includes a component for the speed change (Section 4.10). Vehicles arriving at the speed-change zone with spacings between $T_{\text{min}}$ and $T_{\text{sp}}$ will start their manoeuvre further and further upstream. Conversely if their time spacings are greater than $T_{\text{sp}}$, the manoeuvre start point will move downstream. The range of start points is set by the stochastic properties of the gaps in the incoming vehicle flow. If the start point moves too far up the track so that it moves out of the control zone then safe control is not possible and the emergency controller will operate. (Dia 91, 92, 93)

The trackside controller must determine the location of the manoeuvre start point. To do this it must have available to it sufficiently accurate knowledge about the behaviour of the previous vehicle, in order to make safe predictions about future vehicle movements. This requires good measurements around the control zone and/or highly predictable vehicle movements, which in turn requires a very high quality of vehicle controller.

Packing manoeuvres are carried out in a similar way to that described under vehicle-follower systems. Each vehicle passes through a speed change to an intermediate speed.

This intermediate speed is chosen to close up gaps in the
DIA. 91

vehicles are close packed... start point moves downstream

DIA. 92

large gap... start point moves upstream
vehicle stream. A second speed change to a fixed final speed completes the manoeuvre with vehicles leaving more closely packed and at a different speed to when they arrived.

(Dia 50b)

The trackside controller must adjust the start points for each of the two speed changes and simultaneously choose the intermediate speed. These three operations interact, consequently an iterative procedure must be used to determine the complete trajectory. The algorithm does not present any problems of convergence and is discussed in more precise detail in Chapter Seven.

Comparison of Asynchronous Vehicle-Follower, and Marker-Follower Control - Asynchronous vehicle management allows much more flexible control of vehicle movements than synchronous control. In particular, asynchronous systems can operate for short periods with vehicle flows higher than the system capacity, although queues will propagate steadily and delays increase accordingly.

In steady state operation the capacity of asynchronous systems is no better than synchronous systems. (Except in vehicle-follower schemes, where the headway needs to incorporate a smaller allowance for the tolerance of the vehicle's actual position about its commanded position; this effect would be small).

If a stopping distance headway law is used better junction performances can be achieved because line capacity can be
traded for speed. This may improve the network performance markedly as junctions are usually the capacity limiting elements.

Vehicle-follower control is better than asynchronous marker-follower control in its response to failures. In many situations the emergency controller will not be activated as many common faults can be tolerated by the normal controller, for example, failures which cause a vehicle to run slowly or coast to a rest, or even use full service braking, since the 'normal' vehicle-following control will adjust the speed of the following vehicle accordingly. This advantage is offset by the difficulty of providing inter-vehicle ranging devices that are safe, accurate and inexpensive. Marker-follower control does not have such capabilities and any failure in the normal control system will probably result in emergency control action.

Marker-follower control is better than vehicle follower control in that vehicle movements are decoupled. This makes vehicle trajectories more predictable and may therefore improve junction performance. The difficulties of inter-vehicle ranging are removed, but other problems are introduced. In particular, high quality vehicle controllers are required, or alternatively substantial track to vehicle communications. With both formats, accurate position, velocity and acceleration measurements are essential.
4.13 Actual Vehicle Controllers

The previous discussions presented in this chapter have concentrated on the design of ideal vehicle trajectories. The characteristics of the vehicle and its controller were taken account of by a suitable specification of the normal-running, safety factor. These ideal trajectories have been considered as being input to the vehicle controller whose task is to maintain the actual vehicle trajectory near to the desired trajectory. The accuracy with which the vehicle tracks its inputs depends on the size of the disturbances, the control inputs and the dynamics of the vehicle and controller. The better this accuracy, the smaller the headways that vehicles can be allowed to run at and the higher the maximum track capacity that can be achieved.

A simple block diagram of the vehicle is shown in Diagram 94. The differential equation describing the longitudinal motion of the vehicle is

\[ M(t) \frac{dv}{dt} = -Fa(V, Vw) + F - Fr(v) - M(t)gsin\theta - B \]

where

- \( M(t) \) - mass of the vehicle which varies according to passenger loading
- \( V \) - vehicle velocity
- \( Vw \) - wind velocity (relative to the track)
- \( F \) - propulsion force
- \( \theta \) - gradient of the track
- \( B \) - braking force
Block diagram of vehicle dynamics

- Disturbances: e.g., wind gusts, drag, friction
- Motor dynamics
- Brake dynamics
- Motor input
- Brake input
- F
- B
- Position
- Velocity
- Acceleration
- Thrust
- Acceleration limits
- Jerk and
- Disturbances
Fa - aerodynamic drag force
Fr - rolling resistance

An approximation to the aerodynamic drag force is given by

\[ Fa = \frac{1}{2} p A C_d (V - V_w)^2 \]

where

- \( A \) - frontal area of the vehicle
- \( C_d \) - coefficient of drag
- \( p \) - density of air

and to the rolling resistance is

\[ Fr = (C_s + C_r V) M(t) \]

where \( C_s \) and \( C_r \) are constants.

The propulsion force \( F \) is typically modelled by a

first order lag (representing for example, a separately

excited DC motor).

that is

\[ \frac{dF}{dt} = -\frac{1}{\tau} F + Gi \]

where

- \( \tau \) - time constant
- \( i \) - motor input
- \( G \) - gain constant

Modelling of the braking force \( B \) is more difficult

as it depends on the type of brakes (for example, regenerative,

mechanical fixed-force, closed loop etc)

It is evident that even this simplified representation

of the vehicle dynamics is highly non-linear. Two approaches

have been used by researchers. In one, the equations are

linearised about the vehicle operating point. That is, the
vehicle is assumed to be running in a quasi-steady state and the controller is designed using classical linear or modern control theory to limit perturbations about the operating point. (39-54, 55-62) Some researchers have also considered the sensitivity of controller gains, derived by such techniques, to changes in the nominal operating point, vehicle mass, etc. (50, 54, 62)

In the other approach, simulation or full scale experimentation is used. (63, 64)

In all cases the control system should provide a satisfactory performance in several basic modes of operation, for example, constant speed, and speed transitions. For each mode of operation the controller must meet the usual design criteria on control-loop stability, transient response, bandwidth, and steady state error. In addition the vehicle trajectory must be insensitive to external forces such as wind gusts, variations in friction, and track gradient, yet the controller must not permit the vehicle to exceed specified bounds on acceleration and jerk. Vehicle-follower controllers must in addition, ensure that disturbances decrease in amplitude at successive vehicles, as the disturbance propagates along the vehicle string, that is, a platoon of vehicles must be string stable.

There are many papers concerned with the design of vehicle controllers. A survey of the most important is presented below, however, no attempt is made to analyse in detail the conclusions of the papers surveyed.
The literature covers three classes of vehicle controller.

1. The control of a group of vehicles running in a platoon (string controllers).
2. Control of a vehicle following a track marker.
3. Control of a single vehicle following another vehicle.

Controllers of Vehicle Strings - A large number of papers have been written on the optimal design of controllers for strings of cascaded vehicles travelling along a track.

To formulate the problem, the vehicle equations are linearised and a quadratic cost function defined. From this the optimal linear regulator can be derived. To effect control in such a system all the states of all the vehicles must be measured and transmitted to the controller, and the control signals retransmitted to the vehicles. It is usually assumed that the means of data communication between vehicles and trackside control presents no problems.

Typical of such an analysis are a series of papers produced by Anderson and Powner et al. In references 39 and 41 a cost function taking account of velocity and spacing errors is used. In reference 40 the regulator incorporates Kalman filtering to take account of noisy measurements and random disturbances. Reference 42 extends this work to examine the effectiveness of several different multi-variable controller designs. A controller is derived which combines Kalman filtering with integral compensation and model-
reference control. This controller removes steady-state
errors and is claimed to effectively regulate the vehicles
over a wide range of operating conditions.

Other researchers have carried out similar analyses,
notably Athans and Levine \(^{(43)}\), and Peppard and Gourishanker. \(^{(45)}\)
The latter proposes the use of jerk as a controlled variable
and includes a \( \text{jerk}^2 \) term in the quadratic performance index.
This has the effect of reducing jerk during transients and
so increasing the ride comfort.

The difficulty of supplying adequate communications for
such controllers has been recognised by a number of people.
Chu \(^{(45)}\) develops an optimal decentralised controller that
requires only limited information transfer. He demonstrates
that information about all vehicles is not required to control
each vehicle, as the interactions between the vehicles
diminish rapidly as more and more intermediate vehicles come
between them.

A different approach is used by Porter and Crossley \(^{(46,49)}\)
and Hettrakul and Fortman \(^{(47)}\). They use modal control
techniques to produce a controller requiring fewer com­
munication links than previous controllers.

A model-reference adaptive control policy is described
by Powell \(^{(50)}\). Fixed-gain control laws require a detailed
knowledge of the vehicle characteristics under all operating
conditions. For system responses to be satisfactory over
even a small range of system parameter variations, control
gains have to be precisely chosen. However by using the
adaptive arrangement described, the controller is made insensitive to vehicle loading, wind drag and friction. However, computation of the controller gains requires the real-time solution of a set of simultaneous differential equations.

Although many researchers have tackled the control of vehicle strings, the problem has little practical significance. A bibliography and detailed review of early work is contained in Tabak.\(^{(55)}\)

2 Controllers for Vehicles Following Moving Track Markers

Of much more practical application are controllers designed for marker-follower use.

In one implementation of synchronous slot, a number of track markers are placed along the track. Vehicles receive regular pulses instructing them to advance one track marker. (Vehicles therefore travel separated by an integer number of markers at a speed which depends on the marker spacing and the pulse rate). A vehicle travelling faster than it should be will arrive early, if slower it will be late. An error in arrival time can be converted to approximate position error by multiplying by velocity. This is a sampled data control system where the actual sampling rate varies about the standard pulse rate according to the error in the vehicle arrival time.

This type of controller has been investigated by Whitney and Tomizuka\(^{(44)}\). They show that, a proportional controller
is unsatisfactory (there is a conflict between adequate damping and small steady state error), proportional plus derivative control is feasible but the gains appropriate for small steady state errors give an uncomfortable motion, and proportional plus integral plus derivative can give a good performance.

Brown \(^{(56)}\) also discusses the PID controller and shows that it will track an acceleration limited moving pointer, with small errors and low sensitivity to disturbances.

Smith \(^{(58)}\) covers the optimal sampled data controller. His scheme requires a measurement of position error and uses state estimation to construct an approximate state vector that allows the optimal control to be implemented.

An alternative implementation of marker-following requires continuous track-to-vehicle communication links. The trackside computer polls each vehicle in turn to effect control. A number of papers discuss the design of such longitudinal controllers, using both continuous and sampled-data theory, for example Wilkie \(^{(51)}\) and Kornhauser \(^{(53)}\). The latter derives, for the continuous case, an optimal controller incorporating jerk into the performance index. In \((52)\) he extends this work to take account of finite data rates, sampling and noise in communication links.

In a series of papers, Garrard et al \(^{(54, 57, 53)}\) derive optimal linear regulators for marker follower control. They show that, in the continuous case, the performance of the control system is very insensitive to variations in vehicle
mass. This allows the gain matrices to be pre-computed and stored on-board the vehicle. In reference 54, Kalman filtering is used to estimate measurement signals corrupted by noise. Using simulation they conclude that the jerk component of the performance index is the critical term for determining acceptable levels of noise and minimum sampling intervals.

One paper by Ishii et al\(^5\) reports the simulation of a proportional plus derivative controller. They have included in their simulation a complex braking model, a non-linear drag function and quantization of the measurement signals. They propose a control technique to reduce position errors, whereby the commands that are transmitted to the vehicle have been shaped to take account of the expected vehicle response. By this means, the vehicle can be made to follow a path which is closer to the desired trajectory. The results presented show the effects of varying degrees of measurement quantization but do not consider disturbances or the effect of vehicle loading.

In a notable paper, Hinman and Pitts\(^5\) investigate the distribution of control function between the vehicle and trackside. They discuss the closing of feedback loops either locally on-board the vehicle or via sampled data links to the trackside, and the use of stored profiles on the vehicle to reduce communication requirements. They concluded that, even with full trackside control, sampling rates are relatively low. However, if an on-board profile tracking control
is used sample rates can be very substantially reduced for a given peak position error.

Vehicle-Follower Controllers - A number of constraints particular to vehicle-follower control have to be considered. Firstly, a platoon of vehicles running under headway control must be string stable, that is, a disturbance is attenuated as it propagates down the line of vehicles. Cosgriff has shown that string stability is ensured provided

\[ G(jw) = \left| \frac{V_2(jw)}{V_1(jw)} \right| \leq 1 \text{ for all } w \]

where

\[ V_1(t) = \text{velocity of front vehicle} \]
\[ V_2(t) = \text{velocity of following vehicle} \]

and \( V_1(jw) \) and \( V_2(jw) \) are their respective Fourier transforms.

Satisfying this condition also ensures that a vehicle will have the overdamped response required for passenger comfort.

Secondly vehicle-follower controllers must be designed for two modes of operation, namely, for velocity control when the vehicle is travelling along open track and for headway regulation when the vehicle is following another vehicle at minimum headway. The transition between the two modes is usually achieved by closing a position feedback loop when the two vehicles are sufficiently close together. The switchover is difficult to carry out smoothly without
acceleration and jerk constraints being exceeded, a feature which is usually glossed over in discussions of follower control.

The choice of vehicle follower-law has a strong influence on the design of controllers. Three laws have been discussed earlier, constant spacing, constant capacity and stopping distance. Nearly all the controllers described in the literature use a constant capacity law, as this is easy to implement, (a simple feedback of velocity to the position summing point will achieve the necessary offset). An exception is the control scheme for MBB's CABINTAXI. In this an approximate stopping distance law results from the type of vehicle ranging used, however no details of the design of the control system are available. As a result it is not clear what effect the use of the more useful, but non-linear stopping distance law would have on controller design.

Hinmann and Pitts describe a control scheme based on a fixed block technique for measuring vehicle spacing. They describe initially a simple logic scheme for extracting the spacing information from the received signal aspect. The measurement is sampled data, the sampling rate depends on the speed of the preceding vehicle and guideway block length. This measurement is input to a controller similar to that described by Brown (see below) and is shown to give good results. This scheme is interesting as it allows proven conventional railway signalling techniques to be
adapted for close-headway vehicle operation. (In another paper Pitts discusses in detail the choice of block length). (60)

Brown (60, 61) describes a vehicle-follower control which permits accurate speed and spacing control, whilst being insensitive to vehicle weight variations and wind gusts. The controller incorporates proportional plus integral compensation in the forward path, and a feedback compensator. Input velocity commands are allowed to change stepwise in time, but are pre-filtered by a second order filter to ensure that acceleration and jerk comfort levels are not exceeded, (provided speed changes do not exceed a specified maximum magnitude). The block diagram of the controller is shown in Diagram 95. In the regulation mode, two additional loops are closed; to include velocity and spacing error in the control scheme, as shown in Diagram 96.

In a subsequent paper (25) Brown discusses the transition between velocity control and headway control. He notes that short headway operations require fast acting controllers. These result in a high sensitivity to the initial conditions and errors at the switch-over point. The use of limiters to constrain the maximum values of acceleration and jerk has a destabilising effect, consequently Brown investigated the use of a controller with time varying gains. At large vehicle spacings relatively low gains are used so that large initial spacing errors can be accepted. The gains are then gradually increased to those required for small perturbation
DIA.95 Block diagram of vehicle velocity controller
(from ref.61)
DIA.96 Block diagram of headway controller
(from ref61)

- $V_p$: velocity of the preceding vehicle
- $X_p$: position of preceding vehicle
- $S_o$: nominal inter-vehicle spacing
- $V_l$: line speed
operation at short headways. The controller developed has been shown to be effective for a number of manoeuvres.

Fenton et al(63) discuss an alternative approach which may be more tolerant of the non-linearities inherent in any practical system. Their system is conveniently described using a two-dimensional phase plane. This plane is divided into a number of regions, a certain mode of control being associated with each region. Each region is separated by a switching boundary. Fenton proposes the following:-

Region 1 - headway is sufficiently large for the vehicle to operate under velocity control.

Region 2 - the following vehicle brakes at a constant rate: This brings the vehicle into Region 3.

Region 3 - a linear regulator control maintains minimum vehicle spacing.

Region 4 - a collision could occur and the following vehicle decelerates at a peak rate.

Region 5 - control depends on how the zone is entered. If it is entered from the linear Region 3 the vehicle accelerates at a fixed rate (to close a gap before it becomes too large). If it is entered from Region 4 the vehicle coasts so bringing it into Region 6.

Region 6 - the vehicle accelerates at a fixed rate.

Other control arrangements can be made, reflecting different safety policies, running headways and controller characteristics.
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5. The Emergency Backup to the Longitudinal Control

5.1 Introduction

The public is at risk to some degree anywhere in a transport system. For example, faulty door operations, fire, collisions and falling on the track are all possible hazards. Any practical automated transport scheme will have a series of safety systems and procedures designed specifically to control each of the major hazards. One of the more important safety systems, the one associated with longitudinal control, is discussed in this chapter.

The role of the emergency backup to the longitudinal controller is to provide protection for the system against failures of the normal control system, or unanticipated changes in the environment, particularly those which might lead to death or injury. This emergency backup runs parallel with the normal controller, continuously checking its operation. If a fault is detected, the safety system initiates emergency strategies that override the normal controls and which are designed to ensure passenger safety. The emergency systems as described in the literature are often very simple. Two variables are monitored, intervehicle spacing and vehicle speed. If either variable violates specified constraints (too close, too fast) emergency brakes are applied.
to halt the vehicle. By this means collisions are avoided.

(1,2,3) (In some proposals, collisions of a limited severity are considered acceptable(4), although such a criteria is most unlikely to be adopted for a public transport scheme(3)).

The use of a binary control scheme of this sort (normal/stop) is not compatible with the fail-soft principle of gradual degradation following a failure. Certainly the primary task of the 'fail-soft' emergency backup would remain, the prevention of collisions, these being much the most costly form of system operation. However additional strategies are included which improve the post-fault system performance without significantly reducing safety or reliability or increasing costs substantially.

5.2 The Fail-Soft Emergency Backup

The design of the emergency backup divides into three areas of concern, the level of reliability required, the choice of monitors to establish when the normal control system is malfunctioning, the choice of control strategies to limit the consequences and duration of the failure.

Reliability - If unsafe situations are to be avoided, the availability of the safety backup system must be sufficiently high for there to be a negligible probability of the normal and the backup system jointly failing. This can only be ensured if:-
The backup system is intrinsically very reliable, it is therefore likely to be simple and well understood. The backup system does not ensure complete security, as it may fail occasionally. Consequently the emergency system should be 'fail-safe', a requirement which further emphasises the need for system simplicity. A 'fail-soft' emergency controller requires extra components and more complex structures, in order to achieve the necessary variety of response. This extra equipment should not reduce the safety of the system.

Failures in the safety system are independent of failures in the normal control system, that is separate equipment is used for the normal and the emergency controls even if this entails duplicating functions. Thus typically emergency battery power supplies, a separate braking system and independent monitors would be supplied. (Some sources of common-mode failure such as the vehicle itself, cannot however be removed).

The safety system is regularly maintained and frequently exercised to discover any incipient malfunctions. This latter could be achieved in part by diagnostic tests to check vital functions (motor, brake and communications) used before a vehicle leaves the station or starts a day's work. (5 - 9)

Monitors - The control loop for the normal vehicle controller is represented by a simplified block diagram in Diagram 98.
DIA.98 Block diagram of vehicle control functions
Each block in the diagram denotes a functional unit which can be made more reliable by standard techniques of redundancy and reliability engineering, whose inputs and outputs could be monitored to identify faulty operations and which is treated as a fundamental unit in any reliability analysis. The finer the partitioning of the system, the more complex these analyses become; however the diagnosis (identification and location) of faults can be made more precise, and in principle, a better fail-soft characteristic should result since strategies can be more closely tailored to the exact circumstances of the fault.

Fundamental variables that must be monitored in any scheme are inter-vehicle spacing and vehicle speed. These two variables directly indicate the safety status of the vehicle. If there is not sufficient distance between two vehicles, the following vehicle will not be able to stop without a collision if the leading vehicle should stop suddenly. A vehicle travelling too fast might leave the track at a corner. In the text which follows, 'inter­vehicle spacing' has been interpreted broadly, as meaning, the spacing from the vehicle to any obstacle which might prevent a vehicle travelling safely. Thus the spacing monitor should be able to detect and measure the distance, not only to the next vehicle, but also to debris on the track, missing or damaged track, track switches incorrectly set etc. Very few monitoring techniques can provide such versatility and in general special arrangements have to be made for each
hazard, for example, by designing the system so that the particular fault is very unlikely or by installing special detectors.

These fundamental safety checks can be made either on-board the vehicle or by equipment at the track-side supervising a zone of track. Each trackside monitor is responsible for several vehicles, consequently its failure is more serious than the failure of an equivalent vehicle-based monitor. However, vehicle-based equipment will be more unreliable, both because of the more demanding environment and because more sets of equipment are required. Both the track and the vehicle need to know the safety status of the vehicle (the vehicle, so that it can take the necessary emergency action, the track, so that it can initiate recovery action). Consequently communications will be required. This communication is usually vehicle specific, that is, a vehicle-based system must transmit its status and identity to the track so that it knows which vehicle is faulty (or every vehicle uses a dedicated channel—an unlikely solution); a track-based system must transmit to each vehicle its individual status, which requires each message to be addressed (see Chapter 3). For long-headway systems geographical addressing can be used, the track being divided into zones each of which can only contain one vehicle. For short headway systems, zone addressing cannot be made sufficiently precise to only address one vehicle, consequently, message addressing is required. In this latter case the communication
channel must have a relatively high bandwidth to give the necessary combination of speed of response and reliability.

Fixed-block headway monitoring is invariably proposed for the long-headway systems. It has the advantages of being simple, fail-safe, and in current use on all railway systems. However as headways decrease two factors affect the practicality of fixed-block measurement.

- Costs increase as the block length decreases. (Approximately the trackside costs are proportional to $1/\text{block length}$)

- Engineering difficulties increase as the block length decreases since the precise location of the installed block boundaries is uncertain due to electrical and constructional overlap and tolerance.

For short headway operations, very small blocks must be installed to protect slow-moving vehicles at small separations; however a large number of signal aspects are required to provide adequate protection at higher speeds and correspondingly larger spacings. Thus higher data rates are needed which reduce reliability and increase costs. It is usually considered that fixed-block signalling cannot be used at headways less than six seconds.

There are very severe problems in providing suitable, safe, reliable and accurate spacing measurements by any technique for headways less than 5 - 6 seconds.

The choice of block-size is discussed at length by Pitta(12). Pitta (11) suggests that fixed-block signalling
can be rearranged to provide measurement data for both normal and emergency control in a vehicle-follower type system. Although this introduces a degree of interdependence between the two systems, that may be allowable because of the inherent safety of fixed-block signalling.

In addition to the fundamental safety states, other system variables may be monitored, but the extent to which this is done depends on the benefits which can be realised by having the extra information. Useful supplementary monitors might be: on the vehicle, detectors of brake failure, motor fault, communication error, power supply failure, and unusual vehicle accelerations; and on the track, detection of missing, damaged, or icy track, faulty switch operations, debris, high winds, rain etc. The information from these checks is predictive in that they indicate that the vehicle might in the near future become unsafe and so trigger one of the fundamental safety monitors. The information provided by these supplementary monitors may also help to determine which vehicle is the faulty one when the vehicle separation monitor has detected a fault. (Inter-vehicle spacing depends on the movements of two vehicles, either of which might be faulty). It is these supplementary monitors which provide the extra information that allows appropriate strategies to be deployed and a 'fail-soft' characteristic to be achieved. They also provide an early warning of impending disruption.
5.3 The 'Two-Part' Emergency Backup

The emergency control system can be divided into two parts. Part one operates when one of the fundamental safety variables (inter-vehicle spacing or velocity) shows a fault. The simplest, safe strategy that can be operated is to brake the vehicle at an emergency rate to a halt. Provided the vehicle spacings are sufficient, this will prevent the vehicle colliding. (See Chapter 4) More complex strategies can be devised but these are unlikely to provide the necessary security. (See for example reference 5 or reference 13) Part two of the controller monitors the supplementary variables and activates strategies which are less severe than emergency braking, and designed for those situations where the vehicle has become faulty but is still in a safe state (although the longer the vehicle is faulty and the greater the severity of the fault, the more quickly the vehicle will become unsafe).

This division of roles isolates the fundamental safety assurance from the provision of fail-soft strategies. By this means the vital safety monitoring and braking system is kept simple, can be made independent of the rest of the vehicle equipment and can probably be made fail-safe. The non-vital 'fail-soft' part can be added to the system independently in a controlled and cost effective manner. It does not have to be very reliable and can make use of some of the functions of the normal controller, for example, the normal braking system, the normal measurement and communications equipment.
5.4 Recovery Strategies

Strategies are required to control the system after a fault in such a way that the overall disruption is minimised. The performance of the system deteriorates in two ways following a fault. Firstly the faulty vehicle may be subject to an uncomfortable ride and its passengers delayed. Secondly, the faulty vehicle may interfere with the manoeuvres of other vehicles possibly causing them to be delayed and carry out uncomfortable manoeuvres. The longer the fault persists the greater the disruption. Fault control strategies are therefore concerned with limiting the number of vehicles involved, attenuating the consequences of the fault for those vehicles involved and returning the system to normal operation in the shortest time possible. (7)

A variety of general strategies can be used.

Rerouting - In some networks the spread of a fault can be contained by rerouting the vehicles which would normally use the faulty link. This strategy can only be used in networks where alternative routes are available, if these alternatives are not congested, and if junctions are operated asynchronously. Rerouting may be started even before a faulty vehicle has blocked a link, in anticipation of the likely consequences of the fault, especially where there is little system cost attached to the route change (journeys are a similar length etc). Morse Wade in reference 14 describes a simulation of a number of rerouting strategies.
Removing the Faulty Vehicle - A faulty vehicle ceases to have any immediate deleterious effect on the system once it has been removed from the normal track and its passengers sent on their journeys by another means. The area controller must make the necessary arrangements, for example, to divert the faulty vehicle into the next station, siding or layby, where repairmen and alternative transport can be provided.

The shorter the distance between such turnouts and the faster the area controller can be notified and react to the fault, the quicker can the track be restored to normal service.

A vehicle which actually stops on the main-line track is likely to cause the maximum disruption. Consequently if the vehicle is safe when a fault is reported (that is, only a supplementary monitor indicates a fault) then to stop the vehicle immediately may well be premature. In many circumstances, a less costly strategy would be to allow the vehicle to continue moving (although probably subject to a speed limit that would be safe no matter where the vehicle was in the system). If the vehicle must be braked then a normal braking rate is used and the vehicle slowed to a crawl rather than a halt. The vehicle is then allowed to travel until it can be switched from the main-line track or until a safety constraint is violated and the emergency brakes stop the vehicle. If these procedures are adopted a faulty vehicle may frequently be prevented from interfering with the manoeuvres of other non-faulty vehicles.
Removing the Faulty Vehicle - A faulty vehicle ceases to have any immediate deleterious effect on the system once it has been removed from the normal track and its passengers sent on their journeys by another means. The area controller must make the necessary arrangements, for example, to divert the faulty vehicle into the next station, siding or layby, where repairmen and alternative transport can be provided. The shorter the distance between such turnouts and the faster the area controller can be notified and react to the fault, the quicker can the track be restored to normal service.

A vehicle which actually stops on the main-line track is likely to cause the maximum disruption. Consequently if the vehicle is safe when a fault is reported (that is, only a supplementary monitor indicates a fault) then to stop the vehicle immediately may well be premature. In many circumstances, a less costly strategy would be to allow the vehicle to continue moving (although probably subject to a speed limit that would be safe no matter where the vehicle was in the system). If the vehicle must be braked then a normal braking rate is used and the vehicle slowed to a crawl rather than a halt. The vehicle is then allowed to travel until it can be switched from the main-line track or until a safety constraint is violated and the emergency brakes stop the vehicle. If these procedures are adopted a faulty vehicle may frequently be prevented from interfering with the manoeuvres of other non-faulty vehicles.
Vehicles will however from time to time come to a halt on the main-line as the result of a failure. The procedure then adopted depends on whether the vehicle can move under its own power, is free to move but not motor, or is immovable. In the first case a possible strategy is to allow the vehicle to crawl forward at a low speed once the emergency state has been reset. This will allow the vehicle to reach a switch off from the main-line track. In the second case, a number of researchers have suggested that a vehicle from behind the failed vehicle be instructed to move up, engage the faulty vehicle softly, and push it to the next exit from the track. This strategy has a number of problems; the pusher vehicle must have sufficient power to move the stopped vehicle, but must be designed so that it will not damage itself, particularly if the failed vehicle does not move freely, also safety constraints must be relaxed to allow the pusher to contact the faulty vehicle and thus the question 'How and under what circumstances should safety monitoring be suspended?' must be answered. In the third case of failure the immovable vehicle, repair men are required to clear the track and restart the system.

Although such strategies can be devised to automatically clear the track, it is not certain whether the class of failure can be reliably established automatically. Also it is possible that the complexity of the operations, particularly in class 2, will preclude total automation.
Faulty vehicles are likely to travel more slowly than is demanded by the normal controller. Consequently following vehicles that have not been rerouted will eventually catch up the failing vehicle (unless it is removed from the track before this happens).

The response of the overhauling vehicle in vehicle-follower type control depends on the circumstances of the fault and the design of the controller. If the two vehicles were initially widely separated (that is, the following vehicle was under velocity control) then, when the front vehicle stops due to a fault, the normal control action of the second vehicle should bring it to a halt behind the failed vehicle, without triggering the emergency braking. If, however, the two vehicles were travelling separated by the minimum normal headway (that is, the following vehicle was running under regulator control) then the response of the second vehicle to the sudden stop of the front vehicle depends on the design of the controller. Where the normal controller is designed to accept an emergency stop by the preceding vehicle as a 'normal' manoeuvre then the following vehicle will stop without activating its emergency brakes (although comfort limits on acceleration and jerk may be exceeded). Where the vehicle follower control is designed only to accept normal manoeuvres by the preceding vehicle then when the preceding vehicle executes an emergency stop, the following vehicle will also be forced to emergency stop, (although after a delay and from a lower initial speed.
because the normal controller of the following vehicle will start to slow down the vehicle before the inter-vehicle spacing limit is violated. Thus an emergency stop by the front vehicle of a vehicle string will be successively attenuated for each subsequent vehicle, until eventually, the normal control system carries out all the braking and the emergency system does not operate).

Restart of a vehicle-follower system is relatively simple. Once the faulty vehicle has been removed from the main-line the queue of vehicles can be released to continue their journey and no further trackside control is necessary.

Asynchronous point-follower schemes are more complex to control. Following the failure of one vehicle, the trackside controller must compute the following vehicle trajectories that bring them to a halt in a queue behind the failed vehicle. Restarting the queue is more difficult because each vehicle in turn must be brought in range of a control post so that it can receive the necessary commands to return the vehicle to a normal trajectory. One way in which this might be achieved is for the trackside control to instruct the queue of vehicles to crawl forwards once the emergency situation has been cleared. Eventually the vehicles will reach a command post and rejoin the normal control regime.

Synchronous marker-follower schemes are very difficult to control in a 'fail-soft' manner. In totally synchronous systems (synchronous slot) rerouting cannot be used. Also
as safety at junctions is only guaranteed by the prebooking of journeys a faulty vehicle must shut down the whole system immediately. It is not clear how the system can be re-started under such circumstances.

Some degree of control can be achieved in quasi-synchronous networks. In the absence of any other control action from the trackside, a vehicle behind a failed vehicle will steadily overhaul it until the inter-vehicle spacing constraint is infringed and the vehicle carries out an emergency stop. Consequently whether or not the failed vehicle has stopped eventually following vehicles will be forced to stop and as time progresses a queue of stationary close-spaced vehicles will form. After the faulty vehicle has been removed from the main-line this queue is restarted by commanding each vehicle in turn to accelerate up to the line speed. The start time is selected so that at the end of the manoeuvre, the vehicle will have joined the desired marker trajectory. Control is then transferred to the normal control system. This technique requires each vehicle to be uniquely contacted by the trackside, via a continuous link.

Some vehicles in the stopped queue will be close to the junction at the end of the link. These vehicles will not have synchronised with their markers before reaching the junction and must therefore continue straight on (even if this is not their intended route). Vehicles intending to merge into the faulty link probably will also have to be restricted.
DIA. 99 The propagation of a fault upstream in a synchronous system
With some types of marker-follower system, the speed of a synchronous section of track can be readily changed. This facility can be used to reduce the rate of formation of the stopped vehicle queue (by slowing the track speed). However all vehicles on the link both in front of and behind the failed vehicle will be slowed (and also the faulty vehicle if it still responds partially to trackside signals). Furthermore, the procedure interferes with the synchronism of the markers at junctions, consequently the entire system must be slowed down rather than a single link alone. This is a severe limitation and will probably preclude the use of such a strategy in most networks.

The requirement for a separate emergency communication link to each vehicle is an onerous one. It is not needed provided vehicles when stationary on the track after their emergency stops are spaced at the separations they would have when travelling normally. All vehicles can then restart at one time, accelerate to line speed and synchronise with their respective markers. However, to achieve this spacing requirement all vehicles on a section of synchronous track must simultaneously execute an emergency stop, that is, when any one vehicle carries out an emergency stop all other vehicles must do so too. (After this operation all the vehicles will be spaced along the track at the approximate spacings they had prior to the emergency). The removal of the faulty vehicle is a complex operation as it will usually be sandwiched between stopped non-faulty
DIA.100 Emergency manoeuvres starting at constant times in a synchronous system
vehicles. One unlikely strategy which may be feasible is for all vehicles to crawl forward after emergency braking. The failed vehicle would be pushed by the vehicle behind it until it can be switched from the main-line. The remaining vehicles are then commanded to return to the normal line speed.

During the whole sequence from emergency braking to restart the operation of the junctions at each end of the faulty link must be suspended.


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6. Junction Control

6.1 Introduction

Junctions are usually the capacity limiting elements of a transport system. Consequently, there is a need to develop control policies that allow high flows through the junction yet limit the delays experienced by vehicles and the distances required for the preparatory manoeuvres.

In synchronous systems, junction performance has little meaning. The only parameter of any importance is the average occupancy of the merge points (or fraction of slots passing the merge that are occupied). This depends on the centralised journey booking and routing algorithms, and are therefore outside the scope of this research. (Many references discuss such control schemes in detail, see for example, Yap, Roesler (1,2)).

The research reported in this chapter is concerned with the design of asynchronous junction controllers which form elements of a decentralised control structure. The junction is treated as a processor converting streams of input traffic (having particular stochastic properties) into output streams. Its controller is a device designed to minimise some cost function using information gathered solely from within its zone of influence. In the discussions presented, the junction
is considered to operate independently from the rest of the network of which it is a part, that is, the junction always presents an open door to incoming traffic, and can rely upon its exits always being clear.

6.2 Measures of Junction Performance

Delay - The primary task of the junction controller is to resolve potential conflicts between opposing vehicle streams intending to use a common section of track. To do this, vehicles are delayed by specific amounts, the size and variability of which depend on the stochastic properties of the incoming vehicle stream, the control policy and the layout of the junction. These delayed vehicles form queues preceding the conflict point.

Secondary tasks of the junction controller are to ensure that speed constraints are satisfied and that switches are correctly operated. These operations will also delay vehicles but by smaller amounts than are required for conflict resolution.

Mean delay is the most commonly used measure of junction performance, however, some researchers (3, 4) consider the variance is an equally important measure. In the work reported below, mean delay is used as the principle measure of junction performance and the coefficient of variation (standard deviation/mean) as supporting information.
Capacity - Closely connected with delay is capacity. For junctions, the maximum theoretical capacity can only be realised if infinite queues and delays are allowed. For a more realistic measure, capacity is defined as being 'that level of vehicle flow above which service (delay, variance or some combination) becomes unacceptable'.

Distance Required for Preparatory Maneuvres - The distances available for vehicle manoeuvres will be primarily determined by such factors as street width, station and cross road spacings et cetera. Control schemes which require relatively long manoeuvre zones to achieve desired characteristics of capacity and delay will be at a disadvantage as they may make it impossible to incorporate desirable layouts in restricted urban environments without major modifications to surrounding buildings.

6.3 Geometric Constraints on Junction Layout

New urban transport schemes must generally be built within the confines of the existing city fabric. This may often severely limit the range of junction layouts that can be used and consequently the performance that can be achieved.

In conventional traffic engineering, a junction between two two-way roads is common-place, with one extreme layout being exemplified by the cloverleaf design in which all crossovers are replaced by a network of bridges and merges. At the other extreme, lies the at-grade crossing whose satisfactory
performance depends on sophisticated control. In the latter case some potential capacity is lost.

Proposers of automated transport schemes are usually more concerned with the simpler junctions between two unidirectional traffic streams, in which any crossovers are replaced with bridges. (Dia 101)

All junction layouts can be synthesised by interconnecting elements comprising diverges (switches), merges and crossovers. These last two have similar control characteristics; a crossover being equivalent to a merge followed by a diverge, consequently, in the text which follows the term 'intersection' is used to indicate either a merge or crossover.

The interaction between junction elements determines the performance of the junction and is primarily set by the geometry of a particular layout.

Diverges - The characteristics of the diverge are determined by the type of switching mechanism used. Switch mechanisms can be track-based or vehicle-based. Typical of the former are railway points and of the latter motor-car steering. Track-based switches are more suitable for switching trains as there is little risk of one vehicle being diverted in a different direction to the remainder, a risk which is always present with vehicle-based switches.

Track-based switches can be placed as close together as geometric track layout considerations allow, since all the switches can be set in advance of the vehicle arriving at the

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DIA.101 Some types of junction

DIA.102 Merge junction with escape lane
first switch. Forks with vehicle-based switching, on the other hand, must be spaced sufficiently far apart to permit re-positioning, locking and verification of the mechanism, and for the vehicle to stop safely should any of these actions prove faulty.

The time required to operate the switching mechanism must be incorporated into the headways separating vehicles. This time allowance can be added to all vehicle headways or only to the headway of those vehicles travelling a different route to their predecessor through a junction. In the latter case, the headways between vehicles must be adjusted before a diverge, according to the routes they will follow.

Vehicle-based switches have an advantage for close-headway operations since the mechanisms are usually smaller, lighter and consequently tend to have faster switching times than track-based systems, (although this is not necessarily true, for example, see reference 5). (6,7,8,9)

Commonly one of the branches of a diverge is straight on, the other curved. As the curved part cannot be banked within the switch, it will often have a speed limit slower than straight on. In this circumstance turning vehicles must slow down prior to the switch, and sufficient extra time allowed in the vehicle headway for the manoeuvre to be executed safely.

**Intersections** - At an intersection, vehicles on opposing streams of traffic compete for a limited resource, namely
line capacity, on the section of jointly used track. Effective control prior to the point of intersection is essential as this is a primary factor determining the overall junction performance that can be achieved.

Control prior to an intersection comprises two distinct phases, firstly the order that the vehicles pass through the intersection has to be decided, secondly the manoeuvres required of vehicles to safely merge in the desired order must be determined. In some strategies these two phases may be resolved iteratively.

The length of track required to effect the desired manoeuvres determines the minimum distance which must separate junction elements. Intersections which are spaced closer than this minimum must be considered as part of the same merging procedure.

In common with diverges, curved track at an intersection may impose speed restrictions and must be taken account of in the control strategy.

**Track Links** - Connecting merges, diverges and intersections are track links which add their own constraints to the control of a junction. Comfort limits will define the geometry and speed limits of any curved track. In addition, the length of links will determine the range of manoeuvres that can be carried out along them.

All manoeuvres (speeding-up, slowing-down, cornering, gaining or losing height) are subject to comfort limits. A
constraint sometimes adopted by researchers is that each such manoeuvre must be carried out in sequence, as there is no information on passenger tolerance to combined manoeuvres. (For example, slowing down superimposed on cornering). This is a severe limitation particularly where complex manoeuvring is to be carried out in a confined space. The limitation is probably unnecessary, although if a number of superimposed operations are used, each operation may have to be less severe than if it were executed alone.

Emergency Monitoring - Emergency monitoring at junctions is primarily concerned with detecting the two unsafe conditions:

* the switching of mechanism at a diverge is incorrectly set
* conflicting vehicle movements at an intersection have not been resolved (that is, the preceding vehicle through the intersection has not cleared the conflict point in time).

The consequences of both these faults could be the collision of a vehicle either with the track structure or with another vehicle.

The detection of a faulty state can be used to trigger the standard emergency braking equipment carried on-board the vehicle. Consequently to ensure that the vehicle is able to stop safely, the decision (to brake or not), must be made at least an emergency stopping distance before the fork or intersection.
Constraints on Junction Layout - In quasi-synchronous control (QSC), manoeuvring is achieved by the process of slot slipping. In any practical junction control strategy, situations will occasionally arise where the solution to a merging conflict requires manoeuvres that cannot be carried out within the distance available. If a manoeuvre cannot be carried out then one of the offending vehicles must be re-routed onto an alternative safe path. This however constitutes a routing failure and places a number of constraints on design. Merges are particularly difficult to organise. In the event of a routing failure, either the junction must be stopped, a highly disruptive operation, or one of the offending vehicles must be directed onto an abort lane. If the failed vehicle is temporarily stored in the abort lane and accelerated from rest into a vacant slot when it appears at the second merge, can safety be ensured at reasonable cost.

A crossing junction with an at-grade intersection is similarly vulnerable to unresolvable conflicts. However the layout complexity is much increased, and makes such junctions uneconomic.
Grade-separated junctions do not require supplementary abort lanes to ensure safety as one of the two conflicting vehicles can be routed in the wrong direction, (either the vehicle wishing to turn must be directed straight on, or the vehicle intending to go straight on must be forced to turn).

Review of Research into the Performance of QSC Merging Strategies - Junction control in quasi-synchronous systems has been extensively discussed in the literature. The first work on the subject was carried out by Godfrey. He analysed in great detail the operation of a merge under QSC and considered six strategies.

1 Lane 1 has priority, lane 2 vehicles merge into natural gaps in the lane 1 flow.
2 Priority is switched to the opposing lane if it has a delayed vehicle in it and there are none in the present lane.
3 Priority is switched to the opposing lane if all vehicles on the present lane have been served.
4 First-come first-served with the same lane always having priority in the event of simultaneous arrivals.
5 First-come first-served with simultaneous arrivals resolved randomly.
6 First-come first-served with simultaneous arrivals resolved by giving priority to the lane not served last.

Godfrey studied these strategies both in the steady state and with transient changes in demand. He concluded that scheme 1 was the worst and scheme 3 the best, using
variance of delay as his cost function and taking no account of manoeuvre costs.

Whitney(10) developed a useful state diagram notation which allows the designer considerable freedom to choose how vehicles are to be manoeuvred. He divides the problem of optimal junction control into a two-stage process whereby the merged state and the manoeuvres required to achieve that state are considered independently. Costs are chosen for the merged state, which for example, penalise the creation of large platoons (as they may reduce the performance of downstream junctions). Manoeuvre costs are chosen to penalise the simultaneous movements of a large group of vehicles (which may increase the problem of ensuring safety), or to encourage the use of manoeuvres requiring the fewest number of transitions (which tends to minimise manoeuvre times).

Optimisation then proceeds by choosing merged states according to the merging costs and manoeuvre strategies based only on the manoeuvre costs. Alternatively both the merge costs and manoeuvre costs can be considered together to choose the merged state. Whitney uses the first technique but does not consider such factors as the length of track required.

Brown(11) discussed the control of a one-way full-turning junction as shown in Diagram 103. He presents a strategy designed to minimise routing failures, given that a vehicle can only slip a specified maximum number of slots. Using a Monte Carlo simulation he demonstrates that, using his strategy, less than 5% of vehicles at 80% occupancy need
ENTERING STATE SENSOR

FIXED POSITIONS AT WHICH POINT STATES ARE KNOWN TO THE ALGORITHM

FIXED POSITIONS AT WHICH POINT STATES ARE KNOWN TO THE ALGORITHM

DENOTES A MOVING POINT

DENOTES A VEHICLE AND ITS DESIRED ROUTE

DIA.103 Intersection simulated by Brown (ref II)
to be re-routed, if vehicles are allowed to slip up to 11 slots. However his algorithm tends to bunch vehicles together, which may degrade the performance of downstream junctions.

Caudill and Youngblood\(^{(12)}\) examined the same problem as Brown. They investigated a number of simple strategies which allowed vehicles to slip or advance small numbers of slots. The best strategy, a 'cycles' strategy that allowed vehicles to move anywhere within a range of slots (the cycle), performed best. A 5 slot cycle gave a miss rate of about 20% at 80% occupancy but does require vehicles to be able to advance up to two slots.

It is apparent, from both these papers that many vehicles will be re-routed in quasi-synchronous systems operated near the maximum track capacity. Indeed Caudill and Youngblood note that, while the decision, of which vehicle to re-route, does not affect the assessment of algorithm performance (because the important event is that the conflict was not resolved), it is fundamental to the operation of an actual system. They suggest that instead of always forcing the merging vehicle to re-route, overall network efficiency can be improved by re-routing that vehicle which would be least delayed.

A detailed report on the operation of CABTRACK junctions was produced by the cabtrack team at RAE.\(^{(13)}\) In this, a simple junction (two main lines, cross grade-separated, and are linked by a transfer lane) is analysed, using theory and simulation. Several queuing strategies combined with a number

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of merging policies are discussed. The results presented show for each combination, mean delay, percentage vehicles re-routed and manoeuvre distances as functions of flow.

6.5 Asynchronous Control of Junctions

The control of junctions in asynchronous systems has been almost entirely overlooked in the literature. The only paper on the subject is by Athans. \( ^{14} \) He casts the problem of controlling a merge into a linear optimal regulator problem, using the same approach as used in his paper on optimal vehicle follower control. \(^ {15} \) The two incoming streams of traffic are treated as one, in which vehicles are allowed to 'move over' one another before the merge. The merging sequence is chosen by finding the control cost for each possible sequence and choosing the one with the minimum. Provided the manoeuvres start sufficiently far in front of the merge the vehicles are able to adjust their positions so that when they reach the merge, the two streams combine safely in the desired merged sequence.

By far the most important aspect of junction control in asynchronous systems is the control of merges and crossovers, as it is at these points that capacity is severely limited. Consequently the remainder of this chapter concentrates on this particular problem.
**Capacity** - The capacity of merges and crossovers is limited since the capacity of the intersection point (or common section of track) cannot exceed the capacity of a single line. Consequently the sum of the incoming flows may not exceed this either.

A vehicle plus its normal headway passing a point on the track will occupy the point for the time headway associated with the speed of the vehicle. That is for

\[ H_t(v) = \left( \frac{v}{2ae} + \frac{L}{v} \right)K \]

where

- \( v \) - velocity of the vehicle
- \( ae \) - emergency braking rate
- \( L \) - length of the vehicle
- \( K \) - safety factor.

The occupancy of the point can be defined as the fraction of time that the point on the track is occupied, it indicates how near the track is to saturation.

\[ \text{OCCUPANCY (Occ)} = \frac{\sum \text{time the track is occupied}}{\text{total time}} \]

\[ \text{Occ} = \frac{n H_t(v)}{T} \]

\[ \text{Occ} = F H_t(v) \]

where the mean flow rate is

\[ F = \frac{n}{T} \]

\( n \) - number of vehicles passing in time \( T \).

The occupancy at the intersection point (Dia 104) of a merge or crossover can be similarly defined, except that now the vehicles passing are being supplied from a number of
DIA.104

DIA.105 Single line working

DIA.106 Various headway distributions
(a) exponential (b) shifted exponential (c) uniform
(d) truncated exponential
(spacing in units of minimum line headway)
incoming lanes. The sequence of lane allocation, or alternatively the order in which vehicles pass through the intersection point is termed the merging order.

Often a change-over cost applies at the intersection point. This cost is an extra time that must be allowed when the lane allocation of the intersection point changes. This extra time takes account of the operating time for switching mechanisms. Also it is an allowance for safety that takes account of firstly, the increased control tolerances that must be allowed and secondly the greater difficulty of safety monitoring when vehicles merge (or cross paths) rather than follow from the same lane.

Control of single line working of a track section very closely resembles the control of a crossover. In this case a large change-over cost must be used equal to the time needed to clear the common section of track, before the direction of working can change over. (Dia 105)

In the discussions which follow, the change-over cost has been incorporated into the vehicle headways by using different values for the safety factor $K$. When one vehicle follows another vehicle from the same lane through the intersection a following factor is applied, and when a vehicle follows one from another lane, the crossing factor is used. Thus at a specified speed the working time headways for the following and crossing cases can be evaluated.
where

\[ C - \text{crossing time headway} \]
\[ f - \text{following time headway} \]
\[ v - \text{vehicle speed} \]
\[ K_f, K_c - \text{safety factors - following and crossing respectively} \]
\[ L - \text{vehicle length} \]
\[ a_e - \text{emergency braking rate} \]

The maximum flow through the intersection point when both streams of vehicles travel at the same speed and have the same mean flow is

\[ F_s = \frac{n}{(n-1)f + c} \]

where

\[ n - \text{mean platoon size passing the intersection from either lane} \]
\[ F_s - \text{maximum vehicle flow} \]

The occupancy is therefore

\[ \text{Occ} = F_s(\text{average headway}) \]
\[ \text{Occ} = F_s \frac{(n-1)f + c}{n} \]

As \( n \) increases from 1, \( F_s \) increases from \( \frac{1}{c} \) to \( \frac{1}{f} \)

that is, capacity increases with mean platoon size (as \( f < c \)).

The absolute maximum junction capacity at a given speed is therefore \( \frac{1}{f} \). No junction controller can handle indefinitely an intersection when the sum of the mean input flows exceed this figure.
The values of f and c depend on the speed at which the intersection is negotiated. They will be a minimum when the intersection speed equals the saturation speed \( (V_{\text{sat}}) \) as defined in section 4.9 of Chapter 4.

Any good intersection control strategy will optimise its performance by varying both the platoon size and the intersection speed.

**Slowing Down and Conflict Delay** - Individual vehicles are subject to two sorts of delay. They lose time in slowing to the intersection speed and they are delayed by further random amounts in order to resolve conflicts with other vehicles at the intersection. (This assumes that vehicles can only be commanded to drop back relative to other vehicles, that is vehicles are only allowed to travel slower than the main-line speed).

Lowering the intersection speed will increase the delay due to slowing down but will decrease the conflict delay (provided that the intersection speed exceeds the saturation speed, in which case, reducing the intersection speed reduces headways and hence the extent of potential vehicle conflicts). Thus for a given merging order, there will be some optimum speed that minimises total delay. In more complex strategies it may be possible to vary the target speed from vehicle to vehicle, each vehicle’s target time and speed being chosen simultaneously to minimise delay. However the computational
requirements of such a scheme are severe and the reduction in mean delay that can be realized is small.

**Delay Due to Manoeuvres** - In addition to the slowing down and conflict delays discussed above, vehicles are delayed by an extra amount whilst carrying out speed changes necessary to safely merge the vehicles at the intersection point.

The primary task of the intersection controller is to determine the times that each vehicle is due to arrive at the intersection, and its target speed. These times are chosen so that, given their corresponding speeds, vehicles do not violate their working headways at the intersection. Once the target values have been established, the formula presented in Chapter 4, Section 9 can be used to calculate the speed changes required of the vehicle so that it arrives at the correct speed and time.

However as the vehicle progresses along the track, in many cases, it will be prevented from following the trajectory demanded from the trackside because of the effects of headway infringement.

In the manoeuvre zone prior to the intersection the headways between vehicles are being adjusted. Vehicles are being bunched together into the platoons that will pass through the intersection. The front vehicle of such platoons will not experience any headway infringement, but the subsequent vehicles following close behind will be delayed by amounts that are hard to predict. The larger the platoon and the
bigger the speed changes involved, the bigger will be these delays.

Any vehicle experiencing such delay will reach the intersection later than its target time, and the platoon will pass through the intersection less closely packed than was desired and so reduce junction capacity. Vehicles following one another from the same lane through the intersection will be safe (this being ensured by the normal vehicle controllers). However, when the lane allocation changes over, in the absence of any corrective action, the first vehicle from the new lane will arrive too soon after the last vehicle and will consequently be unsafe (since it will arrive at its target on time, being the front vehicle of a platoon).

The timetable of targets must therefore be regularly updated. By comparing the desired vehicle trajectory with the actual vehicle trajectory, either continuously or at particular points, the amount of 'slip' or extra delay experienced by each vehicle can be measured. This slip is used to adjust the timetable (by making all the targets later by the measured amount) and has the effect of slowing all subsequent vehicles.

This adjustment will never be completely accurate and there will always be some degree of unpredictability in the arrival time of the vehicle at the intersection. This unpredictability being greater the further from the front vehicle of the platoon the vehicle lies. The crossing factor in the headway must be chosen to include the worst case of this error in vehicle arrival time. Clearly, the greater the frequency
of correction, the more predictable will be the vehicle path and the smaller will be the value of the crossing factor required to take account of the errors.

The preceding discussion has been couched in terms of vehicle-follower control, however asynchronous marker-follower schemes are subject to the same sort of delays. In this form of control the vehicle trajectory must be chosen so that the vehicle will not violate safety constraints en route to the intersection. Therefore in the process of determining the best safe trajectory the controller must choose target times that are later than pure close packing consideration demand. The resultant time-table is then very similar to the vehicle-follower timetable corrected for the 'slip' components.

Marker-follower control offers some advantage over vehicle follower control in that the unpredictability of the vehicle arrival time at the intersection depends only on the ability of the vehicle controller to follow a demanded trajectory. It does not, for example, depend on the vehicle's position in a platoon.

Merging Strategies - There are a very large number of possible merging strategies. Four have been selected for examination. These are

1. First-come first-served (FCFS) - This is one of the simplest policies. Vehicles pass through the intersection in the order that they arrive at a predefined control boundary. Vehicle detectors are required, one to each lane.
2 Fixed time cycle (FTC). The intersection is allocated to each incoming lane for a set period of time. If the period is fixed then no specific vehicle information is needed by the controller, however performance is low. A FTC policy is a very suitable backup to other more sophisticated policies for when they fail because of a hardware fault.

The performance of FTC can be improved by measuring the mean flow of vehicles and adjusting the cycle time according to a stored table of signal settings.

3 First-come first-served with hold (FCFS + H) - The intersection remains allocated to the same lane provided each subsequent vehicle arrives within a set 'hold' time after the previous vehicle. Once the hold time has elapsed, the intersection is allocated on a first-come first-served basis. By a suitable choice of hold time the delay characteristics of the intersection can be optimised. In heavy vehicle flows under FCFS + H the intersection would remain allocated to one lane for a very long period. Consequently a fixed maximum cycle time must be imposed to ensure the allocation changes to the other lane within a reasonable time.

In operation FCFS + H allows vehicles from one lane to pass through the intersection until vehicles that have not been delayed start passing through, the allocation then changes to the other lane.

The policy is somewhat similar to the strategy used by many vehicle-operated traffic lights in conventional traffic systems.
Alternate priority (AP) - Consideration of the performance of any strategy is greatly assisted by knowing the absolute performance boundary.

Suppose a junction controller knows the locations of $A$ vehicles in lane 1 and $B$ vehicles in lane 2, all of which are contained within the zones of influence upstream of the intersection. An optimal control policy must evaluate \( \binom{A+B}{A} \) different merging sequences to determine the optimal sequence. \((14)\) This will then determine the next vehicle to pass through the intersection. The merging sequences must then be re-evaluated anew for each subsequent vehicle, taking account of any vehicles to have meanwhile entered the zone of influence. This policy becomes time consuming to compute as the number of vehicles observed increases. Consequently a limited version of the optimal strategy has been assessed, namely alternate priority scheme, which considers only the next vehicle in each lane.

In the AP scheme the order of the vehicles through the intersection is determined from a comparison of two ordering policies.

Case 1 Lane 1 vehicle followed by lane 2 vehicle

Case 2 Lane 2 vehicle followed by lane 1 vehicle

The comparison is carried out using the next vehicle in each lane to be allocated an intersection target. The total delay that would be incurred in each case is compared and the policy offering the lowest delay is the one adopted. This determines the next vehicle through the intersection. The vehicle not
allocated a target participates in the next contest.

In practical junction control a vehicle entering the manoeuvre zone must have a target which is safe and useable. With AP this causes some problems. After a comparison, one vehicle has been allocated an optimal target, the other must be given a provisional target (a target appropriate to it being the next vehicle through the intersection). At the next and subsequent comparisons a vehicle with a provisional target will be given a new target, either an optimal one if it wins the contest or another provisional target. A vehicle with a provisional target therefore experiences several changes in manoeuvre. This may be uncomfortable.

Eventually a vehicle with a provisional target will be too close to the junction to carry out any further manoeuvre changes. Consequently it will pass through the intersection at a non-optimal time.

This distance constraint effectively places a limit on the maximum platoon size that can be formed through the intersection. The longer the observation zone the larger the maximum platoon size.

In operation AP forms platoons according to the mean flows, up to the maximum noted above. At low flow rates it operates similarly to FCFS. AP and FCFS + H operate in a very similar manner. They differ in the detail conditions required to make the lane allocation change. (A summary of the lane allocation conditions for AP is contained in Appendix 4)
6.6 The Performance of Intersection Control Strategies

The data presented below has been generated from a number of simulations.

A simple Monte Carlo simulation was used to investigate the trade off between conflict delay and slowing down delay for each of the merging policies described above. A second, more detailed simulation was used to examine the interaction between a vehicle-follower type controller and three of the merging strategies (FCFS, FTC, and AP). This simulation modelled a cross-over junction with no turning traffic.

A third simulation also modelled a crossover junction but employs a marker-follower type of vehicle control, operated in conjunction with two merging strategies (FCFS, FCFS + H).

More details of these simulations and other supporting work are contained in Chapter 7 and various Appendices.

The Effect of Headway Distribution - The delay due to conflict experienced by vehicles passing through an intersection depends on the flow rate, the speed, and the platoon formation characteristics of the merging policy employed.

For the FCFS policy the platoon size of the merged stream is totally determined by the distribution of headways in the incoming vehicle streams. At low flow rates AP and FCFS + H are similar to FCFS. At higher flow rates AP, FCFS + H and FCT all increase the mean platoon size according to the vehicle flow rate, in a fashion that depends on the policy.
The performance of all the policies also depends to some extent on the distribution of the input headways. To examine the sensitivity of the simulation results to the choice of distribution used to model the input flow headways, two policies FCFS and AP were compared using four different headway distributions.

1. Fixed spacing - all vehicles travel at the same time headway

2. Negative exponential -
   \[ \text{Prob}(H_t = t) = \lambda e^{-\lambda t} \quad \text{where} \quad \lambda = \text{mean flow rate} \]

3. Shifted negative exponential -
   \[ \text{Prob}(H_t = t < H_{\text{min}}) = 0 \]
   \[ \text{Prob}(H_t = t \geq H_{\text{min}}) = Q e^{-Q(\text{t} - H_{\text{min}})} \]

4. Truncated negative exponential -
   \[ \text{Prob}(H_t = H_{\text{min}}) = \int_0^{H_{\text{min}}} e^{-R t} \, dt \]
   \[ \text{Prob}(H_t = t > H_{\text{min}}) = R e^{-Re} \quad \text{(Dia 105)} \]

The last two distributions are more likely to reflect the distributions of headways in practical automated transport systems, since in normal conditions vehicles will not run at spacings less than the minimum headway. The truncated negative exponential distribution has been used in all the simulation studies, as it reflects an intuitive feeling that there will be a high probability of vehicles travelling in platoons, (that is, vehicles are either at minimum headway or large headways). The choice of distribution is however somewhat arbitrary, as there is no foundation of relevant experimental evidence on which to base a decision. Such evidence, when it
is available, may well show that none of the distributions suggested above are a good representation. A recent reference by McGinley\(^{(16)}\) discusses in some detail the choice of distribution and their effect on a simulation of quasi-synchronous PRT systems.

The FCFS policy preserves the order in which vehicles arrive at the junction, consequently the platoon size depends on the distributions, for the negative exponential distribution a mean platoon size of 2 is predicted, and for a fixed spacing platoon size is always 1.(Appendix 5)

At high flow rates the truncated negative exponential looks like a fixed spacing and at low flows tends towards the negative exponential. Consequently, a mean platoon size that tends from 2 to 1 as the flows increase would be expected. Such a trend has been shown in simulation experiments.\(^{(Dia 107)}\)

The effect of different distributions on the delay characteristics for FCFS are shown in Diagram 108. It is demonstrated that small differences result, mostly at the higher flows. Similar observations apply to AP.\(^{(Dia 109)}\)

Conflict Delay

FCFS - The platoon size is set by the input distribution and is small. Consequently FCFS has a low saturation flow.\(^{(Dia 110)}\)

AP - At low flows, AP has the same delay as for FCFS. At higher flows the mean platoon size increases accordingly. The saturation flow can approach the theoretical maximum.
Platoon size for first-come first-served with truncated distribution

Distributions are:
1. Shifted -ve. exp.
2. Truncated -ve. exp.
3. -ve. exp.
4. Uniform

Comparison of various headway distributions: first-come first-served ordering policy
DIA.109 As for dia. 108; alternate priority ordering policy

DIA.110 First-come first-served conflict delay at junction speed of 45 m/s
(that is, infinitely long platoons) but at the expense of long queues forming. (Dia 111)

FCFS + H - This policy operates very similarly to AP. At very high flows it has a lower delay than AP. (Dia 112)

The 'hold' time is a parameter which can be varied according to flow so as to minimise the mean delay. However it does not vary much over the full range of flows. Consequently a single preset value could be used which will give a near optimum performance over the whole range of flows. (Dia 113)

FTC - The fixed time cycle policy is the least effective policy. The maximum platoon size and therefore the saturation flow is limited by the cycle time, the longer the cycle time the higher the saturation flow.

However, the mean delay experienced by vehicles is at least a quarter cycle time and therefore at low flow rates and with long cycle times vehicles will be unnecessarily delayed. Consequently for an efficient operation the cycle time must be varied according to the mean vehicle flow rate. In practice this may be difficult to do if the flow rates change rapidly. (Dia 114, 115)

Diagram 116 shows the four policies together for comparison.

Slowing Down Delay - Delay due to the vehicle slowing down to the intersection target speed is simple to calculate. It is the difference between the time the vehicle actually takes to slow down, minus the time the vehicle would have taken to
DIA.II! Alternate priority conflict delay at junction speed of 4.5 m/s

DIA.III Alternate priority conflict delay at junction speed of 4.5 m/s

DIA.II2 First-come first-served with hold of 3.0 secs. conflict delay at junction speed of 4.5 m/s
Delay (s) hold times
(1) 6.5 s
(2) 4.0 s
(3) 3.0 s
(4) 2.5 s

DIA.113 First-come first-served with hold showing the effect of varying the hold time

DIA.114 Fixed time cycle (15×15 s. cycle time) conflict delay with intersection speed of 4.5 m/s
travel the same distance at full speed. The curve is shown on Diagram 117.

The Choice of Intersection Speed - For all policies the conflict delay is a minimum when the intersection is run at the saturation speed, since the time headways are a minimum at this speed. However the delay incurred by slowing down to the intersection speed and speeding up after it increases as the intersection speed is reduced.

An optimum speed exists for each flow rate and merging strategy, at which the sum of the slowing down and conflicts delay is a minimum. Diagram 119 shows the optimum flow delay curves for FCFS, FCFS + H and AP.

It would be very difficult to choose operating points at which the performance of a FTC strategy is an optimum, as both the cycle time and the junction speed must be adjusted simultaneously. Furthermore, the delay characteristics as functions of speed or cycle time are discontinuous reflecting the fact that one cycle time can only hold an integer number of vehicles.

Although an optimum intersection speed can be found for any particular flow rate, for vehicle flows other than the very low the optimum speed is only slightly above the saturation speed. Consequently there is only a small benefit to be gained by varying the junction speed according to flow, and that with the penalty of increasing the complexity of junction controller.
DIA.115 Fixed time cycle showing the effect of varying cycle time

DIA.116 Comparison of ordering policies conflict delay at junction speed of 4.5 s
DIA.117 Slowing down delay

DIA.118 Optimum junction speed
Manoeuvre Delays - Delays due to headway infringement can be divided into two parts. The part which is accumulated as a vehicle approaches an intersection and the part accumulated as the vehicle accelerates away from the intersection.

Delays after the intersection result when a close-packed platoon of vehicles accelerates to the line speed from the intersection speed. The front vehicle is not delayed but subsequent vehicles are progressively delayed by increasing amounts as they drop back, relative to the front vehicle, to the longer headways appropriate at the higher speed. The larger the platoon, the greater the occupancy at the intersection, and the lower the intersection speed, the bigger the delays. The merging policy used also has a small influence on the delay component but only at high flows. In all cases the component is small by comparison with the conflict delay. (Dia 120)

The mechanism by which delays are accumulated by vehicles manoeuvring prior to the intersection has already been described. These delays are also a function of platoon size and flow rate. They are rather more serious than the speeding up delays discussed above. This is because a delay accumulated on one lane is transferred to the other lane via the timetable, which effectively couples the two lanes together. As a consequence the delays accumulated before the intersection are similar in magnitude to the conflict delay. (Dia 121)
DIA.119 Ordering strategies with optimised junction speed

DIA.120 Alternate priority: showing the component delays
DIA.121 Complete flow delay characteristics of three ordering strategies

(1) FCFS
(2) FTC 15x15
(3) FTC 30x30
(4) AP

DIA.122 Effect of junction speed on delay characteristics of first-come first-served strategy
Junction operated with FF ordering policy at a high flow rate.
Vehicle-follower control
Vehicle trajectories in a vehicle-follower system at a low flow rate
Vehicle trajectories at an intersection in a vehicle-follower system with a high flow rate and using an FTC policy (note the vehicle that missed a cycle)
DIA. 128

Trajectories of vehicles through an asynchronous, marker-follower junction operated with an FCFS+H ordering policy.
Size of the Manoeuvre Zone – Both increasing the flow rate and decreasing the size of the manoeuvre zone have the effect of reducing the mean speed of vehicles through the zone. This has the effect of improving the packing of vehicles through the conflict point and therefore reducing the conflict delay by a small amount. However delays due to manoeuvres, both before and after the intersection increase. The net result is that reducing the manoeuvre zone slightly increases delays at the highest flow rates. Diagrams 123 – 128 show a variety of position/time curves that show the effect of varying the ordering policies, on the manoeuvres that vehicles carry out.

As the manoeuvre zone is reduced in length, the incoming flows tend to back further upstream. However the effect is small unless the incoming vehicle flows exceed the junction capacity, in which case a queue grows steadily. In this situation, the longer the manoeuvre zone, the longer can a junction tolerate transient overloads.

Practical Junction Performance – The performance of practical junction layouts can be estimated by appropriately combining all the components of delay described above. For example:

The simplest junction, a cross-over has a performance characteristic as shown in Diagram 121. The same characteristic will describe a merge-diverge junction, (Dia 129) if the extra delay incurred by running at the intersection speed along the common section x - x is added.
DIA.129 Merge-diverge junction

DIA.130 One-way full-turning junction

DIA.131 Comparative performance of the asynchronous marker-follower and the vehicle-follower schemes with a first-come first-served ordering policy
A crossing junction with low speed turns is similar to a cross-over with no turning, because all the conflict points must be considered as one, there being no room to manoeuvre between them. However the time headways must be increased to take account of the transit time of the vehicle through the set of conflicts.

A crossing junction with high speed turns can be operated differently as each conflict point is sufficiently spaced to allow manoeuvres between them.

The Comparative Performance of Vehicle-Follower and Marker-Follower Control

A simple intersection was modelled in two ways. In one, vehicle-follower control was simulated, in the other marker-follower control. The performance of the two was compared for a FCFS merging policy. The results are shown in Diagram 131. The marker-follower control is only slightly inferior to the vehicle-follower one, and this difference may reflect imperfections in the optimisation routine used rather than any intrinsic lower performance. Both types of controller make very much better use of junctions than quasi-synchronous or synchronous controllers can.

Marker-follower control achieved a level of performance virtually the same as vehicle-follower control but at a very much lower cost. Whereas vehicle-follower control requires costly and technically difficult, inter-vehicle ranging, marker-follower control can achieve the same manoeuvre
DIA.132 Comparative performance of junction control strategies

a) Asynchronous control, junction operated at the saturation speed with infinite platoon size

b) As for a) but with a platoon size of one

c) As for a) but with a junction speed equal to the line speed

d) As for b) but with a junction speed equal to the line speed

e) Synchronous slot capacity for junction run at the saturation speed
capabilities with very limited communication requirements.

The most complex manoeuvre in asynchronous systems is the packing manoeuvre. The asynchronous marker-follower can carry out this manoeuvre by transferring only four pieces of information to the vehicle. These are a speed command and an offset distance, for each speed change. The speed command becomes active when the vehicle has travelled the offset distance from the command post. In marker-follower systems, precise control of the vehicle is essential. It must accurately measure its position (this is not a difficult technical problem, see Appendix 2), and carry a simple micro-processor to generate the required position-time profile. Its controller must be able to follow position commands with small or zero steady state errors, this again is not difficult to achieve. (See Chapter 4)

Vehicle-follower control has better fault control characteristics than marker-follower control. Consequently it has been suggested that a less expensive emergency backup system can be used in vehicle-follower systems, in which the necessary ranging information, required for both the emergency monitor and the normal longitudinal controller, is supplied by the same equipment. (17)
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7. The Computer Simulations

7.1 Introduction

A number of simulations have been written to examine the operation of vehicle controllers and junction control strategies. All these simulations have been designed with a modular structure to allow an evolutionary development. Each important module has been predeveloped using purpose written small programs. These are then incorporated into the more demanding larger scale simulation, for further development. This approach to simulation offers several useful characteristics:

- speed - small programs are rarely complex and therefore easy to develop and quick to run.
- identification - the discipline of writing small programs forces an early identification of the important phenomena. This in turn leads to modular simulation structures which tend to be easier to develop.
- reliability - a repertoire of expected behaviour patterns is built up in a 'programmed learning' manner. This accelerates understanding of the overall system.
7.2 Simulation Models

The main simulation models that have been written were:
- intersection under vehicle-follower control.
- network under vehicle-follower control.
- intersection under marker-follower asynchronous control.
- Monte Carlo models of the four merging strategies discussed in Chapter 6.

7.3 Intersection Under Vehicle-Follower Control

The junction is split into several regions.

Zone of influence - this is the region of the junction where no direct control is exercised over the vehicle. However the results of control action applied to other vehicles may have an effect on the motion of vehicles in this region because of the vehicle-follower control.

Region of control - this is the region of the junction where decisions have been made about a specific vehicle and it is controlled so as to arrive at the intersection correctly.

After the intersection there is another zone of control and influence.

The manoeuvre zone can be further broken down into, a deceleration zone, where vehicles change speed from their incoming speed to the intermediate speed, a queuing buffer, where vehicles travel at their intersection speed, and a further deceleration zone where the vehicle changes speed to the intersection speed.
DIA.133 Schematic of junction layout
Two streams of traffic are simulated representing the two lanes of traffic passing through the intersection. Vehicles are generated at the intersection boundary with time spacings determined according to the headway distribution. The vehicles are integrated forward each time step, according to control requirements until they reach the boundary of influence at the other side of the intersection. There they cease to exist.

In the space between the boundary of influence and the boundary of control normal intervehicle headway control operates. When a vehicle passes the control boundary its target time at the intersection is calculated according to the merging rule. An average speed is calculated for the vehicle and the appropriate accelerations applied to the vehicle. If the control calls for a manoeuvre causing headway infringement, then the signal resulting from the headway controller takes precedence.

When vehicles approach the intersection they are accelerated as required to the intersection speed.

After the intersection the vehicles are accelerated up to the line speed. After the control boundary on the far side of the intersection junction control ceases and the vehicles are subject only to the normal headway control.

The emergency headway monitor overlays the normal control system. This detects unsafe vehicle spacings and stops the vehicle.
Throughout the journey of the vehicle various parameters are measured and stored for processing and printing.

The occurrence of particular events is marked by messages output to a line printer. Also at set times all the data pertaining to the simulation is output. All or any of this data can be suppressed by the appropriate setting of flags at the start of a run.

7.4 Network under Vehicle-Follower Control

The network simulation has a very similar design to the intersection simulation. The network is specified as a directed graph having links (each with an associated control strategy), entrances (with traffic generators) and exits.

This general description can encompass an arbitrarily complex network. Within the simulation arrays hold the geometric details of the network (to enable the layout to be reproduced for display purposes), the lengths of links, their speed limits and inter-connections. A further matrix specifies possible entrance-to-exit routes for vehicles traversing the network.

In operation, vehicles are created at each entrance according to the random generator modelling the desired input stream characteristics. Each vehicle is allocated an exit and is transferred from link to link according to the route matrix until that exit is reached.

The amount of information transfer required for track-vehicle and vehicle-to-track communications is a particularly
Throughout the journey of the vehicle various parameters are measured and stored for processing and printing.

The occurrence of particular events is marked by messages output to a line printer. Also at set times all the data pertaining to the simulation is output. All or any of this data can be suppressed by the appropriate setting of flags at the start of a run.

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In operation, vehicles are created at each entrance according to the random generator modelling the desired input stream characteristics. Each vehicle is allocated an exit and is transferred from link to link according to the route matrix until that exit is reached.

The amount of information transfer required for track-vehicle and vehicle-to-track communications is a particularly
important parameter in the assessment of a control strategy. Within the simulation information transfer points are positioned on the track; the passing of a vehicle calls a servicing routine attached to that particular point. Such an arrangement is sufficiently flexible to allow most strategies to be simulated. It has the particular programming advantages that the necessary information transfer can be explicitly identified and a sub-routine performing a particular control task can be used to service any number of communication points.

**Headway Generation** - A random number generator produces numbers that have an equal probability of lying anywhere between 0 and 1. This generator is called as many times as is necessary for the numbers produced to lie above a specified level. (That is to generate an event). The number of times the random number generator is called, is multiplied by a specific fraction of the minimum headway to give the time separation to the next vehicle. If the time so produced is less than the minimum headway then the time returned by the routine is set to the minimum headway.

**Control Routine** - The main task of the control routine is to calculate the intermediate speed of the vehicle. In both the junction and the network simulation the same technique was used, namely a simple logical selection of the appropriate velocity profile. (Dial 154, 155) For simplicity, jerk was not included in the calculations.
DIA.I34 The set of velocity time profiles used in the calculation of the intermediate speed (see dia.I35)
Dia. 135 flow chart of intermediate speed selection

Where

T - Present time
T₁ - Target time at the intersection
P - Distance to the intersection
Uᵥ - Present velocity of the vehicle
Uᵢ - Target velocity at the intersection

START

Find T, T₁, P, Uᵥ, Uᵢ

Set TTTJ = T₁ - T

yes

is Uᵥ > Uᵢ ?

no

yes

Calculate time to execute profiles P₁, P₂

Calculate Uᵢ according to P₄

is the result complex ?

yes

Change target time according to profile P₆

no

RETURN

yes

is TTTJ > time to execute profile P₁ ?

Calculate Uᵢ according to profile P₅

is the result complex ?

yes

Change target according to profile P₇

no

RETURN

no

Calculate Uᵢ according to profile P₃

is TTTJ > time to execute profile P₂ ?

Calculate Uᵢ according to profile P₅

is the result complex ?

yes

Change target according to profile P₇

no

RETURN
Dia.135  continuation of flow chart

A

Is TTTJ > time of profile P6 ?

- no
  - Is TTTJ > time of profile P9 ?
    - yes
      - Calculate $U_1$ according to profile P10
    - no
      - Calculate $U_1$ according to profile P12

- yes
  - Calculate $U_1$ according to profile P11

Return

Is the result complex ?

- no
  - Return
- yes
  - Change target time according to profile P14

Return

Is the result complex ?

- yes
  - Change target time according to profile P15
Dia. 135 continuation of flow chart

A

Is TTTJ > time of profile P8?
  no
  yes

Is TTTJ > time of profile P9?
  yes
  no

Calculate $U_1$ according to profile P10

Calculate $U_1$ according to profile P12

Return

Is the result complex?
  no
  yes

Change target time according to profile P14

Return

Is the result complex?
  yes
  no

Change target time according to profile P13

Return
The technique breaks down when a complex result is calculated for the intermediate speed, that is, the simultaneous constraints of time and distance cannot both be met. In the simple case the time constraint is relaxed and the vehicle is late at the junction. In the other case, the required intermediate speed is too low and cannot be achieved in the distance available. Consequently the vehicle will arrive too early at the junction, which is unsafe. This event counts as a failure of the control policy.

### Storage of vehicle Queues
Each link of an intersection or network has an associated queue of vehicles. Within the simulation all the variables pertaining to the vehicles are stored in an array, the appropriate set of elements being marked by front and back queue pointers. A vehicle is entered by moving the back queue pointer, a vehicle is deleted by moving the front queue pointer.

Vehicles moving from one link to another are deleted from the old link queue and added to the new link queue. The target speeds and times for each intersection are stored in a table, one table for each intersection, again pointers are used to mark the front and back of the table.

### Headway Controller
No attempt was made to model vehicle dynamics within the simulations. The detail simulation of vehicle dynamics is a study in its own right and for the work reported, unnecessary. Thus initial studies have assumed the
perfect response of a vehicle to demanded inputs. This is clearly unrealistic, and it is commonly accepted that the tolerance of the actual vehicle response about a demanded input is unlikely to be better than 5%. Later simulation studies will have to take this into account as performance limitations of vehicle controllers are likely to have a significant effect on control policies.

The headway controller uses the relationship

\[ \text{acceleration}_{(T + 1)} = \frac{\text{leeway}_{(T)}}{\text{headway}_{(T)}} \times \text{constant} \]

(The leeway is the intervehicle separation minus the headway appropriate to the vehicle speed.

\( T + 1 \) denotes the value during the next time interval (step).

\( T \) denotes the value during the current time interval (step)).

Output of Information - With any complex simulation the clear and detailed presentation of information, such that important phenomena can be readily identified, is a formidable task.

Output can be divided into three groups.

- Monitoring system operation - The noting of events during the course of the simulation enables particular situations to be identified. Such output can be valuable but cannot show unforeseen events.

- Performance Data - A detailed simulation generates large quantities of raw data, most of which requires processing to condense the important characteristics into an intelligible
form. Thus within the simulation simple averages and variances of delay and vehicle spacings are calculated. For more complex output, the relevant variables are saved on magnetic tape for subsequent processing. This subsequent processing included the plotting of histograms and position-time graphs.

With the network simulation, the sets of variables that define the state of the simulation were regularly saved on tape. This allowed the simulation to be restarted anywhere in a previously saved record and allows the simulation to be stepped backwards or forwards to examine in detail, particular events.

- Overview of System Operation - For complex simulations there are considerable problems associated with the 'bird's eye' view presentation of the overall system operation. Line printer outputs of relevant variables are useful for a quantitative survey of situations. However they are ineffective for a general overview and the detection of subtle operational anomalies. For this, a moving picture display is particularly effective. Complex phenomena are clearly presented for which one has an intuitive feel, thus allowing an assessment of the effectiveness of algorithms and the detection of incorrect program operation.

*Moving Picture Display* - The simulations reported here use an interactive moving picture display as a communication medium. Suitably coded information is transmitted in character form, (that is, one start bit, seven information bits, one parity bit, one stop bit) from the host computer (Rank Zerox Sigma 5)
containing the simulation, to the picture processor (Digital Systems GT 40) via a full duplex 1200 baud asynchronous line. A continuously refreshed picture is produced showing the motion of vehicles through the network or intersection.

At any point the display can be stopped and dialogue initiated with the host computer. Any portion of the picture can be magnified to any scale. This coupled with the ability to restart the simulation at an earlier stage and to step backwards or forwards through the pictures enables close detail to be observed.

The picture displayed has the following properties:

- The use of the display does not substantially slow down the simulation.
- A network that can be simulated can also be displayed.
- Vehicles moving through the network are represented by an unambiguous symbol whose length represents headway and so varies according to the speed of the vehicle.

Initial attempts to produce the required display used the FOCAL GT graphics routines (supplied with the GT40 is a simple, flexible, interpretive, language, including some graphics functions, similar to BASIC, and called FOCAL GT). Data transmitted from the Sigma 5 host was received by a FOCAL GT program and used to redraw the vehicle layout in the junction. Accumulation of data simultaneously with drawing the picture output, was not possible and the resulting display was too slow to be effective. The best picture rate achieved was 1 picture/8 secs, (broken up as 3 seconds data transmission time,
5 seconds display time). The excessive display time is the result of the very slow execution speeds of interpretive languages. The long data transmission time results from sending the ASCII character form of a decimal number rather than the more efficient binary form.

These two limitations were avoided in the second display produced. Specialist functions performing segments of the display process were written in assembly code and added to the FOCAL GT structure. This approach minimised the software written and retained the flexibility of programming in a high level language.

The functions correspond to four stages in the creation of a display

- The generation, within the GT40, of a data table holding the XY coordinates (suitably scaled in screen units) of the network to be displayed. The display of the junction layout requires a simple extension of the network representation used to describe the junction geometry. As only straight vectors can be displayed on the GT40 screen, curved network links have to be approximated with a series of straight line segments. These segments are the same length for any given link, this facilitates subsequent display of vehicles. Thus the link identifying number, the length of individual segments and the XY coordinates defining the ends of each segment are transferred from the Sigma 5 to the GT40 data table.

- The display of each network link by referencing the coordinate data table.
The display of vehicles in the junction to produce the moving picture.

The vehicle display routine determines the picture speed. Provided all the necessary calculations can be carried out simultaneously with the receipt of data the picture rate is determined by the data transmission time. The design of the vehicle display therefore reduces to minimising the data required to define a picture and ensuring that algorithms are sufficiently fast. The least complex symbol that could be used to represent the vehicle and its stopping distance is a straight line of variable length. To position the line anywhere on the screen requires the XY coordinates of each end: these, directly transmitted from the Sigma 5 would require four items of data.

If the vehicle is identified as lying on a particular link of the network, then the end coordinates can be calculated knowing the displacement of each end of the vehicle symbol from the origin of the link. This reduces the number of data items required per symbol to two.

The coordinates of a point on a link are calculated according to the algorithm. (Dia 136)

\[
X_p = X_n + \left( X_{n-1} - X_n \right) \times g
\]
\[
Y_p = Y_n + \left( Y_{n-1} - Y_n \right) \times g
\]

where

- \( n \) - integer part of \([D/p]\)
- \( g \) - fractional part of \([D/p]\)
- \( D \) - displacement of point from origin
- \( p \) - length of one link segment
DIA.136 Link details

DIA.137 Showing trajectory segments and variable start points
All the data except D are constants and held in the previously generated data table. To calculate the coordinates of each point requires two multiplications and one division, consequently calculation times can be easily kept within the minimum period of 10ms separating the arrival of data items.

The maximum binary number that can be transmitted from the Sigma 5 in a seven bit character is 127. If, each of the displacements necessary for the XY coordinates of the symbol can be generated using numbers less than 127, then only a single character need be transmitted for each data item.

Three methods of generating the displacement are possible.

- The absolute displacement of a point from the link of origin can be transmitted. As displacements can be considerably greater than 127 screen units (approx 1.25 inches) in general, two characters would be required to define the point (the two characters holding the upper and lower parts of a 14 bit binary number).

- Each point is calculated as an increment on the corresponding point on the previous picture. The data increments are likely to be very small but rounding errors would accumulate from one picture to the next and probably would become unacceptably large.

- Along a given link, a set of points can be specified by sending the spacings of the points and defining the first point as being spaced relative to the origin of the link. For a set of points along a link errors can accumulate but are
X,Y - x y coordinates of link segment start

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- Along a given link, a set of points can be specified by sending the spacings of the points and defining the first point as being spaced relative to the origin of the link. For a set of points along a link errors can accumulate but are
not transferred from link to link. This scheme was implemented for the picture display.

During the picture display communication is maintained with the Sigma 5 host. Any two characters typed from the keyboard terminates the picture display and initiates a dialogue enabling several options to be selected. Namely

- A specified portion of the network can be magnified to any scale. The facility is achieved by calculating and transmitting to the GT40 a new coordinate table holding only the coordinates of the links actually appearing in the display. During the picture display the Sigma 5 sends only data referencing the displayed links, all other is suppressed. To further aid the detail study of the individual vehicle movements, the simulation can be run in slow motion.

- During the simulation run, the variables defining the state of the simulation are regularly dumped onto magnetic tape. This records the simulation results for future data processing. At the request of the operator the simulation can be restarted anywhere on the record. This enables simulation work to be carried on from where it was left off or for any particular event to be studied in depth.

- To assist particular studies a step operation can be selected. On restarting the display the operator can step backwards or forwards one picture at a time, or return to the main dialogue.

- A trace option records the progress of a particular vehicle by printing all the variables pertaining to the vehicle,
regularly to the line printer. To prevent the continuous printing of variables producing a confusing line printer record a message option can be selected and a heading transmitted to the line printer.

Performance of Picture Display - A picture rate of about 2 pictures a second is achieved. (This is determined by the amount of data that needs to be transmitted, consequently the fewer the vehicles displayed, the faster the picture rate).

If a picture is drawn for every second of simulated time (that is, the display runs at approximately a simulation time twice as fast as real time), a clear, moving, but slightly jerky picture is realised, also the display slows the simulation down a certain amount.

If the simulated time between each picture is increased so that the display does not hold up the simulation, there are unacceptably large changes between each picture making it appear jerky. This is because large changes can take place in vehicle position in the increased simulation time between each picture.

7.5 Intersection under Marker-Follower Control

The simulation operates in a different manner to the previous simulations described.

The time of arrival of each vehicle at the junction boundary is determined using the same techniques as described earlier. The time the vehicle passes through the intersection
is determined by the choice of vehicle ordering and intersection speed. This provides sufficient information to calculate the vehicle manoeuvre. The basic manoeuvre is a speed change carried out at SP1, \((\text{Dis} \ 137)\) a constant speed section and a final speed change starting at SP2.

An iterative procedure is used, as follows:- Using a guess for the intermediate speed a trajectory is calculated for the vehicle using the most forward positions of SP1 and SP2 possible. This trajectory is stored in a polynomial form, a different polynomial describing each phase of the manoeuvre. These phases are as follows.

- **Constant line speed input**
- **Constant jerk transition**
- **Constant acceleration**
- **Constant jerk**
- **Constant speed**
- **Constant jerk**
- **Constant acceleration**
- **Constant jerk**
- **Constant final velocity (intersection speed)**

The worst headway infringement during the first speed change manoeuvre is found by subtracting from the position of previous vehicle, the position of the headway locus of the present vehicle. This infringement is used to move the start point SP1 upstream (so that the infringement is reduced to zero). A similar process is carried out for the second speed change. This second manoeuvre adjustment is however more complex.
It may not be possible to remove headway infringement by moving the start point upstream. Consequently the intersection start time must be made later by a specific amount to remove the headway infringements. This corresponds to the 'slip' that must be added into the intersection target time table.

Once satisfactory start points have been determined for each manoeuvre a second iteration loop recalculates the intermediate speed appropriate to the new manoeuvre start points. This slightly modifies SP1 and SP2, consequently the iteration cycle must be repeated, until specified accuracy constraints are satisfied. Although the iteration cycle is rather crude it works well and only 5 - 3 cycles are usually required to evaluate a manoeuvre.

7.6 Monte Carlo Simulation of Merging Strategies

The Monte Carlo simulation of queuing strategies is very simple. The arrival times of vehicles are determined according to the appropriate headway distribution. The target time is determined according to the merging sequence by taking whichever is later, the arrival time of the vehicle, or the earliest time the vehicle can follow the previous vehicle through the intersection, (that is, the crossing or following time headway as appropriate). The difference between the arrival time and the target time is the vehicle delay.
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7.7 Other Programs

Contained in the appendices are the listings of a number of support programs. These include - a program simulating a platoon of vehicles subject to varying types of speed-change operations, - a program to evaluate the changing safety factor and time headways through a jerk-limiting speed-change manoeuvre, - a program to plot position-time graphs from data stored on magnetic tape, - a program to plot the pseudo three-dimensional graphs with hidden-line removal and a program (written in conjunction with Alan Hume) to assemble PAL11 (PDP-11 assembler code) programs into binary suitable for loading into the GT40.
Conclusion

The important conclusions of this thesis can be summarised as follows.

The fundamental choice in the design of control systems for automated transport is between a centralised or decentralised system structure. Decentralised controllers by comparison with centralised controllers, offer the prospects of lower system costs, and better reliability, although with the penalty of a reduction in the ultimate performance available. Dependability of service is a vital characteristic in automated transport systems, and therefore for such systems, decentralised, hierarchical structures have considerable advantages.

There are two basic techniques of vehicle control, marker following or vehicle-following. Marker-follower control can be either synchronous or asynchronous, vehicle-follower control is always asynchronous. Synchronous control tends to be centralised, and asynchronous is usually decentralised.

Previous researchers have only examined in detail the performance of synchronous marker-follower systems. Asynchronous controllers have always been dismissed as being incapable of providing a good system performance, and being expensive to implement. The analysis of asynchronous systems presented in this thesis has shown that these accepted views are...
mistaken. Indeed asynchronous systems can make a substantially better use of track capacity than synchronous systems. This is particularly true for junctions, where a well chosen strategy can achieve nearly twice the capacity available under synchronous control. This, combined with the flexibility of asynchronous controllers allows significant reductions in the complexity and therefore the cost of the civil engineering structures.

The decentralised structure of asynchronous systems ensures a good response to failures and leads to a better service dependability than the equivalent centralised systems. Within the class of asynchronous systems the vehicle-follower type of controller has a better response to failures than the asynchronous marker-follower controller. However the asynchronous marker-follower scheme can achieve as good a performance during normal running as the vehicle-follower scheme, but requires much less communication. This significantly reduces systems costs.

Capacity in asynchronous systems is limited by the ability of the emergency backup systems to safely monitor inter-vehicle spacings. Of the techniques available today only fixed block signalling provides the necessary combination of reliability, 'fail-safe' and reasonable cost. However fixed block signalling cannot be used effectively for vehicle headways less than 6 - 10 seconds. If headways lower than this are demanded a completely different and radical approach to safety must be adopted. The concepts of 'fail-safe' and
'no-collision' design must be abandoned and probabilistic safety criteria used instead. Such criteria are unlikely to be generally acceptable for a long time yet.
APPENDIX 1 Simulation of asynchronous single channel communication link
C SIMULATION OF ASYNCHRONOUS COMMUNICATION LINK WITH CYCLIC STRATEGY.
C
C!FORTRANM 00,8
  DIMENSION CELSAV(1000),NSUM(50)
  DIMENSION TT(20)
  COMMON RLEVEL,TELT
  LOGICAL STOPNOW
  NAMELIST
  STOPNOW='FALSE*,
21 CONTINUE
C INITIALISATION*
  TIMESS=1
  T=TT(I)
  TIMES=10
  AVENUER=1
  TELT*1
  TM=TIMESS*USER/10*
  DELSUM=0*
  TP=PCU/900.0
  TPEX=AVEX
  IRC=0
  QL E=0
  GRIM=5
  NEXT=ONEEXT
  F=P=REQUEST TIME *
  NBUFF=1
  NQ=2
  NQUN=0
5 INPUT(105)
  IF (STOPNOW) STOP
C CALCULATE MESSAGE GENERATION RATE*
  RLEVEL=1-IPC+TELT/NUSER
  BAL=RN(0)
  DD 10 I=1,NUSER
  BAL=RN(1)
  DD 10 I=1,NUSER
  BAL=RN(2)
  DD 10 I=1,NUSER
  BAL=RN(3)
  DD 10 I=1,NUSER
  BAL=RN(4)
  DD 10 I=1,NUSER
  BAL=RN(5)
  DD 10 I=1,NUSER
  BAL=RN(6)
  DD 10 I=1,NUSER
  BAL=RN(7)
  DD 10 I=1,NUSER
  BAL=RN(8)
  DD 10 I=1,NUSER
  BAL=RN(9)
  DD 10 I=1,NUSER
  BAL=RN(10)
  DD 10 I=1,NUSER
  BAL=RN(11)
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  DD 10 I=1,NUSER
  BAL=RN(96)
  DD 10 I=1,NUSER
  BAL=RN(97)
  DD 10 I=1,NUSER
  BAL=RN(98)
  DD 10 I=1,NUSER
  BAL=RN(99)
  DD 10 I=1,NUSER
C IF MESSAGE DEMAND AFTER SERVICE TIME*
  IF (TT(I)+8+TIMIDLE) GRTB 2
  JAG=(TIMIDLE=TT(I))/USER (MST)
ILAG=0
C CALCULATE NO. OF BUFFERS REQUIRED.
   IF (ILAG.LT.NBUF) GOTO 3
C REJECT THESE MESSAGES AS EXCESS.
   IRC=IRC+1
   GOTO 4
C UNUSED MESSAGE SLAT COUNT.
   2. IF=IFC+1
      TI+IDLE=TIMIDE+1
      TIMIDE=1
      GOTO 1
C INCREMENT NEXT TIME IDLE.
   3. DELSUM=DELSUM+TIMIDE=TT(I)
      NCOUNT=NCOUNT+1
C SAVE.
   DELSAV(NCOUNT)=TIMIDE=TT(I)
C TIME IDLE AT TIMIDE.
   TIMIDE=TIMIDE+1
C FINISH WHEN 1000 MESSAGES AVERAGED.
   IF (NCOUNT.EQ.1000) GOTO 5
C CALCULATE NEXT MESSAGE REQUEST TIME.
   4. TT(I)=TT(I)+RN(I)
      CONTINUE
      GOTO 6
   5. AVDEL=DELSUM/NCOUNT
      SDS=0
      DC 12 I=1,50
      NSUM(I)=0
      ICOUNT=0
      DC 7 I=1,NCOUNT
      SDS=SDS+(DELSAV(I)=AVDEL)**2
      IPT=DELSAV(I)*G/NUSER
      IF (DELSAV(I)*G+FLOAT(NUSER)) ICOUNT=ICOUNT+1
      IPT=IPT+1
      IF (IPT.GT.50) IPT=50
      NSUM(IPT)=NSUM(IPT)+1
   7. CONTINUE
      0=IPT+FLOAT(ICOUNT)/FLOAT(NCOUNT)
C CALCULATE VARIABLES AND OUTPUT.

DO 17 I=1,50
   NTST=NTST+NSUM(I)
   IF (NTST.GE.NCOUNT#99/100) GOTO R
17 CONTINUE

8 I=I+1
   DNW=I*TIMEw
   BCC=NCOUNT*TIMESE/1000/TIMEDL
   SD=SQRT(EDS/NCOUNT)
   ARR=FLOAT(IRC)/TIMEDL
   DRU=FLOAT(NCOUNT+IRC)/TIMEDL
   RR=ARR/DRU
   OUTPUT(108) MEAN DELAY STAND DEV % ACCPNCY MESS LN
   CTH NC OF USER WATT TIME AV RJCT R/U DMND RT/HR
   WRITE(108,100) AVDEL,SD,EC+TMESS,NUMER,TIMEw,ARR,DRU
   OUTPUT(108) ' RJCT RATAR 8VRDLY RTIO 99% DELAY
   WRITE(108,197) RR,BDR,DRN
   IPT=50
   DO 71 J=1,10
   DO 73 I=1,50
73 NSUM(I)=DELSAV(I+J-1)+5C)*4.5
71 CALL PRINT(KSUM,IPT,TIMEw)
70 CONTINUE
100 FORMAT(4F14.2,114,F14.2,2F14.4)
197 FORMAT(3F14.3)
END
C GENERATE RANDOM ANNUAL RATE

FUNCTION RN(I)
COMMON RLEVEL,TELT
DIMENSION RNX(20) =1:108,120
INTEGER RNX
IF (I)=1 RETURN
DO 3 II=1,20
3 RNX(II)=II*50+1
RETURN
END

CONTINUE
ICOUNT=0 DO 120 I=1,200 NUMP=120
CONTINUE 140 DO 160 J=1,16
S 170 DE LW,9 =IAS \#I
S 180 DE LW,9 =RNX=1\#4
S 190 MJ,9 =EG, 65539
S 200 NUM=9 AND,J9 =x'7FFFFFFF'
S 210 SM STW,9 =NUM, RNX=1\#4
S 220 LI RN=RNX(I)
S 230 W RN=RNX+4656613E=9
S 240 IF (RN+GE=5 AND+RN+LT+1.5=RLEVEL) GOTO 4
S 250 ICOUNT=ICOUNT+1
S 260 GOTO 7
S 270 RNFLOAT(ICOUNT)*TELT
RETURN END
C OUTPUT HISTOGRAM OF DELAYS.
C
SUBROUTINE PRINTH(NSUM,IPT,TIMEWT)
DIMENSION NSUM(50),LINE(120)
DATA IBLANK/' ',ILAST/' '*
MAX=0
OUTPUT(108): '+'
DO 16 II=1,IPT
HEAD=(II-1)*TIMEWT
NUMP=NSUM(II)
IF (NUMP.GT.120) NUMP=120
IF (NUMP.EQ.0) GOTO 18
DO 17 JJ=1,NUMP
17 LINE(JJ)=ILAST
IF (NUMP.EQ.120) GOTO 16
18 NUMP=NUMP+1
DO 19 JJ=NUMP,120
19 LINE(JJ)=IBLANK
16 WRITE(108,101) HEAD,LINE
OUTPUT(108): '+'
RETURN
101 FORMAT(X,F6.2,X,12A1)
END
Measurement & Communication in Automated Transport

L. Burrow & T. Thomas (Oct '76)

Transport Research Group
Measurement & Communication in Automated Transport

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Abstract

This working paper discusses in detail the major aspects of communication and measurement in an automated transport system.

In part 1 are discussed the underlying system features determining the design and provision of communication and measurement systems in an automated transport network.

In part 2, there follows a catalogue of current communication and measurement techniques indicating their major properties and possible applications to automated systems.

Throughout transport there has been a growing interest in the use of automation to improve the quality of service. Part 3 reviews some examples of techniques that have been applied to metros, buses, and automated systems.
Introduction
Designs for new transport systems seek to improve the service offered to travellers. Better communications in stations and on vehicles enable passengers to understand and use the system more effectively. Improved control strategies and circuits enable the system to respond faster and more accurately to demands made of it.

Increasingly automation is employed. The human content of complex tasks is replaced by automatic equipment, whose predictability, reliability and speed of operation enable a more regular and frequent service to be offered.

Common to all these developments is the more sophisticated use of information requiring fast, error-free communication links, extensive and accurate measurement and monitoring equipment.

Communications in Automated Transport

Communication in an automated transport system is characterised by the need to transfer information regularly between moving vehicles and fixed control centres distributed over a wide area. Bidirectional communications between vehicle and vehicle, vehicle and control centre, control centre and control centre may all be necessary.

The control system engineer would like to have independent communication channels for each information flow. Such provision would however be wasteful, being excessively expensive and under-utilised, although possibly, a more precise control could be achieved. Communication facilities have to be chosen in balance with the rest of the system, enabling adequate information flows to take place whilst minimising capital and running costs. As with all communication systems, time delays, information rates and error rates are important parameters. All can be improved by supplying additional bandwidth, signal power or less noisy channels at an increased cost. (Refs -32)

Measurement in Automated Transport

In automated transport certain tasks of the human operator have been replaced. Extensive measurement and monitoring is required,
both to relay information enabling controllers and algorithms to work effectively and to provide checks designed to ensure the safety of the system.

The state variables of most interest are position and its time derivatives of velocity, acceleration and jerk.

The ability of a vehicle controller to minimise absolute position errors directly influences the maximum flow capacity a system can achieve. Precise operations at merges and stations depend upon both position and speed control. Accurate speed control is required to satisfy safety conditions, for example speed limits on bends and headway constraints when approaching other vehicles.

Passenger comfort is determined by the quality of acceleration and jerk control. Precise acceleration control is difficult to achieve. Closed loop jerk control may not even be attempted, although vehicle response characteristics can be designed to ensure that jerk stays within acceptable limits.

The coordinated operation of a complete transport network requires the systemwide generation of time. Clocks can be easily manufactured to high accuracy but methods have to be incorporated to ensure that all are synchronised, thus creating additional communication requirements.
Part 1: Principles

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1.A.3  - Communications involved in open loop control, closed loop control and fault monitoring
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  - Closed loop
  - Fault control

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1.B.1  - Multiple use of a single channel
  - Direct channel organisation with demand responsive strategy
  - Direct channel organisation with fixed sequence strategy
  - Delay characteristics with direct channel organisation
  - Channel organisation using a central controller
1.B.2 - Addressing
   - The geographical addressing problem
   - Geographical addressing by a centralised unit
   - Geographical addressing operated by the vehicle
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1.C.1 - Measurement and communication
1.C.2 - Position
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1.D.2 - Types of modulation
1.D.3 - Properties of modulation
1.A. System Features

In this section are discussed the general features of transport communications which determine the overall behaviour and capabilities of the transport scheme.

1.A.1 The Degree of Automation Sought

The ability of a human operator to make fast overall assessments of unusual situations ensures that the total automation of systems as complex as a transport network is most unlikely. At some stage it becomes a more effective solution to employ somebody rather than attempt to devise appropriate equipment and strategies. Examples are: the creation of schedules, maintenance and recovery from severe failures.

Of paramount importance is the provision of an effective interface between the automatic equipment and the operator. Humans are particularly effective at identifying patterns of behaviour but are easily overloaded with data. Communication techniques have to be devised which display primary information in easily recognised forms. Safeguards have to be incorporated to reject unsafe or incorrect operator decisions yet allow him adequate flexibility.

Modern railway practice is an illustration of the changing man-machine boundary as automation progresses.

| Manual driving                             | Driver obeys optical signals at trackside. |
| Manual driving with automatic warning      | Driver obeys optical signals but is advised of signal aspects at an appropriate braking distance. |
| Manual driving with cab signalling         | Driver obeys optical signals but is continuously advised of the signal aspects in the cab. |
Automatic vehicle control

- Driver obey optical signals but cab signals automatically brake in the event of overspeed.

Automatic vehicle operation - (fixed block)

- Power and brake controls operated by cab signal equipment.
- Fixed block signalling.
- Driver not strictly necessary.

Automatic vehicle operation - (variable and moving block)

- Continuous two-way data communication facility allows safe headways to be calculated at all times to automatically operate power and brake equipment. Driver is not necessary.
(Ref. 16, 229)

1.1.2 The Structure of Control Systems and its Influence on Information Requirements

A transport control system is a structure of interconnected subsystems. These might include vehicle controllers, station controllers, merge controllers, network controllers, safety monitors, passenger handling systems, power supplies etc., each communicating with some or all other units.

The broadest level of design defines the system organisation. The most appropriate sub-systems and structure are specified to achieve the desired 'whole' system properties. For example good reliability and high safety standards are fundamental factors in any transport scheme and should figure in any cost function relating to whole system operation.

Control structures for an automatic transport system are usually either centralised or hierarchical. Other structures can be devised, for example, mesh structures in which every unit directly communicates with every other. Communication costs are very high and logical fault detection is almost impossible.
Centralised control

In centralised control structures a central decision maker controls all the peripheral subsystems. Information from the subsystems passes to the central unit and is available for use in any other subsystem. Communication costs are high as many long distance and expensive channels are required to link all parts of the network to the central processor. The concentration of control activity and the quantity of communications passing through regions supporting many other activities makes the system very vulnerable to damage and subsequent disruption. However better control may be possible as all the system information is available for processing.

Hierarchical control

In a hierarchical structure control is divided between a number of semi-independent levels. Each element in the structure functions autonomously using only limited strategic information from higher levels.

Information is only selectively directed to other parts of the system, consequently all the system information is not available everywhere in the network. Limited information transfer decouples the system elements. Control decisions are made close to the source of their information and are likely to be less optimal as a result.
The use of hierarchical structures with decision units physically distributed throughout the network reduces the demand for communication links, so reducing costs. The disruption caused by faults is diminished and the modular nature of such systems simplifies the detection and repair of faults. (Ref. 30, 96)

Hierarchical structure

- greater understanding and generality
- longer time scales
- greater detail
- more specific information
- shorter time scales

1.A.1 Communications involved in open loop control, closed loop control and fault monitoring

A 'system' of two interconnecting subsystems can be related in terms of a 'controller' and a 'plant'.

The role adopted by each subsystem depends on the primary direction of information flow. The 'controller' is the upstream element and supplies appropriate inputs to the 'plant' which responds with the 'system' output.

The relationship between the 'controller' and the 'plant' can be either open-loop or closed-loop.
Open loop

Conceptually the controller holds a model of the plant. Using this model and knowing the desired system output the controller generates the necessary plant outputs. The accuracy of the system output is totally dependent on the ability of the model to predict the plant action. As no measure of the actual plant output is used by the controller, noise and other random disturbances cannot be compensated for. Undetected incorrect operations will result from equipment or strategy failures.

Open-loop systems require only one-way communication links. They may be appropriate where the system is predictable, i.e. it is reliable, well defined and subject only to minor random disturbances, or where the cost of two-way communication is excessive e.g. where the communications are constrained to a narrow band, long distance link.
Closed loop

Closed loop systems have the general form:

The controller has access to measures of the actual plant performance. This feedback information allows compensation for minor disturbances such as noise, hardware and environmental variations. More sophisticated controllers may use the feedback information to track the optimal operating point of the system.

In closed-loop systems the controller may not hold a conceptual plant model. However the use of a plant model by the controller improves its ability to compensate for disturbances and enables optimum seeking methods to proceed faster. Such an arrangement is commonly called feed-forward control.

Closed loop control schemes require substantial investment in two way communications, measurement transducers and control equipment. They are essential for good performance in poorly defined, noisy environments with many random disturbances.
Fault control

Fault control systems are always closed-loop. Measures of actual system states are compared with predicted values of the state. The detection of abnormal discrepancies initiates standby strategies assigned to counteract the effects of the failure. The identification of a system fault requires a system model as a reference against which the system operation can be checked.

The model may be explicit or implicit, i.e. the fault monitoring can be integrated with a controller or supplied as independent equipment.

Extra transducers circuitry and communications are required. System disruption is reduced as a faster response to failures is possible.

Within a closed-loop system, elements may be operating locally in an open-loop manner.

Unit B is part of a closed-loop but is itself operating open-loop.

Measurement activities placed further 'downstream' will monitor a wider range of system states. A single transducer can tap information created by several preceding elements. The information yielded is more general, its interpretation more difficult.

Feedback control over several systems becomes more complex to design and delicate to adjust. Fault detection becomes less precise and corresponding strategies more clumsy. There is a balance between the high cost of monitoring every activity and the ineffective monitoring of only a few. This balance fundamentally influences the measurement and communication equipment provided in a complex automatic system.
1.B. Methods of Directing Information to the Correct Recipient

There are two classes of information direction methods. The 'many to one' where several units may wish, possibly simultaneously to communicate with one unit, and the 'one to many' where a single unit may wish to communicate selectively with one of a number of units. The former requires the organised, multiple use of a single channel. The latter is concerned with addressing techniques. These problems arise in all communication systems and have been extensively studied particularly for telephone and computer networks. Consequently only specific situations associated with transport networks are discussed here. (Ref. 137).

1.B.1 Multiple use of a single channel

The large number of links required and the physical separation of network elements dictates the use of control structures and strategies requiring limited information flows.

In many situations a single channel has to be shared between several users. The added requirement for moving point to fixed point communication introduces further complexity, as messages must intercept the desired recipient in time and position.

With an uncontrolled channel serving several independent users there is a finite probability of two or more simultaneous transmissions. Although errors caused by the collision can be identified using coding techniques, strategies designed to ensure the correct message is retrieved cannot be easily devised.

The use of the channel must be organised so that transmissions from independent users cannot take place simultaneously, i.e. the channel is exclusively dedicated to the user for the duration of its transmission, it then becomes available to other users.

Interrupt type systems offer a method of channel synchronisation. However they imply the use of parallel lines one from each user to a priority resolving unit controlling a message channel. In most situations arising in automatic transport systems this is not possible.

A variety of schemes are possible. The channel can be captured by a user in one of two ways.
(a) Directly, requiring each user to listen to the channel
(b) Indirectly, via a central controller

With each, a demand responsive or fixed sequence (time multiplexed) service can be operated.

Direct channel organisation with demand responsive strategy

A user wishing to send a message, transmits immediately if he finds the line clear. If a busy line is encountered the user continues to test the line at fixed intervals until an idle state is found, whereupon it transmits. (If the user transmits immediately a previous transmission finishes there is an increased probability that two or more users, all delayed by the same previous user, will transmit simultaneously.)

Direct channel organisation with fixed sequence strategy

For a fixed sequence type operation each user is allocated the channel in sequence. The fixed sequence must be prearranged and cannot respond to local variations in demanded information flows. Each user must know and be able to identify its position in the sequence. Complications arise where the potential users of the channel can change e.g. where vehicles enter or leave the zone of a link, as this requires the signalling schedule to be loaded into the vehicle each time it enters a new zone.

Synchronisation of individual users to the message stream can be achieved in two ways. If messages are fixed length i.e. all users are allocated the channel for a fixed time slot even if they have no information to transmit, then 'flywheel' type synchronisation is possible. Each vehicle takes its timing information from the received message stream. The failure of any individual user does not halt the message stream.

The use of stop-start codes to define the message boundaries allows vehicles with no information to transfer to use the channel less. The start of each transmission relies upon the end of the previous one but if one user fails to transmit, backup procedures are required to restart transmission.
Direct channel organisation needs little equipment. Demand responsive systems give no indication of failed users, a check which is possible in a fixed sequence system.

Demand responsive services are more effective where information flows from each user are highly irregular and unpredictable.

**Delay characteristics with direct channel organisation**

Demand responsive channel use gives a mean delay which rises steeply when the demand rate exceeds 75% of the channel capacity. Below this demand rate the mean delay is substantially less than for fixed sequence systems. If vehicles have only limited storage for messages pending transmission both systems show significant reject rates, that for the demand responsive system being lower than that for the fixed sequence system.

Fixed sequence systems offer the advantage that delays are bounded, although this is only significant near channel saturation. (Ref. 137)

![Graphs showing delay characteristics](image)
Channel organisation using a central controller

A control unit can be used to organise a communication channel. If only one channel is available between controller and users, the only policy that can be operated is for the controller to poll each user in turn. A demand responsive scheme cannot be operated (as any user initiated message will be independent and therefore uncontrolled).

A link organised using a central controller may however employ two communication channels between the controller and the users. If both channels are of identical design and have the same characteristics then a variety of strategies can be operated. (NB. This is a simplifying assumption, not necessarily a requirement).

One channel can be designated an addressing line, the other, the message line. These channels could be interchangeable enabling some degree of standby service to be provided in the event of a failure.

Any mix of fixed sequence and demand responsive policies can be operated, enabling the advantages of both to be incorporated. Against these benefits must be balanced the alternative gains that would have been achieved by operating each channel independently for the same link. This provides lower delay and reject rates as a consequence of the lower usage of each channel.

1.B.2 Addressing

The successful transmission of information from one place to another in a system requires routing to the correct location and timing to ensure that it can be received.

In transport networks a channel may serve a number of physically separated users. The range of possibilities is represented diagrammatically thus:
A destination may be fixed or moving. If moving the channel routing system must be organised to direct the message to the track segment adjacent to the vehicle. If the segment can encompass more than one vehicle at a time then messages must include vehicle identity in their code. Advance messages can be sent if track segments have storage buffers from which the information will eventually be relayed to the vehicle.

Communication systems linking fixed points have been extensively studied, particularly with respect to distributed computing systems. The extra refinement necessary to correctly and efficiently communicate with moving vehicles is the main concern of this paper.

The geographical addressing problem

Information must be directed to intercept the intended vehicle, i.e., it must be available at an appropriate track-side position and time.

Reference to time-position trajectories of the vehicles yields the following possibilities.

A message can be displayed over the whole track, a track segment or a fixed point. If the vehicle does not act immediately on the received information vehicle storage is required. If the track does not immediately relay the information to the vehicle then track storage is required. (If the track-vehicle link is available over an extended distance, the vehicle and the track can share the same store.)

- Message available over the whole track for an extended time: All vehicles receive the same message. The information changes infrequently and transmitter may be effectively the track store. An example is the transmission of system status, i.e., normal/emergency, fare policy, service option.
Message available over the whole track at a particular time:
All vehicles are contacted. Vehicles store message if necessary.

Message available over a portion of the track for an extended time: Not all vehicles are contacted, only those passing that portion of the track.

Message available over a portion of the track at a particular time: Only vehicles within the zone receive the information. Information can be made vehicle specific if their trajectories are predetermined. The number of vehicles to be contacted and the tolerance on vehicle position determine the length of the zone.
- Message available at a point on the track for an extended time:
  Information is position dependent and contacts all vehicles passing by.
  Information can be made vehicle specific by controlling the display time according to the number of vehicles to be contacted and the tolerance on the scheduled time of arrival.

- Message available at a point on the track at a particular time:
  Vehicles are uniquely contacted but the exact vehicle location is required.

Geographical addressing by a centralised unit

The central unit requires accurate knowledge of vehicle position. This can be derived either by measurement or from predetermined schedules. Successful communications depend totally on the correct working of the controller and system. Disordered, misplaced or undetected vehicles will cause faults as messages become misdirected or lost.
Geographical addressing operated by the vehicle

Some degree of protection against communication failures caused by local running anomalies is provided by using the actual vehicle movements to control both the position and duration of messages. Occasionally even the message contents are generated by the vehicles so requiring no central message controller.

Message addressing

Coding added to a message enables labelled recipients to recognise messages intended for them. Message addressing allows the easy addition or removal of communication units from the network. Security and reliability are strongly dependent on the coding techniques used.

Geographical and message addressing can be provided simultaneously; this duplication of addressing information enables some faults to be detected. The effectiveness of the fault detection depends on the independence of the two systems. If a recipient acknowledges a message with its own identity, a closed loop communication results, enabling the message transfer to be checked and errors corrected.
1.0 Measurement

This section introduces Part 2 of the working paper, with a discussion of the general features of measurement systems. Part 2 expands the discussion with detailed descriptions of both currently used and novel, measurement and communication techniques.

1.C1 Measurement and Communication

To control and operate numbers of vehicles, the control centres must have information from all the vehicles in the system. Essential signals are measurements of position velocity, acceleration and vehicle identity. Some or all of the information will be required by both the control centre and the vehicle. Furthermore some measurements are most conveniently made on-board the vehicle, some at the trackside. Information used at the trackside and measured on the vehicle or vice-versa therefore requires either duplication of measurement or communication from one to the other. Measurement techniques can be associated with the particular form of communication used across the vehicle-track interface. Often a physical property of the signal is modified, e.g. its phase or its amplitude, in a way that does not interfere with the message already being carried by the signal.

Measurements can be made either discretely or continuously in time. The output information may be presented either as a digital or analogue signal. Usually but not necessarily discrete measurement techniques generate digital signals and continuous measures generate analogue signals. The falling cost of digital processing increasingly favours digital signal forms particularly in harsh environments (i.e. noisy channels and low signal strengths) provided adequate bandwidth is available. However continuous signals are usually cheaper and simpler. Transducer signals are directly usable in control loops, whereas in digital systems both analogue to digital and digital to analogue conversions are generally required.

The information in digital signals is not affected by signal attenuation over distance. This allows better accuracies to be achieved for long distance measurements. Digital signals do not drift - an important consideration where measurements are made over a long period of time.
C.2 Position

Vehicle positions are measured along the track relative to some fixed point. They must be known sufficiently accurately to allow successful communications and safe manoeuvres.

Trackside position measurement systems will locate a vehicle to a fixed resolution of the transducers. They are expensive unless precise measurements are only required at a few key points e.g. at stations or station approaches.

On-vehicle position measurement requires instrumentation in each vehicle. Measures made locally on the vehicle must be periodically updated to the track standard to remove any accumulated errors. The frequency of this resetting depends on the transducer and the maximum allowable error.

Position measurement techniques are either

- absolute - in which the full precision of the device is used all the time.
- incremental - in which position increments are counted. Memory is required, signals are narrow bandwidth but the measurement is subject to accumulated error, similar to drift in analogue systems. Such schemes are generally used for long range measurement.

C.3 Velocity

Analogue signals proportional to speed are given by doppler shift methods or those relying on electromagnetic induction. The rate of change of a position measurement can be used as a velocity signal. The output is likely to be noisy and restricted in bandwidth.

Position based speed measures can be made by timing between two markers yielding a discrete measure, or by measuring the frequency of markers, yielding a continuous measure. The first is more appropriate where markers are widely spaced, the second requires close spaced markers. Both are ineffective at low or zero speeds.

C.4 Acceleration and jerk

A signal proportional to acceleration is generated using the relationship force = mass x acceleration. The component of lateral
acceleration can be removed by constraining the instrument to respond only to accelerations in a vertical plane aligned along the vehicle axis. On slopes it is very difficult to dissociate the vertical gravitational component. Usually this is not necessary for passenger comfort as perceived accelerations are the measured values. Jerk (rate of change of acceleration) is not commonly measured.

1.C.5 Time

To ensure synchronism throughout a system, all users must have access to the same time standard. Either local clocks have to be periodically updated from a master clock or continuous, system-wide transmission of time is required.
1.4. Modulation

In this section are outlined the more common techniques of telecommunications and their important features compared. The section is not a comprehensive resume; it is included for the benefit of readers with no specific knowledge of communication principles and should be omitted by others. (Refs. 28, 31, 118)

1.4.1 The need for modulation

Signals

The signal emanating from a source can be either continuous (and therefore analogue) or discrete (and usually digital). Continuous signals vary continuously over time. Discrete signals are discontinuous over time.

Digital signals occur where the information transmitted is defined by a sequence of signal levels, each drawn from a limited set of possible levels. The digital signals most commonly used are binary and have two levels corresponding to 0 and 1.

Using sampling, a continuous analogue signal can be represented to any degree of accuracy by a discrete signal. The Nyquist sampling theorem governs this replacement. It specifies the minimum sampling frequency necessary to allow a subsequent reconstruction of the original signal.

The minimum sampling rate (Nyquist rate) fn = 2 x analogue signal bandwidth

The communication link

A block diagram of a typical communication link is thus:-
The information to be transmitted is contained in the signal output from a measurement transducer or other information generator.

The sending equipment converts this source signal (the baseband signal) into a form appropriate to the communication channel.

The channel is the communication link established between two distant points via a physical path e.g. free space, line or waveguide.

The receiving equipment reforms the channel signal into the original baseband signal for use by the sink. An ideal communication medium would deliver to the sink an identical replica of the signal put out by the source.

For communication purposes, the information attached to (or meaning of) the signal transmitted is unimportant. It is the frequency, amplitude and phase that are the important signal characteristics.

The message is the information to be transferred. The signal is the message modified for transmission.

Modulation

Usually the source signal is unsuitable for direct transmission and modulation is required. This technique

(a) enables the source signal frequencies to be matched to the frequencies appropriate to the transmission medium

(b) enhances the resistance of the transmission to noise and disturbances

(c) permits the use of multiplexing

1.D.2 Types of modulation

Modulation is achieved by having the source signal vary some physical characteristic of a carrier wave. This carrier may be a continuous sinewave or a train of identical pulses occurring at a constant rate.

The use of a sinusoidal carrier wave gives rise to two basic forms of modulation.

Amplitude modulation - where the source signal varies the amplitude of the carrier.

Angle modulation - where the source signal varies the phase of the carrier.
Angle modulation is further subdivided into phase modulation — where the phase varies in proportion to the signal and frequency modulation — where the phase varies as an integral function.

![Modulating waveform]

Frequency modulated carrier

Amplitude modulated carrier

The use of pulse waveforms gives rise to a wide range of possibilities of which pulse amplitude, frequency and position are the more common.

The combination of pulse waveforms and coding techniques yields pulse code modulation.

Amplitude modulation translates the frequency spectrum of the baseband signal up by the carrier frequency.

Baseband frequency spectrum

Amplitude modulated frequency spectrum
The modulated signal contains two sorts of information.

The first is the time varying source signal contained in the two sidebands. Either of the upper and lower sidebands contains all the information of the original modulating signal.

The second, the synchronization or carrier content of the signal, tells the receiver what carrier has been employed, information that is necessary if the receiver is to be able to demodulate the signal.

Three forms of transmission are commonly used.

**Double sideband** — in which the complete signal spectrum is transmitted. A minimum of equipment is required. However the carrier signal carries \( \frac{2}{3} \) of the total signal power and only \( \frac{1}{3} \) is affected by the modulating signal.

**Suppressed carrier** — transmissions have the carrier frequencies removed. All the signal power is contained in the side bands so enhancing the signal to noise ratio. The carrier component of the signal must be generated locally at the receiver and recombined with the received signal for demodulation. Consequently the equipment becomes more complex and costly.

**Single sideband** — only one of the sidebands is transmitted so reducing the bandwidth required to half that for double sideband. Single sideband is complicated to generate and decode.

**Angle modulation** — the power transmitted by an angle modulated signal is unaffected by the modulation. In principle, angle modulated signals have an infinite frequency spectrum. In practice, the signal is transmitted in a finite bandwidth. The narrower the bandwidth used the greater the distortion introduced and the poorer is the noise rejection.

**Pulse code modulation** — is the most important class of pulse modulation schemes. Binary signals are usually employed and the receiver must decide at particular time instants whether a pulse is present or absent. This decision can be reliably made even in the presence of heavy noise, so allowing the effective usable bandwidth of a channel to be much extended.

1.D.3 Properties of modulation

The choice of modulation technique for a particular application depends on a number of factors. Some of these are
(a) The bandwidth and noise resistance required
(b) The bandwidth, interference and distortion characteristics of the channel
(c) The need for multiplexing
(d) The a priori existence of analogue or digital signals in the system
(e) The allowable cost

Double sideband modulation requires the least equipment. The use of suppressed carrier techniques enhances the signal to noise ratio at the cost of greater complexity. Single sideband transmissions save the bandwidth required to transmit a signal but at the expense of reduced noise immunity and extra cost.

Channels subject to fading (i.e. time varying attenuation) severely distort A.M. signals. Provided adequate bandwidth is available frequency modulation can perform better. The use of wider bandwidths with frequency modulation improves noise rejection and distortion.

Pulse code modulated signals require more bandwidth, but are effective in poor quality channels. Bandwidth and signal to noise ratio can be traded for error rates. Further improvements in the reliability of data transmissions are achieved by introducing redundancy into the coding. This redundancy enables transmission errors to be detected and with more complex codes allows corrections to be made. Many different coding techniques exist each offering different trade-offs between noise rejection and bandwidth.

Multiplexing

It is often useful to arrange a number of channels to simultaneously use a single communication link by the use of multiplexing. There are two methods:

- Frequency multiplexing - where each channel is allocated a frequency band stacked in the frequency spectrum.
- Time division multiplexing - where synchronised switches at each end of a communication facility enable samples to be transmitted in turn from each channel to the receiving end.

Basic analogue systems are cheaper than the digital equivalent. However, where more elaborate signal processing is required costs tend to favour digital systems, particularly as digital techniques have been much improved.
(a) The bandwidth and noise resistance required
(b) The bandwidth, interference and distortion characteristics of the channel
(c) The need for multiplexing
(d) The a priori existence of analogue or digital signals in the system
(e) The allowable cost

Double sideband modulation requires the least equipment. The use of suppressed carrier techniques enhances the signal to noise ratio at the cost of greater complexity. Single sideband transmissions minimise the bandwidth required to transmit a signal but at the expense of reduced noise immunity and extra cost.

Channels subject to fading (i.e. time varying attenuation) severely distort A.M. signals. Provided adequate bandwidth is available frequency modulation can perform better. The use of wider bandwidths with frequency modulation improves noise rejection and distortion.

Pulse code modulated signals require more bandwidth, but are effective in poor quality channels. Bandwidth and signal to noise ratio can be traded for error rates. Further improvements in the reliability of data transmissions are achieved by introducing redundancy into the coding. This redundancy enables transmission errors to be detected and with more complex codes allows corrections to be made. Many different coding techniques exist each offering different trade-offs between noise rejection and bandwidth.

Multiplexing

It is often useful to arrange a number of channels to simultaneously share a single communication link by the use of multiplexing. There are two methods:

Frequency multiplexing — where each channel is allocated a frequency band stacked in the frequency spectrum.

Time division multiplexing — where synchronised switches at each end of a communication facility enable samples to be transmitted in turn from each channel to the receiving end.

Basic analogue systems are cheaper than the digital equivalent. Where more elaborate signal processing is required costs tend to favour digital systems, particularly as digital techniques have been much improved.
been much developed in recent years and costs are falling rapidly.

Every conversion from analogue to digital and digital to ana­
logue introduces distortion. This factor weights the choice between
digital or analogue in favour of those that already exist in the
system.
Part 2: Techniques

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2.A. Introduction

This section describes measurement and communication techniques that have applications in automated transport systems.

Rather than present detailed specifications of existing equipment, which rapidly become out of date, descriptions emphasise the general features of particular schemes. The classification chosen, groups devices according to these general features. It is intended not only to detail existing equipment but also to illuminate novel combinations which usefully blend particular attributes.

2.A.1 Classification headings

Position Measurement

Point - a vehicle detects or is detected at a point on the track (referred to as a track marker or vehicle detector respectively).

Area - a vehicle detects or is detected within a length of track.

Continuous - A vehicle can locate itself, or is located continuously over a length of track.

Relative - The separation between two vehicles is measured

Velocity measurement

Absolute - vehicle is measured either continuously or at a point on the track.

Relative - The relative velocity of two vehicles is measured.

Acceleration measurement

Absolute - Vehicle accelerations are measured either at a point or continuously.

Within each of these groups measurements may be either

Track based - where the active equipment and the measurement output is at the track side.

Vehicle based - where the active equipment and measurement output is on-board the vehicle.

This subdivision is not rigid. Many measurement devices can be arranged to give a track-based or vehicle-based measurement, either by exchanging the roles of the vehicle and the track or by the addition of extra equipment.
The use of communication links further blurs the distinction between track-based and vehicle-based techniques. Measurement devices can be simply modelled thus:

```
transducer  processor  user
raw signal  more refined signal
```

The three elements, transducer, processor and user, are often sited in one location. This is not necessary and makes the distinction between track based and vehicle based schemes difficult to define unequivocally.

**Point communications**

A message is transferred at a particular point on the track.

**Area communications**

A message can be transferred anywhere along a section of track. Within these groups messages may have either a fixed or variable information content and be transmitted either from the track to the vehicle, the vehicle to the track, or both.

2.4.2 Indexed table of techniques

The index table lists all the devices described in this report. Their main applications are summarised in an abbreviated form using the code:

- **w** - widely used in this application
- **e** - examples exist of this application
- **f** - feasible to use in this application
- **u** - unlikely for use in this application

The table indicates the applications of a device but does not imply that they can all be achieved simultaneously. More detailed device descriptions follow the table and are indexed using the reference number in the table. A technique having several applications is described completely under one heading. The entry is then cross-referenced in the other appropriate sections.
Abbreviations used

T/B - track based
V/B - vehicle based
V/T - vehicle to track
T/V - track to vehicle
F/M - fixed message
V/M - variable message
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<td>Tibolectric sensor</td>
<td>e</td>
<td></td>
<td>3</td>
<td>vehicle detectors only</td>
</tr>
<tr>
<td>Coaxial sensor</td>
<td>e</td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Treadle</td>
<td>w</td>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Contacting</td>
<td>e e e e e e</td>
<td></td>
<td>6</td>
<td>track marker or vehicle detector can be used for communications</td>
</tr>
<tr>
<td>Mechanical</td>
<td>w e f f f f</td>
<td></td>
<td>7</td>
<td></td>
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<td>Strain gauged bar</td>
<td>f</td>
<td></td>
<td>8</td>
<td></td>
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<tr>
<td>Seismic</td>
<td>f</td>
<td></td>
<td>9</td>
<td>i) vehicle detector only</td>
</tr>
<tr>
<td>Capacitance</td>
<td>e</td>
<td></td>
<td>10</td>
<td>ii) the M.O.V.D. has possible applications as a speed sensor</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>e</td>
<td></td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Magnetic gradient vehicle detector (M.G.V.D.)</td>
<td>e</td>
<td></td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>
| Magnetic                                  | w e e e e e |               | 13   | i) track marker or vehicle detector. All forms of fixed point communi-
| Transverse or reflected beamed energy (radio, light, sound and radiation) | w e e e e e |               | 14   | ii) Radiation energy is safety hazard                                    |

All devices rely on mechanical contact and are subject to wear and reliability problems.
<table>
<thead>
<tr>
<th>Area</th>
<th>Technique</th>
<th>F/B</th>
<th>V/B</th>
<th>T/T</th>
<th>T/V</th>
<th>F/M</th>
<th>V/M</th>
<th>Comments</th>
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<td>Inductive loop</td>
<td></td>
<td>w</td>
<td>w</td>
<td>w</td>
<td>w</td>
<td>w</td>
<td>15</td>
<td>- very versatile and widely used</td>
</tr>
<tr>
<td>Track circuit</td>
<td></td>
<td>w</td>
<td>w</td>
<td>w</td>
<td>w</td>
<td>w</td>
<td>16</td>
<td>- widely used in railways for vehicle detection and short message transfers to vehicle</td>
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<td>Check-in, check-out</td>
<td></td>
<td>w</td>
<td>w</td>
<td></td>
<td></td>
<td></td>
<td>17</td>
<td>- uses any form of vehicle detector</td>
</tr>
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<td>Continuous position</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free space techniques</td>
<td>(Propagation time, signal strength, direction finding radar)</td>
<td>w</td>
<td>w</td>
<td>e</td>
<td>e</td>
<td>e</td>
<td>e</td>
<td>18</td>
</tr>
<tr>
<td>Guided radio techniques</td>
<td>(Propagation time, signal strength)</td>
<td>e</td>
<td>e</td>
<td>e</td>
<td>e</td>
<td>e</td>
<td>e</td>
<td>19</td>
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<tr>
<td>Linear synchro</td>
<td></td>
<td>e</td>
<td>f</td>
<td>f</td>
<td>f</td>
<td>f</td>
<td>20</td>
<td>- more commonly encountered as rotary instruments for measuring shaft rotation</td>
</tr>
<tr>
<td>Linear cam</td>
<td></td>
<td>f</td>
<td>f</td>
<td>u</td>
<td>u</td>
<td>u</td>
<td>u</td>
<td>21</td>
</tr>
<tr>
<td>Linear digitiser</td>
<td></td>
<td>f</td>
<td>f</td>
<td>u</td>
<td>u</td>
<td>u</td>
<td>u</td>
<td>22</td>
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<tr>
<td>Integration</td>
<td></td>
<td>f</td>
<td>w</td>
<td></td>
<td></td>
<td></td>
<td>23</td>
<td>-</td>
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<tr>
<td>Wheel revolution count</td>
<td></td>
<td></td>
<td>w</td>
<td></td>
<td></td>
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<td>24</td>
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<td>Incremental measures</td>
<td></td>
<td>w</td>
<td>w</td>
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<td></td>
<td></td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>Dead reckoning</td>
<td></td>
<td>f</td>
<td>w</td>
<td></td>
<td></td>
<td></td>
<td>26</td>
<td>-</td>
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</table>

**Application**

<table>
<thead>
<tr>
<th>Meas.</th>
<th>Communication</th>
</tr>
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<tbody>
<tr>
<td></td>
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</table>

**Continuous position**

<table>
<thead>
<tr>
<th>T/B</th>
<th>V/B</th>
<th>T/T</th>
<th>T/U</th>
<th>F/M</th>
<th>V/M</th>
<th>Ref.</th>
<th>Comments</th>
</tr>
</thead>
</table>

**Value column**

- F/B: Follower/Batcher
- V/B: Vehicle/Batcher
- T/T: Target/Tracker
- T/U: Target/Unrelated
- F/M: Follower/Monitor
- V/M: Vehicle/Monitor
<table>
<thead>
<tr>
<th>Continuous position</th>
<th>Measurement</th>
<th>Communication</th>
<th>Ref.</th>
<th>Comments</th>
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<tr>
<td>Combinational techniques</td>
<td>e</td>
<td>e</td>
<td>27</td>
<td>These combine systems to provide better accuracy</td>
</tr>
<tr>
<td>Relative position techniques</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical probe</td>
<td>u</td>
<td>f</td>
<td>u</td>
<td>u</td>
</tr>
<tr>
<td>Capacitive inductive magnetic probe</td>
<td>u</td>
<td>f</td>
<td>u</td>
<td>u</td>
</tr>
<tr>
<td>Fixed block methods</td>
<td>u</td>
<td>w</td>
<td>w</td>
<td>w</td>
</tr>
<tr>
<td>Poupe's coded track (oct)</td>
<td>u</td>
<td>f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Differentiating</td>
<td>f</td>
<td>f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free space systems</td>
<td>u</td>
<td>e</td>
<td>f</td>
<td>f</td>
</tr>
<tr>
<td>Guided radio systems</td>
<td>u</td>
<td>e</td>
<td>f</td>
<td>f</td>
</tr>
<tr>
<td>Velocity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency rate</td>
<td>e</td>
<td>e</td>
<td>35</td>
<td>Requires track markers. Both give an estimate of speed which lags the actual speed</td>
</tr>
<tr>
<td>Time interval</td>
<td>e</td>
<td>e</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Correlation</td>
<td>e</td>
<td>e</td>
<td>37</td>
<td>Widely used in industrial applications</td>
</tr>
<tr>
<td>Velocity</td>
<td>( \frac{V}{B} )</td>
<td>( \frac{V}{B} )</td>
<td>f</td>
<td>f</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------------</td>
<td>---------------------</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>'Flicker Rate'</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Inductive</td>
<td>e</td>
<td>e</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doppler</td>
<td>e</td>
<td>e</td>
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</tr>
<tr>
<td>M.O.V.D.</td>
<td>f</td>
<td>u</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integration</td>
<td>e</td>
<td>e</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Differentiation</td>
<td>f</td>
<td>f</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Relative velocity</th>
<th>( \frac{V}{B} )</th>
<th>( \frac{V}{B} )</th>
<th>f</th>
<th>f</th>
<th>f</th>
<th>f</th>
<th>f</th>
<th>f</th>
<th>44</th>
<th>Doppler</th>
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<tr>
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<td>Difference</td>
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<td>Differentiation</td>
</tr>
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<td></td>
<td></td>
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<td></td>
<td>Free space</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Guided radio</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Acceleration</th>
<th>( \frac{V}{B} )</th>
<th>( \frac{V}{B} )</th>
<th>f</th>
<th>e</th>
<th>50</th>
<th>Acceleration is difficult to measure accurately</th>
</tr>
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<tbody>
<tr>
<td>Accelerometers</td>
<td>w</td>
<td></td>
<td></td>
<td></td>
<td>49</td>
<td>Acceleration is difficult to measure accurately</td>
</tr>
<tr>
<td>Differentiation</td>
<td>f</td>
<td>e</td>
<td></td>
<td></td>
<td>50</td>
<td>Acceleration is difficult to measure accurately</td>
</tr>
</tbody>
</table>
2.B. Measurement Techniques

2.B.1 Point position techniques

Contacting vehicle detectors

All contacting systems are subject to mechanical wear. They have short lives and require frequent maintenance and replacement. All are inexpensive in equipment but are expensive to install and maintain. All are unaffected by climatic conditions. Only mechanical levers (no. 7) give direction of travel information. Only mechanical lever and contacting circuits (nos. 6, 7) can be used as track markers or for communications. (Refs. 39, 55, 63, 68, 88, 89, 98, 126)

1) Pneumatic Tube

Wheel pressure of a passing vehicle on a soft walled tube, sends a pressure impulse to a pressure sensitive switch at one end. Pneumatic tube vehicle detectors have been extensively used for vehicle actuated traffic lights. They are now being superseded by inductive loop (see no. 15) and magnetometer devices (see nos. 11, 12)

- Stopped or slow moving vehicles are not detected.
- Fast or heavy vehicles and vehicles not perpendicular to the tube may generate spurious pulses.
- The number of axles passing are counted.
- Size is typically 2m x 15cm x 15cm.
2) **Hydraulic tube**

Wheel pressure of a passing vehicle on a liquid-filled soft walled tube displaces fluid (white spirit). This moves a float which is detected, usually optically.
- Slow or stationary vehicles stopped on the device are detected.
- Otherwise similar to pneumatic tube (no. 1)

![Diagram of hydraulic tube](image)

3) **Triboelectric sensor**

The vibrations of a passing wheel cause the triboelectric element to develop a potential difference. The element is a flexible conductor covered with a dielectric. Shaking this produces a charge separation and hence a potential difference.
- As the device has a very high impedance, impedance matching and amplification are required to extract the signal.
- Was devised as an improvement on the pneumatic detector (no. 1)
- It has similar characteristics to the pneumatic detector (no. 1) but is less vulnerable to damage.

4) **Coaxial cable sensor**

Wheel pressure is transmitted to a coaxial cable. This produces a voltage across the device proportional to the pressure and length of squashed zone.
- Slow moving and vehicles stopped on the device are detected.
- Has similar properties to the triboelectric sensor (no. 3)
5) **Treadle**

Wheel pressure on normally separated contacting strips, usually carried in a flexible tube, closes an electrical contact.

- Slow vehicles or stopped vehicles on the device are detected.
- Other characteristics are similar to the pneumatic detector.
6) Contacting circuits
A conducting vehicle probe completes an electrical circuit with a track mounted contact. Contacting circuits differ from track circuits (no. 16) in that the current path of the signal through the vehicle is clearly defined (i.e. through the probe). The current path through a vehicle on a track circuit is not so defined (being through the wheels and chassis of the vehicle).
- Contacting track circuits can be used for communications (see no. 56)
- Detects stationary vehicles
- Can be used as a track marker

7) Mechanical lever
The passage of a vehicle operates a lever mechanism.
- Can be used either as a vehicle detector or track marker
- Yields direction of travel information
- Detects slow or stopped vehicles adjacent to the device
- Variable height levers can be used to transmit simple messages
(see fixed point communications no. 51-54)

Non-contacting vehicle detectors
Non-contacting vehicle detectors are buried in the roadway and are consequently less prone to wear and damage. None give direction of travel information, none can be used for communications, none can be used as track markers. Apart from the capacitance probe (no. 10) none are affected by the weather. (Ref. 130)
8) **Strain-gauged bar**
   A beam beneath the road is deflected by the vehicle. The resultant change in strain can be measured and used to give an output.
   - Stationary or moving, wheeled or wheelless vehicles are detected
   - Sufficiently heavy obstacles are detected on the track
   - With calibration it may be possible to approximately weigh vehicles.

![Strain-gauged bar diagram](image)

9) **Seismic detector**
   Using geophones or accelerometers, the ground vibrations generated by moving vehicles are detected and used to indicate a vehicle passing.
   - Only wheeled vehicles are detected
   - The system has been demonstrated as feasible. However the unpredictability of seismic propagation has impeded development. (Ref. 115)

10) **Capacitance probe**
    A vehicle passing over a metal plate in the track causes a change in capacitance. This is detected using similar techniques to inductive loop detectors (no. 15)
    - The device can be arranged to provide short range relative position measurements (see no. 29)
    - Rain and snow reduce the effectiveness of capacitance schemes.
    (Ref. 64).
11) **Magnetometer**

Vehicles containing ferrous materials locally increase the earth's magnetic field. A track mounted detector indicates the disturbance. This detector comprises three windings on a magnetic core. The primary winding is excited with an A.C. signal that saturates the core twice a cycle. By magnetometer action an A.C. voltage is developed in the secondary coil, whose amplitude is proportional to the component of the earth's magnetic field parallel to the probe axis. A further coil supplied with a D.C. current adjusts the probe to its local magnetic environment.

- Detector is small (typically 6cm long by 2cm diameter).
- Vehicles are detected in a circular zone approximately 1.5m dia.
- Immune to radio frequencies but not to interference from nearby power supplies.
- Sensitive detection, an average road vehicle causes a 20% signal change. However correct operation depends critically on the initial adjustment.

12) **Magnetic gradient vehicle detector (MOVD)**

As the vehicle approaches the transducer eddy currents are induced in the vehicle metal work by a transmitter coil. The resulting magnetic fields couple into two receiver coils, connected in phase opposition, causing a corresponding change in the phase and voltage of the output signal.

- M.G.V.D. offers better lateral resolution than the inductive loop (no. 15) and gives much larger signal changes.
- The device can be used to measure speed as the detector output varies approximately linearly with the distance of the vehicle front from the detector.
- Device is typically 12mm x 35mm x 2m and is less expensive to install than an inductive loop.
Non-contacting point position methods

Such schemes can be operated as vehicle detectors, track markers and communication links.

13) Magnetic

There are two arrangements

(a) Magnetic vehicle detector

The equipment consists of a single winding of a large number of turns of wire on a core. A remnant magnetic field is carried by a vehicle as a result of its prior movements in the earth's magnetic field. This induces a voltage in the detector coil.

- Detector signal varies according to the size and speed of the vehicle. Slow and stopped vehicles are not detected.
- The probe is typically 45 cm long by 6 cm diameter giving a 1.2 m diameter detection zone.

(b) Magnetic vehicle detector/track marker/communication link

Vehicle mounted magnets are detected at the track using magnetically biased relays which change state when the local field reaches a threshold. Alternatively a detector coil as described in (a) above may be used.

Communication link

Simple messages can be transferred using magnets whose polarities are arranged to represent binary information. Variable messages can be transferred using electromagnets.

An alternative method of transferring a fixed message uses a notched steel bar. The spacing of the notches encodes the message.
Before reading a coil magnetizes the bar leaving a remnant field that is non-uniform at the notches.

--- Static magnetic fields cannot be precisely resolved. For reliable resolution between adjacent magnets there should be approximately the same distance between them, as between the magnets and the detector. This restricts the amount of information that can be transmitted, as complex messages become either physically large or the track vehicle clearance unacceptably small.

- Modern permanent magnets are unaffected by vibration, high temperatures, climatic conditions and A.C. fields. Only ferromagnetic dirt (e.g., dust from cast iron brake shoes) affects their performance.

- Vehicle detection using permanent magnets is sometimes used for last vehicle proving and vehicle detection on railways, as the method is very reliable. (Ref. 117)

14) Beamed Radiation
A narrow beam of energy transmitted from the trackside can be used to detect vehicles, measure their speed, and transfer information.
Infra-red or visible light, microwave radio and ultrasonics have all been used. $\alpha$-particles and $\beta$-rays have also been proposed.

The performance of light systems is reduced by high ambient light levels, rain, snow, fog and grime. Infra-red is less vulnerable to such factors.

Ultrasound systems are affected by strong winds which deflect the beam and heavy rain which attenuates it.

Microwave radio systems are unaffected by environmental factors but are more expensive.

$\alpha$-particles and $\beta$-rays are unaffected by the environment but in the intensities that are necessary would be a health hazard. (Refs. 22, 81, 105)

(a) Transverse methods

A beam of energy is transmitted across the track to a detector mounted opposite. As the beam is focussed onto the receiver, good signal to noise ratios are achieved, giving reliable operation in adverse conditions.

1) Vehicle detector - passing vehicles intercept the beam
2) Position marker - vehicle mounted receiver intercepts the beam and identifies the position.
3) Communications - a mask, placed in the path of the beam can be used to transfer a fixed message from the vehicle to the trackside. This is only feasible with optical or radiation beams (see also point communications - section 2.C.1.)
- Transverse schemes, mounted horizontally, require two accurately aligned trackside mountings, vertical mounting requires a gantry. These considerations increase the installation costs of transverse schemes.

- Transverse schemes are very simple and have well defined detection zones.

15) Reflected Methods

Energy transmitted from the track side is reflected by the vehicle. A receiver mounted next to the transmitter detects the reflected energy. The signal to noise ratio is generally poor and sophisticated techniques must be adopted to give reliable operation in adverse conditions. There are three possible schemes.

1) A carrier signal is transmitted continuously. The receipt of the echoed signal indicates vehicle presence. There is no discrimination between echoes resulting from the vehicle and those from nearby structures or between the transmitted signal and others at the same frequencies.

Discrimination can be achieved in several ways.

Vehicles can be equipped with specially coded reflectors which uniquely modify the characteristics of the returned energy. This allows the echoes resulting from a vehicle to be distinguished from others (see fixed point communications - section 2.C.1).

Also the carrier can be modulated and the receiver designed to respond only to the modulation. This technique is commonly adopted with optical systems. The beam of light is modulated using a mechanical shutter. The receiver responds only to the shutter frequency.

Better performance is achieved by increasing the signal to noise ratio at the receiver. A reflector is required capable of returning a large proportion of the incident energy from the transmitter, back to the receiver. This is possible for optical and microwave radio, by using retro-reflective reflectors (i.e. Incident energy is reflected back on its incoming path, e.g. a mirror is retro-reflective only to normal light, whereas our reflectors are retro-reflective to all light arriving within a certain conical acceptance angle.
2) The time delay between a transmitted signal and the received signal is measured (see also free space techniques of continuous position location - section 2.B.3 no. 18)

Only echoes corresponding to ranges in a certain band are accepted, thus discriminating between vehicle echoes and others.

In principle the time delay method can be used with optical, sonic and radio transmissions. However at the short ranges generally required for vehicle detection only sonic systems give measurable time delays. This results from the slow speed of sound propagation in air, (approx. 335 m/sec).

3) Doppler method - A continuous carrier wave is transmitted. Signals reflected back from moving objects are frequency shifted (i.e. the doppler shift) by an amount proportional to the vehicle speed, according to the relationship

\[ \Delta f = \frac{V_r}{C} f_0 \]

- \( f_0 \) = transmitted frequency
- \( V_r \) = vehicle velocity resolved along the direction of propagation of the signal
- \( C \) = speed of propagation of the signal
- \( \Delta f \) = frequency change
- \( V \) = vehicle speed
If the transmitter is mounted so that the transmissions are nearly perpendicular to the vehicle movement then the resultant doppler shift will be small as the vehicle passes in range of the transmitter, regardless of vehicle speed.

**Doppler used for speed measurement**

A beam directed longitudinally down the track such that $\Theta \rightarrow 0$ allows vehicle speed to be deduced from the doppler shift.

A transmitter installed on the vehicle can be used for on-board vehicle speed measurements. The beam is directed at the track and measurements are made on the back scattered energy.

---

**Communications**

See fixed point communications section 2.C.1.

**Characteristics of reflected energy methods**

- As only one mounting is required and alignment is less critical than for transverse methods, installation costs are lower.
- Light beam systems are inexpensive and have well defined zones of action.
- Ultrasonic and microwave systems are more expensive. Their zones of action are less well defined and closely spaced equipment can interfere. (Typically an ultrasonic beam subtends an ellipse $30^\circ \times 18^\circ$ and a microwave beam $20^\circ \times 60^\circ$).

- Doppler systems do not register on vehicles moving slower than 1 m/s but are accurate and give direction of travel information.

2.B.2 Area (block) vehicle detection

15) Inductive loops

The inductive loop comprises one or several kinds of wire, often rectangular, laid on or under the track surface. It is connected to trackside equipment and energised with a signal of between 10 khz and 150 khz for vehicle detectors, and up to mega hz for communication links.

1) Vehicle detector

Vehicle proximity causes a net decrease in the loop inductance. Several methods are used to detect this change.

(a) Self-tuning method — A circuit is used to track the resonant frequency of the loop. Only changes faster than a certain rate generate an output indicating a vehicle. Stationary or slow vehicles are not detected.

(b) Other methods — These detect vehicle by monitoring the phase changes or balance in a bridge circuit caused by changes in loop inductance. These schemes require initial setting up and possibly routine adjustments. All vehicles, stationary or moving, are detected.

2) Communications

The mutual inductance between a vehicle mounted coil and the track allows the two-way transmission of modulated A.C. signals (see area communications section 2.C.2 no: 58).

3) Track marker

(a) A vehicle mounted loop antenna receiving transmissions from a small track loop yields a track marker device.

(b) A transposed inductive loop will introduce a $180^\circ$ phase change in the received signal as the antenna crosses the transposition. This can be detected as a track marker.
4) Other devices

(a) If one of the two conductors is laid in a triangular form, an approximately sinusoidal modulated signal is received by the vehicle.

The modulation frequency = speed/L. The arrangement can be used either to provide a speed signal (with fixed L) or to encode track information read by the vehicle (with variable L) (see section 2.C.3 fixed point communications).

(b) A rectangular layout of the track conductors allows binary information to be encoded onto the track.
(c) Careful design of the vehicle antenna and track loop dimensions allows a signal to be coupled from the vehicle to the track so that the received amplitude varies approximately sinusoidally with position.
Characteristics of inductive loops

- Electromagnetic induction fields are unaffected by the environment. They can be produced over a very wide range of frequencies, propagated for controlled distances and used to transfer energy. They are generally limited by the frequency and power restrictions imposed by broadcasting authorities. The range of layouts is unlimited and combined with the use of wide bandwidth communications makes inductive loop equipment very versatile.

- Inductive loops are vulnerable to R.F. interference.

- Adjacent loops can interfere unless their operating frequencies are sufficiently different.

- Buried detectors are free from wear but road surface movements can damage the cable.

- The cable is expensive.

- If surface mounted, cables are vulnerable to damage and place constraints on maintenance.

- Sensitivity - the average road vehicle causes about a 2% change in the loop inductance, but this is proportional to loop area, and makes small loops difficult to design.

- Sensitivity is reduced by the resistance of the lead cables, limiting the maximum range to about 300m. (Refs. 17, 19, 49, 50, 59, 121, 122, 132).

16) Track circuit

A signal fed into one end of an isolated section of steel rail track is detected at the other end, often by using the signal to hold on a relay. A passing vehicle shunts the signal so preventing it reaching the other end. This releases the detector relay. The simplest track circuits are D.C. with insulated breaks in the signal rails to isolate each circuit.

With continuous welded rails audio frequency A.C. signals are used. Isolation of track segments is achieved using impedance bonds across the two rails which do not allow traction currents to pass but offer a low impedance to track circuit frequencies.
The reliability of track circuits depends upon the effectiveness with which the train shunts the track circuit signal. In some cases, e.g. with lightweight vehicles, or infrequently used tracks, vehicles do not provide a reliable low resistance shunt. This problem can sometimes be overcome by using higher track circuit voltages of up to 100 V. To reduce their safety hazard pulsed signals may be used.

Communications

Pulse modulation of audio-frequency track circuits allows messages to be transmitted to vehicles at very limited data rates. Usually detection is by inductive coils mounted above the signal rails. Equivalent communication from the vehicle to track is not possible as the transmission characteristics of railway lines are unsuitable. (Refs. 36, 40, 58, 71, 74, 76, 110, 193).

Characteristics of track circuits

- Operating frequencies are generally less than 1 kHz, typically 60-120 Hz.
- Circuits may be several kilometers long.
- The electrical characteristics of track circuits vary considerably with the environment. Careful design is necessary to ensure that a vehicle shunt can be distinguished from wet rails.
- Wheel-less or pneumatic tyred vehicles can use their power rails as track circuits.
- Audio frequency track circuits are vulnerable to interference from traction equipment, particularly if thyristor control is involved.
- Derailed vehicles are not detected.

17) 'Check-in' - 'check-out'
At the beginning and end of each track section is placed a vehicle detector. Any form of detector can be used. (See section 2.B.1 point position techniques).

A vehicle travelling in the correct direction will actuate the first detector which sets the block as occupied.

The second detector resets the block as empty when the vehicle passes it. Further logical checks can be incorporated, which hand a vehicle on from one block to the next, so increasing the reliability of the system.

Check-in check-out schemes are often used where track circuits are unreliable, or cannot be used.

2.B.3. Continuous position methods

18) Free space techniques

There are three principal location systems based on measurements of

1) Propagation time
2) Signal strength
3) Signal direction

In each the measurements made allow position loci to be plotted on which the vehicle must lie. The intersection of several loci, created from independent measurements, enables the unknown vehicle position to be identified.

Most existing location systems use radio transmissions; however in principle optical and ultrasonic transmissions can also be used. (Refs. 27, 29, 53, 54, 73, 87, 104, 120, 123, 138)

1) Propagation time

Electromagnetic and sonic signals propagate at a constant speed in straight lines. Thus, from a measure of the time a signal takes to travel from the transmitter to the receiver, the shortest path distance from one to the other can be calculated. Two approaches are used to generate the position loci.

(a) Time of arrival (TOA) - The actual propagation time of the signal from a transmitter to receiver is measured. Two methods are used.

1) A signal from a fixed transmitter is received by the vehicle and rebroadcast back to the transmitter after a set delay. The delay allows the vehicle return signal to be distinguished from spurious reflections, as the delay is a fixed function of the receiver.
reflections. In environments where these spurious reflections are negligible the signal reflected from the vehicle structure can be used as the vehicle return signal. No active vehicle participation is required but range is limited, (see reflected beamed signals no. 14, and fixed point communications section 2.0.1).

(2) Both the vehicle and the fixed transmitter station are equipped with synchronised clocks. The transmission delay measurements are made at the receiver.

The time delay is proportional to the distance separating the vehicle and the fixed station. One measurement establishes the vehicle as lying on a circle centred on the fixed station. Three measurements at different stations locate the vehicle

(b) Time difference of arrival TDQA — The vehicle broadcasts a signal. Three fixed stations measure the arrival time of the signal. This is subtracted from the arrival time of the same signal at one of the other stations. The information locates the vehicle as lying on a hyperbolic curve symmetrical about the base line between two stations. TDQA requires the base stations to have synchronised clocks.
Methods used to measure the propagation time of signals

(a) The phase of the received signal is measured relative to a reference signal. This gives ambiguous results – a delay of $t$ could be an actual delay of $t + NT$ where $T$ = period of the signal and $N = 0, 1, 2$.

(b) The arrival time of the leading edge of a pulse is identified. This cannot be accurately established when the signal is distorted and contaminated with noise. The result is unambiguous.

Pulse systems require a much wider bandwidth transmission than phase comparison systems.

Often the better precision of phase comparison is combined with pulse delay measurements to remove the ambiguity. Alternatively the number of ambiguous possibilities can be reduced by making phase measurements at a number of different frequencies. This can yield
very precise results in controlled environments and is the basis of land surveying using tellurometers etc.

2) **Signal Strength**

A number of remote stations measure the signal strength of a standardised vehicle transmission. Using previously plotted signal strength contour lines, the most likely vehicle location is determined.

3) **Direction Finding**

The bearing of transmissions from a vehicle is measured at a number of base stations.

A combination of direction finding and propagation time methods enables one base station to uniquely locate a vehicle. This is commonly called RADAR (radio systems), SONAR (sound systems), LADAR (light systems).

**Characteristics of free space systems**

Free space location techniques are attractive because they offer, at a low cost, the capability of locating any number of vehicles within a specified area. However errors caused by clutter (extraneous reflections from physical features in the area of the vehicle), multipath reflections and variable propagation speeds make all the schemes
extremely inaccurate in urban environments, although using many independent measurements, averaging techniques may improve estimates of vehicle location.

Even if these problems can be overcome the overcrowding of the radio spectrum is likely to limit the application of any free-space radio system. Light systems are ineffective except for line of sight applications and sonic systems are unlikely to have a useful range.

All the schemes described can be arranged so that the location measurements are made either on the vehicle or at the fixed base station. Measurements made on-board the vehicle require the vehicle to identify which fixed station has been ranged. Measurements made at the fixed base require the ranged vehicle to be identified (see fixed point communication section 2.C.1.)

19) Guided radio techniques

In all the preceding free space location systems, radio signals propagated along transmission lines or waveguides (see continuous communications nos. 57, 59) can be substituted for the free space radio link. The controlled and stable characteristics of transmission lines and waveguides removes most of the disadvantages associated with the free space version. Errors occasioned by multipath reflections, variable propagation speeds and poor signal/noise ratios are much reduced. Radio spectrum usage is minimised as the radiation from the waveguide or transmission line is only significant for short distances away from the guide. However only vehicles adjacent to the guide can be located, so limiting applications to fixed route vehicles.

Relative position measurements

A particular feature of guided radio systems is the ability to couple energy into and out of the transmission line or waveguide and to propagate signals in one direction only down the line, without contacting or breaking the line or guide. This allows each of the techniques described above to be arranged to provide measurements of vehicle position from the track or vehicle, and vehicle to vehicle spacing.

The general arrangement of such a scheme is thus
Transmissive —

all energy removed from track guide

energy coupled into track guide

non-contacting couplers signal propagates in one direction along guide

Reflective —

receiver and transmitter

non-contacting passive reflector transmitting and receiving couplers

1) Propagation time

Commonly called guided radar — A pulsed or modulated microwave signal is dispatched down a waveguide. Obstacles adjacent to the waveguide or specially designed vehicle mounted reflectors coupling with the waveguide reflect the signal back to the transmitter. The range is calculated from the delay of the returned signal.

2) Signal strength

A standard signal is coupled into a transmission line with regular attenuation properties. The receiver measures the signal strength and hence calculates the range to the transmitter.

In a variant of this principle a standard voltage is injected into a wire of constant resistance/unit length. Diodes in the wire ensure the one way propagation of the signal. A receiver measures the voltage and hence calculates its range to the transmitter.
With both these schemes, the coupling losses between the vehicle and transmission line must be accurately known.

None of the schemes discussed above can be made fail-safe. An out of range vehicle cannot be distinguished from a vehicle in range but not detected because of a fault. As relative position and speed measurements are usually associated with vital safety control, this is a severe disadvantage.

**Speed measurements using guided radio**

Guided radio techniques can be used to measure the speed of a vehicle. A signal reflected back from a moving vehicle will be doppler shifted according to its speed (see Beamed Radiation no. 14).

If the transmitter is another vehicle then the relative speed of the two vehicles will be measured. (Refs. 51, 72, 102, 109, 113, 124)

20) **Linear synchro**

The vehicle transmits a fixed frequency signal using a rectangular antenna. This couples with two inductive loops laid on the track, each regularly transposed and out of phase with each other (see inductive loops no. 15).

The antenna and track loop dimensions are chosen so that the signal amplitude coupled into the inductive loop varies approximately as a sine function of distance.
The relative phases of the signals received from the track loops can be converted into vehicle position. The measurement produced is ambiguous, a position \( n \) corresponds to \((x \times 2nL) n = 0, 1, 2 \ldots\). This ambiguity is conveniently removed by counting the phase reversals of the received signal when the antenna passes the transpositions in the inductive loops.

As only the relative phase of the two signals is used to calculate position variable coupling losses between the vehicle and the track do not affect accuracy. However, significant errors are introduced if there are long transmission distances from vehicle to the receiver. These errors result from the unavoidable parameter differences of the two inductive loops.

21) Linear Cam

Sited alongside the track is a device whose position from a datum varies as a function of distance. Vehicle mounted follower equipment senses the position of the device and decodes it into vehicle location. This system may have applications for slow speed precision manoeuvring over short distances.

22) Linear Digitiser

A coded strip extends along the track on which the code changes at regular intervals. A reader fitted to the vehicle reads this coded strip enabling its position to be determined.

Continuous code structures can be read anywhere along their length to determine a position. As the code changes only at discrete points, schemes can be devised whereby only these points are marked — the vehicle memorizing each until the next is read. Any technique of fixed point communication (section 2.0.1) can be used to create such a structure, each change point being represented by a signpost holding the code for the next section.
Digitisers are an absolute location system. An error at one point can be corrected at the next, and consequently systematic position errors do not build up.

23) Integration

Integration of speed measurement yields a continuous position measure. Accuracy is limited by the precision and drift characteristics of the integrator. Errors tend to increase as a function of time and periodic resetting is required with supplementary position measurement devices.

24) Wheel revolution counter

Continuous position measurement on wheeled vehicles is made very conveniently by measuring wheel revolution. This is equivalent to mechanical integration. Systematic errors are caused by variable vehicle loading and tyre wear which alter the effective radius of the wheel (these effects are particularly important with pneumatic tyres). Wear can be periodically compensated for but variable loading cannot and causes errors up to $\theta$.

25) Incremental measures

Track markers are detected by the vehicle (see fixed point communications 2.C.1). These markers may be regularly spaced in which case a count is proportional to distance. Alternatively markers can be irregularly spaced. A table is required holding the distances between markers.

The table may be held by the vehicle or the track (see stored maps no. 27) or can be written onto the track as a message read by the vehicle at each marker (see fixed point communications 2.C.1) indicating distance to the next marker.

Characteristic of both systems is the possibility of missed or spurious markers resulting in errors which cannot be corrected.
26) **Dead reckoning**

Variable route vehicles can be located using dead reckoning. Measurement of distance travelled (see nos. 18-25) and direction of motion are made. From these the vehicle position relative to a known starting point can be calculated. The method is subject to large systematic errors.

Several schemes can be used to supply the direction of travel information.

(a) - Magnetic compass — cheap, moderately accurate  
(b) - Gyro compass - expensive, poor long term accuracy  
(c) - Differential wheel rotation - simple, very inaccurate  

(Ref. 11)

27) **Combinations of techniques yielding better precision**

Two main criteria influence the choice of position measurement schemes for a transport network.

(a) The zone over which a vehicle location must be uniquely identified  
(b) The accuracy to which the vehicle must be located

All continuous location methods will uniquely locate a vehicle to a given accuracy over a limited range. Measurement schemes offering adequate accuracy usually do not have sufficient range to cover the entire length of a transport route. This coverage can be supplied by regularly repeating the measurement scheme and using a supplementary measurement scheme to resolve ambiguity. This second measurement must have sufficient resolution to identify a single period of the finer measurement scheme.

An example of such schemes is the use of dead reckoning and stored maps to control long term errors. This has been proposed for vehicles following variable routes for which continuous location is important — e.g. taxis, delivery vans, buses, and emergency vehicles.

Dead reckoning measurements are often combined with electronic signposts to reset the measurements and is particularly applicable to fixed route vehicles.

Dead reckoning measurements can be reset using a street map stored in a computer. At frequent intervals the vehicle position is compared with the stored map, and constrained to lie on a street. The method can go disastrously wrong if accumulated errors result in the selection of the wrong road when a vehicle turns a corner, although in some cases
computer algorithms may be able to discover and correct the error.

2.B.4. Relative position techniques

28) Mechanical probe

A telescopic probe extends in front of a vehicle and contacts the next vehicle or obstacle. A measure of the probe extension indicates the separation distance.

Maximum range is determined by the length of probe used. This is limited by possible interference with the track structure and other vehicles and rigidity considerations.

29) Capacitance, inductive, magnetic probes

The proximity of another vehicle alters the capacitance measured by a probe on the front of the vehicle. The capacitance varies as a function of vehicle size and separation. Similar schemes can be devised using inductive loops or magnetic field detectors (see nos. 11, 13, 15).

These schemes have a detecting range of the same order as the physical dimensions of the detecting element. This is limited by the size of the vehicle and is thus only suitable for close proximity ranging.

30) Fixed block methods

The track is divided into blocks (sections of track). A vehicle detected in one block causes coded messages to be displayed at each block upstream of the vehicle. A second vehicle following the first reads these messages and interprets them as the distance (in units of block length) separating the two vehicles. Track circuits, inductive loops, and check-in check-out schemes (nos. 15, 16, 17) can be used to delineate the track segments and detect the vehicles. Any track to vehicle communication technique (see section 2.C.1 and 2.C.2) can be used, point communication devices being located at the entrance of the block to which they apply.

The use of area communication techniques allows a better measurement of vehicle separation, as changes in the block message, caused by the movement of the front vehicle, are communicated immediately to the following vehicle.
31) 'Poupes' coded track circuit

Signal generators are connected across the signal rails. Each signal is modulated to give pulses $T/N$ long repeated every $T$ ($T$ is the cycle time, $N$ is the maximum number of blocks to be measured). Each signal generator is one pulse out of phase with its neighbours. Passing vehicles short the signal rails so that the number of pulses received by the vehicle gives the number of blocks separating the vehicles. The system is fail-safe; if a signal generator fails a smaller separation is then indicated. (See also track circuits no. 16). (Ref. 163)
32) **Differencing**

Each vehicle measures its own position and transmits it, either to the vehicle following, or to all vehicles in the vicinity. In the latter case vehicles select the signal from the nearest neighbour.

Differencing is the only method by which a track-based measurement of vehicle spacing can be made. Any continuous position measurement scheme (see section 2.B.3) can be combined with an area communication link (see section 2.C.2) to produce such a scheme.

The same techniques can be applied to produce relative velocity signals.

33) **Free space systems**

All of the free space measurement techniques (see no. 18) can be arranged to provide vehicle to vehicle ranging. However several particular disadvantages make such schemes very unattractive except in specialised environments.

(a) Reflections from nearby trackside obstacles confuse measurements. The use of coded reflectors (see point communications, section 2.C.1) and narrow beam widths improve the situation.

(b) Usually it is track distance separating vehicles which is of interest. On bends, line of sight instruments measure the chord of the curve. This is the wrong quantity and corrections must be made.

Either of these techniques can be extended to the situation at the beginning of section 2.B.3.

34) **Summary**

2.B.3

35) **Conclusions**

All the above techniques have been described in this chapter. If the measurements are to be used to determine vehicle to vehicle spacing then the appropriate return measurement range must be calculated by section 2.B.2.

36) **Appendix**

The following gives a summary of the main points of this chapter.

37) **References**

The above techniques have been given in section 2.B.3.
(c) The ranging beam must illuminate the appropriate vehicle. Either the beam must be sufficiently wide for satisfactory operations on bends yet satisfy the constraints of (a) or the transmitter must be equipped with a homing device to actively direct the ranging beam at the leading vehicle.

(d) None of the schemes can be fail-safe, an important consideration as the correct operation of ranging equipment is vital for safety. (Refs. 65)

34) Guided radio systems
  See section 2.B.1, no. 19.

2.B.5 Velocity Measurement

35) Frequency rate
  Regularly spaced track markers (see section 2.B.1, point position techniques) can be used to provide a vehicle based speed measurement. If the vehicle speed is sufficiently high and the markers closely spaced, the frequency that markers are passed yields a continuous measure of speed. The measurement will lag the actual vehicle speed and will not follow correctly speed changes faster than that determined by the Nyquist theorem.

36) Time interval
  For low vehicle speeds or wide marker spacings frequency methods cannot be used. Instead the time elapsed as the vehicle moves from one marker to the next is measured. This inverted yields the average speed of the vehicle between the last two markers.

37) Correlation
  Two sensors mounted on the vehicle detect signals transmitted from the vehicle and scattered back by the track. The irregularity of the track surface modulates the reflected signal with a fixed spatial pattern or signature. The two received signals are cross-correlated to give the time delay as a track point moves past one sensor to the next. From the delay and the known separation of the two sensors the speed is calculated.
38) 'Flicker' rate

The image of a passing vehicle is directed onto a slotted plate.
(a) Behind the slots are photocells detecting the variations in light level as the image moves past. The light signature of the image falling on each photocell in turn is time shifted by an amount proportional to speed. The delay can be measured using correlation techniques and hence the vehicle speed calculated.

(b) The total light transmitted is detected by a photo detector. The light from each area element of the moving image is modulated at a fundamental frequency

\[ f_0 = \frac{\text{velocity} \times \text{magnification factor}}{\text{line spacing}} \]

Due to the randomness of the surface the resulting signal is not a pure sine wave but has a power density spectrum spread around \( f_0 \). The frequency has to be extracted by a tracking filter following the spectral peak.

In both situations the use of coherent (laser) light improves the signal to noise ratio. (Refs. 21, 46, 125)

39) Inductive tachometer

A wire moved through a magnetic field generates a potential difference across its ends proportional to the speed of the wire and the magnetic flux density.

This principle is used in a tachometer to measure speed. Conventional tachometers are rotary and generally connected to the wheels of the vehicle. Linearised versions can be devised giving an output either at the track or on the vehicle without the use of wheels. Tachometers are expensive to make and accurate to about 1%.
40) **Dopplar methods**

See beamed radiation (no. 14) and free space or guided radio (nos. 18, 19).

41) **Magnetic gradient vehicle detector**

See M.G.V.D. no. 12.

42) **Integration**

Integration of acceleration yields speed (see no. 23).

43) **Differentiation**

Differentiation of a position signal gives a velocity signal. Both a high quality position measurement and careful filtering are required to limit noise on the output.

2.B.6 **Relative velocity measurements**

44) **Doppler**

The relative velocity of two vehicles can be measured using Doppler shift methods. (See beamed radiation, no. 14, free space systems no. 18 and guided radio no. 19).

45) **Differencing**

(See no. 32)

46) **Differentiation**

Relative position differentiated yields relative velocity (see no. 43).

47) **Free space systems**

(See no: 18)

48) **Guided radio systems**

(See no: 19)

2.B.7 **Acceleration**

49) **Accelerometers**

All accelerometers apply the equation \( \frac{\text{force}}{\text{mass}} = \text{acceleration} \)

(a) Ball on an inclined plane.

The ball will roll up the plane if the acceleration > \( g \tan \Theta \)

\( (g = \text{acceleration due to gravity}) \)
for small displacements
\[ x = k.N.a. \]
\[ M = \text{mass} \]
\[ k = \text{spring rate} \]
\[ a = \text{acceleration} \]

All these transducers require considerable sophistication in design to produce a sensitive linear response with reasonable damping. All must be vehicle mounted and measure acceleration only in one plane.

50) **Differentiation**

Differentiation of velocity yields acceleration (see no. 43).

This is the only available method for track based acceleration measurement.

\[ \theta = \tan^{-1} \frac{a}{g} \]
2.C. Communication Techniques

There are two classes of communication

(a) **Point** - where the vehicle can transmit/receive messages to/from the track only over a short section of track.

(b) **Area** - where track/vehicle communications can take place over an extended section of the track. (Refs. 7, 24, 86, 111)

2.C.1 Point Communications

Fixed point communications can be organised in a variety of configurations offering different characteristics. Each one can be implemented using any of a wide range of hardware techniques.

Many communications involve the transfer of a single fixed message. Such devices are variously called transponders, labels, signs, coded masks or reflectors according to their application. This section details devices for which the mechanism required to change a message is clumsy and would only be used infrequently, i.e. the device transmits essentially a fixed message. In some cases the equipment may allow a simple change in message, e.g. by switching between elements. Most of the devices are described as a vehicle to track communication link. Usually the same equipment can be turned around to provide track to vehicle communications. (Refs. 3, 4, 8, 9, 12, 13, 14, 15, 16, 41, 43, 56, 62, 77, 100, 114, 119)

51) **Coded mask**

A mask mounted on the vehicle is arranged to intercept a beam of energy transmitted across the track. Apertures in the mask, spaced according to the message to be encoded, amplitude modulates the beam. Trackside equipment receives the modulated signal and decodes it (see beamed radiation no. 14).
52) **Coded reflector**

A vehicle mounted label reflects energy to a receiver when illuminated with an appropriate signal from a trackside transmitter (see beamed radiation no. 14).

Information is coded onto the reflector using a number of techniques.

(a) The label is designed to reflect only specific frequencies, any other signal frequencies falling on the label are absorbed. Alternatively the label reflects back all the signal except for specific frequency components. Messages are encoded using particular combinations of frequencies.

(b) The label is made up of alternate reflective and absorptive surfaces. The positioning of the coding elements is used to encode the message.
Methods of interrogating labels

(a) For frequency selective labels
- The label is illuminated with a wideband signal covering the frequency spectrum used in the labels. The reflected energy is received and the frequency modifications decoded. This returns all the label information in parallel to the reader.
- The label is illuminated with a narrow band signal which scans through the frequency range. The receiver identifies the coded frequencies in turn giving a serial readout. The scheme gives better noise immunity but takes longer to read a message.

(b) For position encoded labels
- A narrow beam of energy sweeps across the label illuminating each element in sequence. The scanning of the label is achieved either by using the forward motion of the vehicle to move the label past a fixed beam or by using mechanical devices to sweep the beam across the label. The former is cheaper, the latter can read stationary or slow moving labels.

Common devices used

Optical - Black, white or coloured, panels, studs or bars are illuminated with white (broad band) light. Colour filters are used to isolate the frequency spectrum components. Noise rejection is enhanced by using modulated light beams and retroreflective materials (see beamed radiation no. 14). (Refs. 1, 35, 63, 106)

Radio - a) Tuned cavity resonators absorb specific frequencies (Refs. 5, 6, 33, 70)
   b) Dipoles reflect a narrow beam of microwave energy.
   c) A suitably shaped waveguide will redirect energy back the way it came. They are more efficient but less compact than b).
Schemes b) and c) use position to encode messages.

Radio systems are relatively free from interference and use low power signals. Interrogation speeds can be very fast. (Refs. 67)

Inductive fields - Inductive/capacitive (L/C) or piezo electric crystal circuits tuned to particular frequencies couple inductively with a vehicle circuit. Both wide band and narrow band interrogation methods are used. Some designs of equipment allow the tuned circuits to be switched on or off to give a simple variable message device.

Ultrasonics - Ultrasonic transducers are not wideband nor easily
varied in frequency. Consequently their application to message communications is limited.

The preceding schemes can only send limited amounts of information, as only a small number of encoding elements can be physically incorporated into a label. They can all be made into very reliable communication links at low cost and are extensively used in rail transport (signalling and automatic vehicle identification), and road transport (bus, commercial and military vehicle identification, and for electronic position signposting and selective vehicle signalling in vehicle location schemes.)

In addition to the devices described above any track marker (see section 2.B.1) can be used to convey information to a vehicle. A sequence of markers, whose spacing encodes the message is fixed to the track. Passing vehicles measure the distance between markers and decode the message.

53) **Stimulated transmissions**

A beam of energy is transmitted from the tracks side to a vehicle mounted transducer. This receives the signal, rectifies it and uses it to power a solid state circuit. This circuit transmits back to the track a coded message at a different frequency. As message lengths are only restricted by the speed of retransmission and the time available complex messages can be easily communicated.

Inductively coupled devices (see no. 15) are most commonly used although microwave systems exist (see no. 14).

54) **Continuous transmissions**

A continuous coded transmission is radiated from the track. It is received by any vehicle receiver in range. Such schemes use radio frequency inductive links although microwave systems have been proposed.

2.C.2 **Area communications**

55) **Coded track circuits**

Only track to vehicle communications at very low data rates are possible. The coded track circuit is however very reliable and can be made fail-safe. Traditionally coded track circuits have been used to communicate vital control information on most modern railway systems (see track circuits no. 16). (Ref. 95)
56) **Contacting circuits**

A modulated carrier is coupled into the power supply circuit of the vehicle. Both vehicle to track and track to vehicle data and voice communications are possible. Carrier frequencies of 100-150 khs have been used. Heavy signal attenuation and interference reduce the effectiveness of such circuits (see also no. 6, contacting circuits).

*(Refs. 2, 20)*

57) **Radiating cables ('leaky coax')**

Specially designed coaxial cables with incomplete screening can be used to transmit signals longitudinally with low attenuation and to simultaneously radiate a signal which decays rapidly in strength away from the cable.

Radiating cable communications have been extensively used in mines and on railways. Low transmitter powers can be used and provided cable attenuation is balanced by the use of repeater amplifiers, range is unlimited. Incorrect line termination leads to standing waves being set up along the cable. These can substantially reduce local signal strengths and adversely affect communication. Signals of bandwidth up to megahertz can be transmitted with little interference. Two way communications are practical both for high speed data links and multiplexed voice channels. *(Refs. 18, 25, 26, 34, 37, 66, 79, 80, 91, 92, 93, 101, 108, 178)*

58) **Inductive loops**

Inductive loops allow the two way transmission of messages over track sections from a few metres up to several kilometers. A wide frequency range can be used with the most usual frequencies being around 100 khs. Inductive loops are widely used in many transport modes for two way data and voice communications. They have the particular advantage that the signal can be closely confined around the region of the loop (see inductive loops no. 15). *(Ref. 82, 84, 194)*

59) **Waveguides**

The use of a waveguide gives a very high capacity communication link (up to Ghs frequencies) and allows the use of radar techniques for obstacle detection and collision avoidance (see guided radio no. 19).

Signals are propagated along waveguides such that an external field is produced through which the vehicle antenna passes. This field is produced by one of two methods:
(a) By the controlled radiation of energy away from the guide.
(b) By the use of surface waves in which the energy travels along the guide but is partially external to it. This scheme produces a field which decays very rapidly away from the guide and requires less power than (a).

A variety of waveguides have been developed, each with different characteristics. They all must be accurately formed and are consequently difficult and expensive to fabricate. There has been much interest in waveguide applications to railway operations, particularly in Britain, America and Japan. (Refs. 23, 66)

60) **Free space radio**

Although free space radio offers the capability of very flexible communications between all parts of a system at low capital cost, its effectiveness is much reduced by several factors.

(a) There is already overcrowding of the radio spectrum and frequently there is substantial interference from other users.
(b) The field pattern associated with V.H.F. radio in an urban environment is very complex. It comprises a fixed pattern due to multiple reflections from fixed objects, and shadows in cuttings and tunnels. On this is superimposed a varying pattern due to the movement of the vehicle and other vehicles around it. The result is an indeterminate transmission path between the vehicle and base which changes constantly. Voice transmission is usually intelligible even with the resultant rapid fading. Data transmission requires good paths and can be readily corrupted by fast fading. Over a good speech path data error rates of about 2% are achieved.

However radio is often the only economic solution where continuous communications are required, particularly with variable route vehicles. Free space radio is widely used on the railways for emergency services, taxis, buses and delivery vehicles. (Refs. 42, 45, 78, 112, 195)
Part 3: Examples

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3.4.1
The system cost is 80 min.
BART (Bay Area Rapid Transit)

The Bay Area Rapid Transit is a computer supervised automatic rapid transit system in San Francisco. It features an extensive central control designed to optimise train running, and an innovative signalling system which is claimed to give a better, safer performance at a lower cost than could be attained using conventional techniques.

There are 120 km of track and 34 stations. Average journey speed is 80 km/h with a maximum speed of 130 km/h. Station stops are 20s and minimum headways are 90s.

The control system structure is divided into two sections
(a) Train operating system
(b) Train protection system
Central supervision

The central computer performs the following roles.

a) Traffic regulation. The timetabled service is compared with the actual service. For small deviations from the schedule the train performance is modified. (This allows up to 10% reduction or 50% increase in travel times between stations).

More severe deviations are compensated using variable dwell times, alternative routing, station skipping and turning back trains.

b) The dispatch of trains from maintenance and storage yards.

c) The provision of routing instructions via stations and wayside equipment, to align switches.

d) The control of a large operator display showing train location and the status of equipment.

All communications involving the central computer are handled by a data telemetry system hardwired to local station and track controllers.

Local line supervision

Communication with individual trains is directed via station and trackside equipment. There are four types of communication involved.

a) Train identity (TID)

b) Station stop signals

c) Speed information and train detection

d) Train attendant communications

a) TID signals

The TID system is a data storage and two way communication link between track and vehicle. Data is transmitted serially using frequency shift keying (F.S.K.), the telegrams containing the following information:

1) The train identity (serial number, destination, length)
2) Performance modifications
3) Door open/closed status

Throughout its journey the train transmits its TID signal. This is received at every crossover switch or diverge. The wayside equipment determines any switching action, stopping a train if the change cannot be effected in time.

At stations the door status information confirms the door operation. As the train leaves the platform, new performance modifications for the next journey stage are transmitted to the vehicle and stored in the TID registers.
b) Station stop signals

An independent track conductor loop transposed every 300mm is laid from the point at which braking starts, to the station. To stop a train the loop is energised enabling the train to detect the crossovers. An on-board processor calculates the distance to go and outputs a speed signal. The power and brakes are regulated accordingly to give a stopping accuracy of ± 1.5m. Tones transmitted from the track open and close the doors.

c) Speed information and train detection

Jointless coded track circuits are used for train detection and track to train communication of speed commands. Each block is delineated by a short circuit between the rails. Signals are inductively coupled into the track circuit by a transmitter loop at the short circuiting band; a similar loop detects the signal at the other end of the block. Speed information is broadcast serially using F.S.X. of the track circuit signal. To ensure isolation of adjacent track circuits three pairs of frequencies are used.

The track circuits receive their speed commands via a time-multiplexed information channel, timing information being provided by a synchronising pulse line.

At each time slot access a binary 0 or 1 is placed into the track circuit transmitter, indicating which frequency state is to be output. This information is saved until all the track circuits have been addressed, whereupon all the transmitters change state simultaneously. A baud rate of 576 bit/s is used giving three complete 6 bit speed commands/sec to each track circuit. Similar time multiplexing is used to check block occupancy, the data being transmitted to the local safety protection unit.

![Diagram of track circuit](image)
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Wayside Multiplex Unit (W.M.U.)
d) **Train attendant**

The train attendant has no control of the train when it is operating automatically. His function is to observe and to communicate with the passengers. He has two overrides:

1) **Emergency stop**

2) **A manual mode** — The operator is directed by the system supervisor using voice radio. The train speed is limited to 40 km/h and running is line of sight. The manual mode is the only means by which the train protection system can be overruled.

**Safety systems**

Speed commands are issued by units, located at the stations, which handle all the functions of the train protection system. The codes issued to a block are determined by the distance to the occupied block ahead and by the physical characteristics of the track (e.g., curves and grades). To ensure the correct speed commands are transmitted in each block, each transmitted frequency state is checked by observation of the track circuit receiver output. Any failure of this monitoring operation causes an emergency stop.

The train receives all three frequency pairs from the track. Crystal filters separate the frequencies and identify the reference speed command. A 'vital' circuit compares the actual train speed measured by an axle driven tachometer and the reference speed. The error is used to control the power and the fail-safe braking.

The integrity of the speed command received from the track is ensured by using 'comma free' codes (a repetitive sequence of any one code can never be confused with another irrespective of the time selected as the beginning of the message). A further check on operation is made by ensuring that the vehicle receives a speed command every 1/3 second.

**Safety philosophy**

Fixed block headway protection is used, the length of individual blocks varying according to its track speed limit. The wayside train protection system does not check the train speed. It is considered a sufficient safeguard to ensure that an unsafe speed cannot be transmitted and that whatever speed is commanded will not be exceeded. However, there is a very heavy dependence on unproven fail-safe digital circuitry and already the wrong-side failure of an on-board A.T.C.
component has sent a train through the end stops at Fremont.

As a consequence of this and other malfunctions several modifications have been made, both to the hardware and operation of the system.

One serious problem was the occasional inability of the system to detect a train. This resulted from a combination of factors.

(a) The very low track circuit voltages used (less than 2v)
(b) The light weight of the BART vehicles
(c) The use of disc brakes which do not clean the wheel treads

The addition of mechanical wheel scrubbers and stainless steel beading welded onto little used sections has improved train detection, although it is not completely reliable. A permanent backup system has been added called sequential occupancy release (SOR). This uses a series of minicomputers in redundant pairs installed at 26 trackside locations. They provide an independent check-in, check-out of trains in subsequent blocks. Each track circuit is looked up until the train is positively detected in the next one.

Other important modifications included
(a) Redesign of the speed command circuits for fail-safe operation.
(b) Better information provision for the train attendant enabling him to form an effective backup to the automatic system.
(c) Better information provision to the central control to allow more accurate assessments of system status.
(d) More involvement of the central computer as a safety back-up in train detection, redundant monitoring and validity checks on manual instructions. (Refs. 143, 144, 145, 169, 170, 171, 173)

3.4.2 Victoria Line

The Victoria line, opened in 1969, is a Metro in London, serving sixteen stations over fourteen miles of track. It uses an automatic train control system developed by London transport. An attendant is retained on the train with duties to operate the doors, the starting signal and take over control of the train in emergencies.

The Victoria line employs no signalmen, all junctions are set automatically by a programme machine and whole line is supervised from one central control point at Euston.

Automation has been applied to
(a) Reduce staffing requirements

(b) Improve service regularity, both by making driving technique more consistent and by improving recovery from abnormal conditions.

(c) Enable close headways to be maintained safely in station areas. Signalling on the Victoria line has been designed on a basis of an 82 sec. headway.

(d) Reduce energy consumption

The automatic train control equipment comprises two systems, the safety system and the train command system.

**Safety system**

Fail safe fixed block signalling and coded track circuits provide basic safety and command information.

For the train to proceed under automatic control it must receive one of the signalling codes from the track. There are four codes used, each transmitted by the amplitude modulation of a 125 hz carrier. These are:

- **120 pulses/min.** - This is not detected by the train. It is used by the track circuit for train detection.
- **180 pulses/min.** - This allows the train to run at 35 km/h but not to motor.
- **270 pulses/min.** - This allows the train to run at a regulated speed of 35 km/h. The brakes are applied if the speed exceeds 37 km/h and the power applied if speed falls below 33 km/h. The governed speed of 35 km/h was chosen as this gives the best headway through stations. It is also the standard speed restriction used by London Transport for crossovers, junctions and track constraints.
- **420 pulses/min.** - This permits the train to run at maximum speed (up to 80 km/h) limited by tractive effort and train resistance.

If no code is received by the train or if the 180 or 270 codes are received and the train exceeds 40 km/h the emergency brakes are applied. Speed monitoring is by a mechanical axle mounted governor of proven reliability fitted with a manual adjustment for tyre wear.

**Train attendant**

Facilities are provided for the train attendant to operate the train manually at a speed not exceeding 35 km/h if code is being received from the track or 16 km/h if it is not. Overspeeding results in emergency braking.
The attendant also has two devices for communicating with the central supervisor.

(a) Bare copper/cadmium wires are mounted in the tunnel. In an emergency these are used to trip the traction supply circuit breakers. The driver can communicate with the controller by clipping a portable telephone to the wires. This system has the disadvantage of having to stop the train.

(b) Full duplex in-cab communication is provided called 'carrier-wave', which can be used at any time. A frequency modulated low frequency carrier signal is applied to the two conductor rails that carry the traction current. The track transmitter uses a frequency of 150 kHz.

The system works well under normal conditions when the trains are well spaced. However, the low impedance of the train (5 ohms) compared with the 200 ohms characteristic impedance of the conductor rails, causes considerable attenuation if several trains become bunched and occupy the same section simultaneously. This makes communication unreliable at the time when it is most wanted.

Trials are being conducted on leaky feeder and radio telepathy systems which may offer better communications.

The command system

The train command system is used to stop trains at signals and platforms and to initiate coasting at appropriate points on the line. These commands are conveyed to the train by 'spots' positioned on the line. These spots are audio-frequency signals fed into short lengths of the running rail and detected by the train coils.

A 2.5 kHz signal is applied to a profile of six carrier frequencies in the range 480 to 16 kHz.

The command is a binary code of six signals.

Train

The system is designed to operate with trains being in the gap called a rest, a rest.
A 20 kHz signal gives the instruction for the train to stop if the signal is at danger.

A 15 kHz signal cuts off the motors and allows the train to coast.

Further spots are used to stop the train at a station. A braking profile is written onto the track at the approach to each station. The speed at which the train should be travelling in order to be on the normal braking curve is represented by local speed spots whose frequencies are scaled so that 1.6 km/h = 100 Hz. Along the profile spots are located at 8 km/h intervals starting at 88 km/h and finishing at 16 km/h.

The train braking equipment uses acceleration feedback to give one of three standard braking rates, maximum, normal and minimum. The actual train speed is measured using a tacho generator and compared with the required speed read from the track. The braking rate is then selected according to whether the train is overspeeding, correct or underspeeding. If the train speed is more than 20% less than the commanded speed the brakes are released completely.

To ensure the integrity of the commanded speed signal the braking command signals are applied in pulses of 127 cycles followed by a pause of similar duration. This allows the train to recognise only genuine signals.

Train identification

To convey train identification information to the track the 'Identra' system is used. In this a track mounted fixed coil couples inductively with a train mounted tuned coil, the resonant frequency of this coil being manually set at a journey start. One out of eight frequencies in the range 60-90 kHz is used to set the train ID.

London transport is now experimenting with a more complex system called positive train identification. With this a pulsed 50 kHz signal is transmitted to the train. When the train is in range this stimulates a response signal. This response is a digital telegram timed by the stimulating transmission. The total message time is 28 ms and can be used for speeds up to 77 km/h. (Refs. 20, 179, 210, 201, 107, 141, 159)

3.A.3 Morgantown

The Morgantown project is both an UMTA demonstration of automated urban transport and a public transport service for Morgantown. The
The proposed system contained 5.8 km double guideway, six stations and 90 vehicles. The scale of the project has since been considerably reduced. The route is now 3.5 km long with 3 stations.

The system operates both a scheduled and a demand responsive service. The minimum headway is 15s, top speed is 48 km/h, average speed is 30 km/h.

The Morgantown project has been extremely costly; $64m for a system originally estimated to cost $18m, with an estimated further $50m for expansion to the original design. Although the cost escalation was caused partially by unrealistic deadlines and design criteria, the technical difficulties of such an advanced system were seriously underestimated.

In particular commercially available components allowed rates of failure which are much too high for automated public transport. Military and space hardware could achieve the required reliability but at a much higher cost.

**Morgantown Control and Communications System (C & CS)**

The C & CS is divided into three functions:

(a) Central control and communications

(b) Station control and communications

(c) Guideway control and communications

(a) Central control

A central computer carries out the automatic management functions, receiving destination service requests from the stations and transmitting commands for vehicle routing and dispatching to stations. A system operator at the central office takes control of the system during conditions of failure, start-up and shut down.

(b) Station control and communications (S.C.C.)

The S.C.C. controls vehicles and station operations in response to central supervisory commands. Signals from the station control are transmitted to vehicles using inductive loops embedded in the guideway. Communications are in the form of F.S.K. telegrams and fixed frequency control tones.

The station computer controls vehicle switching, station stopping and door operations. It also operates the station information displays and receives passenger destination demands. At each station there is a collision avoidance system (CAS) which is a back up to the primary control.

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control.

The CAS consists of

1) Duplicated passive vehicle detectors (reed relays activated by vehicle carried magnets). These detect vehicle entry into a block of track.

2) Inductive communication loops which transmit a safetone (10.2 kHz with a 50 Hz modulation) to the vehicle in the block.

3) A redundant control system which determines block occupancy. (The redundancy is achieved by having one logic path go via the station computer and uses software to achieve the block control. The other logic path uses special purpose logic circuitry. Both logic paths must agree or the safetone is removed from the affected zone).

(c) Guideway control and communications

Buried in the track are various inductive loops performing different functions.

1) Station stop loops (36.3 kHz). The station control transmits a tone signal which tells the vehicle to begin its stopping manoeuvre. The vehicle is arranged to enter the stop loop at 1.2 m/s and is designed to stop + 15 cms from the centre of the station unloading gates.

2) Switching tone loops (28.3 kHz). These loops when energised command the vehicle to steer left or right at merges and diverges, (i.e. select the appropriate wall to follow). The vehicle must verify that switching has been accomplished, otherwise it will be brought to a halt.

3) Calibration loops (36.3 kHz). These give a measured position reference to the vehicle. It is used to recalibrate the on-board odometer to remove accumulated errors.

4) F.S.K. loops - 129/121 kHz transmission, 104/96 reception. The F.S.K. transceiver unit transmits speed commands, door commands and identification requests to the vehicles. A second set of loops is used to receive vehicle I.D., door responses and fault status signals transmitted from the vehicle.

Voice communications

The communications operator is responsible for communications with passengers. He can enable or disable vehicles using UHF radio control. He monitors T.V. displays of strategic points in each station. Passengers on-board vehicles can call the operator using the vehicle UHF radio.
Similarly the operator can address any or all of the vehicles. One-way radio communications are provided from the control centre to the individual station public address system. A separate 2-way UHF radio system is provided for maintenance staff and vehicles.

3.A.4 Bus Location

There is considerable interest in schemes designed to improve bus services, particularly regularity and punctuality. Two trends are apparent:

(a) The use of bus transponders which actuate traffic lights. These enable buses to gain priority at intersections so reducing their delay at the expense of some increase in delay for other users, e.g. in Glasgow, Leicester, Nottingham, Southampton.

(b) The use of centralised bus supervision schemes which offer real time monitoring and control of bus movements. These allow schedules to be stabilised and bunching minimised. Four transport authorities have installed such systems for evaluation, namely London, Bristol, Chicago and Hamburg.

This section on bus location will only consider the second of these trends.

There are three types of bus control systems:

(a) Control by roadside inspectors - Roadside inspectors time buses at strategic points and give instructions verbally to drivers. The roadside inspectors communicate by telephone to a controller who decides what control to apply and informs the inspectors accordingly.

(b) Control using radio telephone - Buses are equipped with two-way radio. Drivers report their position to and receive instructions from the controller.

(c) Control using radio and automatic vehicle location - Bus positions are automatically monitored and displayed at a central office. A controller assesses the information and instructs drivers by radio.

A simulation evaluation of these systems suggests that radio telephone control alone offered the most cost effective situation. However automatic vehicle location reduces demands on radio spectrum and may reduce staff costs. The four systems briefly described below are all examples of the third type. However, recently many authorities have begun installing the second type although mainly for reasons of driver security rather than for improved control.
(a) **London** (BESI - Bus Electronic Scanning Indicator)

This was an early experiment in bus location. The scheme comprises bus identification plates mounted on the bus and kerbside readers, spaced at approximately 15 minutes running time apart. Transmission units send the information to a bus route display panel at the central office.

**Operation**

A modulated light beam is projected from the kerbside reader onto the bus I.D. plate. This comprises two rows of reflector studs, the upper row are coloured white and form the time base. The lower row are coloured red and are the running number of the bus in binary coded form.

The light beam is reflected back to the reader, colour separated, filtered and the code identified. A sender transmits the information to the control centre via telephone lines. There it is decoded and displayed. Originally control action was applied by roadside inspectors. Later developments used two-way voice radio communications with the driver.

The principal faults with the BESI system are that:

(a) Large vehicles can block the scanner from the bus  
(b) As there is no code redundancy no error checking can be carried out.  
(c) Misaligned or stationary buses can be misread.

The BESI system has been superceded by apparatus devised by Marconi and installed on bus route 11 in 1973. In this the vehicle uses an axle mounted odometer to determine its position. The bus is linked to the control centre by two-way radio which transmits either the location data or operator/driver conversations.

After compensation for errors due to tyre wear a position accuracy of about 1% is claimed. A computer system at the control centre polls each vehicle in turn, processes the bus location information and drives a visual display unit.

**Bristol**

The Marconi system used in London has also been applied to buses in Bristol. The principal difference is the position location equipment. A vehicle mounted optical reader interrogates passive coded reflector plates fixed frequently along the bus route. These can be read from up to 3m.
Chicago

In Chicago beacons are placed at approximately 3km intervals. These transmit a 16 bit code at 150 MHz indicating their identity. As a bus passes a beacon (within 60m) the signal is received and stored. Simultaneously a counter starts recording twelve second increments. A central computer polls each bus in turn by radio on a 2-minute cycle. The bus when interrogated transmits to the control centre the identity of the last beacon passed and the subsequent elapsed time. The central computer estimates the bus position and informs the operator of buses out of schedule, lost or showing an alarm. Control instructions are passed to the driver by radio.

Hamburg

A similar system is operated in Hamburg. However, position is measured by an axle mounted odometer, which is reset every 5-10 km to control errors. The beacons use an inductive loop antenna and transmit 2 out of 6 frequencies to identify the location. (Refs. 52, 103, 133, 146, 148, 191, 206, 213, 226, 214).
Bibliography

The bibliography is divided into two sections.

Section 1 contains references whose predominant emphasis is on the design or characteristics of particular pieces of equipment or techniques.

Section 2 contains references describing applications of equipment or techniques.
BIBLIOGRAPHY PART 1

**THIS PART OF THE BIBLIOGRAPHY CONTAINS REFERENCES PREDOMINANTLY CONCERNED WITH EQUIPMENT**

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APPENDIX 3  DERIVATION OF FORMULA FOR INTERMEDIATE SPEED

\( a_1 \) - acceleration reached in 1st speed change
\( a_2 \) - " " " 2nd " " "
\( j_1 \) - value of jerk used in 1st " " "
\( j_2 \) - " " " 2nd " " "
\( T_1 \) - time taken for 1st " " "
\( T_2 \) - " " " 2nd " " "
\( D_1 \) - distance " " 1st " " "
\( D_2 \) - " " " 2nd " " "
\( v_1 \) - velocity at start
\( v_2 \) - velocity at end
\( v_i \) - intermediate speed.
\( T \) - time for whole manoeuvre
\( X \) - distance " " "

\( T_1 = \frac{(v_i - v_1)}{a_1} + a_1 \) \( \text{where } a_1 = |\frac{a_1}{j_1}| \)
\( T_2 = \frac{(v_2 - v_i)}{a_2} + a_2 \) \( \text{where } a_2 = |\frac{a_2}{j_2}| \)
\( D_1 = \frac{(v_i + v_1)}{2} \cdot T_1 \)
\( D_2 = \frac{(v_i + v_2)}{2} \cdot T_2 \)
\( v_i = \frac{X - (D_1 + D_2)}{T - (T_1 + T_2)} \quad \ldots \ldots \ldots \ldots \quad (1) \)

\( (T_1 + T_2) = (v_i - v_1) a_1 + (v_2 - v_i) a_2 + a_1 a_2 (a_1 + a_2) \)
\( (D_1 + D_2) = \frac{1}{2a_1 a_2} \left((v_i^2 - v_1^2) a_2 + (v_2^2 - v_i^2) a_1 + a_1 a_2 (a_1 + a_2) v_i^2\right) + a_1 a_2 (a_1 + a_2) v_i \)
From 0 \[ V_i \left( T - \left( T_1 + T_2 \right) \right) = x - (A + D_2) \]

LHS = \[ T V_i - \frac{V_i}{a_i a_2} \left[ (V_i - V_1) a_1 + (V_2 - V_i) a_2 + a_i a_2 (a_1 + a_2) \right] \]

RHS = \[ x - \frac{1}{2a_i a_2} \left[ (V_i^2 - V_1) a_1 + (V_2^2 - V_i) a_2 + a_i a_2 (a_1 + a_2) V_i \right] \]

multiply by \( 2a_i a_2 \) and collect terms

\[ V_i (a_1 - a_2) + V_i 2(a_1 a_2 T + a_2 V_i - a_1 V_i - a_2 (\frac{a_1 + a_2}{2}) \]

\[ + (a_1 a_2 (Q_1 V_1 + Q_2 V_2) - 2a_1 a_2 x - a_2 V_i^2 + a_2 V_2^2) = 0 \]

using the standard solution for a quadratic equation and setting

\[ T = \left( \frac{Q_1 + Q_2}{2} \right) \]

\[ y = Q_1 V_1 + Q_2 V_2 \]

the final solution can be obtained after some algebraic manipulation, namely

\[ V_i = \frac{1}{(a_1 - a_2)} \left\{ a_1 V_2 - a_2 V_1 - a_1 a_2 (Z \pm (Z^2 + \frac{1}{a_1 a_2} (V_1 - V_2)^2 + \right\}

\[ \left( a_2 - a_1 \right) (y - 2x) + 2 (V_1 a_2 - V_2 a_1) x) \right\}^{\frac{1}{2}} \]
A. PENDIX 4 Summary of lane change conditions for alternate priority

TA - time last vehicle passed through the intersection taken arbitrarily as from Lane 1.
T1 - The earliest time after TA a lane 1 vehicle may arrive.
T2 - The earliest time after TA a lane 2 vehicle may arrive.
T3 - Earliest time after T1 a lane 2 vehicle may arrive.
T4 - Earliest time after T2 a lane 1 vehicle may arrive.
TB - The time the next lane 1 vehicle would arrive at the intersection with no delay.
TC - The time the next lane 2 vehicle would arrive at the intersection with no delay.

Intersection

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Time diagrams

\[ T_1 = T_A + f \]
\[ T_2 = T_A + c \]
\[ T_3 = T_A + f + c \]
\[ T_4 = T_A + 2c \]

Diagram

The conditions for a change of lane allocation at the intersection may be summarised as follows.

1. If \( T_B < T_1 \)
   \( T_C < T_2 \)
   i.e. both vehicles will be delayed in both cases 1 and 2.
   then vehicle B goes first, i.e. the lane allocation of the intersection will not change.

2(a). If \( T_B > T_4 \)
   \( T_C < T_2 \)
   then the lane allocation will change from 1 to 2, vehicle C will go first.

2(b). If \( T_C > T_3 \)
   \( T_B < T_1 \)
   then lane allocation will stay with lane 1, vehicle B will go first.

3. If \( T_B > T_4 \)
   \( T_C > T_3 \)
   then a first-come first served system operates.

4. In the situation where
   \( T_1 < T_B < T_4 \) or \( T_2 < T_C < T_3 \)
   The change of lane occurs for a variety of conditions dependent upon the actual situation.
APPENDIX 5

MEAN PLATOON SIZE

FOR NEGATIVE

EXPONENTIAL DIST

\[ p(z) = \lambda e^{-\lambda z} \]

is probability density

that there is a gap of

length \( z \).

The probability of platoon size \( i \) is

\[ P_i = \int_{z=0}^{\infty} P(i; z) p(z) \, dz \]

\[ P(i; z) = \frac{k^i}{i!} e^{-k} \quad \text{where} \quad k = \lambda z \]

\[ dz = \frac{dk}{\lambda} \]

\[ \therefore P_i = \int_{k=0}^{\infty} \frac{k^i}{i!} e^{-k} \lambda e^{-k} \, \frac{dk}{\lambda} \]

\[ = \frac{1}{i!} \int_{k=0}^{\infty} k^i e^{-2k} \, dk \]

\[ = \frac{1}{i!} \left[ -\frac{1}{2} \left[ k^i e^{-2k} \right]_0^\infty + \frac{1}{2} \int_0^{\infty} k^{i-1} e^{-2k} \, dk \right] \]

\[ = \frac{1}{i!} \left[ \frac{i}{2} \cdot \frac{i-1}{2} \cdots \frac{1}{2} \int_0^{\infty} e^{-2k} \, dk \right] \]

\[ = \frac{1}{i!} \left[ \frac{i!}{2^i \cdot 2} \right] = \frac{1}{2^{i+1}} \]

\[ \therefore P_0 = \frac{1}{2}, \quad P_1 = \frac{i}{2}, \quad P_2 = \frac{1}{2} \quad \text{etc.} \]

If platoons of zero size are discounted

then mean platoon size

\[ = \sum_{i=1}^{\infty} i P_i \]

where \( P_i = \frac{P_i}{1-P_0} \)

\[ = 2 \]
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TRAFFIC SIGNALS
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WINTER P.
SWISS EXPERIMENTS WITH TRACK TO TRAIN COMMUNICATIONS
S 3900 CONTROL OF OTHER FORMS OF SURFACE TRANSPORT

WANTTAG G E
AUTOMATED RAILWAY TRANSPORTATION CONFIGURATIONS
G M C RESEARCH DEPT REPORT 10.1.1972
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SWISS EXPERIMENTS WITH TRACK TO TRAIN COMMUNICATION
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A number of papers have been published on the work reported in this thesis. They are as follows:


2) L. Burrow -- The simulation of junctions in automatic urban transport systems using interactive graphic displays -- United Kingdom Simulation Council conference on computer simulation, Bowness-on-Windermere, 6-8 May, 1975 (to be published in the Simulation Council series 'Simulation')

3) L. Burrow -- The design of control systems in automated transport systems -- IFAC workshop 'Optimisation applied to transportation systems', Vienna, Austria, 17-19 Feb, 1976

4) L. Burrow -- The 'fail soft' design of complex systems -- I.E.E. conference 'Distributed computer control systems', Birmingham, 26-28 Sept, 1977
THE PERFORMANCE OF JUNCTION CONTROL STRATEGIES IN A HIERARCHICAL URBAN TRANSPORT SYSTEM

L. Burrow and T. Thomas

Introduction

Where the introduction of a new transport system, into the fabric of an existing city, is proposed, any scheme requiring bulky civil engineering structures will be at a severe disadvantage. There is thus a considerable incentive to develop structurally compact layouts, particularly for complex components such as stations and junctions.

Several approaches to the design of junction structure are in use. One extreme is exemplified by the extravagant cloverleaf layout, in which all potential intersections of traffic streams are replaced by a network of bridges and merges. At the other extreme lies the on-grade crossing, whose satisfactory performance depends upon sophisticated control.

Some potential junction capacity is lost when control is substituted for civil engineering. As junctions are usually the capacity determining elements of a transport system, there is a need for control policies that allow high flows through the intersection, yet limit delays and the distances required for preparatory manoeuvres.

Synchronous (marker following) headway control, at least in its simple form, is not well suited to maximising junction capacity. It uses fixed time-headways calculated for maximum speed, and it therefore offers no means of realising the reduced headways available at lower speeds. By contrast asynchronous control permits a local trade-off between capacity and speed.

Synchronous headway control is often associated with centralised network control, while asynchronous headway control is more appropriate in hierarchical systems. In these latter, each major component is semi-autonomous, only selected information being passed up or down the hierarchy. Autonomy gives protection against widespread failures and reduces communication costs. Local junction controllers can form part of a hierarchical system.

Provided a junction always presents an open door at its entrances and can rely upon its exits being clear, it can be analysed in isolation from the rest of the network of which it is a part. It can be treated as a processor converting streams of input traffic (having specific statistics) into output streams. Its controller becomes a device designed to minimise some cost function using information entirely gathered from within its boundaries.

A good cost function, by which different control schemes can be reliably compared, will be complex. It should incorporate not only measures of delay, capacity and junction size, but also take account of economics, psychological comfort etc. It would be attractive to study the control of a full-turning two-way junction using a realistic cost function; however such a junction is an interacting network of merges, links and intersections and this direct

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approach is not practicable. The work reported here is concerned with a single junction element, viz. an intersection of two traffic streams with no provision for turning. The performance of various control strategies have been compared, using as cost function, the mean delay experienced by vehicles arriving randomly but with a specific mean flow rate.

**Headways**

The distance headway between two vehicles is taken as the spacing between them plus the length of either. For uncoupled vehicles, safety demands that headway is maintained above some minimum value that is dependant on speed. It is convenient and conventional to designate this minimum or emergency headway as vehicle length plus the stopping distance, and to calculate the latter using a reliably attainable emergency braking rate. The safety supervision equipment is assumed to apply emergency braking whenever this emergency headway is infringed.

Such an application during a deliberate manoeuvre is most undesirable. Vehicle running control is therefore designed to maintain headways above their emergency values. A working headway can be designated and used as a set point for longitudinal control. Working headway is also likely to be a function of speed and can be expressed as emergency headway times a factor. The multiplier chosen reflects both the desired safety margin and the expectation of headway infringement during particular manoeuvres.

Suppose, for example, that a junction controller wishes to slow down a closely packed string of vehicles. One technique would be to simultaneously command every vehicle to decelerate. Another technique would be to command the leading vehicle only to decelerate, and to rely upon feedback headway controllers in the following vehicles to slow them down as their working headways become infringed. In the latter case, non-infringement of the emergency headways depends on the severity of the leader's manoeuvre and on the efficiency of the feedback controllers. In the second case the proper definition of the working headway is important.

The term 'brick-wall stop' has been applied to a vehicle undergoing an infinite rate of deceleration. The emergency headway defined above is based on the possibility of a brick-wall stop by the vehicle ahead. There has been much debate about the acceptability of shortening the emergency headway on the grounds that brick wall stops are not possible. A variant of this argument allows the factor relating working to emergency headway to be less when vehicles are following each other, than when they are crossing. Both instinct and conventional road transport experience seem to support this distinction. In the work being reported here, the working headway has been taken as 1.2 times the emergency headway, but the factor has been raised to 2.0 for crossing vehicles. The existence of such a distinction has a marked effect on junction performance under various strategies.

Time headway is a more nebulous concept than distance headway but is useful where pairs of vehicles are moving at constant speed. In such a case time headway is distance headway divided by the speed. Vehicle flow rate is, in turn the reciprocal of time headway. Thus for a steady speed, saturation flow rate can be taken as speed divided by the working headway. Plotting saturation flow against speed gives the familiar hill shaped curve which identifies the maximum flow (or capacity) and the corresponding 'saturation speed' (diagram 1). For reasons of performance and flow stability practical transport systems have line speeds well above their saturation speed.
At a specified speed, one can evaluate working time headways for the following and crossing cases (f and c respectively). The saturation flow through the intersection when both streams travel at this speed will be

$$F_s = \frac{n}{(n-1) f + c}$$

where \( n \) is the mean platoon size passing the intersection from either line.

As \( n \) increases from 1, \( F_s \) increases from \( 1/c \) towards \( 1/f \). The junction capacity is the value of \( F_s \) when the speed at the crossing point equals the saturation speed. Clearly capacity increases with mean platoon size, and any good junction control strategy must make use of this property. The ultimate junction capacity equals \( 1/f \) defined at the saturation speed. No junction controller can handle an intersection when the sum of the mean input flowrates exceeds this figure.

**General Features of a Control Strategy**

Any junction control scheme must establish a trajectory for each vehicle from its entry point to the intersection, and from the intersection to the exit point. System constraints such as acceleration limits must be observed. The trajectories should collectively minimise the chosen cost function.

The critical features of a trajectory are its intersection arrival time and its intersection speed: the primary task of the control algorithm is to determine these target values. The times must be such that, given their corresponding speeds, vehicles do not violate their working headways at the intersection. Before these times can be determined, the vehicle order through the intersection must be decided. In some algorithms, order and timing are chosen by an iterative process.

Individual vehicles are subject to two sorts of delay. They lose time in slowing to the intersection speed and speeding up again; they lose further time in manoeuvres to avoid conflict with other vehicles. The target intersection arrival time allows for both delay elements. Lowering the intersection speed will increase the former element but decrease the latter. (Provided intersection speed exceeds saturation speed, any reduction in it will reduce headways and hence the extent of potential vehicular conflicts.) Thus there will be some optimum speed that minimises total delay. According to the algorithm chosen, it may be possible to vary the target speed from vehicle to vehicle, or it may be necessary to give the same value to every vehicle.

With suitably sophisticated longitudinal control, and with a sufficient manoeuvre distance, the target times and speeds would always be attainable. In the practical case, the necessary manoeuvres may cause infringements of working headways, resulting in additional, vehicle-determined, control action. This action will always take the form of braking and hence result in yet further delays. These are generally quite slight compared with the delay elements mentioned above, but may attain significance with particular control algorithms.

As the flow rate through the junction is increased, a condition will eventually be reached where vehicles experience intrusion of their working headways even before they reach the junction control boundary. This defines the stage at which the junction ceases to behave as an autonomous system component.
Possible Junction Control Strategies

'Fixed Time Cycle'

The intersection is allocated for a set period to each lane in turn. The policy creates platoons, the size depending on the flow characteristics and limited by the length of the period.

Conventional traffic light control is the simplest manifestation of a fixed time cycle. However in this form the intersection is inefficiently used, primarily because only the speed of the front vehicle of a platoon, formed at the junction, can be optimised. The remaining vehicles pass the junction at a speed determined by headway control.

A more sophisticated control ensures that all vehicles pass through the intersection at an optimal speed. This requires the vehicles to be allocated their target times and speeds some distance before the intersection. If only a limited distance is available for organisation then headway infringement will make it impossible to achieve the optimum targets. Increased delay will result; also the ultimate average platoon size will be reduced, lowering the saturation flow.

The results obtained demonstrate these effects of headway infringement. (dia 4) Diagram 2 shows that increasing the period length increases the ultimate capacity, but also increases the delay at lower flows.

The results of optimising the junction speed and period length for particular flows are shown on diagram 3. Operating points on this curve would be difficult to realise in practice as the performance is very sensitive to parameter changes.

Fixed Platoon Size

This alternative policy has many similarities to the fixed time cycle. However the strategy appears particularly inflexible and no studies have been carried out.

'First Come First Served'

The vehicles pass through the intersection in the order with which they arrive at a predefined control boundary.

The platoon size is only dependent on the input vehicle headway distribution. (The work reported here employs a modified Poisson arrival distribution; average platoon size = 1.4 vehicles.) The ultimate capacity of the system is therefore fixed. The effects of headway infringement are small, as the platoon size is small. The curves (diagram 5) for the simulation with and without headway constraints confirm this. As expected, the system exhibits small delays for flows below saturation, but saturation flow is low. (dia 6)

The 'Alternate Priority' Scheme

Consideration of the performance of any strategy is greatly assisted by knowledge of the absolute performance boundary. A strategy which goes some way to providing such a boundary is the "alternate priority" scheme.

The order of the vehicles through the intersection is determined from a comparison of two ordering policies.
Case 1) a vehicle from Lane 1 is followed by vehicle from Lane 2
Case 2) a vehicle from Lane 2 is followed by a vehicle from Lane 1

The comparison is carried out using the next vehicle in each lane to be allocated an intersection target.

The total delay that would be incurred in each case is compared and the policy offering the lowest delay is the one adopted. This determines the next vehicle through the junction. The vehicle not allocated a target then participates in the next 'contest'.

The condition for the change of lane allocation can be summarised as follows.

At the intersection the following times are defined.

- $T_A$ - time last vehicle passed through the intersection taken arbitrarily as from Lane 1.
- $T_1$ - The earliest time after $T_A$ a lane 1 vehicle may arrive.
- $T_2$ - The earliest time after $T_A$ a lane 2 vehicle may arrive.
- $T_3$ - Earliest time after $T_1$ a lane 2 vehicle may arrive.
- $T_4$ - Earliest time after $T_2$ a lane 1 vehicle may arrive.
- $T_B$ - The time the next lane 1 vehicle would arrive at the intersection with no delay.
- $T_C$ - The time the next lane 2 vehicle would arrive at the intersection with no delay.

The conditions for a change of lane allocation at the intersection may be summarised as follows.

1. If $T_B < T_1$ and $T_C < T_2$, i.e., both vehicles will be delayed in both cases 1 and 2, then vehicle B goes first, i.e., the lane allocation of the intersection will not change.

2. If $T_B > T_4$ and $T_C < T_2$, then the lane allocation will change from 1 to 2; vehicle C will go
first.

2(b) if \( T_C > T_3 \)
\( T_B < T_1 \)

then lane allocation will stay with lane 1, vehicle B will go first.

3 if \( T_B > T_4 \)
\( T_C > T_3 \)

then a first-come first served system operates.

4 in the situation where

\[
T_1 < T_B < T_4 \\
T_2 < T_C < T_3
\]

The change of lane occurs for a variety of conditions dependent upon the actual situation.

The policy forms platoons according to the input flows and bears a close resemblance to the operation of a roundabout in conventional traffic.

Results obtained from a simulation without headway infringement demonstrate the low delay high ultimate flow characteristic of the scheme. (dia 7)

Conclusion

In an asynchronous headway control system the line capacity is a function of line speed. This property, may be used in a particular strategy to locally increase the line capacity by reducing the line speed.

If a distinction is drawn between two situations; a vehicle following another and a vehicle crossing the path of another, two 'working headways' can be defined. This distinction has a fundamental effect on the operation of control strategies. In particular a policy favouring the formation of platoons allows the intersection to cope with a greater ultimate flow.

However if the control policy starts a manoeuvre at a single-fixed point before the intersection, headway infringement will cause vehicles to incur extra delay. This extra delay increases with platoon size.

Better performance may be achieved using more complex control strategies which enable manoeuvres to start at a point dependent upon individual vehicles.

The conceptually simple 'fixed time cycle' policy permits high saturation flows to be achieved but with relatively higher delays at low flow rates.

Conversely the 'first-come first-served' system takes advantage of local headway distribution. This yields a low delay but with a low ultimate flow.

The 'alternate priority' policy generates platoons dependent upon the flow rate. This gives low delays at low flow rates but allows a high ultimate flow rate to be achieved.
**Appendix I**

The simulation parameters used were:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line speed</td>
<td>12.0 m/sec</td>
</tr>
<tr>
<td>Emergency deceleration</td>
<td>2.5 m/sec^2</td>
</tr>
<tr>
<td>Normal acceleration</td>
<td>1.25 m/sec^2</td>
</tr>
<tr>
<td>Following headway factor</td>
<td>1.2</td>
</tr>
<tr>
<td>Crossing headway factor</td>
<td>2.0</td>
</tr>
<tr>
<td>Vehicle length</td>
<td>4.0 m</td>
</tr>
</tbody>
</table>

For the simulation including headway constraints control commenced 300 m before the intersection.
DIA 5
"First-come first-served"
Comparison of simulation with and without headway restraints (intersection speed = 4.5 m/sec)

DIA 6
"First-come first-served"
Optimised intersection speed
No headway restraint

DIA 7
"Alternate priority"
Optimised intersection speed
No headway restraint
INTRODUCTION

The continuously rising costs associated with conventional transport systems, those of congestion, pollution, the profligate use of energy, etc., have stimulated considerable interest in alternative transport systems.

Of particular interest are automated transport systems, which potentially offer the flexibility, speed and comfort of private vehicles, combined with the public transport benefits of economy and freedom from stress. The faster, more predictable, response of automatic controllers, by comparison with the human operator, may also give increased capacity and better safety (1,2,3).

Where the introduction of a new transport system into the fabric of an existing city is proposed, any scheme requiring bulky civil engineering structures will be at a severe disadvantage. Control can be substituted for civil engineering at the expense of some loss of potential system capacity. There is thus great incentive to devise sophisticated control schemes, which provide the desired service characteristics yet permit compact structures to be designed, particularly for stations and junctions.

This paper reports the simulation of junctions in an automatic transport system. Automatic transport control, its structure and operational philosophy, is introduced briefly to define the environment within which the simulation studies have been carried out.

Large general simulations are evolutionary in nature. The design of simulation structures to allow free development, is examined emphasizing the need to develop submodels of the system. These can then be introduced into the main body of the simulation, after their behaviour has already been investigated in some detail.
In this context, the implementation of the junction simulation is described highlighting the essential elements.

The data output requirements of a simulation are defined. For a general overview of system operation a moving picture is useful, and the implementation and the interactive display used with the simulation is described in detail.

Finally, some results are presented showing a few of the programme capabilities.

TRANSPORT CONTROL

The control structure for an automatic transport system may be centralised or hierarchical. Central control can provide better performance by using all the system information. However, communication costs are high and failures anywhere in the system can cause extensive disruption.

In a hierarchical structure, control is divided between a number of semi-autonomous levels, with only limited information transfer between levels. The autonomy localises failures and communication costs are reduced.

Control strategies may be classed as either deterministic or stochastic. Deterministic control requires complete knowledge of every vehicle's present and future positions: it is generally associated with centralised control. Stochastic control implies that only a limited knowledge of vehicle positions is available: it is particularly applicable in hierarchical control environments. It is also generally associated with 'vehicle following' algorithms (in which a vehicle obeys a speed command whilst on open track and when following a vehicle, adjusts its speed to some function of the distance to the vehicle in front).

MERGE CONTROL

Merge control in deterministic systems is relatively simple. Vehicle journeys are prearranged so that conflicts never arise at a merge.

In Stochastic systems, vehicles arrive at junctions randomly and are merged under local control. As junctions are usually the capacity limiting elements of a transport system, there is a need to develop control policies that allow high flows through the intersection, yet limit delays and the distances required for preparatory manoeuvres.

K1 -E-
The simulation reported here has been designed to test and compare algorithms for the local control of an isolated junction in a stochastic system. Provided a junction always presents unrestricted entrances to incoming traffic and can rely upon its exits being clear, it can be studied in isolation from the network of which it is a part. Its controller is thus a device for minimising some cost function, using information gathered entirely from within its boundaries (4, 5, 6).

SIMULATION

Analytic description of a system as complex as a junction is unlikely to be helpful. Even if an accurate mathematical description could be produced, the complex highly constrained, non-linear interaction of variables is almost certain to defy solution. In this situation simulation can be used to study specific situations, with the implicit assumption that the results will enable the significant characteristics of the general solution to be identified(7).

A simulation can only model the major system features since intricate detail studies are very expensive in programming and running times. These important features can frequently be predeveloped using an efficient specific program. Further development can then be carried out in the more demanding larger scale simulation environment.

This approach to simulation offers several useful characteristics.

Speed - because small programs are easy to develop and quick to run.

Identification - since submodels can be isolated within the main body of the problem which in its turn leads to modular simulation structures.

Reliability - because a repertoire of expected behaviour patterns is built up, leading to a better comprehension of the overall system.

A modular simulation structure allows such development to take place in parallel with the main simulation. Provided the structure created accurately represents the system and still allows sufficient flexibility to incorporate subsequent developments, then the simulation can evolve easily as the understanding of the system grows.
THE JUNCTION SIMULATION

The essential components of a junction can be identified as:-

(1) Track
(2) Vehicles
(3) Track-vehicles communications interface
(4) Track-control communications interface
(5) Control system

TRACK

A junction can be specified as a directed graph having links, nodes, entrances (traffic generators) and exits (traffic sinks). This general description can encompass an arbitrarily complex network. Simulation of track uses arrays to hold the geometric details (to enable the layout to be reproduced for display purposes) the lengths and speed limits of links and their interconnections. A further matrix specifies possible entrance-to-exit routes for vehicles traversing the network.

In operation vehicles are created at each entrance according to a random generator modelling the desired input stream characteristics. Each vehicle is allocated an exit and is transferred from link to link according to the route matrix until that exit is reached.

VEHICLES

The detail simulation of vehicle dynamics is a study in its own right. Junction modelling requires only crude vehicle simulation, incorporating realistic constraints on velocity, acceleration and jerk (rate of change of acceleration). Initial studies have assumed the perfect response of a vehicle to demanded inputs. This is an unrealistic assumption: it is commonly accepted that the tolerance on the practical vehicle specification is unlikely to be better than 5%. Later simulation studies will have to take this into account as performance variations are likely to have a very significant effect on control policy decisions.

TRACK-VEHICLE AND TRACK-CONTROL COMMUNICATIONS

The amount of information transfer required for track-vehicle and track-control communication is a particularly important parameter in the assessment of a control strategy. Information transfer is expensive, requiring sophisticated apparatus of high reliability. To communicate less is cheaper, to communicate more allows a better control to be achieved.
which may reduce costs elsewhere in the system. Careful simulation of the information transfers enables the balance between these factors to be studied.

As communication at points along the track is likely to be used in a real system, the simulation models this. Other communication arrangements can be readily modelled without a change in the simulation structure.

Within the simulation information transfer points are positioned on the track; the passing of a vehicle calls a servicing routine attached to that particular point. Such an arrangement is sufficiently flexible to allow most strategies to be simulated. It has the particular programming advantages that the necessary information transfer can be explicitly identified and a subroutine performing a particular control task can be used to service any number of communication points.

CONTROL SYSTEM

The control system is a decision making process. The control commands dispatched to vehicles are determined knowing the ideal response of the system, (i.e. a conceptual model of the system is held in the controller) and some past and present information.

Two control systems are required in an automatic transport system—One, the normal running control system, the other, an independent safety control system. The latter oversees the former and is generally a system monitoring the single condition 'is the vehicle separation adequate for the speed of the vehicle?'. It is essentially a controller, holding a very simplified system model, capable of issuing only one command (e.g. brake at the emergency rate to zero velocity).

Autonomy from the normal control system is essential to ensure that failures in the normal control system are independent of failures in the safety control system, so reducing the likelihood of a joint and possibly catastrophic failure.

The normal control system has two paths of action, normal or abnormal. The choice depends on a comparison of actual system performance with the performance predicted by the conceptual model held by the controller.
Normal control is exerted when the comparison shows no serious deviations. There are two interdependent decisions involved.

(1) What future state is required of the vehicles?
(2) What commands should be transmitted now to achieve that state?

For example, in the vicinity of a merge decisions have to be made about:-

(1) The future order of vehicles through a merge.
(2) The longitudinal control action that has to be applied to each vehicle, such that they achieve the order efficiently and safely.

Abnormal control results when the comparison reveals a serious error. If the cause of the fault can be identified (e.g. an unusually slow vehicle) then the normal controller may be able to handle the situation without major disturbance (effectively by modifying temporarily its conceptual system model). If not, then the emergency braking system will have to be actuated. The control structure is summarised by diagram (1)

![Control Diagram](image)

Careful simulation of the control strategies is important as there is much dispute concerning the criteria, that should be adopted, to ensure a high degree of safety, concomitant with a reasonable level of technology and implementation cost.

Of particular interest, especially with systems operating near maximum capacity is the interaction between the normal and emergency control systems. There are costs associated with both, unnecessary emergency
manoeuvres and undetected unsafe situations. The satisfactory balance of these two costs will be an important design criterion in any comprehensive junction control policy.

SIMULATION OUTPUT

With any complex simulation the clear and detailed presentation of information, such that important phenomena can readily be identified, is a formidable task. Output can be classed into three groups:

(1) Monitoring system operation

The noting of events during the course of the simulation enables particular situations to be identified. Such output can be valuable but cannot show unforeseen events.

(2) Performance data

A detailed simulation generates large quantities of raw data. A majority will require processing to condense the important characteristics into an intelligible form. A careful design of these output packages is required to ensure that valuable information is not lost.

(3) Overview of system operation

For a system as complex as a junction there are considerable problems associated with the 'birds-eye view' presentation of the overall system operation. Line printer outputs of relevant variables are useful for a quantitative survey of situations. They are ineffective for a general overview and the detection of subtle operational anomalies.

PICTURE DISPLAY OF SYSTEM OPERATION

A picture display clearly presents complex phenomena for which one has an intuitive feel, thus allowing an assessment of the effectiveness of algorithms and the detection of incorrect program operation.

The simulation being reported here uses an interactive moving picture display as its main communication medium. Suitably coded information is transmitted in character form from the host computer (Rank Zerox Sigma 5) containing the simulation, to the picture processor (Digital Systems GT 40).
via a full duplex, 1200 baud, asynchronous line. A continuously refreshed picture is produced showing the motion of vehicles through the junction.

At any point the display can be stopped and dialogue initiated with the host computer enabling a portion of the picture to be magnified to any scale. This coupled with the ability to restart the simulation at an earlier stage and to step backwards or forwards through the pictures allows close detail to be observed.

The Sigma 5 is a process control computer with simultaneous real-time Fortran and batch job operation. The simulation described uses about 11k of memory and runs as a Fortran job.

The GT 40 graphics terminal is a continuous refresh type display driven by a PDP 11/05 computer. It can display alphanumeric or graphical data in any combination. The GT40 can be operated as a general purpose computer, either in a stand-alone function, or as a peripheral to a host computer. Supplied with the GT40 is a simple, flexible, interpretive language, including some graphics functions, similar to BASIC, and called FOCAL GT.

PICTURE DISPLAY STRUCTURE

The picture displayed had the following properties:-

(1) The use of the display does not substantially slow down the simulation.
(2) Any junction network that can be simulated can also be displayed.
(3) Vehicles moving through the junction are represented by an unambiguous symbol, whose length represents the headway (vehicle length plus stopping distance) of the vehicle and so varies according to the speed of the vehicle.
(4) The picture replacement rate is sufficiently fast to give an impression of motion.

Initial attempts to produce the required display used the FOCAL GT graphics routines. Data transmitted from the Sigma 5 host was received by a FOCAL GT program and used to redraw the vehicle layout in the junction.
Accumulation of data simultaneously with drawing the picture output was not possible and the resulting display was too slow to be effective. The best picture rate achieved was 1 picture/8 secs (broken up as 3 secs data transmission time, 5 secs, display time). The excessive display time is the result of the very slow execution speeds of interpretive languages. The long data transmission time results from sending the ASCII character form of a decimal number, rather than the more efficient binary form.

These two limitations were avoided in the second display produced. Specialist functions performing segments of the display process were written in assembly code and added to the FOCAL GT. This approach minimised the software written and retained the flexibility of programming in a high level language.

The functions correspond to four stages in the creation of a display

1. The generation, within the GT40, of a data table holding the XY co-ordinates (suitably scaled in screen units) of the network to be displayed.
2. The display of individual network links.
3. The display of vehicles in the junction to produce the moving picture.
4. The setting and resetting of a display clock showing simulation time.

STATIC NETWORK DISPLAY

The display of the junction layout requires a simple extension of the network representation already used to describe the junction geometry. As only straight vectors can be displayed on the GT40 screen, curved network links have to be approximated with a series of straight line segments. These segments should be the same length for any given link, to facilitate subsequent vehicle displays.

The link identifying number, the length of an individual segments, and the XY co-ordinates defining the segments are transferred from the Sigma 5 to a data table within the GT40. The table can then be referenced by a second function to generate a picture of the junction network.
DYNAMIC VEHICLE DISPLAY

The vehicle display routine determines the picture speed. Provided all the necessary calculations can be carried out simultaneously with the receipt of data, the picture rate is determined by the data transmission time.

The design of the vehicle display therefore reduces to minimising the data required to define a picture and ensuring that algorithms are sufficiently fast.

The least complex symbol that could be used to represent the vehicle and its stopping distance is a straight line of variable length. To position the line anywhere on the screen requires the XY co-ordinates of each end: these, directly transmitted from the Sigma 5 would require four items of data.

If the vehicle is identified as lying on a particular link of the junction network, then the end co-ordinates can be calculated knowing the displacement of each end of the vehicle symbol from the origin of the link. This reduces the number of data items required per symbol to two.

The co-ordinates of a point on a link are calculated according to the simple algorithm:

\[
\begin{align*}
X_p &= X_n + \left( X_{n-1} - X_n \right) \times g \\
Y_p &= Y_n + \left( Y_{n-1} - Y_n \right) \times g
\end{align*}
\]

where \( n \) = integer part of \( D/P \)
\( g \) = fractional part of \( D/P \)
\( D \) = displacement of point from origin
\( P \) = length of one link segment

Diagram 2
All the data except D are constants and held in the previously generated data table.

To calculate the co-ordinates of each point requires two multiplications and one division, consequently calculation times can be easily kept within the minimum period of 10 m/secs separating the arrival of data items.

**DATA TRANSMISSION**

The maximum binary number that can be transmitted from the Sigma 5 in a seven bit character is 127. If each of the displacements necessary for the XY co-ordinates of the symbol, can be generated using numbers less than 127 then only a single character need be transmitted for each data item.

Three methods of generating the displacement are possible.

(1) The absolute displacement of a point from the link origin can be transmitted. As displacements can be considerably greater than 127 screen units (approx 1.25 inch) in general, two characters would be required to define the point (the two characters represent the high and low order parts of a binary number).

(2) Each point is calculated as an increment on the corresponding point on the previous picture. The data increments are likely to be very small but rounding errors would accumulate from one picture to the next and probably become unacceptably large.

(3) Along a given link, a set of points can be specified by sending the spacings of the points and defining the first point as being spaced relative to the origin of the link. For a set of points along a link, errors can accumulate, but these are not transferred from link to link or from one picture to the next. This scheme was implemented in the picture display.

**COMMUNICATION WITH THE SIGMA 5 HOST**

During the picture display communication is maintained with the Sigma 5. Any two characters typed from the keyboard terminates the picture display and initiates a dialogue enabling several options to be selected.

(1) A specified portion of the network can be magnified to any scale.
The facility is achieved by calculating and transmitting to the GT40 a new co-ordinate table holding only the co-ordinates of links actually appearing in the display. During the picture display the Sigma 5 sends only data referencing the displayed links, all other is suppressed.

To aid the detail study of individual movements the simulation can be run in slow motion if required.

(2) During a simulation run, the variables defining the state of the simulation are regularly dumped on magnetic tape. This records the simulation results for future data processing.

At the request of the operator the simulation can be restarted anywhere on the record. This enables simulation work to be carried on from where it was left or for any particular event to be studied in depth.

(3) To assist in this study a step operation can be selected. On restarting the display the operator retains control. After each picture he has the options, to step backwards or forwards one picture, to dump data, or return to the main dialogue.

(4) To prevent the continuous dumping of variables producing a confusing line printer record a message option can be selected and a heading transmitted to the line printer.

(5) A trace option records the progress of a particular vehicle by printing all the variables, pertaining to the vehicle, regularly to the line printer.

SYSTEM PERFORMANCE

A picture rate of about 2 pictures/sec is achieved. If a picture is output every one second of simulated time (i.e. the display is running approximately at a simulation time twice as fast as real time) a clear moving jerky picture is realised, however the display slows the simulation down a certain amount.

If the simulated time between each picture is increased so that the display does not hold up the simulation, each picture jumps in unacceptably large steps to the next picture. This is because large changes in vehicle position can take place in the increased simulated time between each picture.
A very approximate estimate of calculation times within the GT40 suggests that, with a few programming alterations, a picture rate of 10 pictures/sec could be achieved, provided a fast enough data link was available. Faster than this may result in timing problems, with the GT40 being unable to keep up with continuous data transmission.

SOME RESULTS

Some of the features of the program are demonstrated in the results shown below:

The junction simulated is a one way no-turning intersection. Continuous communication channels between vehicles and between vehicle and controller are assumed to exist.

Three strategies have been simulated. Each determines the order of vehicles through the intersection in a different manner. In each, there is the same penalty attached to changing the lane allocation of the intersection. In all of the strategies, vehicles are commanded to follow a velocity profile designed to bring them to the intersection at the appointed times (which are determined by the vehicle order) and with a set speed.

Diagram (3) shows the flow delay characteristics of each of the policies.

(1) This is a first-come first-served algorithm. The order of vehicles through the intersection is determined by the order vehicles pass a control boundary in front of the intersection. Note the low delay and low saturation flow of the scheme.

(2) In this policy the intersection is allocated to each lane in turn for a set period. The method is similar to fixed period traffic lights. Note the higher delays involved and the high ultimate flow achieved.

(3) This is a more complex policy designed to reduce delays. A particular lane holds priority at the intersection until a natural break appears in the incoming stream. The priority then switches to the other lane. This scheme operates as a first-come first-served system at low flow rates and offers lower delays than the fixed time cycle system at high flow rates.
CONCLUSIONS

Although only a limited amount of work has been carried out on this simulation, the picture display has more than proved its worth. Its main advantage lies in being able to readily tie up particular phenomena with line printer data output. This is particularly useful in program development where considerable time can be saved as a result.

ACKNOWLEDGEMENTS

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Control of automated transport systems involves many interacting operations. People have to be informed, guided and regulated. Vehicles have to be manoeuvred, directed and dispatched. Failures and faults must be identified and rectified. Safety must be ensured.

Many of those aspects have been extensively studied, often with optimisation in mind, yet, when extended to whole system operations, most schemes do not perform well. Either necessary vehicle manoeuvres cannot be easily performed, or the system response to fault conditions is inadequate, or unstable modes of operation appear.

Operating schemes are required which will enable the system to operate well under all practical conditions. In complex systems, governed by cost functions embracing qualitative and quantitative economic, social and technical factors, design policies must attempt to find the best operating regions.

To aim for the global optimisation of such intricate systems is unrealistic. Even in the event that an accurate mathematical description of the cost function and system could be produced, the complex, highly constrained, non-linear interaction of variables is certain to defy solution. At best only local optima can be found and by careful design, combined to form an overall 'good' system.

The benefits which accrue from a judicious design of the control structure far outweigh those that can be achieved by optimisation at a detailed level.
This paper will consider a systematic approach to the design process which may help move effective control systems to be evolved.

Good reliability and high safety standards are fundamental factors in any transport control scheme and must figure in any cost function relating to the operation of the whole system. The paper will survey the response of a transport scheme to failures, outlining the requirements for a 'fail soft' system and discuss the use of hierarchical structures to achieve such a characteristic.

Optimisation

The process of optimisation is often presented as a highly exact process. Yet, if optimisation is taken in the general sense of meaning, the systematic approach to a situation, with a view to obtaining the best possible outcome, using what previous knowledge is available, then only in a few situations is this true.

To gather the information necessary to decide upon an improvement takes time. Better forecasts require more time. Optimisation processes cannot work faster than the systems they are trying to improve. Consequently the evolution of good transport schemes may take several decades, whereas the on line optimisation of parameters in a vehicle controller may take only seconds.

Design

The creation of a 'good' system is part of an optimisation process. The designer, by assembling together his previous experience, attempts to create a new system whose properties more closely approach the design specification.

An important part of the design process is the accurate specification of the design environment or a definition of all the influences on the system of interest. These include disturbances for which the design must cater, criteria, fixed information and measures of performance.
There are few direct design precedents for automatic transport control systems. The feedback link labelled 'previous experience' is weak. Nevertheless a good design process will make the maximum use possible of what transferable experience exists.

Designs can be evolved at three levels
1) Structure
2) Subsystem
3) Parameter or equipment

Structural level of design

A system can be considered as a structure of interconnected subsystems. Potentially every subsystem is itself a system. The original system is a subsystem in a more general system. The design problem is limited by the designer. A control engineer will take as fixed the transport policy determining the particular niche his system will fill. Similarly he will take as fixed the range of components available for use in his circuits. Effectively an upper and lower boundary to the problem has been prescribed.
A system is typically much more complicated than a man can overview, only a piece at a time can be considered and so a set of subsystems has to be defined. The most general level of design defines the system organisation. It specifies the most appropriate subsystems and structure to achieve the desired 'whole' system properties.

The choice of subsystems in a system is determined by several factors. Some subsystems are immediately apparent as they correspond to necessary functional units in the system: junction controllers, signalling systems, emergency backup systems are all possible units in a transport control structure.

The choice of subsystems may reflect a degree of complexity, related to the ability of one or more people to fully understand it within a given time. A unit too large to be understood is unlikely to perform well and when it fails will be time-consuming to repair and probably too big to replace.

A subsystem may be chosen because it corresponds closely to an already developed scheme, so reducing the design effort required.

The choice of a structure for a system is less obvious. Some work exists on the theory of structures (refs. 1, 2). However generally the choice of an appropriate structure can only be made on the basis of comparison with other systems exhibiting desirable properties. Direct solutions may not be found but the comparison may constitute some demonstration of feasibility.

Likely control structures for an automatic transport system are either centralised or hierarchical (Ref. 3).

In centralised control structures, a central decision making unit controls all the peripheral subsystems. Information from the subsystems passes to the central office and is available for use in any other subsystem.
Communication costs are high and the centralization of control makes the system very vulnerable to faults.

Well understood centralized control structures can probably offer a better level of control by using all the system information. However, the complexity of interactions between subsystems makes the system less easy to understand.

This has two effects:

1) The system becomes more prone to software faults. An incomplete specification of subsystem states is more likely and may lead to undefined unsafe conditions. The greater number of subsystem states makes fault monitoring and rectification more difficult and costly.

2) The greater number of feedback loops tends to increase the chance of unstable system responses. This forces lower gains to be used and results in a poorer control action.

In a hierarchical structure control is divided between a number of semi-autonomous levels. Hierarchy decouples elements of a system. Each element in the tree is an autonomously functioning subsystem using only limited strategic information from the level above. Frequently this information can be transmitted discontinuously. Communication is in two directions: A command or parameter down the hierarchy specifying what should happen. A feedback or check up the hierarchy saying what is happening.

Hierarchical organisation reduces the number of unwanted feedback loops in the system, so allowing the interaction of subsystems to be more confidently predicted.

Hierarchies show a graduation in properties which are summarised in the diagram.
A hierarchy can be considered as a filter, each layer being concerned only with a range of frequencies. Together the subsystems cater for the entire range of frequencies apparent in the system.

**Subsystems Level of Design**

To a subsystem the rest of the system is its environment. Where the subsystem is designed in isolation, as often will be the case, its interface or connections with the outer world have to be accurately specified, otherwise incompatibilities will arise.

The designer of a subsystem wants to minimise his own particular cost function. This will generally be achieved at the expense of the outside system. The balancing component from the outside must be made visible to the subsystem so that an overall balance can be achieved, i.e., the subsystems should be given boundary conditions suitable for approximating the total optimisation.

The use of simulation is often an appropriate aid to the design of a subsystem. Simulation is a means of modelling approximately the important system interactions, at an accelerated time scale. By investigating a large number of specific situations a more complete picture of the process is built up, hopefully enabling better solutions to be found.

Computer simulations have been extensively used in the analysis of transport control systems, particularly for network design studies, vehicle management and operation strategies (refs. 4, 5, 6 give a selection of representative work in this field).
Parameter Optimisation

At the level of the interaction with the real world, parameter optimisation can frequently be approached mathematically, although in transport control the many parameter constraints and non-linearities prevent general solutions from being found and recourse has to be made to iterative techniques.

In some circumstances an optimal solution to the problem can be found at the design stage and incorporated into the system hardware. Alternatively the designer can structure the hardware in such a way as to allow optimisation to take place 'on line'. This may lead to a better control but at the cost of added complexity of equipment, measurements and communications.

Dynamic optimal controllers are often proposed for vehicle position and speed controllers whilst merge control algorithms may well be optimised at the design stage. (Refs. 7, 8, 9)

'Failsoft' transport control

In the design of large complex transport systems the quality of service is strongly influenced by the reliability of the system and its ability to cope with faults as they occur. Reliability of individual components can be assured up to some limit, failures will however still occur. It has been estimated that given reasonable standards of reliability for a medium sized auto taxi system a failure can be expected somewhere every couple of minutes. A system which is very sensitive to faults is going to be at a severe disadvantage. 'Fail soft' systems can be defined as systems which, as failures occur, progressively become degraded in performance, rather than collapse completely. The design of a control structure to have this sort of property is a 'black art' for which no systematic approach appears to have been developed.
By the systematic application of the standard techniques of reliability, standby and redundancy, to all levels of the design process, to the structure, subsystems and equipment, it is hoped that the effects of a fault can be minimised, its zone of influence circumscribed and its duration minimised, so leading towards the creation of a 'failsoft' system.

Failures of a transport system cause disruption of service and often create unsafe situations. To ensure the safe running of a system requires two control systems. One the normal running control, the other an independent safety control system. The latter oversees the former and is generally a simple controller activated by the single condition 'is the vehicle separation inadequate for the speed of the vehicle?' and issuing one command (e.g. brake at an emergency rate to zero velocity). The safety control system must be autonomous from the normal control system to ensure that failures in normal control are independent of failures in the safety control system, thus reducing the likelihood of a joint and possibly catastrophic failure.

The disruption caused by a fault is particularly dependent upon the severity of the fault. This severity depends on the area of the system affected, the subsequent propagation of the fault through the system and the time duration of the fault.

All these factors are made less significant by designing subsystems to operate as independently as possible over localised regions of the track.

This independence, necessary also for backup safety systems is an intrinsic property of hierarchical structures. Hierarchy allows structures to expand or contract locally without influencing the remainder of the system. The modular nature of such systems reduces maintenance and repair times by simplifying the detection of faults and their repair.
Conclusions

The design of a complex transport control system must integrate all the facets of a transport scheme. Good system availability, safety and fail soft characteristics are especially difficult to design into a system yet are fundamental to its operation.

Hierarchical structures are more readily broken down and understood. They appear to offer characteristics which allow effective designs to be evolved. Other structures may allow better results to be achieved but probably at the cost of much greater design effort.

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INTRODUCTION
Automation is increasingly complex systems. Most of the design, build and operational benefits are high but so are the costs of faulty running. Faults in complex systems have consequences. Contemporary automated systems of control lack flexibility and frequently are disabled by almost any fault. Thus, system reliability is an important aspect of all systems. Although complexity in a system may reduce operational effectiveness, it may be reduced in the system reliability. Operational effectiveness is improved if the greater reliability is achieved by a reduction in system performance levels, it may be attained if the greater reliability is achieved by a reduction in system performance levels. The Perfectionist Approach

The simplest and most common approach is the perfectionist approach. The design of reliable components, combined with operating techniques that reduce the risks of component failure, are better designed to achieve system reliability. The avoidance of novel components and the use of components with a comprehensive reliability record will occur. By reducing the risk of failure, operational effectiveness will be improved. This requires that maintenance costs be reduced. This is implicit in the perfect solution. The assumption is that failures will occur. The price of the improved system performance is the reduced cost of maintenance costs.

Techniques for the assessment of the reliability of components are widely used. Similarly, the reliability of the system is not maintained, but maintained, is of great variety of reliability in the system. The Failure Tolerant Approach

Further improvements to the system can only be achieved by reducing the costs of failures when the design conveniently splits into the following two techniques:

1) 'Fail operational'
2) 'Fail soft' design

Both techniques are concerned with the consequences of a failure detected and the ability to reduce system disruption.

Fail operational. This system at strategic points
the avoidance of novel unproven technology. As a system at strategic points, spare equipment, which, as such, can be replaced, is placed with the provision of flexibility and frequently use computers which are disabled by almost any fault. As a result they usually experience severe reliability problems. (1)

Reliability is an important parameter in the design of all systems. Although the use of increased complexity in a system may allow potentially higher performance levels, it can also increase the cost of failures when they occur. Fail operational design assumes a high cost for any partial or whole system failure. Such design is relevant wherever repair is difficult or impossible and total system operation is vital. Space or military applications are typical examples. However, where such design criteria are not important the 'fail operational design philosophy usually results in unnecessarily expensive schemes. (3)

Fail soft. In many cases 'fail soft' engineering is a more appropriate philosophy. 'Fail soft' is a quality of planned graceful system degradation following a failure. Systems, so designed, attenuate the consequences of a failure, not necessarily by preventing a fault affecting system performance but by effecting an optimal compromise between the degradation of system performance and the provision of extra 'fault proofing' equipment. There has been much discussion of fail operational techniques. The fail soft option has however been neglected, although one or two recent papers acknowledge its importance. In this paper some aspects of the fail soft problem are examined. This may help designers to more accurately specify their reliability problems and assist them to translate an overall system characteristic of 'fail soft' into specific requirements for subsystem.

SYSTEM ASPECTS OF FAIL SOFT DESIGN

A system is a profitable enterprise created and run by an operator and providing a service to the user. Surplus = value of the system to the user - cost of the system to the user. Effective design and operation of the system maximises this surplus, i.e. maximises the system performance. The cost of a failure is disruption which is the loss resulting from a fault, (the increased costs incurred by the operator e.g. repair and replacement costs and the decreased system value to the user e.g. the degradation of service, resulting from the fault).

Disruption = function (intensity, extent, duration) Extent = area of the system affected by a fault Intensity = the importance of the erroneous information to the affected subsystem Duration = the time taken to restore the system to full operational effectivenes.

Fail soft design is based on this equation. At each stage in the design and operation of the system, strategies and equipment are set up so to balance the cost of precautions against the potential disruption of an anticipated fault. Fail soft design is an optimal compromise between the cost of precaution and the consequences of a failure. Fail soft design requires that the system can be degraded gracefully in a way that is not catastrophic. Fail soft design is a quality of a system that can be degraded gracefully in the face of a failure, not necessarily by preventing a fault affecting system performance but by effecting an optimal compromise between the degradation of system performance and the provision of extra 'fault proofing' equipment. There has been much discussion of fail operational techniques. The fail soft option has however been neglected, although one or two recent papers acknowledge its importance. In this paper some aspects of the fail soft problem are examined. This may help designers to more accurately specify their reliability problems and assist them to translate an overall system characteristic of 'fail soft' into specific requirements for subsystem.

The Perfectionist Approach

The simplest and most commonly employed tactic for improving system reliability is the use of more reliable components, combined with design and operating techniques which minimise the failure rates of components in active use. This requires components that are better designed and manufactured, the use of derating, 'burn in', and planned replacement, and the avoidance of novel unproven technology. As completely reliable components do not exist failures still occur. By reducing the system downtime resulting from failures, availability and hence the operational effectiveness of the system can be improved. This requires the use of faster more expensive maintenance and repair techniques e.g. modular construction, online monitoring etc. Implicit in this perfectionist approach is the assumption that failures are costly compared with the price of the improved components, more conservative design practice and better repair provision.

Techniques for the assessment of system reliability from the knowledge of the failure characteristics of components are widely covered in the literature. Similarly the reliability of networks, both maintained and not maintained, is extensively explored, for a wide variety of reliability indexes. (2)

The Fail Tolerant Approach

Further improvements to the operational effectiveness of a system can only be achieved by reducing the costs of failures when they occur. Fault tolerant design is divided into:

1) 'Fail operational' design

2) 'Fail Soft' design

Both techniques are concerned with the provision of flexibility in a system to make it less sensitive to the effects of a failure. In both errors are detected, alternative strategies deployed which reduce system disruption resulting from faults.

Fail operational. This technique incorporates into the system at strategic points, spare equipment, which, as faults occur is progressively substituted for the failed equipment. The original system performance is maintained until at some point the spare capacity is exhausted, whereupon the system fails completely. Fail operational design assumes a very high cost for any partial or whole system failure. Such design is relevant where repair is difficult or impossible and total system operation is vital. Space or military applications are typical examples. However, where such design criteria are not important the 'fail operational design philosophy usually results in unnecessarily expensive schemes. (3)

Fail soft. In many cases 'fail soft' engineering is a more appropriate philosophy. 'Fail soft' is a quality of planned graceful system degradation following a failure. Systems, so designed, attenuate the consequences of a failure, not necessarily by preventing a fault affecting system performance but by effecting an optimal compromise between the degradation of system performance and the provision of extra 'fault proofing' equipment. There has been much discussion of fail operational techniques. The fail soft option has however been neglected, although one or two recent papers acknowledge its importance. In this paper some aspects of the fail soft problem are examined. This may help designers to more accurately specify their reliability problems and assist them to translate an overall system characteristic of 'fail soft' into specific requirements for subsystem.

THE 'FAIL SOFT' DESIGN OF COMPLEX SYSTEMS

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important weapon controlling the disruption resulting from a system failure.

Methods for dealing with anticipated faults are introduced into the system design from the outset. Each strategy can be considered as the optimal use of a new system. This new system being the original system now charged by having a faulty component. Three running states can be identified.

Normal - the system is operating along its most profitable, maximum performance trajectory through the system state space; a path previously anticipated by the designer.

Faulty - the system is operating below its maximum performance trajectory, but on a trajectory optimal for the system with a failed component. Again the path is previously anticipated by the designer.

Extraordinary - the system is being guided along a path in the system state space by real time design decisions made by the system operator. He covers for all unanticipated situations. His success depends on his ability, knowledge (training) and whatever functions of the system are available. He takes direct control of these functions via man-machine interfaces, whose good design is essential for effective operator control. Notwithstanding its importance, the operator and his interface will not be further discussed here.

Thus throughout its life the system can be envisaged as following the best trajectory available to it. At any particular time the system will be running at a certain performance.

Performance = actual rate of profit generation
[maximum rate of profit generation]

Faults reduce the system performance, an effect which is shown schematically on diagram 1. The shaded area corresponds to the disruption caused by the fault. Fail soft strategies seek to minimise this area. The quality of gradual degradation is achieved by minimising sudden losses in performance resulting from failures and by suitable design multiple faults cause only a proportionate loss of performance.

The Effect of System Structure on Disruption

Timescales

Associated with any system is a range of timescales, a range of signal frequencies that the system will respond to. The measurement and control actions, at the system interfaces with its environment, generate the raw signals containing all these system frequencies. A system comprises functional subsystems, local components, and areas of activity, which process input information and generate outputs accordingly. Associated with these processors is the property of 'decision time'. This is related to the maximum bandwidth (or range of frequencies) the processor can handle (analog processes) or to the computing time required to process a sample of input information (digital processes). Thus, with each function in a system can be associated a minimum time or maximum frequency that it can respond to. Only information changing slower than the processor limit can be accepted from the input or transmitted from the output. There will be at minimum a decision time delay before a change at an input affects an output.

The Spread of Faulty Information

The erroneous information generated by a failure will propagate through the system along any available information routes. Most of these routes will be the 'formal' channels comprising the information structure of the system. The remainder will be the 'informal' routes resulting, not from design requirements but from a casual interaction of system components that has no part in normal running. For the predictable operation of systems, these informal routes must be identified and duly considered. Often for successful control they must be eliminated.

Disruption

The disruption resulting from a fault is a function of:

Integrity of the fault
Extent of the fault
Duration of the Fault (Time to restore normal service)

Intensity. The intensity of a fault is in the loss in value to the system of the information output by the failed function. Information transmitted from any point in the system contributes some degree to the system performance. During normal running this contribution is a maximum. Errors in the information will reduce the value of this contribution. The worst case error will have the lowest possible system value. This worst case error will usually cause a lower system performance than not having the information at all i.e. the erroneous information could be a distinct disadvantage to the system performance. The maximum intensity of a fault corresponds to this worst case error.

To reduce a fault intensity implies a reduction in the importance of a function, and hence the worst case error. This might be achieved by simplification and therefore a corresponding reduction in system performance or by a more widespread use of monitoring to partition the system into smaller sections whose individual importance is thus reduced.

Extent. The extent of a failure is a measure of the area of a system influenced by a fault. It is the set of subsystems to which a failed component can send erroneous information to. The extent of a fault is related to the autonomy of the function. The higher the autonomy the fewer the interconnections and the smaller the extent of the fault. Increasing autonomy implies more local measurement and control, the transmission only of selected information, the receipt only of strategic commands and the use of open loop operations. All of these policies reduce the potential performance of a system but improve their resilience to faults and therefore, may, with good designs improve, the operational performance of the system.

Time to restore service. System intended to have a useful life long with respect to the time between failures must be repaired. The disruption caused by a fault is dependent on its duration. However, changes on the system output cannot be faster than the signal producing that change and consequently information output by a rate limited function, even if it is faulty will not change the system faster than that limit will allow. This suggests that it is not the absolute duration of the fault which is important but rather the duration of the fault in units of the failed processor decision time (a non dimensional measure) i.e. the effect on system performance of a fault in a high speed processor will become noticeable more rapidly than if the processor were a low speed function. (see dia 2)

Repair times however depend on the complexity of the function involved. Thus for functions of similar complexity repairs are likely to take about the same time. As a result a failed high speed function of similar complexity to a failed low speed system will cause a proportionately greater disruption. (see dia 3,4)

From the argument it is apparent that measures which control disruption by minimising fault duration times are more effective on faster functions.

The Effect of Delay

Each functional unit in a system introduces delays into a signal flow. The longer the delay a signal experiences the more up to date it will be and the more value it will have for control. The one-way
Methods for dealing with anticipated faults are introduced into the system design from the outset. Each strategy can be considered as the optimal use of a new system. This new system being the original system now changed by having a faulty component. Three running states can be identified.

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The Collection of Faults

Faults reduce the system performance, an effect which is shown schematically on diagram 1. The extent of the disruption caused by the fault. Fail soft strategies seek to minimize this area. The quality of gradual degradation is achieved by simulating chosen slow in performance resulting from failures and by suitable design multiple faults cause only a proportionate loss of performance.

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Associated with any system is a range of timescales, a range of signal frequencies that the system will respond to. The measurement and control actions, at the system interface with its environment with itself generate the raw signals containing all these system frequencies. A system comprises functional subsystems, local concentrations of activity, which process input information and generate outputs accordingly. Associated with these processors is the property of ‘decision time’ or processor speed. This is related to the maximum bandwidth (or range of frequencies) that the processor can handle (analogous processors) or to the computational time required to process a sample of input information (digital processors). Thus with each function in a system can be associated a minimum time or maximum frequency at it can respond to. Only information changing slower than the processor limit can be accepted from the input or transmitted from the output. There will be at least a decision time delay before a change at an input affects an output.

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Dissipation

The dissipation resulting from a fault is a function of

- Extent of the fault
- Intensity of the fault
- Duration of the fault (Time to restore normal service)

Intensity. The intensity of a fault is the loss in value to the system of the information output by the failed function. Information transmitted from any point in the system contributes some degree to the system performance. During normal running this contribution is a maximum. Errors in the information will reduce the value of this contribution. The worst case error will have the lowest possible system value. This worst case error will usually cause a lower system performance than not having the information at all i.e. the erroneous information could be a distinct disadvantage to the system performance. The maximum intensity of a fault corresponds to this worst case error.

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Repair times however depend on the complexity of the function involved. Thus the functions of similar complexity repairs are likely to take about the same time. As a result a failed high speed function of similar complexity to a failed low speed function will cause a proportionately greater disruption.

The Effect of Delay

Each functional unit in a system introduces delays into a signal flow. The longer the delay a signal experiences the more up to date it is and the more value it will have for control. The current
arguing suggests that the greater the delay given to erroneous information the lower the effect it will have on the system. This suggests a means of controlling disruption. For example, system performance can frequently be traded for system speed. If this cannot be achieved, then some control strategies can be made to operate faster than the forecasted error propagating mechanism so as to form of forward error control is possible. In the general case, functions should be designed to operate at the slowest speed consistent with them fulfilling their desired role.

Potential Performance, Disruption and operational effectiveness

To achieve the highest potential performance for a system each item of information is used to its maximum value, i.e. the information is believed, and used as fast as possible and everywhere possible. However, if the information is in error, then the performance then achieved may well be lower than if the information had not been used. Thus increased system complexity, aimed at extracting the maximum value from information, may increase potential system performance, and decrease actual performance. Altering the increased complexity may be used to improve reliability; potential performance is not increased but the actual performance may.

SYSTEM STRUCTURES

There are two distinct structures in a system.
1) The physical structure i.e. the distribution of system hardware around the region and the supply of communication channels.
2) The information structure i.e. the definitions of functions, tasks and the data flows required between them.

Often, particular functions correspond to particular modules of equipment, and particular data flows correspond to certain communications equipment. However, hardware communication facilities allow the information processing in a system to be geographically distributed anywhere in the locality. The degree to which this is done depends on the relative provision costs of processing and communication equipment. The cost of a single processing module can be approximately characterised as the sum of two terms. One proportional to the functional capability of the module the other a fixed term governed by the module quality (e.g. reliability).

Similarly for communications equipment there is a standing cost and a variable cost dependent on bandwidth and range. The current trend of decreasing module fixed costs with large scale integration reduces the overheads associated with physically distributed systems. Processing power is becoming cheaper relative to communications. This favours the use of local autonomous processing and reduced communication requirements.

Centralised Systems

Measurement data is supplied to a central controller which consequently must operate at maximum system speeds everywhere so maximising the potential system performance. Centralised systems usually exploit the control variables. The data is progressively condensed as it moves up the structure. Decision times become longer, control action is more general and information has a more global context. Each unit in the hierarchy operates semi-autonomously in a dedicated role. It receives limited strategic commands from its superior mode. It passes on delegated commands to its subordinate units. In the absence of specific commands the unit has a regulating function it can execute alone using its previous command. Information is only selectively directed up the hierarchy consequently not all the system information is available everywhere in the network. The limited information transfer degrades the system bus at the expense of reducing potential system performance.

The structure of hierarchies provides substantial built-in protection against the propagation of faults. This is particularly true if every function is placed as high up the hierarchy as possible, each function controlling the narrowest band of signal speeds possible.

Distributed Systems

An array of locally sited processors performing particular tasks are interconnected using communication links. The characteristics of such systems are dependent on the style of organisation chosen.

Networks. All units in the system are connected to all others. Depending on the organisation of the measurement and control functions, the connections may be high bandwidth or low.

In one common arrangement all the system units are multiplexed onto a high capacity bus. This has the advantage that substantial connectivity can be provided at low cost. System organisation is almost totally determined by software since interconnections are made by message addressing. This facilitates substantial reconstructions of the system to counteract faults. As the bus is a shared resource its performance is typical of queuing phenomena. The bus itself is very vulnerable to failures causing a total system shut down i.e. it is a particularly vital component. Also system resistance to faults is substantially reduced by the ease with which faults can propagate along 'informal' paths created as a result of addressing failures. However, the hardware simplicity of the scheme makes the use of fail safe designs and high reliability techniques realistic.

The ease of reconfiguration allows the system to expand gracefully to cope with increased system requirements so reducing the problem of escalation. Duplication of equipment can be connected to the bus so enabling redundancy to be very flexibly applied, particularly if one unit may be used to replace any of several similar ones performing different roles. Bus-type structures are particularly suited to digital systems and if units are standardised there are advantages in maintenance, diagnostics and repair.

Hierarchical distributed systems. A hierarchy is a multi-layer control organisation. It can be considered as a filter, each processing layer being associated with a range of frequencies or band of time scales. Together the layers cater for the entire range of frequencies apparent in the system. Only at the first layer are found the actual physical measurement and control variables. The data is progressively condensed as it moves up the structure. Decision times become longer, control action is more general and information has a more global context. Each unit in the hierarchy operates semi-autonomously in a dedicated role. It receives limited strategic commands from its superior mode. It passes on delegated commands to its subordinate units. In the absence of specific commands the unit has a regulating function it can execute alone using its previous command. Information is only selectively directed up the hierarchy consequently not all the system information is available everywhere in the network. The limited information transfer degrades the system bus at the expense of reducing potential system performance.

The structure of hierarchies provides substantial built-in protection against the propagation of faults. This is particularly true if every function is placed as high up the hierarchy as possible, each function controlling the narrowest band of signal speeds possible.
FAULT CONTROL

Fault control systems are either open-loop or closed-loop.

Open-loop. Open loop fault control is sometimes called built-in redundancy. An equipment structure is used which is more elaborate than the minimum necessary to achieve the desired function. All the components are active all the time but the configuration is such that when a failure occurs the function as a whole does not fail. The construction and effectiveness of such systems relies upon the fault modes of a device being known. Two approaches are possible. In the first a failure makes the failed unit transparent to the rest of the function e.g. relays, diodes, network i.e. the transfer function with m components

\[ F(n) = F(n-1) = F(1) \]

and the reliability with m components. 

In the second approach failures cause a change in the transfer function of the unit and the redundancy is such that the sensitivity to faults is reduced. In this case the function has an expected transfer function which depends on the faults that have occurred. e.g. transducer circuitry with protection or queuing systems.

Closed-loop. Substantially more important are closed-loop fault control systems. Although greater expense is involved, in principle any fault condition can be so controlled.

A monitor measures the actual system state and compares it with a prediction generated by an implicit or explicit model. The detection of discrepancies initiates strategies designed to counteract and remedy the failure. (See dia 5)

The output of the monitor may be continuous or discrete. The design of fault controllers using continuous error signals is allied to that of closed loop automatic control for which an essential concept is the use of test equipment so reducing costs that are otherwise incurred. This propagation of information is desirable to that of closed loop automatic control for which a substantial body of theory exists. The onset of a failure can be considered as changing the transfer function of a system or as random disturbances introduced into the system. In all cases there are substantial problems of formulation and analysis. Usually fault protection is carried out using discrete fault monitoring, the detection of a fault causing a specific alternative strategy to be selected.

Failures

A failure is an event after whose occurrence the output state of a device shifts outside permissible limits.

The output state of a device depends on

1) Its design
2) Its environment
3) Its initialisation
4) Its interface
5) Its operation

Initial conditions

Failures can arise at any of these phases.

Monitoring

The physical event of a failure causes a change in a variable at the point of failure. This propagates downstream in errors. The monitor detects these errors, not the fault itself, and before any fault control action can take place a monitor must detect an error. The function sees classes of information associated with a function.

The states which correspond to the function specification exist. The onset of a failure generates the correct states accepted by the monitor. Ideally these three sets should overlap, in practice they do not because of limitations and errors in both the function and the monitor.

The 'coverage' of the monitor is the fraction of errors the monitor detects. The 'restrictiveness' is the fraction of normal states classified as faulty. Inadequate coverage is expensive because of uncontrolled faults. Excessive restrictiveness is expensive because the normal system performance is constrained. Usually there is a trade-off between the two.

Only a limited number of monitors can be deployed testing the most important variables i.e. monitors are sited where information has the most value, where in the event of a failure disruption would be a maximum and outweighs the cost of monitor provision. The information yielded by these monitors is the only information available for locating and controlling failures. More error checks allow more comprehensive monitoring of system states, a better identification of the failure site and a more appropriate selection of alternative strategies. However, greater expense is involved and as the error detecting mechanism is in series with the processor being checked the system reliability is reduced and the system response slowed.

Error Recovery

The objective of the error recovery phase is the restoration of normal system functioning after a failure, with the minimum of disruption. Recovery from a failure is governed by three factors.

1) The timescale of the failed function
2) The repair time
3) The interim control of system disruption.

Timescales. The time dependency of disruption is governed by the timescale of the failed function. If repair times are short with respect to the failure time scale then there need only be minimal control of system disruption. If repair times are long with respect to the function time scale then more elaborate measures are required. Repair times must be made shorter, and more sophisticated interim control strategies operated (see dia 4).

Repair times. The overall time to restore the original service depends on the repair arrangements. Plug-in replacement modules restore service rapidly at high cost. Remove, repair, replace strategies give high system downtime but are cheaper to operate.

The provision of on-line monitoring allows more precise rapid fault location and better interim control. Off-line monitoring improves system reliability and makes better use of test equipment so reducing costs that way. Repair times may be lessened by diminishing system complexity between monitors e.g. by reducing monitor spacing or by the use of more standardised equipment.

The use of marginal testing and preventative maintenance is a means of identifying and controlling faults for minimal system disruption since by for example maintaining the system at weekends or during the night the necessary loss of service has minimal cost.

Interim Control of System Disruption

Switching System

The monitor is an error detecting interface through which information flows from one function to another. During normal running this information has its maximum value to the system. Faults reduce this value. In the place of particular faulty units, disruption control strategies provide an alternative supply of information having the best possible system value, given the available resources. The more information about the current running state of the system that can be used, the more effective can the control be made.

Interim measures for fault control are selected by switching i.e. the system structure is reorganised. The rearrangement may reduce the information requirement.
merits in terms of correspondingly lowering the system performance or it may maintain the original performance. The more closely the original performance is to be maintained the more expensive is the provision of substitute processing capacity for the interim fault control.

There are several techniques of interim control. 1) The failed element is replaced by another unit. Apart from switching transients there is no major service disruption. For fast acting functions the switching must be online and automatic. For slow acting functions off-line switching can be used in the form of module replacement by repairmen. The replacement function may fulfill the same role as the failed functions or have a simplified role yielding a lower system performance but at a lower cost. In some circumstances several alternatives may be provided for a given function if it is sufficiently important or unreliable. Direct function replacement depends for its effectiveness upon the failure being located in the replaced function (otherwise faulty information will not be controlled). Direct function replacement is expensive and is therefore only installed where the costs of failure are high and strongly time dependent.

2) The failed function is isolated and the downstream structure modified so that it no longer requires (or is less affected by) the now faulty information. This feed forward type of control necessarily entails some loss of system performance. However, it is much less expensive and does not require fault location for its effective use.

3) The failed function is disconnected and substitute standardized information is input. The information is chosen specifically to minimize subsequent disruption. Examples might be:
   a) An average value command is given
   b) The last correct command is used
   c) A predetermined satisfactory value is sent
   d) A human operator input.

Vital Functions

Although a hierarchy of fault protection strategies can be incorporated into a system to attenuate the consequences of most faults some vital points will remain vulnerable. It is at these points that components with a high intrinsic reliability need to be placed, since no alternative action can be devised to control disruption. Such points may often be the switching nodes for other fault control equipment.(7)

CONCLUSIONS

This paper discusses some of the important facets of 'fail soft' engineering. The subject has been approached deterministically. Every error has a causative failure, every failure has an evaluable consequence and probability of occurrence. However, only general rules have been developed, whose implementation demands a very high degree of system analysis at the design stage. Methods have been developed and are well surveyed in the literature, which enable some of this analysis to be achieved. Often they fail or are unreliable in the complex situations that arise in practice. Systems must be made intelligible by design simplification and analytic approximation and assumption, i.e. system complexity must be reduced. The use of low complexity may reduce potential performance but the decrease in design overheads and improvement in operational effectiveness may more than compensate.
Dia. 1 - Time dependency of system performance following a fault

Dia. 2 - Fault performance of low speed function compared with that of a high speed function

Dia. 3 - Effect of complexity on repair time

Dia. 4 - Performance of faulty slow and fast functions with fixed repair time

Dia. 5 - Schematic of system and fault controller
APPENDIX 8  Computer programs

In the course of the research reported in this thesis, a number of computer programs have been written. A selection of the more important are contained in this appendix. They are as follows -

1) A program to simulate an intersection in a vehicle-follower type system
2) A program to simulate a network in an asynchronous transport system
3) The programs required in the GT40 to produce the moving picture display (these are written in PAL II or FOCAL)
4) A program to simulate the control of vehicles in an asynchronous, marker-follower type control system
5) A FOCAL program that provides the rolling graph display used by 4)
THIS PROGRAM SIMULATES AN INTERSECTION WITH CONTINUOUS VEHICLE-FOLLOWER TYPE CONTROL.

C

C STD (L0,LP),(DO,LO),(LL,LO)
C PAUSE T3 TO TO
C EXTRABOO
C ALLOBT (FILE,05),(RSI,30),(FAR,B),(FSI,950)
C IBANHAK 00=8
   COMMON TARGET(100,4),VENA(2,8,50),ITARG(2,50),ITPRINT(2,2),
   CMAR(101),IPPRINT(2),IFLOW(2),ITYPE,ITIME,DELT,LSPAX,
   CBLPNML,ACCNML,ACCEMP,INTPOS,CRLPOS,SPEED,CONCON,FFHDWW,FCHDWW,
   CVEL,JNC,IFLOW,TIME,AFLOW(3,3),LFLOW(3,2),IPARAM,TCOCC,COCC,JNC,
   CTOBIP,NVEH,DELAY(2,2,20),AVDEL(2,3),FADEL(6,9),
C CMAM,TOTAL,TIMLAG,IBTA(2,2,50),AHDMY(100,2),MA(2,2),
C CP(2),PCOCCP(2),PEROCC(2),STPTB(2),TARRY,ITARRY
C NXVH(2)
C NPBACK(100)
C KOUNT(2,2)
   INTEGER TBLACK
   DIMENSION MSTA(50)
   REAL LSPAX,LSPNML,INTPOS
   DIMENSION ASPACE(2),NN(2)
C READ IN RUN DATA.
   READ(105,1)DELT,LSPAX,LSPNML,ACCNML,ACCEMP,INTPOS,CRLPOS,SPEED,
   CONCON,FFHDWW,FCHDWW,VL
   READ(105,2)JFLOW,IPPRINT,ASPACE(1),ASPACE(2),NN(1),NN(2)
   READ(105,22)IPARAM,NVEH
C INIT READ(105,110) TIMLAG,TOTAL,TSTOP
   READ(105,111)TBLACK,NB,LANE,IPLOT
   READ(105,62)MAR
   READ(105,300)P(1),P(2)
GOTO 5
6 STOP
C WRITE HEADER:
   WRITE(108,79)
   CALL ANO
PAUSE
C INITIALISE MOVING PICTURE DRAWING BY SENDING NETWORK TABLE TO GT40.
    CALL GRAPH1(0,FALSE,0,IPL0)
8 CONTINUE
    IF (ITIM+DELT+LT+TSTOP) GOTO 20
ENDFILE 1
C END FILE ON MAGNETIC TAPE RECORD.
    CALL WRFIN
    STOP VNOVER
20 CONTINUE
    IF (KFLOW+NE+JFLOW) GOTO 101
C CALCULATE HISTOGRAM.
    CALL DISTRI(N,NE+1,GOTO 16)
    KFLOW=0
101 CONTINUE
    IF (NPARAM+NE+IPARAM) GOTO 226
C CALCULATE MEANS AND STANDARD DEVIATION.
    CALL CRIT
C OUTPUT OF MEAN AND VARIANCE, LANE BY LANE.
NPARA=0
226 IF (INPRINT+NE+IPRINT) GOTO 102
C OUTPUT DATA TO LINE PRINTER.
C OUTPUT DATA TO MAGNETIC TAPE FOR SUBSEQUENT PLOTTING.
    CALL WRITELANE(N)
C (ALL NPLOT=0 AVERAGE TOGETHER).
103 CONTINUE
    IF (INPRINT+NE+IPRINT) GOTO 102
16 IF (NNO+NE+NC) GOTO 19
    IF (ITBLOCK+EO+1) GOTO 19
C OUTPUT NEXT FRAME OF MOVING PICTURE.
280 CALL GRAPH1(JFLAG)
    IF (JFLAG+EQ+1) GOTO 60, RECYCLE TIMER 11
281, NN0=0
282, IC0=0
283, IC1=0
284, IC2=0, NEUREX(0)
285, RETURN
C INCREMENT COUNTERS.
    IF (NPLOT+EQ+1) GOTO 280, INCLUDE TIME FOR 101/140.
225 KFLOW=KFLOW+1
294 RETURN
C MANOEUVRE VEHICLES:
CALL VMANOV
CALL VMOVE2
NPLPT=(NPLPT+DELT=STIME)/TILAG
IF (NPLPT=EQ.0) GOTO 8
STIME=STIME+DELT
IF (MARR(I,J,K)=NE=0) GOTO 16
IF (MARR(I,J,K)=NE=0) GOTO 13
DO 10 I=1,Z
DO 10 J=1,Z
DO 11 K=1,Z
11 HSTA(I,K)=FLOAT(ISTA(I,J,K))/FLOAT(KOUNT(I,J))
C OUTPUT HISTOGRAMS OF HEADWAYS (LANE BY LANE)
10 CALL PLOTER(HSTA,50,TRUE,STIME,DELT,J,I)
GOTO 16
13 CONTINUE
DO 14 I=1,Z
14 CONTINUE
DO 15 K=1,Z
15 CONTINUE
16 CONTINUE
CALL DIS
GOTO 8
220 FORMAT(1HO,'PARAMETER TIME STEPS',T30,'NO OF VEH IN DELAY AV:',
CT60,'RECYCLE TIME 1',T80,'RECYCLE TIME 2')
221 FORMAT(I10,T30,I10,T60,F10-3,T80,F10-3)
223 FORMAT(1HO,'PLOT ITER STEPS',T20,'AXIS TIME FOR 10IN',T40,
C'DATA REF NO',T60,'PLOT LANE NO')
225 FORMAT(T2,I9,F20-3,F20)
224 FORMAT(//)
1  FORMAT(6F10.3,/F10.3)
2  FORMAT(2I10.2F10.7/2I10)
3  FORMAT(2I9.120/2F20.7/2I20)
4  FORMAT(1H1,'RUN CONSTANTS ARE')
5  FORMAT(1H6,'TIME INTERVAL',T20,'MAX LINE SPEED',T40,'NORMAL LINE SPEED',T60,'NORMAL ACCN',T80,'EMERGENCY ACCN',T100,'POSN OF INTERSECTION')
6  FORMAT(2I10)
7  FORMAT(1H0,'POSN OF CONTROLS',T20,'INITIAL JUNC SPEED',T40,'SERVO CONSTANT',T60,'FOLLOWING FACTOR',T80,'CROSSING FACTOR',T100,'VEHICLE LENGTH')
8  FORMAT(1H0,'FOLLOW VEHICLES',T20,'PRINT TIME STEPS',T40,'C/HEADWAY TYPE 1',T60,'C/HEADWAY TYPE 2',T80,'NO OF VEH/HDWY FRACT

9  FORMAT(1H12) 200  300  400  500  600  700  800  900  EMD
10  FORMAT(F10.3,F10.3,F12.2)
C THIS ROUTINE MOVES VEHICLES, ADDS VEHICLES AT ENTRANCE
C AND DELETES THEM AT EXIT.
C
SUBROUTINE VMOVE
REAL LEHAY
REAL LSPMAX, LSPNML, INTPOS
DIMENSION DTACK(10, 2)
DIMENSION SPACE(12)
DIMENSION NA(2)
LOGICAL EMERG(12, 20)
COMMON TARGET(100, 4), VEH(2, R, 50), ITARG(2, 50), IPTNT(2, 2),
CMAR(10), JPOINT(2), IFL(2), ITYPE, ITIME, DELT, LSPMAX,
CLSPNML, ACCNML, ACCEMG, INTPOS, CRLPOS, SPEED, CONCON, FFHWDY, FCHWDY,
CVELUNL, JFLW, FTIME, AFLOW(3, 3), LFLOW(3, 2), IPARM, PCCC, OCCNC,
CTB, LIP, VNEH, DELAY(2, P, 20), ADEL(2, 3), FACDEL(6, 4), VPE,
CNOAM, TOTAL, TIMLAD, ISTA(S, 2, 50), AHDWY(100, 2), MA(2, 2),
CP(12), PCCCP(12), PERCC(12), SLTPT(12), TARR, ITARY

C INI
CENDBACK(100)
C COUNT(12, 2)
C DIMENSION DTIME(2)
C DIMENSION ISCT(2)
C IF (VEH=EQ.0) NOAM=20
C IF (VEH=NE.0) NOAM=VEH

C INITIALISATION
C FRACCOUNT = 0,
SSECT(1)=1, 0.1,
ISCT(1)=1, 0.5
MA(1)=1, 100, 1,
C NAD MA(1, 2)=1
MA(2)=1, 100, 1,
MA(2)=1, 100, 1,
C TB DTIME(1)=0, 10, 10, 10
C DTIME(2)=0, 10, DELT, SPACE(T), DELT, T, 2, 10
C DB D=1, 12
D(20) J=1, 2
DB 20 J=1, 50
VEHA(I=3,J)=0.0
20 EMERG(I,J)=FALSE
   IPOINT(I,J)=50
   IPOINT(I,J)=2
   VEHA(I,J)=0
   VEHA(I,J)=LSNML
   VEHA(I,J)=0
   EMHDWY = (LSNML - LSNML/2*ACCMG)*VL
   VEHA(I,J)=EMHDWY*FFHDW
   VEHA(I,J)=0
   VEHA(I,J)=9999
   VEHA(I,J)=EMHDWY
   N*1(J)=1
   LFLOW(I,J)=1
   LFLOW(I,J)=0
   LFLOW(I,J)=0
   DO 209 J=1,2
   DO 209 K=1,NCAH
209 DELAY(I,J,K)=0
9 CONTINUE
CALL SPACE(Spacen(I,1)
   CALL SPACE(Spacen(2,2)
   RETURN
C
ENTRY VMOVE
   DO 10 I=1,2
   C FRONT VEHICLE
   N2 = IPOINT(I,J)=1
   IF (N2*EDO 0) N2=50
   POSN=9999*EMHDWY*FFHDW
   C NO VEHICLES IN LANE
   IF (N2*EDO IPOINT(I,J)) GOTO 1
   POSN = VEHA(I,J,N2)
   C IS VEHICLE DUE TO ENTER JUNCTION
   IF (ABB*TIME*DELT-Spacen(I)) GT*DELT/1.5) GOTO 11
   12 N2 = IPOINT(I,J)
   CALL PRINT(I1*VEHICLE ENTERING JUNCTION AT*TIME*DELT,28,I,N2)
C INITIALISE VARIABLES
  VEHAI(I+1,N2) = 0, I = 1, 2, 3, 4
  VEHAI(I+2,N2) = LSPNMLSCD, 114
  VEHAI(I+3,N2) = DLT
  VEHAI(I+4,N2) = EMHDWY*FFHCLUDED
C FIND VEHICLE IN QUEUE POINTER.
  IPONE(I+2) = IPONE(I+2) + 1
  IF (IPONE(I+2) EQ 51) IPONE(I+2) = 1

C FIND HEADWAY TO NEXT INCUMING VEHICLE.
  CALL SPACE(SPACEI(I+1))
  CALL DISTR(SPACEI(I+1), N1)

C DEP. SPACEDI(I+1) = SPACEI(I+1) + ITIME*DELT
  LFLOW[I+1,I] = LFLOW[I+1,I] + 1
  IF (IN2*EQ*IPONE(I+1)) GETNO 10
  N1 = IPONE(I+1) + 1  FSC(I+1)*I
  IF (N1*EG+51) N1 = 1
  POSN = VEHAI(I+3,N1)
  BOUNJ = 2*INTPS
C HAS VEHICLE LEFT JUNCTION?
C SAVE IF (POSN = BOUNJ) 14, 15 INFORMATION FOR DISTRIBUTION CALCULATION.

13 LFLOW[I+1,I] = LFLOW[I+1,I] + 1, EXIT(I+1)*PO*1ST
  CALL PRINT1(VEHICLE LEAVING JUNCTION AT, ITIME, DELT, 28, I, N1)

C SAVE DELAY VARIABLES
  DELAY(I+1,N4(I)+1) = VEHAI(I+2,N1)
  DELAY(I+2,N4(I)+1) = VEHAI(I+3,N1)
  DSAVE = VEHAI(I+5,N1)
  N1 = 1
  CALL DISTR(VEHAI(I+5,N1), I)
  CALL CRIT4(DSAVE, I)
  VEHAI(I+3, N1) = 0

13 IPONE(I+1) = N1
  N1 = N4(I) + 1
  N4(I) = N4(I) + 1
  N4(I+1) = N4(I+1) + 1
  N4(I+2) = 5
  IF (N4(I) = EQ+NOAH+1) N4(I) = 1
  IPONE(I+1) = N1
  N1 = N4(I) + 1
  IF (N1*EG+51) N1 = 1
IF (N3*EG=0) N3=50
POS1=VEHA(I,3,N3)
POS2=VEHA(I,3,J)
DIST=POS1-POS2
C CHECK THAT VEHICLES ARE SEPARATED BY MORE THAN MINIMUM HEADWAY.
IF (VEHA(I,6,J)) 16,5,10,2
16 EMHDW=VEHA(I,7,J)
IF (DIST=EMHDW) 18,1,3
18 IF (EMERGI(I,J)) GOTO 21
CALL PRINT1: EMERGENCY HEADWAY INFRINGED AT: TIME*DELT=31, I,J
EMERGI(I,J) = TRUE
STOP 1
21 ACCN = ACCEM
GOTO 22
19 IF (*NOT EMERGI(I,J)) GOTO 23
CALL PRINT1: EMERGENCY DECN END AT: TIME*DELT=22, I,J
EMERGI(I,J) = FALSE
23 GOTO 24
17 IF (ITARG(I,J)*NE=0) GOTO 25
C CALCULATE ACCELERATION TO APPLY TO VEHICLE.
24 ACCN = VEHA(I,6,J)*CONVEH/VEHA(I,4,J)
IF (ABB*ACCM>LTEM*ACCNML) GOTO 26
25 ACCN = SIGN(ACCNML*ACCN)
26 VEL = VEHA(I,2,J)
IF ((VEL*LE=0)+AND*(ACCN=LTEM=0)) ACCN=0
IF ((VEL*GE=LBPHAX)+AND*(ACCN=GT=0)) ACCN=0
IF (ITARG(I,J)*EQ=0) GOTO 22
IF (VEHA(I,1,J)*LT*ACCN) ACCN=VEHA(I,1,J)
22 CONTINUE
VEHA(I,1,J)=ACCN
25 CONTINUE
IF (J*EQ=N2) GOTO 58
J=J+1
IF (J*EQ=N3) J=1
GOTO 19
58 N1=IPINT(I,1)+1
IF (N1*SEQ=51) N1=1

ACCN = ACCEM
GOTO 22
23 GOTO 24
17 IF (ITARG(I,J)*NE=0) GOTO 25
C CALCULATE ACCELERATION TO APPLY TO VEHICLE.
24 ACCN = VEHA(I,6,J)*CONVEH/VEHA(I,4,J)
IF (ABB*ACCM>LTEM*ACCNML) GOTO 26
25 ACCN = SIGN(ACCNML*ACCN)
26 VEL = VEHA(I,2,J)
IF ((VEL*LE=0)+AND*(ACCN=LTEM=0)) ACCN=0
IF ((VEL*GE=LBPHAX)+AND*(ACCN=GT=0)) ACCN=0
IF (ITARG(I,J)*EQ=0) GOTO 22
IF (VEHA(I,1,J)*LT*ACCN) ACCN=VEHA(I,1,J)
22 CONTINUE
VEHA(I,1,J)=ACCN
25 CONTINUE
IF (J*EQ=N2) GOTO 58
J=J+1
IF (J*EQ=N3) J=1
GOTO 19
58 N1=IPINT(I,1)+1
IF (N1*SEQ=51) N1=1

ACCN = ACCEM
GOTO 22
23 GOTO 24
17 IF (ITARG(I,J)*NE=0) GOTO 25
C CALCULATE ACCELERATION TO APPLY TO VEHICLE.
24 ACCN = VEHA(I,6,J)*CONVEH/VEHA(I,4,J)
IF (ABB*ACCM>LTEM*ACCNML) GOTO 26
25 ACCN = SIGN(ACCNML*ACCN)
26 VEL = VEHA(I,2,J)
IF ((VEL*LE=0)+AND*(ACCN=LTEM=0)) ACCN=0
IF ((VEL*GE=LBPHAX)+AND*(ACCN=GT=0)) ACCN=0
IF (ITARG(I,J)*EQ=0) GOTO 22
IF (VEHA(I,1,J)*LT*ACCN) ACCN=VEHA(I,1,J)
22 CONTINUE
VEHA(I,1,J)=ACCN
25 CONTINUE
IF (J*EQ=N2) GOTO 58
J=J+1
IF (J*EQ=N3) J=1
GOTO 19
58 N1=IPINT(I,1)+1
IF (N1*SEQ=51) N1=1
N2=IPOINT(I,2)=1
IF (N2=EQ=0) N2=50
J=N1
27 CONTINUE
U=VEHAI(I,2,J)
IF (U=EQ=0) GOTO 208
208 U=0
C MOVE VEHICLES FORWARD ONE TIME INCREMENT T=DELT
C TIME
U=VEHAI(I,1,J)
C=VEHAI(I,2,J)
C=VEHAI(I,2,J)+DELTA/2
LDEL=DELT/2+CDEL+1./VEL
U=VEHAI(I,1,J)+S*CDEL+1./VEL+LDEL/2
IF (U=EQ=0) GOTO 28
U=ACCEL
N3=J-1
IF (N3=EQ=0) N3=50
LLEWAY=VEHAI(I,2,J)+N3=POSN+HDWY
VEHAI(I,2,J)=LLEWAY
28 VEHAI(I,2,J)=EMHDWY
VEHAI(I,2,J)=HDWY+LLEWAY
IF (J=EQ=2) GOTO 10
J=J+1
GOTO 27
10 CONTINUE
C RETURN
C END
C
C

SUBROUTINE VEHANC

LOGICAL FLAG

REAL LSPLMAX,LSPNML,INTPOS

COMMON TARGET(100),VEHA(2,8,50),ITARG(2,50),IPoint(2,2),

CMAR(101),JLINT(2),LFLOW(2),ITYPE,ITIME,DELT,LSPLMAX,

C

CLSPNML,ACCML,ACCEN,INTPB,CRLPOS,SPEED,CONCON,FFCHAWY,FCHAWY,

C

CTELLN,VEH,FTIME,LFLOW(3,3),LFLOW(3,2),IPARAM,PCOCX,OCX,INC,

C

CFIELD,VEH,DELAY(2,2,20),AVDEL(2,3),FADEL(6),VL,

C

CMNAM,TLMLEN,STA(12,2,50),HNDY(100,2),MA(2,2),

C

CP(2),PCOCX(2),PERCC(2),SLTPB(2),TARRY,ITARY

A5 C\#VNH(12)

C\#BACK(100)

C\#KOUNT(12,2)

THDWAY=SPEED(12,2,ACENM)+VL/SPEED

THDWAYC=THDWAY+FFHAWY+FFHAWY/2,

200 IF BA=LSPLNML=LSPLNML/ACCML

DO 37 I=1,2

N1=IPoint(I,1)+1

N2=IPoint(I,2)+1

IF (N1 EQ 51) N1=1

IF (N2 EQ 40) N2=40

IF (N1 EQ IPoint(I,2)) GO TO 37

J=N1

6 PBN=VEHA(I,3,1)

FLAG=FALSE

ACCNM=0

IF (PBN=CRLPOS) 39,40,46

C HAS VEHICLE ENTERED JUNCTION CONTROL ZONE?

40 IF (PBN=INTPOS+40,314,1,42,42

41 NP=ITARG(I,2)

IF (NP=0) GO TO 44

200 CALL PRINT1(VEH CROSSING CONTROL BOUNDARY AT,ITIME*DELT,33)

C\#DJ

C GIVE IT A TARGET NUMBER.

CALL TAG3(I,2)
C=UV*UV+UJ*UJ-2*DTTJ*ACCNML
D4=B+B++A+C
IF (D4+GE+0) GOTO 207
ACCN=ACCEMG
CALL PRINT1: EMERGENCY DECN TO REACH INT VELO AT1, ITIME=DELT,
C3B,J=J
STOP 2
GOTO 39
207 D3=SQR(D4)
UI=(-B+D3)/12*A
57 CONTINUE
IF (UI LE LSPMAX) GOTO 209
UI=LSPMAX
FLAG=TRUE
209 IF (ABS(UI-UV)*LT+1) GOTO 203
IF (UI=UV)200,201,202
200 ACCE=ACCNML
GOTO 203
201 ACCE=0
GOTO 203
202 ACCE=0
IF (UI=UV) GT 0 ACCE=ACCNML
203 GOTO 39
42 H=ITARG(I,J)
C VEHICLE HAS PASSED INTERSECTION.
IF (I+LE+0) GOTO 46
IF (ITIME=DELT=TARGET(M,1)*GT+0) GOTO 45
CALL PRINT1: VEH IS TOO EARLY AT JUNCTION AT1, ITIME=DELT,
C32,J=J
45 IF (ABS(ITARGET(M,2)-VEHA(I,2,J))*LT+1) GOTO 38
CALL PRINT1: ERROR IN VEH SPEED OF 'VEHA(I,2,J)=TARGET(M,2),
C32,J=J
38 CALL TAG4(I,J)
GOTO 47
46 IF (I+EQ+0) GOTO39
47 IF (VEHA(I,2,J)*GE*LSPNML) GOTO 48
ACCE=ACCNML
WRITE MESSAGE TO LINE PRINTER.

SUBROUTINE PRINTI (M, K, I, J)
COMMON TARGET (100, 8), VEHA (2, 8, 50), ITARG (2, 50), IPINT (2, 2),
CHAR (101), JPINT (2), IFLOW (2), ITYPE, ITIME, DELT, LSPMAX,
CLBPML, ACCML, ACCEMG, INTPLS, CRPLS, SPEED, CONCM, FFMDW, FCHDW,
CVEL, JMC, IFLOW (3), AFLOW (3), LFLOW (3), IPARAM, PCOC, OCC, OCCJNL,
CTBLSIP, NVEH, DELAY (2, 2, 20), AVDEL (2, 2, 3), FACDEL (6, 2), VL,
CNDAM, TOTAL, TLMA2, TLTA2 (2, 2, 50), AHDWY (100, 2), MA (2, 2),
CP (2), PCOC, CP (2), PEROC (2), SLPITD (2), TARRY, ITARY
C = N, V, M (2),
CNBACK (100)
CKOUNT (2, 2)
DIMENSION M (20)
IF (MAR (6) .NE. 0) RETURN
K1 = K / 4
KE = K / 4
IF (1(K2 = LT) * K1 = K1 + 1
WRITE (100, 78) K1, (MJ) * JJ = 1, X, MJ)
78 FORMAT (12X, 5X, 10X, 3X, 2X, 'LANE NO', 12, 2X, 'VEHICLE NO', 13)
RETURN
ENDE
DO 2, C, I + 1
C = CALCULATE AVERAGE FLOW.
2 AFLOW (1) = IFLOW (1) / IFLOW (1) + IPAR + DELT
1 AFLOW (1, 3) = IFLOW (1, 3) + LFLOW (1, 3) / (IPAR + DELT)
DO 3, I = 1, 2
DO 3, J = 1, 2
3 LFLOW (1) 
C = PERCENTAGE FUNCTION OCCUPANCY.
PCOC = 100 * OCCJNL / (OCCJNL + TCLSLIP)
PCOCP (1) = 100 * PEROC (1) / (PEROC (1) + SLPITD (1))
PCOCP (2) = 100 * PEROC (2) / (PEROC (2) + SLPITD (2))
DB = 1
MOD = I
DO 8, DB = DB, I + 1, 2
8 MOD = MOD
TOTAL (1, 1) = DELAY (1, 1) + TOTAL (1, 1)
C CALCULATES VARIABLES OF INTEREST.

SUBROUTINE CRIT

DIMENSION TVLY(2), TVLY50(2), MOUNT(2)
DIMENSION TDDEL(2,2), VARS(2,2)
COMMON TARGET(100,4), VEH(2,850), ITARG(2,50), IPINT(2,2)
CHAR(10), JPOINT(2), IFLOW(2), ITYPE(2), ITIME(2), DELT, LSPHAX
CLBPNML, ACCNML, ACCSML, INFOS, CRPNS, SPEED, CONCN, FCHDWY, FCHDNY
CVELMN, JFLOW, PTIME, AFLW(3,2), IPARM, PCOCC, OCCJNC
CTBLSLIP, NVAH, DELAY(2,2,20), AVDEI(2,3), FACDEL(6), TDL;
CDBAH, TOTAL, TLMAB, ISTA(2,2,50), TANDWY(100,2), MA(2,2)
CP(2), PCOCC(2), PEROCC(2), SLPTE(2), TARRY, ITARRY
C, NVM(2)
C, NBAC(10)
C, KOUNT(2,2)
DIMENSION NO(2)
DO 7 I=1,2
DO 7 J=1,2
VAR(1,1)=1.
7 TDDEL(I,J)=0.
DO 1 I=1,3
DO 2 J=1,2
C CALCULATE AVERAGE FLOWS.
2 AFLW(I,J)=(AFLW(I,J)+AFLOW(I+1,J+1))/IPARM+DELT)
1 AFLW(I+1,J)=AFLOW(I,J)+AFLOW(I+1,J+1)/IPARM+DELT
DO 3 I=1,3
DO 3 J=1,2
C PERCENTAGE JUNCTION OCCUPANCY.
PCOCC = 100*OCCJNC/100CCJNC+TDBLSLIP
PEROCC(I) = 100*PEROCC(1)/(PEROCC(1)+SLPTE(1))
PEROCC(2) = 100*PEROCC(2)/(PEROCC(2)+SLPTE(2))
DO 4 I=1,2
NO(I)=NOAH
DO 5 J=1,NOAH
TDDEL(I,J)=DELY(A,1,J)+TDDEL(I,J)

C
VARIS(2,I)=VARIS(2,I)+DELAY(2,I,J)*#2
5 TOTDEL(2,I)=DELAY(2,I,J)+TOTDEL(2,I)

C AVERAGE DELAYS
AVDEL(1,I)=TOTDEL(1,I)/MCOUNT(1)
AVDEL(1,I)=TOTLY(I)/MCOUNT(1)
AVDEL(2,I)=TOTDEL(2,I)/MCOUNT(2)
AVDEL(2,I)=TOTLY(2)/MCOUNT(2)
AVDEL(1,3)=(TOTDEL(1,1)+TOTDEL(1,2))/(NO(1)+NO(2))
AVDEL(1,3)=(TOTLY(1)+TOTLY(2))/(MCOUNT(1)+MCOUNT(2))
AVDEL(2,3)=(TOTDEL(2,1)+TOTDEL(2,2))/(NO(1)+NO(2))

DO 6 I=1,2
FACDEL(I+3)=SORT(TDLYSQ(I)/MCOUNT(I)=AVDEL(1,I)*#2
6 FACDEL(I)=SORT(VARIS(2,T)/NOAH=AVDEL(2,I)*#2)
FACDEL(6)=SORT(VARIS(2,1)+VARIS(2,2)/(MCOUNT(1)+MCOUNT(2))=
*AVDEL(1,3)*#2)
FACDEL(3)=SORT(VARIS(2,1)+VARIS(2,2)/(2+NOAH)=AVDEL(2,3)*#2)
IF (NVEH=NE,0) GOTO 8
DO 9 I=1,2
DO 9 J=1,NOAH
DELAY(1,I,J)=0;
9 DELAY(2,I,J)=0;
8 RETURN

C ENTRY CRIT1(DL1+LANE)
TDLY(LANE)=TDLY(LANE)+DL.1
TDLYSQ(LANE)=TDLYSQ(LANE)+DL.1*#2
MCOUNT(LANE)=MCOUNT(LANE)+1
RETURN
END
C GENERATES RANDOM NUMBERS WITH UNIFORM DISTRIBUTION BETWEEN 0 AND 1.

SUBROUTINE RANDOM(IY, YFL)
    IY = IX = 66539
    IF (IY) 5, 6, 7
    5 IY = IY + 2147483647 + 1
    6 YFL = IY
    RETURN
END

C INCLUDES THE MODULE FOR THE GENERATOR

C ENTRY SPACE(SPACE)
C IF APPROPRIATE, HEADWAY IS READ FROM DISK BUFFER WHEN RECYCLING
C OUTPUT TO INPUTS:
    IF (ISPACE(1110E+1)) GOTO 64
    IF (ISPACE(111LT+0)) GOTO 60
C FINDS THE TIME HEADWAY TO THE NEXT INCOMING VEHICLE.
C
SUBROUTINE SPACE(SPACE, SPACEN, I)
REAL LSPMAX, LSPNM, INTPOS
COMMON TARGET(100, 4), VEHA(2, 8, 50), ITARG(2, 50), IMINT(2, 2),
CMAN(10), IMINT(2), IFLOW(2), IMTD, ITIME, DELT, LSPMAX,
CLSPNM, ACCNM, INTPS, CRLPS, SPEED, CONC, FFHDWY, FCHDNY,
CVELJNC, IFLOW, FTIME, AFLOW(1, 3, 3), LFLOW(1, 3, 2), IPARM, PCOCC, OCCJNC,
CTBLSP, NVEH, DELAY(2, 2, 20), AVDEL(2, 3), FACDEL(6), VL,
CMODH, TOTAL, TIMLAG, ISTA(2, 2, 50), AHDWY(100, 2), MA(2, 2),
CP(2), PCOCCP(2), PERCC(2), SLIPT(2), TARRY, ITARRY
C, NXYH(2),
C, NBACK(100)
C, KOUNT(2, 2)
DIMENSION TL(2)
DIMENSION SPACE(100, 2), N(2)
DIMENSION ASPACE(2), NNN(2)
DIMENSION II(2), JJ(2)
II(1) = 1
II(2) = 1
TL(1) = TIMLAG
TL(2) = TOTAL
CALL RANDOM(II(1), JJ(1), RN)
CALL RANDOM(II(2), JJ(2), RN)
DO 49 K = 1, 2
IF (ASPACE(K) .GE. 0) GOTO 49
49 CONTINUE
RETURN
C
ENTRY SPACE(SPACEN, I)
C IF APPROPRIATE HEADWAY IS READ FROM DISK BUFFER WHEN RECYCLING
C OUTPUTS TO INPUTS.
IF (ASPACE(1) .GE. 1.0) GOTO 84
IF (ASPACE(1) .LT. 0) GOTO 60
C
SUBROUTINE SPACES(NN, ASPACE)
REAL LBMAX, LSPNML, INTPOS
COMMON TARGET(100, 4), VEHA(2, R, 50), ITARG(2, 50), IPOINT(2, 2),
CMAR(10), IPOINT(2), IFLOW(2), ITYPE, ITIME, DELT, LBMAX,
CLSPNML, ACCNML, ACCEMG, INTPOS, CRLPOS, SPEED, CONC, FFHWDY, FHWDY,
CVELJNC, JFLOW, FTIME, AFLW(3, 3), AFLW(3, 2), IPARAM, PCBCC, BCCJNC,
CTOBLIP, NVHE, DELAY(2, 2, 20), ABDL(2, 3), FACDEL(16), VL,
CMNAN, TOTAL, TIMLAG, ISTA(2, 2, 50), AHWDY(100, 2), MA(2, 2),
CP(2), PCBCCP(2), PERBCC(2), SLTPTB(2), TARR, ITARY
C=NVXH(12),
C=NBACK(100),
C=KOUNT(2, 2),
DIMENSION TL(2),
DIMENSION SPACEA(100, 2, N(2)),
DIMENSION ASPACE(2, NNN(2)),
DIMENSION III(2), JJ(2),
N(1)=1,
N(2)=1,
TI(1)=TIMLAG,
TL(2)=TOTAL,
II(1)=1,
II(2)=7,
CALL RANDOM(II(1), JJ(1), RN),
CALL RANDOM(II(2), JJ(1), CN),
DO 49 K=1, 2,
IF (ASPACE(K) .GE. 0) GOTO 49
49 CONTINUE
RETURN
ENTRY SPACE(SPACEC+1)
IF APPROPRIATE HEADWAY IS READ FROM DISK BUFFER WHEN RECYCLING
C OUTPUTS TO INPUTS:
IF (ASPACE(1) .GE. 1.0) GOTO 84
IF (ASPACE(1) .LT. 0) GOTO 60
IF (ITIME*DELT+LT+TL(I)) GT eq 111.
ASPACE(I) = 1.
CALL DISKRD(N(I), SPACEA(1, I), I)
SPACE = SPACEA(MA(I), I)
MA(I) = MA(I) + 1
CV(I) = CV(I) + 1.
N(I) = N(I) + 1.
RETURN
1.
EMHDWY = LSPNML/(2*ACCEM) + VL/LSPNML.
CDWY = EMHDWY*FFHDW.
II = 0.
CALL RANDOM(I(I), II(I), RN)
II = I(I) + 1
IF (RN <= ASPACE(I)) GOTO 217
GOTO 212.
C CALCULATE HEADWAY ACCORDING TO DISTRIBUTION.
217 GAP = FLOAT(I(I), HDWY/NNN(I))
IF (GAP > LT + HDWY) GAP = HDWY
RETURN
60 CONTINUE.
SPACE = SPACEA(MA(I), I)
MA(I) = MA(I) + 1
IF (MA(I) < 90) GOTO 61
MA(I) = 100.
RETURN
61 CONTINUE.
C 84 SPACEN = 99999
50 FORMAT(2F10.3)
RETURN
END.
C ROUTINE TO OUTPUT VEHICLE DATA TO LINE PRINTER.

SUBROUTINE PRINT
REAL LSPLMX, LSPMLX, INPOS
COMMON TARGET(100,4), VEH(2,8,50), ITARG(2,50), IPON(2,2),
CMAR(10), JPOINT(2), IFLOW(2), ITYPE, ITIME, DELT, LSPLMX,
CLSPMLX, ACCMLX, ACCEMX, INPOS, CRHPOS, SPEED, CNDN, FFHDMY, FCPLMY,
CVELNC, JFLOW, FIME, AFLOW(3,3), LFLOW(3,2), IPARAM, PCORCC, OCCNCC,
CTSLIP, NVEH, DELAY(2,2,20), AVDEY(2,3), FACDEY(6,6), VL, V2
CNBAY= TOTAL+TIMLAX+ISTA(2,2,50)+AHDMY(100,2)+MA(2,2),
CP(2), PCORCC(2), PER0CC(2), SPlptE(2), TARRY, ITARRY
50 C-NXVH(12)
60 CNBACK(100)
70 C-KEFJU(2,2)
80 IF (MAR(1) * NE 0) RETURN
90 TIME = ITIME * DELT(IJ)
100 WRITE(108,403) TIME
110 WRITE(108,405) TIME
120 IF (MAR(2) * NE 0) GOTO 63
130 WRITE(108,406)
140 DO 66 I = 2, N, 1
150 N1 = JPOINT(I,1) + 1
160 N2 = JPOINT(I,2) + 1
170 IF (N1 * EQ 51) N1 = 1, 2, 1
180 IF (N2 * EQ 0) N2 = 51, 2, 1
190 WRITE(108,407) AVDEY(I,2,1)
200 WRITE(108,408) FACDEY(I,2,1)
210 IF (N1 * EQ JPOINT(I,2) + 1) GOTO 64
220 JF = 100, 409, FACDEY(I,1,1)
230 CONTINUE
240 C VEHICLE DATA
250 WRITE(108,601) (VEH(1,1,2,50), J = 1, 7), ITARG(I, J)
260 IF (J = EQ 51) J = 100, 64, 51
270 IF (J = EQ 51) J = 100, 64, 51
280 GOTO 100
290 M + VEHICLE DATA
300 C URL = NAVE, SLATE 60, j = 1, 2
66 CONTINUE

67 IF (MAR(3) .NE. 0) GOTO 73

68 WRITE (108, 104)

69 WRITE (108, 71)

70 WRITE (108, 74)

71 M1 = JPOINT(1) + 1

72 M2 = JPOINT(2) + 1

73 IF (M1 .EQ. 101) M1 = 1

74 IF (M1 .EQ. JPOINT(2)) GOTO 73

75 IF (M2 .EQ. 0) M2 = 100

76 JGMS = 

77 CONTINUE

78 IF (TARGET(J, 1) .EQ. 0) GOTO 1

79 TARGET DATA = 

80 WRITE (108, 72) J, TARGET(J, 1), TARGET(J, 2), TARGET(J, 3), 

81 C

82 IF (J .EQ. ME) GOTO 73

83 J = J + 1

84 IF (J .EQ. 100) J = 1

85 GOTO 80

86 IF (MAR(4) .NE. 0) GOTO 75

87 WRITE (108, 76)

88 WRITE (108, 240) AFLOW(1, 1), AFLOW(1, 2), AFLOW(1, 3)

89 WRITE (108, 240) AFLOW(2, 1), AFLOW(2, 2), AFLOW(2, 3)

90 WRITE (108, 240) AFLOW(3, 1), AFLOW(3, 2), AFLOW(3, 3)

91 WRITE (108, 77) AVDEL(2, 1), AVDEL(2, 2), AVDEL(2, 3)

92 WRITE (108, 77) AVDEL(1, 1), AVDEL(1, 2), AVDEL(1, 3)

93 WRITE (108, 243) FACDEL(1), FACDEL(2), FACDEL(3)

94 WRITE (108, 243) FACDEL(4), FACDEL(5), FACDEL(6)

95 WRITE (108, 244) PCBC

96 IF (P(1) .LE. 0.0 .AND. P(2) .LE. 0.0) GOTO 75

97 WRITE (108, 2) PCBCCP(1)

98 WRITE (108, 2) PCBCCP(2)

99 WRITE (108, 104)

100 FORMAT (X, 'TIME = ', 'F10.3)

101 FORMAT (100, 'VEHICLE DATA')

102 FORMAT (X, 'LANE NO = ', 'I1')
FORMAT(8X,'VEH NO.',11X,'ACCN',12X,'VEL',11X,'POSN',11X,'HDWY',
    C10X,'DELAY',9X,'LEEWAY',9X,'EMHDWY',X,'TARGET NO.')
103 FORMAT(///)
104 FORMAT(///)
69 FORMAT(11H0,'TARGET DATA')
71 FORMAT(15F20.3,T40,F10.3,T60,F10.3,T80,F10.3,T100,F10)
74 FORMAT(11H0,'TARGET NO.',T20,'TARGET TIME',T40,'TARGET VELOCITY',T60,
    C8,'TARGET HDWY',T80,'TARGET B/END / A TIME',T100,'BACK PRINT')
76 FORMAT(11H0,T20,'LANE NO 1',T40,'LANE NO 2',T60,'TOGETHER')
77 FORMAT(X,'AVERAGE DELAY',T18,F10.3,T38,F10.3,T57,F10.3)
240 FORMAT(X,'ENTRY FLOW',T18,F10.3,T38,F10.3,T57,F10.3)
241 FORMAT(X,'JUNC FLOW',T18,F10.3,T38,F10.3,T57,F10.3)
242 FORMAT(X,'EXIT FLOW',T18,F10.3,T38,F10.3,T57,F10.3)
243 FORMAT(X,'DELAY VARI',T18,F10.3,T38,F10.3,T57,F10.3)
244 FORMAT(X,'PERCENT USE OF JUNC',2X,F10.3)
2 FORMAT(X,'PERCENT USE OF P1',4X,F10.3)
3 FORMAT(X,'PERCENT USE OF P2',4X,F10.3)
75 RETURN
C INTERSECTIONS TARGET CALCULATING ROUTINE

C SUBROUTINE TAG1
DIMENSION ENDP(2), LASTV(2)
DIMENSION NFV(2), ART(2), PART(2)
DIMENSION TDART(2)
DIMENSION IPO(2), IPANE(2)
EQUIVALENCE (ENDP, IP), (LASTV, IPANE)
LOGICAL FLAG
REAL LSPMAX, LSPNML, INTPOS
COMMON TARGET(100,4), VEH(2,8,50), ITARG(2,50), IPOINT(2,2),
CMAR(10), JPOINT(2), IFLOW(2), ITYPE, ITIME, DELT, LSPMAX,
CLSPNML, ACCNML, ACCEMG, INTPOS, CRLPOS, SPEED, CONCMG, FFHDWY, FCHDwy,
CVELJNC, JFLOW, FTIME, AFLLOW(3,3), LFLOW(3,2), IPARAM, PCOC, OCCJNC,
CTOSLIP, NYEH, DELAY(2,2,20), AVDEL(2,3), FACDEL(6,6), VL,
CMOAN, TOTAL, TIMLAG, ISTA(2,50), AHDWY(100,2), MA(2,2),
CP(2), PCOCCP(2), PERCC(2), SLEPT(2), TARRY, ITARY
C, NXVH(2), NBACK(100)
C, XBLKVH(100)
C, KBEST(100)
C, KBEST(100)
C, T-best(100)
C, T-best(100)
C, NXVH(2)
C, NXVH(2)
C, KPOINT(1)
C, VEJNC=1
C, S=ABS(SPEED)*SPEED-LSPNML*LSPNML/(2*ACCNML)
C, POSN=VEHA(1,3,1)
C, TA=INTPOS*POSN+S)/LSPNML+ABS(SPEED-LSPNML)/ACCNML
C, OFFSET=INTPOS*CRLPOS*S)/LSPNML+(LSPNML*SPEED)/ACCNML

C INITIALISATION
C, START=TA
C, ITYPE=1
C, JPINT=100
C, JPINT=2
C, TARGETS1=TA
C, TARGETS1=TA
C, TARGETS2=VEJNC
C, TARGETS3=0
VEHA(1,8,1)=((TA=(INTPOS=PESN)/LSPNML)*2+1)
ITARG(1,1)=1
IFLOW(1)=1
ITYPE=1
TARRY=0
OCJNC=0
PERGCC(1)=0
PERGCC(2)=0
TSSLIP=0
THDWE=SPEED/(2*ACCEKG)*VL/SPEED
THDWC=THDWE*FCHDWE
THDWF=THDWE*FFHDFY
IF ((P(1)+LE+0)+AND+(P(2)+LE+0)) RETURN
ENDP(1)=TA+P(1)
ENDP(2)=TA+P(1)+P(2)
TARGET(1,3)=0
TARGET(2,1)=ENDP(1)+THDWC
TARGET(2,2)=VELJNC
TARGET(2,3)=THDWC09
TARGET(1,4)=TA+P(1)+TIME*DELT
TARGET(2,4)=TA+P(1)+P(2)
VEHA(2,8,1)=VEHA(1,8,1)
ITARG(2,1)=2
IFLOW(2)=1
CALL LASTV(2) TARGET FOR A FIXED TIME CYCLE STRATEGY.
LASTV(2)=2
RETURN
ENTRY TAG2_YC
FLOW=FLOAT(IFLOW)/TIME*DELT=FTIME
IF (IFLOW(1)=IFLOW(2)) 29, 30, 30
RATIO = FLOAT(IFLOW(2))/FLOAT(IFLOW(1))
GOTO (31) + JPOINT(2)
RATIO = FLOAT(IFLOW(1))/FLOAT(IFLOW(2))
A=1/(2*ACCEKG)
IF (A<1) GOTO 32
C  CALCULATE FIRST COME FIRST SERVED TARGET.
    TDYN=THDWF

32  GOTO 33
    TDYN=THDWF
33  TYPE=11
    IF (M2=1)

32  CONTINUE
    JP2=JP2+1
    IF (JP2=END)

30  C  CALCULATE MINIMUM DELAY.
    TDYN=TDYN
    IF (JPOINT(2) EQ 1)

29  C  CALCULATE NEXT ALTERNATE PRIORITY TARGET.
    TDYN=TDYN
    IF (ART(1)=ART(2))

2000  STAR=TARGET(POINT(1))
    TDYN=TDYN
    IF (ART(1)=ART(2))

2001  ART(1)=ART(2)
    TDYN=TDYN
    IF (ART(1)=ART(2))

2002  RETURN
    TDYN=THDWF

2000  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2001  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2002  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2003  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2004  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2005  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2006  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2007  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2008  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2009  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2010  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2011  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2012  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2013  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2014  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2015  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2016  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2017  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2018  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2019  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2020  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))

2021  RETURN
    TDYN=THDWF
    IF (ART(1)=ART(2))
C FIND A VEHICLE TO BE GIVEN AS TARGET
   LNEXT=168+10I-804
   IF (TDART(2)*LT+TDART(1)) LNEXT=220+10
   KPOINT=KPOINT+1
   IF (KPOINT*EG=10I) KPOINT=1
   LPNEXL=NXVH(LNEXT)
   NPST=ITARG(LNEXT,LPNEXL)
   DO 2003 I=1,N
       TARB2=TARGET(KPOINT,I)
       TARGET(KPOINT,I)=TARGET(NPST,I)
   2003 TARGET(NPST,I)=TARB2
   THDWN=THDWC
   IF (LNEXT*EQ+JTYPE) THDWN=THDWF
   STAR1=STAR1+THDWN
   IF (ART1(LNEXT)+GT+STAR1) STAR1=ART1(LNEXT)
   TARGET(KPOINT+1)=STAR+THDWN
   TARGET(KPOINT+3)=THDWY
C EXCHANGE PLACES IN TARGET QUEUE (IF REQUIRED)*
   700 NXVH(LNEXT)=NXVH(LNEXT)+1
   IF (NXVH(LNEXT)*EQ+5I) NXVH(LNEXT)=1
   ITARG(ITARG,LNEXT,LPNEXL)=KPOINT
   NO=NBACK(KPOINT)
   LANE=1
   10 IF (NO*LE=50) GO TO 2004
   NO=NO+50
   LANE=2
   2004 ITARG1LANE,NO)=NPST
   JTYPE=LNEXT
   NBACK(KPOINT+1)(LNEXT+1)=50*LPNEXL
   GO TOB(KPOINT+1)=LANCE+50+NO
   13 N1=KPOINT+1
   IF (N1*EG=10I) N1=1
   IF (N1*EG=JPOINT(2)) RETRN
   N2=UPVOUT(2)+1
   IF (N2*EG=10I) N2=100
   12 J=N1
   IF (N1*EG=N2) GO TO 13
11 IF (JJ EQ 101) JJ=1
12 IF (TARGET(JJ,4) GE TARGET(JJ,4)) GOTO 10
13 DO 4 I=1,4
14 TARBUF=TARGET(JJ,4)
15 TARGET(JJ,4)=TARGET(JJ,4)
16 TARGET(JJ,4)=TARBUF
17 NQ=NBACK(JJ)
18 NBACK(JJ)=NQ
19 DB 700 I=1,2
20 JQ=J
21 IF (I EQ 2) NQ=JQ
22 IPQ(I)=NBACK(NQ)
23 IPANE(I)=I
24 IPQ(I)=IPQ(I)-500 \* (CCJH/C)
25 IF (IPQ(I) LE 50) GOTO 700
26 IPQ(I)=IPQ(I)-500 \* (CCJH/C)
27 IPANE(I)=IPANE(I)+2 \* JAGE WHEN A VEHICLE PASSES THROUGH INTERSECTION.
28 700 CONTINUE: TIME=DEL + JCCJH/TA
29 NQ=ITARG(IPANE(I), IPQ(I))
30 ITARG(IPANE(I), IPQ(I))=ITARG(IPANE(I), IPQ(I))
31 ITARG(IPANE(I), IPQ(I))=NQ
32 MARK(I)=1
33 TIME=DEL + JCCJH/TA + IPQ(I)*IPQ(I) + JCCJH/TA
34 10 JJ=J
35 IF (J NE N2) GOTO 11
36 IF (MARK EQ 0) GOTO 13
37 N2=N2+1 \* (CCJH/C)
38 N2=100 \* (CCJH/C)
39 IF (N2 GE 0) N2=100
40 MARK=0
41 GOTO 12 \* XPOINT LT JPOINT(I) AND JPOINT(I)+LT JPOINT(I) \* XPOINT(I) MA=100
42 CONTINUE: LT JPOINT(I) AND JPOINT(I)+LT JPOINT(I) \* XPOINT(I) MA=100
43 N2=JPOINT(I)+1 \* XPOINT(I)+4 \* N2 \* 100
44 IF(N2 EQ 0) N2=100
45 ITYPE=JTYPE \* 1 \* 10 \* XPOINT(I)
46 J=KPOINT
47 JJ=J+1 \* XPOINT(I) \* (CCJH/C) LANE=2
48 IF (JJ EQ 101) JJ=1
80 LANE=1
81 IF (NBACK(JJ) GT 50) LANE=2
82 THDYN=THDYN+1
83 IF (LANE EQ ITYPE) THDYN=THDYN+1
84 TARGET(JJ,1)=TARGET(JJ,1)+THDYN
85 J=JJ
86 ITYPE=LANCE
87 IF (J EQ N1) GOTO 40
88 GOTO 50
89 CONTINUE
90 RETURN
C
ENTRY TAG 4(I1,I2)
A13 M=ITARG(I1,I2)
A16 TCJNC=TARGET(M,3)+8CCJNC
C CALCULATE SLIPAGE WHEN A VEHICLE PASSES THROUGH INTERSECTION.
TOSLIP =TIME+DELTA CCJNC=TA
IF (P(I1)2 EQ 13)
C A3 CONTINUE
5 PERCC(I1)=TARGET(M,3)+8PERCC(I1)
SLIP(I1)*(TIME+DELTA=TA)*P(I1)/(P(I1)+P(2))=PERCC(I1)
GOTO 1
2 CONTINUE
IF NV=ITARG(I1,I2)+1
9999 IF (NV EQ 0) GOTO 60
99 99 NA=0
IF (NB=0X114) BT=60
5 BLANE=2
THDIF(KPOINT+LT*JPOINT(2)+AND*JPOINT(2)+LT*JPOINT(1)) NA=100
IF (N1=0) B=0+JPOINT(2)+AND*JPOINT(2)+LT*JPOINT(1) NB=100
SLIP(KPOINT+NB=LE*KPOINT+NA) GOTO 60
KPOINT=PPOINT+1
35 IF (KPOINT EQ 101) KPOINT=1
C CALC LANE=1 SLIP CORRECT BECAUSE VEHICLE CANNOT ACHIEVE TARGET.
IF (NBACK(KPOINT) GT 50) LANE=2
NXVH(LANE)=NXVH(LANE)+1
IF (NXVH(LANE)+EG=51) NXVH(LANE)=1
60 CONTINUE
1 CONTINUE
LFLOW(2,1)=LFLOW(2,1)+1
SLIP=TIME*DELT+TTARG
IF (SLIP) 35,35,36
36 M=M+1
IF (M+EG=101) M=1
IF (P(1)+LE=0.0 AND P(2)+LE=0.0) GOTO 415
IF (SLIP+LE=2) GOTO 35
M=ITARG(11,12)
N=0
I=I2
FLAG=TRUE
GOTO 409
413 FLAG=FALSE
GOTO 35
415 I=M
M=JPOINT(2)=1
IF (M+EG=0) M=100
NSLANE=11
C ADJUST ALL LATER TARGETS.
5 TARGET(I,1)=TARGET(I,1)+SLIP
IF (I+EQ+10) GOTO 35
MM=I N=I
I=111
II=111
IF (I+EQ+101) I=111
N=111
NH=NODE(N)
NFRAME=N
NFRAME=N+DELT
IF (NBACK(I)+GT+50) NFRAME=2
THDFYN=THDFYC(0.5) GOTO 310
IF (NFRAME+EQ+NFRAME) THDFYN=THDFYS GOTO 360
SLIP=TARGET(MH,1)+THDFYN TARGET(I,1)
IF (SLIP) 35,35,5
35 ITARG(11,12)=ITARG(11,12)
C CALCULATE SLIP EN_ROUTE BECAUSE VEHICLE CANNOT ACHIEVE SET TARGET.
401 M=ITARG(11,12)+1
IF (I1+1=I1) THEN
M1=JPOINT(I1)+1 IF (I1+1=I1+100) M1=1
807 IF (M1+M1=0) GOTO 860 IF (M1=GOTO 400)
JPOINT(I1)=M1+1 IF (M1=GOTO 11)
808 M1=M1+1 IF (M1=GOTO +101) M1=1
815 IF (M1+M1+GPOINT(2)) GOTO 59 M1=1
IF (TARGET(M1,1)+GT.0+) GOTO 59
JPOINT(I1)=M1+1
GOTO 800

59 CONTINUE(111)
CALL PRINT1(VEH HAS PASSED JUNCTION LATENESS=',SLIP,35,I1,I2)
TARRY=ITIME+DELT
400 ITARRY=IEND+P11+P11
RETURN
460 TARGET(M1,1)=C.1+2
GOTO 59 GEND+P11+IEND+TWY
C105 ENTRY: TAG5(I1,I2,UI1)
103 M=ITARG(I1,12) TO +2
TTARG=TARGET(M,1)
UJ=TARGET(M,2)
UV=VEMA(I1,12)
POSN=AMEA(I1,13)
TTJ=INTPOS=POSN
T=(TDTJ+(UJ+UV=UV=2+UI+UI)/(2+ACCNML))//UI
402 C+12+UI=UV=UJ/ACCNML
TARGET=ITIME+DELT=U1
SLIP=TTARG=TTARG
980 IF (SLIP=LE.0+5) GOTO 210
IF (P11+LE.0+AND+(P2=LE.0+)) GOTO 350
N=0
412 I=2 IF (M1+I=TARGET(M1,1)+BLIP)
409 BLEND=TARGET(M1,1)+BLEND1 N2=N1+1
GOTO .10
401 BLEND=BLEND+P11+P2
I3=1
IF (I1=EG+1)  I3=2
TARG=BLEND+P(I3)+THD+WYC
GOTO 408

407 IF (TARGET(M2)<GT+BLEND) GOTO 400
SLIP=TARGET(M1)+THD+WYC-TARGET(M2)
IF (SLIP)<01+01 SLIP
410 TARGET(M1)=TARGET(M1)+SLIP

414 IF (TARGET(M1)<GT+BLEND) N=N+1
I=I+1
IF (I=EG+51) I=1
MM=M
M=ITARG(I1+1)
IF (M+NE=0) GOTO 407
GOTO +01

400 BENDN=BLEND+P(1)+P(2)
I3=1
IF (I1=EG+1)  I3=2
TARG=BLEND+P(I3)+THD+WYC

408 N1=N
IF (N1=EG+0) GOTO +11

403 IF (N=EG+0) GOTO 402
I=I+1
IF (I=EG+0) I=60.
M2=ITARG(I1+1)
TARGET(M2)+BLNDN
N=N+1
GOTO 403

402 M3=ITARG(I1+1)
TAGN=TARGET(M3)+1
SLIP=TAGN-TAGN
950 CONTINUE
BLNDN=BENDN
N2=0

419 TARGET(M3)<TARGET(M3)+SLIP
IF (TARGET(M3)<GT+BLEND) N2=N2+1
N=N+1
IF (N=EQ+N1) GOTO 404
C CELL I=I+1 DISTRIBUTION see PLOTTING PRINTED PAPER
C IF (I+EQ=51) I=1
M3=ITARG(I+1)
GOTO 412  /* PRET(100)+VARKR(I+1)+TARG+901+PRINT(PLOT1)+*/
404 TARG=TARG(I+1)+THDWYF  /* TYPE TIME DELTA TPARMA */
N=N2  /*ACCMPLSS+CRNG+INTEC+ERPL+C001+SECO+SHNG+PHMT+PLOT */
I+1  /*ACCFAC+EACF+EDBC+RBET+ */
IF (I+EQ=51) I=1  /* FINISH */
M=ITARG(I+1)  /* K=1+TA(I+1)+TARG+100+K+PAR(2)+*/
IF (M+EQ=0) GOTO 401  /* SLIP+TARG+TARG */
TARG=TARG(I+1)
SLIP=TARG+TARG
IF (SLIP+NE=0) 410
350 CONTINUE  /* FINISH SLIP*/
M2=UPINT(I+1)  /* NEWFIL(I+1)+PAVAR(I+1) */
IF (M2+EQ=0) M2=100  /* MCNT(I+1)+B+I+90+*/
I=M2  /* VALENCED+/BSTA+/BST */
N=FLANE=I  /* NE+0+GOTO+1 */
211 TARG(I+1)=TARG(I+1)+SLIP
227 IF (I+EQ=20) GOTO 210  /* ARAW+1200+LANE+I+FA+1+RAR+FLANE+2+R+R+11 */
17 K=I+1  
IF (K+EQ=101) K=1  
SLANE=1  
IF (HBACK(K)+GT=50) N=SLANE+2  
THDWY=THDWYC  
IF (N=SLANE+EQ=FLANE) THDWY=THDWYF  
SLIP=TARG(I+1)+THDWY=TARG(K+1)  
IF (SLIP+LE=210) 212
212 FLANE=SLANE  
K=K=1  /* SLIP+FLANE */
411 CONTINUE  
IF (FLAG) GOTO 413
210 RETURN  /* I+2 */
END UN)  /* I+1+30 */
D D
C CALCULATES DISTRIBUTIONS AND PLOTS LINE PRINTER HISTOGRAMS.

SUBROUTINE DIS
COMMON TARGET(100*4), VEH(2,8,50), ITARG(2,50), IPINT(2,2), CMAR(10), JPOINT(2), IFLOW(2), TYPE, TIME, DELT, LSPMAX,
CLSPNML, ACCHNL, ACCEMG, INTPOS, CRILPOS, SPEED, CONCN, FFHDWY, FCHDNY,
CVELJMG, JFLOW, FTIME, AFLOW(3,3), LFLOW(1,3,2), IPRAM, PCOGC, BCC, NC,
CTOSLIP, NVEH, DELAY(2,2,20), AVDEL(2,3), FACDEL(6), VL,
CMAN, TOTAL, TMLAG, ISTA(2,2,50), ANDWY(100,2), MA(2,2),
CP(2), PCOGC(2), PEROCC(2), SLIPT8(2), TARRY, ITARRY
C, NXYM(2),
C, NBACK(100),
C, KBUNT(2,2),
REAL LSPMAX, LSPNML, INTPOS
DIMENSION KPLAT(2), NCOUNT(2), PAVE(2)
DIMENSION DSTA(30,2), MCOUNT(2), QSTA(30)
EQUIVALENCE (DSTA, QSTA)
IF (MAR(1) NE 0) GOTO 17
WRITE(100,227)(PAVE(I), I=1,2)
227 FORMAT(100,I0) AVERAGE PLATEAN SIZE LANE 1',F6.1,5X,'LANE 2',F6.1)
17 CONTINUE
DO 1 I=1,2
KPLAT(I)=1
NCOUNT(I)=0
PAVE(I)=0
DO 1 J=1,2
KOUNT(I,J)=0
DO 1 K=1,50
1 ISTA(I,J,K)=0
MDWY = LSPNML/(2*ACCEMG) + VL/LSPNML*FFHDWY
RETURN

C ENTRY DIS
DO 5 I=1,2
NCOUNT(I)=0
DO 5 J=1,30
5  DBSTAJ(i)=0.  KOUNTIJ=AKX+1
   RETURN  E6+11:07C  9

   ENTRY DISTR1
   IF (iMAR(i)=EQ+1) GOTO 7
   IF (iMAR(i)=EQ+0) GOTO 8
   DO 6 I=1:30
   6  DBSTAI=DS(AI)/MCOUNT(I)
   CALL PLOTER(DS,30,TRUE,ITIME=DEL2,2,-1)
       DO 9 I=1:30
   9  DS(AI)=DBSTAI(DS(AI),MCOUNT(2))
   CALL PLOTER(DS,30,TRUE,ITIME=DEL2,2,-2)
   GOTO 10
   DO 11 I=1:30
   11  DBSTAI=(DBSTAI+DBSTAI(DS(AI),MCOUNT(2)))/(MCOUNT(1)+MCOUNT(2))
   CALL PLOTER(DS,30,TRUE,ITIME=DEL2,2,-3)
   DO 12 I=1:2
   12   MCOUNT(I)=0
   DO 12 J=1:30
   12   DBSTAJ(i)=0.
   RETURN

   ENTRY DISTR2(iDEL,JIM)
   I=JIM
   INT=DEL2+1
   IF (INT**=LT+1) INT=1
   IF (INT**=GT+30) INT=30
   DBSTAI(INT+I)=DBSTAI(INC+I)+1
   MCOUNT(I)=MCOUNT(I)+1
   CONTINUE
   RETURN

   ENTRY DISRIB(I,II,KK)
   INT=((HDY+HDY)**10+HDY**5+5)+1
   IF (INT**=GT+50) INT=50
   IF (INT**=LT+1) INT=1
   ISTAT(I,II,KK,INT)=ISTAT(I,II,KK,INT)+1
5 DBTA(J,I)=0.
RETURN
C
ENTRY DISTR1
IF (MARI(I),EQ.1) GO TO 7
IF (MARI(I),EQ.0) GO TO 8
DO 6 I=1,30
6 DBTA(I)=DBTA(I)/MCOUNT(1)
CALL PLOTER(DBTA,30,TRUE,**TIME*,DELT,2)=1
DO 9 I=1,30
9 DBTA(I)=DBTA(I,2)/MCOUNT(2)
CALL PLOTER(DBTA,30,TRUE,**TIME*,DELT,2)=2
GOTO 10
8 DO 11 I=1,30
11 DBTA(I)=(DBTA(I)+DBTA(I,2))/(MCOUNT(I)+MCOUNT(2))
CALL PLOTER(DBTA,30,TRUE,**TIME*,DELT,2)=3
10 DO 12 I=1,2
12 MCOUNT(I)=0
DO 12 J=1,30
12 DBTA(J,I)=0.
RETURN
C
ENTRY DISTR2(DEL,JIM)
I=JIM
INT=DEL/2+1
IF (INT=LT+1) INT=1
IF (INT=GT+30) INT=30
DBTA(INT,I)=DBTA(INT,I)+1
MCOUNT(I)=MCOUNT(I)+1
7 CONTINUE
RETURN
C
ENTRY DISRIB(HDWY,II, KK)
INT= ((HDWY-HDWYM)*10/HDWYM+5)+1
IF (INT=GT+50) INT=50
IF (INT=LT+1) INT=1
IBTA(II,KK,INT)=IBTA(II,KK,INT)+1
KOUNT(II,KK)=KOUNT(II,KK)+1
IF (KK=EQ+1) GOTO 3
I=II
IF (HDWHY=GT+1+1#HDWHY) GOTO 2
KPLAT(I)=KPLAT(I)+1
GOTO 3
2 NCOUNT(I)=NCOUNT(I)+1
PAVER(I)=PAVER(I)*(FLOAT(NCOUNT(I))+1)/FLOAT(NCOUNT(I))
&+FLOAT(KPLAT)/FLOAT(NCOUNT(I))
KPLAT(I)=1
3 CONTINUE
RETURN
END
IF (MAR(5) + NE = 0) RETURN
J = 1
RETURN

ENTRY WRIFIN
IF (MAR(5) + NE = 0) RETURN
END FILE 1
ML, ACCER, ATPOS, CL, POS, SPEED, CONC, ETCH, FLAME, LICENSE
RETURN
ML, PT, TIME, RET, DEL, DEPT, TYPE, SELECT
END
ML, H (NAME), DEL (2), DEP (2), (NAME), (ML) (NAME), O (NAME), R (NAME)
NAME, TOTAL (NAME), (NAME), (NAME), MOV (2), (NAME), (NAME)
NAME, (NAME), (NAME), (NAME), (NAME), (NAME), (NAME)
RETURN
ML, (NAME), (NAME), (NAME), (NAME)
REAL LMPMAX, CBOHL, IDTPOS
LOGICAL FLAG
IRI(TX) = TX + CPLPOS * F E + TX + 10 + 6
EI(TY) = TY + CPLPOS * R E + TY + 10 + 6
DIST(R) = INTRP(R) * R
GFACT(760) / DIST
DO 100 1 = 1, 10
CALL LOAD2D
IF (NINE = 1) GOTO 101
CALL LOAD1D
CALL NODE9
PAUSE
TIME = IPTBY + DEL + 10
TIMES = TIMES + 1
IF (TIME < 10) GOTO 100
D EDT COORDINATES OF PICTURE OF INTERSECTION
DO 2 = 1, 10
TTIME = TIMES / 10
TIMES = TIMES / 10
TA = TIMES + TTIME + 10/10
TA = TIMES + TTIME + 10/10
TM = TIMES + TTIME + 10/10
TIMES = TTIME
TIMES = TTIME
CALL LOAD2D
CALL LDWD1
C 2 CONTINUE
CALL LDWD2

SUBROUTINE GRAPH1(FLAG, IFLOT)
COMMON TARGET(100,5), VEMA(2,8,50), ITARG(2,50), IPINT(2,2),
CMAR(10), JPINT(2), IFLOW(2), I_TYPE, ITIME, DELT, LSPMAX,
CLSPNML, ACCNML, ACCEMG, INTPOS, CRLPOS, SPEED, CONCN, FFHDWY, FCHDWH,
CVELJNC, JFLOM, FTIME, AFLOW(3,3), LFLOW(3,2), IPARAM, PCOC, OCCJNC,
CTNBLIP, NVEL, DELAY(2,2,20), AVDEL(2,3), FACDEL(6), VL,
CNOAM, TTOTAL, TIMLAG, ISTA(2,2,50), AHDWY(100,2), MA(2,2),
CP(2), PCOCQP(2), PEROC(2), SLIFT(2), TARRY, ITARRY
C=NXYM(2)
C=NXBKM(100)
REAL LSPMAX, LPNML, IPNRM
LOGICAL FLAG
102 IFIX(X)=X+CRLPOS*SFAC+100*5
IFIX(Y)=Y+CRLPOS*SFAC+100*5
DIST=2*X*(INTPOS*CRLPOS)
SFAC=760/DIST
100 DO 101 I=1,3
CALL LDWD2(0)
IF (I+NEQ) 078 101
CALL LDWD1(0)
CALL NHSEND
PAUSE
ITIME=IPLOT*DELT#10
ITIME=ITIME#DELT#10
ITIME=ITIME+ITIME
IF (ITIME.LT.0) ITIME=1000#0+ITIME
C SEND CO-ORDINATES OF PICTURE OF INTERSECTION
DO 2 I=1,5
ITIME=ITIME+ITIME
ITIME=ITIME+ITIME
ITIME=ITIME+ITIME
ITIME=ITIME+ITIME
ITIME=ITIME+ITIME
CALL LDWD2(IA)
CALL LDW20(I1)
CONTINUE
CALL LDW20(I0)
CALL WDBEND
PAUSE
RETURN
101 CALL LDW(I1)
IDATA=2+1(INTPOS=CRLPOS)*SFAC
CALL LDW(I1,IDATA)
IF (I.EQ.2) GOTO 102
CALL LDW(I1,ICXTX(CRLPOS))
CALL LDW(I1,ICTY(INTPOS))
CALL LDW(I1,ICXTX(2*INTPOS=CRLPOS))
CALL LDW(I1,ICTY(INTPOS))
GOTO 100
102 CALL LDW(I1,ICXTX(INTPOS))
CALL LDW(I1,ICTY(CRLPOS))
CALL LDW(I1,ICXTX(INTPOS))
CALL LDW(I1,ICTY(2*INTPOS=CRLPOS))
100 CONTINUE
C
ENTRY GRAPH(JFLG)
DB 200 I=1:2
PLAST=CRLPOS
CALL LDW20(I)
CALL LDW(I1)
N1=IPOINT(I,1)+1
N2=IPOINT(I,2)+1
IF (N1.EQ.51) N1=1
IF (N2.EQ.0) N2=50
IF (N1.EQ.IPOINT(I,2)) GOTO 200
J=N2
300 CONTINUE
IF (VEHA(I,3,J).*LT.CRLPOS.OR.VEHA(I,3,J).*GT.2.*INTPOS=CRLPOS)
&GOTO 700
IPOS=(VEHA(I,3,J)-PLAST)*SFAC+2.5
IF (IPOS.EQ.0) IPOS=1024+1
CALL LDWD2(IP05)
PLAST=VHAI(I,3,J)
C SEND MOVING PICTURE FRAME
IMHNY=VHAI(I,4,J)*SFAC=1.5
CALL LDWD2(IMHNY)
PLAST=PLAST+VHAI(I,4,J)
700 IF (J+EQ+NI) GOTO 200
J=J+1
IF (J+EQ+0) J=50
GOTO 300
200 CONTINUE
C INTEG
CALL LDWD1(O)
CALL LDWD2(O)
CALL WDSEND
RETURN WRITE(LIBUT,0,ICHAR,INT)
END=0
IST=0
CALL ACSET(I,30,0)
RETURN
ENTRY LDWD1(IN)
INTEND=NO
IMHNY=IN/128
ILORD=IN*IN/128
DO 1 I=1,3
IN=IMHNY(I)
C SEND BYTES OF INFORMATION
C=IN+1
C=IN+1
IN=IN+1
1 CONTINUE
RETURN
C

SUBROUTINE ILMD
DIMENSION IBUF(25), IBK(3)
DIMENSION INBL(100), INBG(3)
LOGICAL FLAG
NAMELIST LNT.
DATA BBUF(1, M)

LIST = 0
INPUT
ICLAR = 4
CALL BCKRTEIL(132, 0)
IPT = 0
IST = 0
CALL BCKSETIL(19, 0)
RETURN

C INITIALISE CCC COMMUNICATIONS.

ENTRY LDMD (MN)
INTEG = INTEG + 1
IF (IST < 128)
LDMD = LDMD + 1
ELSE
LDMD = LDMD + 1
ENDIF
IF (IST < 128)
LDMD = LDMD + 1
ELSE
LDMD = LDMD + 1
ENDIF
ENDIF

IF (IST < 128)
LDMD = LDMD + 1
ELSE
LDMD = LDMD + 1
ENDIF

C SEND BYTES OF INFORMATION
C
C
CONTINUE
RETURN.
ENTRY LDWD2(MNC)
INTEG=MNC
N=1
IARR(1)=INTEG
IF (INTEG+LT+128+AND+INTEG+GE+0) GOTO 4
ISIGN=0
IF (INTEG+5+6+6)
5  ISIGN=64
INTEG=INTEG
6  IMIORD=INTEG/128
    ILORD=INTEG=IMIORD*128
    IF (ILORD+NE+0) GOTO 10
    ILORD=1
    IMIORD=IMIORD+8
10 CONTINUE
    INTEG=0
    IARR(1)=0
    IMIORD=IMIORD+ISIGN
    N=3
4  DO 7 I=1,N
    INTEG=IARR(I)
7        LW,*4     IPT
4        LW,*9     INTEG
S        STB,*9     IBUF,*4
        IPT=IPT+1
        IF (IPT+NE+100) GOTO 7
INDEX=1
GOTO 9
7  CONTINUE
8  RETURN
C
ENTRY WDSEND
INDEX=2
9  CALL CHECK(L,IM,IST,IBC)
    IF (IAND(IST,2)+EQ+2) GOTO 9
CALL BCWRITE(L,IBUF,*4,IPT,IST)
C 7 LINEX=STAR
C PLLOTS HISTOGRAMS ON LINE PRINTER.
C 8 LINEXK=STAR

SUBROUTINE PLOTER(XN, BAR, TIME, NPOS, LANE)
   REAL X(N), HEAD(10), EF=1.9, +1
   INTEGER LINE(100), BLANK, STAR
   LOGICAL BAR
   DO TO 10
   WRITE (108,502) NE
   DO 1 I=1,100
   1 LINE(I)=BLANK
   2 XM=1.070
   3 XMIN=1.0E70
   502 DO 2 I=1, N
   3003 IF(X(I)*LT+XMIN) XMIN=X(I) CONTINUE
   3004 IF(X(I)*GT+XMAX) XMAX=X(I) CONTINUE
   3005 CONTINUE
   IF(XMAX=XMIN) 25, 3, 4
   3003 XMAX=XMIN+1.0E7, BLANK = X(I) +1.0E7
   3004 XMIN=XMIN+1.0E7, BLANK = X(I) +1.0E7
   6004 CONTINUE
   507 DO 5 I =1,100
   508 Z=1.0E7, BLANK = X(I)
   509 HEAD(I)=(XMAX+XMIN)*7/100+XMIN
   3005 IF (IABS(LANE)+EQ+3) WRITE(108,3005)
   3005 IF (IABS(LANE)+LT+3) WRITE(108,3005) LANE
   3005 IF (LANE+GT+0) WRITE(108,3005) LANE
   3005 IF (LANE+LT+0) WRITE(108,3005) LANE
   3005 WRITE(108,507) XMIN, HEAD
   3005 IF (LANE+GT+0) WRITE(108,3005)
   3005 IF (LANE+LT+0) WRITE(108,3005)
   DO 6 I=1, N
   3005 KPLTX=(I(X(I)=XMIN)/XMAX+XMIN)+100.05
   3005 IF (KPLTX+GT+100) KPLTX=100
   3005 IF (KPLTX+EQ+0) GOTO 11
   3005 IF (+NOT+BAR) GO TO R

00300080
00300090
00300100
00300110
00300120
00300130
00300140
00300150
00300160
00300170
00300180
00300190
00300200
00300210
00300220
00300230
00300240
00300250
00300260
00300270
00300280
00300300
00300330
00300350
SUBROUTINE PLOTER(X,N,BAR,TIME,NPOS,LANE)
REAL X(N),HEAD(10)
INTEGER LINE(100),BLANK,STAR
LOGICAL BAR
DATA BLANK,STAR/-1,1/,*/*
IF(N+LT=1)GO TO 25
WRITE (10,B502)
DO 1 I=1,100
1 LINE(I)=BLANK
XMAX=1+E70
XMIN=1-E70
DO 2 I=1,N
2 IF(X(I)=LT+XMIN) XMIN=X(I)
3 IF(X(I)=GT+XMAX) XMAX=X(I)
2 CONTINUE
3 IF(XMAX=XMIN)25,3,4
4 XMAX=XMIN+1.
5 XMIN=XMIN-1.
4 CONTINUE
5 DO 5 I=1,10
6 K=I
7 IF(ABS(LANE)+LT=3) WRITE(10,B3003)
8 IF(ABS(LANE)+LT=3) WRITE(10,B3004)
9 IF(LINE+GT=0) WRITE(10,B3001)TIME,NPOS
10 IF(LINE+GT=0) WRITE(10,B3002)TIME,NPOS
11 WRITE (10,B507) XMIN,HEAD
12 IF(LINE+GT=0) WRITE(10,B3002)
13 IF(LINE+GT=0) WRITE(10,B3006)
14 DO 6 I=1,N
15 IF(X(I)=XMIN) (X(I)=XMIN)+(XMAX-XMIN)*100+5
16 IF(KPLOTX+GT=0) KPLOTX=100
17 IF(KPLOTX=EQ=0) GOTO 11
18 IF(NOT+BAR) GO TO 8
   0O}
DO 7 K=1,KPLOTX
7 LINE(K)=STAR
CONTINUE
DO 8 LINE(KPLOTX)=STAR
8 SUBSPACE=9+(I*111+BUFFER,10)
IF(LANE=LT,10) SPACE=I*2,-1.
WRITE(108,508) SPACE,X(I),LINE
IF(*NOT*BAR) GO TO 10
DO 9 K=2,KPLOTX,BUFFER,10
9 LINE(K)=BLANK
10 LINE(KPLOTX)=BLANK
6 CONTINUE
RETURN
25 WRITE(108,506)
RETURN
502 FORMAT (1H1)
3003 FORMAT (1X,'LANES 1 & 2 AVERAGED TOGETHER',/
3004 FORMAT (1X,'LANE',15,3X,'AVERAGED',/
3005 FORMAT (20X,'TIME',15,1H4,15,3X,'POSITION',15,10X,'PROBABILITY OF DELAY
& X')
3006 FORMAT (1X,9HDELAY )
3007 FORMAT (1X,6HSECS),15,1H1K,2X,1H1,10(9X,1HI)
504 FORMAT (1X,24,1H=),1H=20(5H---- ),1H=)
507 FORMAT (16X,1I9,3,1H1))
508 FORMAT (1X,F3,2X,F3,1I4,1H1,99A1,A1)
506 FORMAT (1X,12HPLTIER ERROR )
3001 FORMAT (20X,'TIME ',15,1H4,15,3X,'POSITION ',15,10X,'PROBABILITY OF SPA
CCING X')
3002 FORMAT (1X,9HSPACING )
C1X,16H(* MIN HEADWAY )
END
C WRITES AND READS FROM A PARTICULAR DISK SECTOR.

SUBROUTINE DISKRD(I,SUBF,IN)
SUBREAD I=I$10
GOTO 1

ENTRY DISKWT(I,SUBF,IN)

LI 1 F12
LI 0 J0A
LI 2
STALL BNE I=21,302,30
SI J=100000010
STA J=LW 9 F13
STA I=STB 9,1 R1 1
STA LW 2 CT=*
STA LI 3 35
STA LI 4 35
SEXT IW 5 SUBF
S BGEZ *+2
S LW 5 *+5
S LW 5 360
S LW 7 *=ISA
S BGEZ *+2
S LW 7 *+7
S CAL1 1

RETURN
2 PAUSE 'PRG DISK ERROR'
END
CIMACRSYM SI,GO
DEF BCWRITE,BCREAD,BCSET,BCM0VE
REF CWRITE,CREAD,CSET,CM0VE

BCWRITE
LI,12 CWRITE
B BCOC

BCREAD
LI,12 CREAD
B BCOC

BCSET
LI,12 CSET
B BCOC

BCM0VE
LI,12 CM0VE

BCOC
LD,4 14
CAL3,0 0
B +5,4

END

CIYELLOW (F1,2X2),(FS1,80)
CILOAD GO,(UDCB,5),(PUBLIC,GLOBAL)
CIASS (F1,2X0)
CIASS (F1,2X1,lb1)
CIASS (F1,3X1,lb2)
CIASS (F1,T0)
CIASS (F1,20,GC)
CIEXTRABGD
C THIS PROGRAM SIMULATES NETWORKS.

C FORTRAN

COMMON /CONST/SPEED,PPM,ACCM,TAB,FFHDWY,FCHDWY,SIDEA
&/SPEED,PEND(20),SPEEDL(20),XTAB(20),ASPACE(4),PROB(4,4)
&/CRL(20),CONST1,CONST2,ACCJL,DELTV,HEIGHT,WIDTH
COMMON /CONST/ IBUF(20),LEN0(20),JNEV(4,4,5),NLINKS,NIN,NOUT
&/MAR(10),ICBDE(20),ICRL(20),JPRINT,JPLOT,JPIC,APL,APRL,MAG,APLMAG,TRANS(100),ITPR
&/BAL1(21,4)
&/BAL2(14)
&/BAL3(21)
&/BAL6(5)
&/BAL17(3)
COMMON /VREAD/ IBC,IST,LIM,IBUF1,10)
COMMON /CONST/ LINKST(20),IPST(20),SFAC
COMMON /WRT/ SETTIM,ISTIM,TOK,IFL,PT,SAVE,ITR
&/ITRACE,ILINK,IWE
&/ITM
&/NOSTOP
COMMON /CARRY/ NODE,HSTORE,WSTORE
&/SCST,SCSTY
FLAG=1
HEIGHT
CALL SEGLOAD(1)

C INPUT DATA AND UNITS HEADER.
CALL DATARD
NDUM=NLINKS=4
DO 6 I=0,NDUM
IF (I.EQ.0) GOTO 10
C SET UP LINK VEHICLE QUEUE PRINTERS.
LINKP(1+I+1)=LEN(I+1)+1
GOTO 6
6 ANOM(1+I+1)=1
10 LINKP(1+I+1)=1
C (1+1,2)=LEN(I+1)+1 ENTRANCE.
C INITIALISE LOCAL COUNTERS.
   ISTEP=0
   ITIME=0
   NPRINT=0
   NPLOT=0
   NPICT=0
   NLOG=0
   NPARAM=0
   NMAG=0
   DO 950 I=1,5
950 LINKST(I)=0
C ITRANS TRANSFORMS ARRAY POSITION INTO VEHICLE NUMBER FOR LINK.
   DO 960 I=1,100
960 ITRANS(I)=0
   TSAVE=-1.
   IPRT=0
   NONSTOP=0
   ITRP=1
   FLAG=3
   CALL SEGLOD(3)
   CALL ILOAD
   ITEST2=1
   ITM=0
   IKNOW=0
   IFLG=0
   HSTORE=MHEIGHT
   WSTORE=MWIDTH
   FLAG=2
   CALL SEGLOD(2)
C INITIALISE SUBROUTINES.
   CALL PRINT2(1)
   CALL SPACES(0)
   CALL INBD
   LI=7
   CALL RANDOM(LI,LI,RAND)
   CALL ICONTROL
C INITIALISE A VEHICLE AT EACH ENTRANCE.
C IFLDO 7 I=1,NIN
   J=LINKP(I,J)
   CALL ENTRY(I,J)
   7 TIMES(I)=SPACE(I)
   FLAG=4
   CALL SEGLOD(4)
   CALL WRIFIN
   CALL WRITER
   GOTO 93
C INCREMENT TIME
   TIME=TIME+DELT
C IF (IPRT=EQ,1) GOTO 500
C SKIP READ CHECK
   IF (ISTEP)320,322,500
C CHECK READ
   322 CALL CHECK(I,IM,IST,IBC)
   IF (IAND(IST,1)*EQ,1) GOTO 500
C HERE IF READ FINISHED
   PBYTE=0
   IST=0
   CALL BCMEVE(I,IBUF1,IBYTE,IR,IST)
   320 CALL SEGLOD(3)
C STOP PICTURE DISPLAY
   CALL PSTEP
   I=2
   SEGLOD(1)
C CHECK IF MAIN DIALOGUE TO BE SKIPPED
   IF (ICH(IBUF1,I)*EQ,2247) NONSTOP=1
   IST=0
C MAIN PICTURE OF VEHICLE
C SET UP READ FOR TIMING CHARACTER
   CALL BCREAD(I,IBC,IST)
   CALL SEGLOD(4)
93 CONTINUE
   FLAG=4
C BRANCH TO DIALOGUE
C REVISE CALL DECIDE
500 CONTINUE
C IFLG = 1 FOR MAGNIFIED PICTURE.
   IF (IFLG*NE.1) GOTO 334
   IFLG=3
   CALL SEGLOD(3)
C DRAW MAGNIFIED PICTURE OF NETWORK.
   CALL NEWPIC
   ITM0=0
   IFLG=0
C IFLG = -1 FOR NORMAL PICTURE.
334 IF (IFLG*NE.-1) GOTO 335
C IFLG = 0 FOR NO CHANGE.
   FLAG=3
   CALL SEGLOD(3)
C DRAW NORMAL PICTURE OF NETWORK.
   CALL PICT2
   ITM0=0
   IFLG=0
335 CONTINUE
C PRINT FLAG SET?
   IF (IPRT*EQ.1) GOTO 42
C TIME TO PRINT?
   IF (NPRINT*LT*JPRINT) GOTO 40
   NPRINT=0
42 FLAG=1
   CALL SEGLOD(1)
C PRINT OUT DATA.
   CALL PRINT
   IPRT=0
C TIME FOR PICTURE OF VEHICLES.
40 IF (IPRT*EQ.1) GOTO 42
   IF (NPICT*LT*JPICT) GOTO 41
   NPICT=0
   IF (1*KNOW*NE.-1) GOTO 324
   FLAG=4
   CALL SEGLOD(4)
C MOVE BACK ONE STEP ON MAG TAPE.
   CALL BACK
ITEST1 = 1
324 CONTINUE
IF (ITEST1EQITEST2) GOTO 31
ITMO = ITEST1
31 ITEST2 = ITEST1
TIME STEP
FLAG = 3
CALL SEGLOAD(3)
IF (ITMOEQ50) GOTO 30
C CHANGE CLOCK IF DIRECTION OF STEPPING CHANGES.
CALL CLOCK(ITMO)
ITMO = 50
30 CONTINUE
C SEND VEHICLE PICTURE.
CALL VEHPIC
NPIC = 0
IF (ITRACEEQ1ORNPRI NT EQ 0) GOTO 41
FLAG = 1
CALL SEGLOAD(1)
C PRINT IF TRACE OPTION SELECTED.
CALL PRINT
41 CONTINUE
C IF STEPPING BACKWARDS IGNORE WRITE TO MAGNETIC TAPE.
IF (INKNOWEQ1) GOTO 44
IF (NMAGLTJMAG) GOTO 44
IF (FLAGEQ4) GOTO 45
CALL SEGLOAD(4)
FLAG = 4
C OUTPUT TO MAG TAPE
45 CALL WRITER
NMAG = 0
44 CONTINUE
C LOAD CORRECT SEGMENT.
IF (FLAGEQ2) GOTO 43
FLAG = 2
CALL SEGLOAD(2)
43 CONTINUE
C STOP CONDITION.
IF TIME<LESTOP, GOTO 46

STOP CONTINUES ONE TIME STEP.
C MOVE C RECHECK CALL ECHKD(1)
C CALL ECHKD(0) CALL VMOVE CALL ASVEH
C INCREMENT LOCAL COUNTERS.
ITIME=ITIME+1
NPRINT=NPRINT+1
NPLOT=NPRINT+1
NFL=NFL+1
NPARAM=NPARAM+1
NMAG=NMAG+1
GOTO 20 END
C C VEHICLE CONTROL SUBROUTINE

SUBROUTINE ICONTROL
COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDNY,SIDEA
& CSPEDP,PEND(20),SPFEDL(20),XTAB(20),7),ASPACE(4),PRB(4,4)
& CRL(20),COMMON /CONST2/,IBUF(20),LENK(20,3),JNEY(4,4),NLINKS,NIN,NOUT
& MARI(10),ICODE(20),ICR(20),JPRINT,JPLT,JPICT,JFLW,JPARAM,JMAG
COMMON /VAR/,TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWS(100),SFAC
& IVEHA(100,4),LINKP(20,2),LJ,NCRL(20)
& ,TIME,PRINT,JPLT,JPICT,NFLW,NPARAM,NMAG,ITANCES(100),ITRP
& BAL1(21)
& ,BAL2(14)
& & ,OFFSET,KPOINT,POINT,LLANCE,LLVEH,THDWY,THDWN
& ,THDWYF,DTIME,KLINK,NF(2),LANE(2),PART(2),ART(2),TDEL(2)
& & ,BAL6(5)
& & ,BAL7(3)
& LOGICAL FLAG
& FLAG=FALSE

C INITIALISATION

DO 21 I=1,5
GOTO (23,24,25,26,27) 1
23 N=1K=J
M=10 37
28 N=0K=J
DO 33 J=1,NLINKS
31 IF (NCRL(J)*EQ,0) GOTO 33
27 N=0K=NCRL(J)
26 DO 34 K=1,N
27 IF (ICR(K),NE,1) GOTO 34
21 LANE(N)=J
N=2
C POSN=PEND(J)
34 CONTINUE
M=M+NCRL(J)
33 CONTINUE
SPNML=SPEED(LANE(1))
S=ABS(SPNML*SPNML*CSPED)/ACCNML
OFFSET=(POSN-1)/SPNML+ABS(SPNML*CSPED)/ACCNML
KPOINT=LINKP(LANE(1),1)
JPOINT=LINKP(LANE(2),1)
NFV(1)=KPOINT
NFV(2)=JPOINT
KLANE=1
LLVEH=KPOINT
THDWEY=CSPED/(2*ACCEF+VL)/CSPED
THDWY=THDWEY+FCHDWY
THDWYF=THDWEY*FFHDWY
24  GOTO 21
25  N=1
M=1
NO=0
DO 35 J=1,NLINKS
IF (NCRL(J),EQ,0) GOTO 35
NO=NO+NCRL(J)
36  K=M+1
IF (ICRL(K),NE,3) GOTO 35
DTIME=PEND(J)/CSPED
KLINK=J
GOTO 37
36  CONTINUE
M=M+NCRL(J)
35  CONTINUE
26  GOTO 21
27  GOTO 21
21  CONTINUE
RETURN
C
ENTRY CONTROL(JJ,PPB&M,NSTRAT)
J=JJ
POSN=PPB&M
VEHA(J,8)=VL
GOTO (10,110,12,13,14) NSTRAT
10 IF (J=EQ+KPOINT) GOTO 20
IF (J=NE+JPOINT) GOTO 40
KPOINT=JPOINT
JPOINT=0
C CALCULATE ALTERNATE PRIORITY TARGET
NFV(2)=MARK(LANE(2),IARS(NFV(2)),1)
KLANE=2
GOTO 28
20 NFV(1)=MARK(LANE(1),IARS(NFV(1)),1)
JPOINT=0
28 LLVEH=KPOINT
VEHA(KPOINT,4)=OFFSET+TIME
I=KLANE
MPOINT=1
GOTO 11
40 DO 16 I=1,2
16 IF (KFV(J)=EQ+J) NFV(1)=NFV(I)
DO 1 I=1,2
IF (NFV(I)>GT+0) GOTO 1
NFLANE=IVHA(ILLVEH,2)
NBLANE=IVHA(J,2)
TDWYN=THDWYC
THDWN=THDWYN+THDWYF
VEHA(J,4)=VEHA(ILLVEH,4)+THDWYN
IVHA(ILLVEH,4)=J
82 CONTINUE
LLVEH=J
MPOINT=1
I=NBLANE
GOTO 11
1 ART(1)+VEHA(NFV(J),5)+OFFSET
ST=VEHA(KPOINT,4)
DO 2 I=1,2
THDWN=THDWYC
IF (I=EQ+KLANE) THDWYN=THDWYF
PART(1)=STAR+THDWYN
IF (ART(1)$GT$PART(1)) PART(1)=ART(1)
PART(2)=PART(1)+THDWYC
IF (ART(3)$GT$PART(2)) PART(2)=ART(3)
TODDEL(1)=PART(1)+ART(1)+PART(2)=ART(3)
LNEXT=1
IF (TODDEL(2)$LT$TODDEL(1)) LNEXT=2
THDWYN=THDWYC
IF (LNEXT$EQ$KLAGE) THDWYN=THDWYF
K=NFV(LNEXT)
VEHA(K,2)=STAR+THDWYN
IF (K$NE$J) GOTO 50
KSTORE=IVEHA(KPoinT,4)
CALC
IVEHA(KPoinT,4)=K
IVEHA(K,2)=KSTORE
NXVEH=K
NLANE=IVEHA(KPoinT,2)
IF (KSTORE$EQ$0) GOTO 61
K1=KSTORE
NLANE=IVEHA(KPoinT,2)
THDWYN=THDWYC
IF (NLANE$EQ$NFLANE) THDWYN=THDWYF
SLIP=VEHA(NXVEH,4)+THDWYN=VEHA(KPoinT,4)
IF (SLIP$LT$L) GOTO 61
VEHA(KPoinT,4)=VEHA(KPoinT,4)+SLIP
NXVEH=K
NFLANE=NLANE
GOTO 61
NXVEH=IVEHA(KPoinT,4)
IF (NXVEH$EQ$K) GOTO 52
OUTPUT(109) TARGET TABLE FAILURE, TIME
IVEHA(KPoinT,4)=K
KPoinT=NFV(LNEXT)
KLANE=LNEXT
NFLANE=LNEXT
NFV(LNEXT)=$MARK$ (LANE(LNEXT), KPoinT, 1)
NXVEH=KPoinT
GOTO 51
D2=ABS(UJ-UV1/ACCNML
T1=(DTTJ+D1)/UJ+D2
T2=(DTTJ+D1)/UV+D2
IF (UW+GT+UJ) GOTO 70
IF (TTTJ+GT+T2) GOTO 4
IF (TTTJ+GT+T1) GOTO 5
GOTO 71
70 IF (TTTJ+GT+T1) GOTO 4
IF (TTTJ+GT+T2) GOTO 5
71 CONTINUE
A=2
B=2+TTTJ+ACCNML+2+(UV-UJ)
C=UV+UV+UJ+UJ=2+ACCNML+DTTJ
D3=B+B=4+A+C
IF (D3+GE+O+) GOTO 6
VEHA(J,J)=SPNML
FLAG=TRUE
GOTO 8
6 D3=SORT(D3)
VEHA(J,J)=(B+D3)/(2+A) TURN
GOTO 8
5 VEHA(J,J)=(DTTJ+D1)/(TTTJ-D2) PD REQU WD LCP AT TIME TIME2
GOTO 8
4 A=2+TIME
B=2+TTTJ+ACCNML+2+(UV-UJ)
C=UV+UV+UJ+UJ=2+ACCNML+DTTJ
D3=B+B=4+A+C
IF (D3+GE+O+) GOTO 7
CALL PRINT1("INTERSECTION SPEED REQU WD LOW",TIME,J,J)
VEHA(J,J)=1.
GOTO 8
3 D3=SORT(D3)
VEHA(J,J)=(B+D3)/(2*A)
8 IF (VEHA(J,J)+LT+SPNML) GOTO 9
VEHA(J,J)=SPNML
GOTO 62
FLAG=TRUE
9 IF (*NOT*FLAG) GOTO 90
FLAG=FALSE
UI=VEHA(J+7)
T=(DTJ+(UJ+UJ+UV-UV=2/UI+UL)/(2*ACCML))/(UI+(2*UI-UV-UJ)/ACCML)
TTARGN=TIME+T
SLIP=TTARGN-VEHA(J+4)
NXVEH=J
15 VEHANXVEH+4)=VEHA(NXVEH+4)+SLIP
NFLANE=IVEHA(NXVEH+2)
KSTORE=IVEHA(NXVEH+4)
IF (KSTORE=EQ.0) GOTO 90
K1=KABS(KSTORE)
NFLANE=IVEHA(K1+2)
THDWYN=THDWYC
IF (NFLANE=EQ.FNLANE) THDWYN=THDWYF
SLIP=VEHA(NXVEH+4)-VEHA(K1+4)+THDWYN
NXVEH=K1
IF (SLIP.90,90,15.
90 GOTO (91,61) MPDINT
91 CONTINUE
IF (VEHI(J+7).GE.+1) RETN
VEHA(J+7)=1.
CALL PRINT1('INTERMEDIATE SPEED REGU.T LOW TIME I,J)
RETURN
12 VEHANJ+4)=VEHA(J+4)+D TIME
I=KLINK
GOTO 11
13 VEHAINJ+4)=O.
BPML=SPEEDL(IVEHA(J,2))
VEHA(J+7)=SPML
RETURN
14 VEHAINJ+7)=VEHA(J,6)
RETURN
110 CONTINUE
DO 92 I=1,2
IF (J=NE*NFV(I)) GOTO 92
NFVEH=J
GOTO 93
92 CONTINUE
IF (J.NE.KE POINT) GOTO 97
NFVEH=IVEHA(KE POINT,4)
IF (NFVEH.NE.0) GOTO 93
KPOINT=NFV(1)
JPOINT=NFV(2)
KLANE=1
GOTO 97
93 IVEHA(KPOINT,4)=IVEHA(KPOINT,4)
KPOINT=NFVEH
LNET=IVEHA(KPOINT,2)
DO 95 I=1,2
95 IF (LANE(I).EQ.LNET) KLANE=I
DO 94 I=1,2
IF (NFV(I).EQ.KPOINT) GOTO 96
94 CONTINUE
96 NFV(I)=MARK(LANE(I),NFV(I),1)
99 KSTORE=IVEHA(NFVEH,4)
IF (KSTORE.NE.NFV(I)) GOTO 98
NFV(I)=NFV(I)
GOTO 97
98 IF (KSTORE.EQ.0) GOTO 97
NFVEH=KSTORE
GOTO 99
97 MPOINT=1
I=IVEHA(J,2)
GOTO 11
RETURN
END
SUBROUTINE ILDWD
COMMON /CIDWD/ IPT, IBUF(25), IARR(3)
COMMON /VREAD/ IBC, IST, LIM, IBUF(10)
COMMON /WRITE/ SETTIM, ISTEP, IKNOWN, IFLG, TSAVE, IPRT
& ITRACE, ILINK, IVND
& ITHO, IMC
& NONSTOP, ITPE, NLKG
COMMON /VAR/ TIME
COMMON /CONST2/ IBUF(20), LEND(20, 3), JNEY(4, 4, 5), NLINKS, IN, NODE
DIMENSION IWORD(100)
C IF MOUT.EQUIVALENCE (IARR(1), INTEG), (IARR(2), IHORD), (IARR(3), ILORD)
C NAMELIST L, ITSAVE, RELATIVE, INCREMENTS
C INITIALISATION
10 IF ITYPE(NODE+9) . LE 0
   GOTO 6
C IPT=0
5 INPUT(20)
6 IST=0 . INT
C COMMON(IKNOW=NMG, BYTE TYPE,)
7 IF RET(NODE+128)
C RETURN(RET)
C ENTRY LOWD1(MND) NODE
   INTEGER MND(MND, 1)
   INTEGER NMG(NMG, NMG, 128)
C IHOLD SAVES DATA FOR DEBUGGING.
C ADD IHOLD2(IPT+1) . INT
   IPT=IPT+1 . INT
C DIVIDE NUMBER INTO A HIGH ORDER AND LOW ORDER COMPONENT BREAKPT 2**8
   IHORD=INTEG/128
   ILORD=INTEG MOD 128
C SAVE BYTES IN OUTPUT BUFFER.
   DO 1 I=2, 9
   INTEG=IARR(I)
   SAVE IN LM=1, IPT, IBUL, IAUB (IN=3) ZER, HIORDER, LOWORDER,
   OR (IN=1), LM=5, INTEG
   DO ST8=9, IBUF, 4

   C FOR ENCODING AND TRANSMITTING PICTURE ROUTINE CHARACTERS.
   C FOR ENCODING AND TRANSMITTING PICTURE ROUTINE CHARACTERS.
IPT=IPT+1
IF (IPT=NE=100) GOTO 1
INDEX=3
GOTO 9
1 CONTINUE
RETURN
C ENTRY LDWP1(MNC)
INTEG=MNC
IMORD2(IPT*1)=INTEG
IPT2=IPT2+1
N=1
IARR(1)=INTEG
C IF NUMBER ONE BYTE SIZE AND NOT EQUAL TO ZERO (CONTROL CHARACTER)
C CHANGE SIGN BIT SINCE NEGATIVE INCREMENT:
IF (INTEG=LT=128 AND INTEG+GE=0) GOTO 4
ISIGN=0
If (INTEG)=6566
5 ISIGN=64
INTEG=INTEG
C CONVERT TO TWO BYTE TYPE:
6 IMORD=INTEG/128
IL0ORD=INTEG%128
C ENSURE LOW ORDER NOT ZERO:
IF (IL0ORD=NE=0) GOTO 10
IL0ORD=1
C ADD ZERO FLAG BIT:
7 IMORD=IMORD+R
10 CONTINUE
INTEG=0
IARR(1)=0
C ADD SIGN BIT:
7 IMORD=IMORD+ISIGN
N=3
C SAVE N CHARACTERS IN ARRAY (NOTE (N=3) ZERO, HIORDER, LOWORDER,
C OR (N=1) LOWORDER ONLY)
4 DO 7 I=1,N

INTEG=1

IWORDS=0,16

S
IF W=4 IBUF=1
S
IF W=9 IBUF=INTEG
S
IF STB=9 IBUF=1

IF (IBUF*NE*100) GOTO 7

INDEX=1
CONTINUE
7
RETURN

ENTRY WDSEND
INDEX=1
CONTINUE
9
CONTINUE

C HAS PREVIOUS WRITE ENDED
CALL CHECK(L,IM,IST,IBC)
IF (IAND(IST,2)*EQ*2) GOTO 9

C YES - SEND NEW BLOCK DATA
IST=0
CALL BWRITE(L,IBUF,0,IPT,IST)

CONTINUE

FORMAT(INO,1C10(X,10I10/))
IPT=0
IF (INDEX*NE*2) GOTO 200
IF (ISTEP*NE*1) GOTO 200

C ONLY HERE IF STEP OPERATION SELECTED
IKNOW=0
IPRT=0
IBC=0

CALL CHECK(L,IM,IST,IBC)
C HAS READ ENDED
IF (IAND(IST,1)*EQ*1) GOTO 310

BYTE=0
IST=0
CALL BMOVE(L,IBUF,IBYTE,IBC,IST)
DO 310 I=1+2

C TWO OPTIONS CAN BE SELECTED EACH STEP
IF (ICH(IBUF1,I)·EQ·2ZD4) GOTO 222
IF (ICH(IBUF1,I)·EQ·2ZC5) ISTEP=1
IF (ICH(IBUF1,I)·EQ·2Z8D) GOTO 210
IF (ICH(IBUF1,I)·EQ·2Z4F) INRW=1
IF (ICH(IBUF1,I)·EQ·2Z50) IMPRT=1
GOTO 210

222 OUTPUT (108) TIME
C OUTPUT DATA SAVED TO LINE PRINTER.
    WRITE(108,100) (IMOLD2(II),II=1,II1)
    IPT2=0
    IF (STEP=1) GOTO 100

210 IST=0
    LAST RECORDED TIME ON TAPE
    IBC=2
    TIME
    CALL BREAD(L,IBC,IST,IVE,1540,IST,N)
    CONTINUE
G READ GOTO (17,36,41) INDEX T.
    END.
ENTRY WRFIN.
ENTRY READ.
C END FILE UNLESS ALREADY ENDED ELSEWHERE.
    IF (TIME·LE·TSAVE) GOTO 30
    ENDFILE.
    RETURN.
ENTRY HEAD.
INDEX=1
    IF (SETTIME·LE·TIME) GOTO 32
    IF (SETTLM·LT·TIME) GOTO 30.
C MOVE POSITION ON DATA TAPE FROM TIME TO SET TIME.
    IF (TIME·LT·TSAVE) GOTO 32
    CALL BUFFER(INP1,TSAVE,1540,IST,N)
    IF (IST·LE·3) GOTO 28
    INDEX=3
    GOTO 20
C BUFFER IN MORE.
    28 IF (TIME·LT·SETTLM) GOTO 31
SUBROUTINE DECIDE
COMMON /WRIT/, SETTIM, ISTEP, IKNOW, IFLG, TSAVE, IPRT,
& ITRACE, LLINK, IVN6
& ITMO, IMESS, RT, PI, PI2, 3.14, 8Z0D0000000
& NONSTOP
COMMON /CARRY/, NODE, STORE, WSTORE, 8Z0D0000000
& SCST, SCSTY
COMMON /CONST, SPNML, ACNM, ACCEMG, VL, FFHDDY, FCHDDY, SVIDA
& CSPEED, PEND, LPEND, LSPDDL, LXTABB, LYSTAB, LSPACE, LPRB
& CRL
DIMENSION IMES1(5), IMES2(8), IMES3(9), IMES4(9), IMES5(11), IMES6(5)
& IMES7(11), IMES8(1), IMES9(4), IMES10, IMES11, IMES12(5)
DIMENSION IMESS(4)
DIMENSION IMESS(5)
COMMON /VREAD/, IBC, IBFIL, IM, IBUF(10)
DIMENSION IMESS11(10)
DIMENSION IMES4A(9), IMES21(10), IMES12(5)
DIMENSION IMESS13(6)
DIMENSION IMES9A(12)
COMMON /CON1, FILL1, PICT1
COMMON /VAR, FILL1, PICT
COMMON /VA1, FILL1, TIME
DIMENSION LNKTP(20,2)
DIMENSION ITRANS(100)
EQUIVALENCE (FILL1(1308), LNKTP(1,1))
EQUIVALENCE (FILL1(1376), ITRANS(1))
DIMENSION IMES10(1)
DIMENSION IMES14(7)
EQUIVALENCE (FILL1(164), MAR(1))
DATA ICR/8Z0D0000000/
DIMENSION IMESS1/IC TYPE CONTROL T1, 8Z0D0000000/
DATA IMESS2 ('WHICH OPTION IS ', 'REQUIRED X', '8Z0D0000000/'
DATA IMESS3 ('RESET TIME #R ST!', 'EP PICTURES #S', '8Z0D0000000/')
DATA IMESS4 /"WRONG CHARACTER '","INPUT TRY AGAIN'",RZ0D000000/
DATA IMESS5 /"INPUT IN SECS CH',"ANGE IN TIME REQ','UIRED'",RZ0D00
&000/
DATA IMESS6 /"STEP OPERATION'",RZ0D000000/
DATA IMESS7 /"TYPE CONTROL '"," & INDICATE TO C","ONTINUE'",RZ0D00
&000/
DATA IMESS8 /"D 1.1 G 1.3'",RZ0D000000/
DATA IMESS9 /"WHICH NODE '",RZ0D000000/
DATA IMESS10 /"HEIGHT & WIDTH '",RZ0D000000/
DATA IMESS11 /"NO OF TIME STEPS'"," BETWEEN PICTURE'S '",RZ0D0000
&00/
DATA IMESS12 /"MAGNIFY PICTURES'"," NO MESSAGE ",RZ0D000000/
DATA IMESS13 /"INPUT LINE & VEH'"," ICLE'",RZ0D000000/
DATA IMESS14 /"SCREEN X & Y COX'," RGS ",0<X<1000 '"," 0<Y<760'",RZ
&0D000000/
DATA IBL/RZ40404040/
DATA IMESS15 /"DIAGNOSTIC SUPRE',"SSION '",RZ0D00000000/
C CHECK READ FINISHED FOR TIMING CHARACTER FROM GT40.
  9 CALL CHECK1,TM,IST,IBC
     IF (IAND(IST,1).EQ.1) GOTO 9
     IST=0
     IBYTE=0
     CALL BCHV(E(L,IBUF,IBYT,IBC,IST
     IFL=0
     ISTEP=0
     ITARGS=0
     ITH0=50
     LBAD=0
     RAI(1)=0
C CHANGE CDC STATUS TO ECHE.
     CALL BCSET(L,132,0)
C SKIP CHANGES IF NONSTP SET.
     IF (NONSTP.EQ.1) GOTO 54
C CHANGE GT40 STATUS SCREEN/PROGRAM.
     52 CALL BCWRITE(L,IMESS7,0,41,TST)
     IBC=1
IST=0
C READ ONE CHARACTER TO CONTINUE:
   CALL BCREAD(L,IBC,IST)
   ADD CALL CHECK(L,IM,IST,IBC)
C CHECK IT HAS ARRIVED:
   IF (AND(IST,R) .NE.+R) GOTO ACO
   IST=0
   IBYTE=0
   CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
   IF (LOAD.EQ.0) GOTO 12
C INPUT FOCAL PROGRAM IF LOAD = 1:
   CALL BREAD
   LOAD=0
   IST=0
   GOTO 52
20 CONTINUE
   IST=0
C WRITE TO GT40 'WHICH OPTION REQUIRED?'
   CALL BCWRITE(L,MESS2,0,29,IST)
   GOTO 6
7 IST=0
C WRITE OUT OPTION AVAILABLE:
   CALL BCWRITE(L,MESS3,0,33,IST)
6 IBC=10
   IST=0
C READ IN MAXIMUM IO CHARACTER:
   CALL BCREAD(L,IBC,IST)
   ADD CALL CHECK(L,IM,IST,IBC)
   IF (AND(IST,R) .NE.+R) GOTO 1
   IST=0
   IBYTE=0
C ONLY FIRST TWO COUNT AND ONLY ONE LETTER SELECTS OPTION:
   CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
C CHECK BENSE CHARACTER FOR OPTION REQUIRED:
   DO 3 K=1,2
3 IF (ICH(IBUF,K).EQ.27D9) GOTO 4
   END IF (ICH(IBUF,K).EQ.27E2) GOTO 5
IF (ICH(IBUF,K)EQ-27D4) GOTE 22
IF (ICH(IBUF,K)EQ-27D0) GOTE 10
IF (ICH(IBUF,K)EQ-2708) GOTE 21
IF (ICH(IBUF,K)EQ-27C6) GOTE 40
IF (ICH(IBUF,K)EQ-27E3) GOTE 41
IF (ICH(IBUF,K)EQ-27D3) GOTE 51
3 CONTINUE
C WRONG CHARACTER INPUT
   IBT=0
   CALL BCWRITE(L,IMESS,0,33,IST)
   IBT=0
C OPTION AVAILABLE
   CALL BCWRITE(L,IMESS,0,33,IST)
   GOTE 7
22 IBT=0
C MESSAGE OPTION
   CALL BCWRITE(L,IMESS12,0,17,IST)
25 IBT=0
   IBC=80
C READ IN MESSAGE,
   CALL BCREAD(L,IBC,IST)
23 CALL CHECK(L,IST,IBC)
   IF (IAND(IST,8)NE8) GOTE 23
   IBT=0
   IBYTE=0
C FILL BUFFER WITH BLANKS,
   DB 26 I=1.20
26 IM0(I)=IBL
C LOAD WITH MESSAGE
   CALL BCMOVE(L,IMB,IBYTE,IBC,IST)
C END WITH CR
   IF (IBC=EQ-1) GOTE 20
C WRITE TO LINE PRINTER
   WRITE(10,24) IMB
24 FORMAT(1X,20A1)
   GOTE 25
C ENDFILE ON TAPE AND STOP.
ENDFILE 1

STOP

C LOAD FOCAL PROGRAM.
51 LOAD=1
GOTO 52

C SET TRACE OPTION.
41 ITRACE=1
IST=0
CALL BCWRITE(L,IMES$13,O,21,IST)
IST=0

C READ IN LINK NUMBER AND VEHICLE FOR TRACING, COUNTED FROM END OF LINK.
IBC=20
CALL BCREAD(L,IBC,IST)

C CALL CHECK(L,IM,IST,IBC)
42 IF (IAND(IST,8)+NE+8) GOTO 42
IST=0
IBYTE=0
CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
DECOD(10,103,1BUF+N) ILINK,IVNO

FORMAT(215)
IVNO=IVNC-1
J=MARK(ILINK,ILINK(2),ILINK(2)+IVNO)
IVNO=ITRANS(J)
IST=0

C EVENT DIAGNOSTIC OUTPUT CANCELLED.
CALL BCWRITE(L,IMES$14,O,25,IST)
IST=0
IBC=2
CALL BCREAD(L,IBC,IST)

84 CALL CHECK(L,IM,IST,IBC)
IF (IAND(IST,8)+NE+8) GOTO 84
IST=0
IBYTE=0
CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
IF (ICH(IBUF+1)-EQ+2ZEB) MAR(3)=1

C RETURN TO OPTION SELECT.
C READ GOTO 20 SCALE FACTORS.
21 IFLG=1
C SET FLAG
    IST=0
    CALL BCWRITE(L,IMESS9,0,13,IST)
    IST=0
C CHOOSE CENTRE NODE OF MAGNIFIED PICTURE.
    IBC=5
    CALL BCREAD(L,IBC,IST)
80 CALL CHECK(L,IST,IBC)
    IF (IAND(IST,B) NE 8) GOTO 80
    IST=0
    IBYTE=0
    CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
    IF (ICH(IBUF,1) NE 229) GOTO 120
    IFLG=1
C RESTORE NORMAL SIZED PICTURE IF D9 (R) TYPED.
    HIEWO=MSTORE
    WIND=WSTORE
    GOTO 20
120 CONTINUE
    DECODE(5,101,IBUF,N) NODE
101 FORMAT(15)
    IST=0
C READ IN NEW CO-ORDINATES FOR CHosen NODE.
    CALL BCWRITE(L,IMESSA,0,45,IST)
    IST=0
    IBC=16
    CALL BCREAD(L,IBC,IST)
83 CALL CHECK(L,IST,IBC)
    IF (IAND(IST,B) NE 8) GOTO 83
    IST=0
    IBYTE=0
    CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
    DECODE(16,102,IBUF,N) SCSTX,SCSTY
    IST=0
C READ IN NEW SCALE FACTORS.
    CALL BCWRITE(L,IMESS10,0,17,IST)
IST=0
IBC=16
CALL BCREAD(L,IBC,IST)
82 CALL CHECK(L,IST,IBM)
IF (IAND(IST,B)=NE+R) GOTO R2
IST=0
IBYTE=0
CALL BCMVE(L,IBUF,IBYTE,IBM,IST)
DECODE(16,402,IBUF,N) MIEGHT,WIDTH
102 FORMAT(2F8+2)
C RETURN FOR NEW OPTION
GOTO 20
+ IST=0
C ASK CHANGE IN TIME REQUIRED,
C BWRITE(L,IMESS,0,41,IST)
IST=0
IBC=10
CALL BCREAD(L,IBM,IST)
2 CALL CHECK(L,IBM,IST)
IF (IAND(IBM,R)=NE+R) GOTO 22
IST=0
IBYTE=0
CALL BCMVE(L,IBUF,IBYTE,IBM,IST)
DECODE(10,100,IBUF,N) DISP
100 FORMAT(F5+1)
C NEW TIME FOUND.
C TIM+TIME+DISP
C CHANGE TAPE POSITION ACCORDINGLY.
C CALL READER
12 CONTINUE
C WRITE TO BT+O TIME NOW FOR SCREEN DISPLAY.
ENCODER(24+10,IBUF,N)TIME+ICA
110 FORMAT(PRESENT TIME)F10+3+4+1)
IST=0
CALL BWRITE(L,IBUF,0,N,IST)
C RETURN FOR NEW OPTION
GOTO 20
5    ISTEP=1
901   CALL CHECK(L,IM,IST,IBC)
         IF (IAND(IST,2)+EQ+2) GOTO 901
         IST=0
C TELL GT40 OPERATION HAS BEEN SELECTED.*
         CALL BWRITE(L,IMES+0,17,IST)
10   IST=0
         IF (IABS(IFLAG)+EQ+1) GOTO 905
         CALL BWRITE(L,IMES+0,41,IST)
55   NAGSTOP=0
         IBC=1
C TYPE CONTROL T AND INDICATE.*
C COME HERE IF NO CHANGE OR FINISHED.*
C READ INDICATE CHARACTER TO CONTINUE.*
         IST=0
         CALL BCREAD(L,IBC,IST)
903   CALL CHECK(L,IM,IST,IBC)
         IF (IAND(IST,8)+NE+8) GOTO 903
         IST=0
C SEND GT40 PICTURE START COMMANDS.*
         CALL BWRITE(L,IMES+0,13,IST)
         ITH=0
C CHANGE CBC STATUS TO NO ECHO.*
         CALL BCS ET(L,19;0)
         IST=0
         IBYTE=0
         CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
      IST=0
         IBC=1
C READ TIMING CHARACTER FROM FICAL PROGRAM.*
         CALL BCREAD(L,IBC,IST)
904   CALL CHECK(L,IM,IST,IBC)
         IF (IAND(IST,1)+EQ+1) GOTO 904
         IST=0
         IBYTE=0
         CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
         IST=0
C IBC=$2 

C SET UP TWO WAY CHARACTER READ FOR STOPPING READ. 
CALL BCREAD(L,IBC,IST) 
ADC,CSET,CMOVE 
BWRITE RETURN 
905 IST=0 
BCC 
C ASK FOR NUMBER OF TIME STEPS BETWEEN PICTURES, ONLY COME HERE IF 
C PICTURE SIZE IS CHANGED. 
RSET CALL BCWRITE(L,TIMESP11,0,37,IST) 
IBC=10 
BCC 
IST=0 
BCC 
CALL BCREAD(L,IBC,IST) 
SAVE RETURN ADDRESS 
906 CALL CHECK(L,TM,IST,IBC) ENTER PDD PHDR 
IF (IAND(IST,8) .NE.8) GOTO 906 
IST=0 
CALL IBYTE=0 
CALL BMOVE(L,IBUF,TBYTE,IRC,IST) 
CALL IF (IBC.EQ.1) GOTO 907 
CALL DECODE(10+101,IBUF,N) UPICT 
907 RETURN 
END 
CIRC 
CLOS 
CSEQ 
CISEQ 
CISEQ 
CISEQ 
CISEQ 
CIASS 
CIASS 
CIOV 
C THE FOLLOWING ROUTINES ARE COMPILED SEPARATELY WHEN RUNNING 
C THIS PROGRAM. 
C END-TRANBC.R 
C SET NEXT LINK TO VEHICLE ROUTE
CIMACRBSYM: SI, GC

DEF, /CDB, BCWRITE, BCREAD, BSET, BCMOVE

BCWRITE, LI=12, CWRITE

BCREAD, MA=12, IREAD

BSET, LI=12, SET1, 200, P=LT, N=NC, T=20

BCMOVE, BA=12, MOVE

BCOC, LD=4, 14, SAVE RETURN ADDRESS

CAL=3, 0, 0, ENTER FGD PROG

END

CIALLOBT (FIL=1, (FSI=300)

CIALLOBT (FIL=2, (FSI=120)

CIALLOBT (FIL=3, (FSI=10)

CIALLOBT (FIL=4, (FSI=10)

CIALLOBT (FIL=5, (FSI=10)

CLOAD (UDCB=3, (PUBL=CB, PCLTR), (TEMP=400)

CIROOT (FIL=BT, (GB=2), (PLB=MT, 2)

CISEG (LINK=2), (PLB, MB, 1), (FIL=BT, GB=1), (PLB, MT=8)

CISEG (LINK=3), (PLB, MT=1), (FIL=BT, GB=1), (PLB, MT=4)

CISEG (LINK=4), (FIL, BT, GB=3)

CIASS (F=20, CR)

CIASS (F=21, MT)

CIASS (F=10, MT)

CIASS (F=9, EDITEOUT)

C THE FOLLOWING ROUTINES ARE COMPILED SEPARATELY WHEN RUNNING
C THIS PROGRAM
C
C IF THERE IS NO LAST LINK, REPERM NOT AVAILABLE THEREFORE FAULT AND
C IF FORTRAN, BG=8
C
C GET NEXT LINK IN VEHICLE ROUTE
C
C 0810 4
FUNCTION NLINK(J)

COMMON /CONST1/SPML,ACCHNL,ACCEMG,VL,FFHNY,FRHNY,SSIDE
&/SPEED,PENDI,SPEDL(20),XYTAR(20),1,ASPACE(4),PROB4,4,
&/CR(20),CONST1,CONST2,ACCJK,DELT,HIGHT,WIDTH

COMMON /CONST2/ IBUF(20),LEN(20),NYT(4,4,5),NLINK,IN,NCUT
&/MARI(10),IMGE(20),ICRL(20),JPRINT,JPLOT,JPIC,T,FLOW,PARAM,FMAG

COMMON /VAR/ TIME,TSTOP,VEHA(100,41),TIMM(4),HDWS(100),SFAC
&/MRE(100,41),LINK(200,21),LI,NCRL(20)
&/TTIME,NPRINT,NPLOT,NPIC,NFLO,NPAR,NMAG,TRANS(100),ITN
&/BAL1(21)
&/BAL2(14)
&/BAL3(21)
&/BAL4(5)
&/BAL5(3)

L=IVEH(A,j,1)
M=IVEH(A,j,2)
M=M-NIN

C IF LINK NOW NOT START LINK BRANCH PICK UP FIRST INTERMEDIATE
C LINK, IF ZERO THEN NEXT LINK IS LAST LINK
IF (L=NE-M) GOTO 3
NLINK=JNEY(L,M,1)
IF (NLINK=EQ0) NLINK=IVEA(H,J,3)
RETURN
3 DO 1 I=1,5
1 IF (JNEY(L,M,1)=EQ0 OR JNEY(L,M,1)=EQ0) GOTO 2
C FIND PRESENT LINK IN TABLE
CALL PRINT1('UNABLE TO ACCESS NEXT LINK',TIME,N,J)
STOP
2 I=1+1
C FIND NEXT LINK
NLINK=JNEY(L,M,1)
C IF ZERO THEN LAST LINK, NEGATIVE NOT AVAILABLE THEREFORE FAULT AND
C EXIT WITH NLINK = NEXT LINK
IF (NLINK=EQ0) GOTO 4
6 NLINK=IVEH(A,J,3)
GOTO 4
C

FUNCTION MARK(I,J)
COMMON /CONST/,SPML,ACCNML,ACCENG,VL,FFHDDWY,FCHDWWY,SIDEA
&CSPEED,PEND(201),SPEEDL(201),XTAR(201,7),ASPACE(4),PROB(4,4)
&CRL(201),CONST2,ACCJ,DELT,MIEGT,WIDTH
COMMON /CONST2/,IBUF(20),LEND(20,3),JKEY(1,4,5),NLINKS,NIN,NOUT
&MAR(101),ICIDE(201),ICRL(201),JPRINT,JPLST,JPCT,JFLOA,JPARAX,JMAG
COMMON /VAR/,TIME,TSTOP,VEHA(100,8),TIMEN(4),MDWYS(100),SFAC
&JFLOA(100,4),LINKP(20,2),LT,ICRL(201)
&JTIME,JPRINT,NPLST,JPCT,JFLOW,NPARAX,NMAG.ITRANS(100),ITRP
&BAL1(1)
&BAL2(14)
&BAL3(1)
&BAL6(1)
&BAL17(1)
MARK=I+J
N=N-1
NN=0
C CONVERT QUEUE POSITION INTO ARRAY LOCATION.
C N = LINK NUMBER  I = PRESENT POSITION  J = DISPLACEMENT.
  IF (N+NN-0) GOTO 1
  IF (J+TGT-0) GOTO 2
  IF (MARK+JGT-0) GOTO 1
  MARK=LEND(I-1)=NN+MARK
  GOTO 1
  Mk=NN-MARK=LEND(N-1)
  RETURN
C CONVENU SPACES INTO INFORMATION.
C OUT BY EACH SPACING TURN INFORMATION.
10 RETURN
C
NUMBER(1)=0
CONTINUE
WRITE(108,22)
22 FORMAT(1X,D10.0)
21 IF(NEQ.1) WRITE(108,14)
20 FORMAT(1H1,28X,I4)
19 IF(N.NE.1) RETURN

C INITIALISE PRINT. NN = 1 OTHERWISE OUTPUT ANY REMAINING MESSAGE.
C
ENTRY PRINT2(NN)
IF (NN.NE.1) GOTO 5
L=1
NUMBER(1)=0
NUMBER(2)=0
RETURN
5 IF (L.EQ.1) RETURN
C WRITE SINGLE MESSAGE.
WRITE(108,3)(K(N),N=1,8),A(I),I(1),J(1)
GOTO 10
3 FORMAT(1H1,28X,A(8),AT,F7.1,2X,'LINK',I3,2X,'VEN',I4,' ')
END
ACCEHL,ACCML,ACCMG,VL,FFHNY,ECHNY,SIENA
L=1
RETURN
C THE STEP FOR OUTPUT.
READ(105,E3) PRTHY,PRTHY.IF (CT.IEQ.6) WRITE(108,14)
READ(105,14) LEN(I),I=1,30
14 DD(I)=0)
READ(105,14) LEN(I),I=1,30
READ(105,14) LEN(I),I=1,30
C VEHICLE GENERATOR LEVELS.
READ(105,14) SPACCA(I),I=1,30
C WRITE TO HEADER.
WRITE(108,22) ISUF
WRITE(108,20)
WRITE(108,20) SPACCA(I),ACCEHL,ACCML,ACCMG,VL,FFHNY,ECHNY,SIENA,L=1
C INPUTS DATA AND WRITES HEADER.
C
SUBROUTINE DATARD
COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
&CSPEED,PEND(20),SPEEDL(20),XYTAR(20,7),ASPACE(4),PROB(4,4)
&CR(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NMUT
&MAR(10),ICODE(20),ICRL(20),JPRINT,JPLMT,JPICT,JFLOW,JPARAM,JMAG
COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SFAC
&IVEHA(100,4),LINKP(20,2),L1,NCRL(20)
&ITIME,NPRINT,NPT,L,NPLOT,NFST,NS,PARAM,NMAG,ITRANS(100),ITRP
&BAL1(121)
&BAL2(14)
&BAL3(21)
&BAL6(5)
&BAL7(3)
C TITLE=
READ(105,100) IBUF
C PRINT FLAGS=
READ(105,111)(MAR(I),I=1,10)
C RUN CONSTANTS=
READ(105,101) SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA,DELT,
&CSPEED,TSTOP,CONST1,CONST2,ACCJK
C TIME STEPS FOR OUTPUT=
READ(105,102) JPRINT,JPLMT,JPICT,JFLOW,JPARAM,JMAG
READ(105,110)(LEND(I,1),I=1,20)
DO 12 I=2,20
12 LEND(I,1)=LEND(I-1,1)+LEND(I,1)
READ(105,110)(LEND(I,3),I=1,20)
READ(105,110)(LEND(I,2),I=1,20)
C VEHICLE GENERATOR LEVELS=
READ(105,104)(ASPACE(I),I=1,4)
C WRITE TO HEADER=
WRITE(106,200) IBUF
WRITE(106,201)
WRITE(106,202) SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA,DELT,
ACBSPEED, TSTOP
WRITE(108, 20)
WRITE(108, 21) CONST1, CONST2, ACCK
WRITE(108, 203)
WRITE(108, 204) JPRINT, JPLST, JPICT, JFLOW, JPARAM, JMAG
WRITE(108, 207)
C NETWORK DEFAULTS.
WRITE(108, 208) (ASPACE(I), I=1, 4)
C READ FOR EACH LINK CO-ORDINATE DETAILS AND LINK SPEED LIMIT.
READ(105, 103) NIN, NOUT, NLINKS, HIEGHT, WIDTH
DB 1 I=1, NLINKS
READ(105, 105) (XYTAB(I,J), J=1, 7)
READ(105, 120) SPEEDL(I)
A=XYTAB(I,1)=XYTAB(I,3)
B=XYTAB(I,2)=XYTAB(I,4)
RADIUS=XYTAB(I,7)
IF (XYTAB(I,7) NE 0) GOTO 3
PEND(I)=SORT(A*A+B*B)
SPEEDL(I)=A 1(NM, SPEEDL(I))
GOTO 1
3 RADIUS=ABS(RADIUS)
IF (RADIUS*GT 1.1) GOTO 4
C CALCULATE RADIUS FROM SUBTENDED ANGLE
RADIUS=SORT(A*A+B*B)/(2*IN(RADIUS/2))
C CALCULATE LENGTH OF ARC LINK.
4 PEND(I)=2*RADIUS*ASIN(SORT(A*A+B*B)/(2*RADIUS))
SPEEDL(I)=A 1(SPEEDL(I), SORT(SIDEA*RADIUS))
XYTAB(I,7)=SIGN(RADIUS*XYTAB(I,7))
CONTINUE
DB 2 I=1, NIN
DB 2 J=1, NOUT
C INPUT FOR EACH INPUT EXIT COMBINATION ROUTE AND JOURNEY PROBABLE.
C (NEGATIVE FOR NOT POSSIBLE)
2 READ(105, 106) (JNEY(I,J,K), K=1, 5), PRR(I, J)
WRITE(108, 209)
WRITE(108, 210) (I, I=1, 4)
WRITE(108, 212)
C WRITE TO HEADER.
  DO 5 I=1,NIN
  WRITE(108,211)I,(JNEY(I,J,K),K=1,5),PRGB(I,J),J=1,NOUT
  WRITE(108,213)
  M=1
  NO=0
  DO 9 I=1,NLINKS
    READ(105,112) NCRL(I)
    IF (NCRL(I).EQ.0) GOTO 8
    NO=NO+NCRL(I)
C READ IN DETAILS OF CONTROL POINTS.
  READ(105,113) (CRL(J),ICRL(J),J=M,NB)
  WRITE(108,214) I,(CRL(J),ICRL(J),J=M,NB)
  M=M+NCRL(I)
  GOTO 9
C WRITE REST OF HEADER.
  8 WRITE(108,215) I
  CONTINUE
  WRITE(108,231)
  DO 900 I=1,NLINKS
  900 WRITE(108,230) I,LEN(I,3),LEN(I,2),SPEED(I)
  WRITE(108,130)
  130 FORMAT(/)
  RETURN
  120 FORMAT(F10.3)
  230 FORMAT(3110,10X,F10.3)
  231 FORMAT(1HO,10X,LINK NO',2X,'START NO',2X,'END NO',8X)
 &SPEED LIMIT/30(1'=1/)
  106 FORMAT(510,F10.3)
  209 FORMAT(1HO,'JOURNEY MATRIX  INPUT TO EXIT & INTERMEDIATE LINKS')
  210 FORMAT(X52(1'=1/3X,'EXIT',3X,4(12X,I2,12X))
  212 FORMAT(X,'INPUT')
  211 FORMAT(6X,5I3,3X,F4.2,14X)
  103 FORMAT(3110,2F10.3)
  105 FORMAT(7F10.3)
  100 FORMAT(20A4)
  111 FORMAT(10I1)
101 FORMAT(10F8.2/10F8.2)
102 FORMAT(610)
110 FORMAT(2014)
104 FORMAT(4F10.8)
200 FORMAT(1H1,2O4//X,120('=1',/X,'CONSTANTS',/X,10('=1'))
201 FORMAT(1HD,2X,'LINE SPEED',4X,'NML ACCN',4X,'EMG ACCN',2X,
     &'VEH LENGTH',X,'FCTR HDWY F',X,'FCTR HDWY C',3X,'MAX LATAX',3X,
     &'TIME STEP',3X,'INT SPEED',3X,'STOP TIME')
202 FORMAT(X,10F12.3)
203 FORMAT(1HD,'NO OF TIME STEPS FOR B/P',7X,'PRINT',5X,'PLAT',5X,'PIC
     &TRUE',3X,'FLLW CALC',2X,'PARAM CALC',5X,'MAG B/P')
204 FORMAT(X,24('=1',/6I12)
207 FORMAT(1HD,'VEH GENERATORS',15X,'LEVEL 1',5X,'LEVEL 2',5X,
     &'LEVEL 3',5X,'LEVEL 4')
208 FORMAT(X,13('=1',/11X,4F12.6)
220 FORMAT(1HD,2X,'PSN CONST',3X,'VEL CONST',4X,'MAX JERK')
221 FORMAT(X,3F12.3)
213 FORMAT(1HD,'LINK NO / CONTROL POINTS AND ASSOCIATED STRATEGIES',/
     &B0(1='1')/
112 FORMAT(15)
113 FORMAT(5(F10.3,15)/)
214 FORMAT(X,15,5X,5(F10.3,110)/)
215 FORMAT(X,15,5X,'NO CONTROL')
END
C OUTPUT SIMULATION DATA

SUBROUTINE PRINT
COMMON /CONST1,SPML,ACCONML,ACCEMG,VL,FFHDWY,FCHDWWY,SIDEA
&CBpeed,PEM+200,SPESDL,20,XTAB(20,7),ASPACE(1),PROM(0)
&CBRLE(20),CONST2,ACCJK,DELTA,HIGTH,WIDTH
COMMON /CONF2, TBUF(20),TEND(20,3),JNEY,4,4,NLrlNKS,NIN,NOUT
&JAR(10),ICOD(E(20),ICRL(20),JPRINT,JPICT,JFLW,JPARAM,JMA
COMMON /VAR, TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWY(100),SFaCT
&IVEHA(100,9),LINKP(20,21),LT,NCR(20)
&TIME,PRINT,JPICT,NFLW,NPARAM,NMAG,TRAN(100),ITRP
&BAL1(21)
&BAL2(14)
&BAL3(21)
&BAL4(5)
&BAL7(3)
COMMON /KRT/FILL(6),ITRACE,ILINK,IVNS
DIMENSION ISAVE(25,2)
IF (MAR(1)+NEO.O) RETURN
CALL PRINT(2)
IF (TRACE+EQ+1.AND.NPRINT+NEO.O) GOTO 10
WRITE(108,105)
WRITE(108,100) TIME
WRITE(108,101)
C FOR EACH LINK
DO 2,1=1,NLINKS
J=LINKP(i,1)
C REACHED END OF QUEUE FOR LINK.
IF (MARK(I,J)+NE+1.1)+EGLNKPI(1,2)) GOTO 2
WRITE(108,102)
1 L+0
IF (IVEHA(J,4)+EQ+0) GOTO 5
L=ISIGN(TRANABS(IVEHA(J,4)),IVEHA(J,4))
5 CONTINUE
C WRITE VEHICLE DATA
WRITE(108,103) TRAN(J),(VESA(J,K)+K=1,7),HDWY(J),IVALHEA(J,K),K=1
&3)jLV
IF (J.EQ.LINKP(I,2)) GOTO 2
J=MARK(I,J;1)
GOTO 1
2 CONTINUE
IF (MAR(I)+NE.0) GOTO 3
N=0
DB 4 J=1,100
C SKIP IF NO VEHICLE:
IF (ITRANS(J).EQ.0) GOTO 4
N=N+1
ISAVE(N,1)=ITRANS(J)
ISAVE(N,2)=J
IF (N.NE.25) GOTO 4
C OUTPUT TRANSLATION TABLE:
WRITE(108,104) (ISAVE(J,1),J=1,25)
WRITE(108,104) (ISAVE(J,2),J=1,25)
N=0
4 CONTINUE
WRITE(108,104) (ISAVE(J,1),J=1,N)
WRITE(108,104) (ISAVE(J,2),J=1,N)
N=0
3 CONTINUE
104 FORMAT(X*25I4)
WRITE(108,102)
WRITE(108,105)
105 FORMAT(X*120='1')
RETURN
10 CONTINUE
C TRANSLATE TRACE NUMBER (IUNUM) INTO ARRAY LOCATION:
DB 20 J=1,100
20 IF (ITRANS(J).EQ.IVNB) GOTO 30
30 CONTINUE
L=0
IF (IVEHA(J,4).EQ.0) GOTO 50
L=-SIGN(1)*ABS(IVEHA(J,4))/IVEHA(J,4))
50 CONTINUE
6,3)LV
  IF (J*EQ+LINKP(I, 2)) GOTO 2
  J=MARK(I, J, 1)
  GOTO 1
2 CONTINUE
  IF (MAR(5) NE @0) GOTO 3
  N=0
  DO 4 J=1,100
  C SKIP IF NO VEHICLE.
  IF ((ITRANS(J) EQ 0) GOTO 4
    N=N+1
    ISAVE(N, 1)=ITRANS(J)
    ISAVE(N, 2)=J
    IF (N GE 25) GOTO 4
  C OUTPUT TRANSLATION TABLE.
    WRITE(*, 108)(ISAVE(J, 1), J=1, 25)
    WRITE(*, 108)(ISAVE(J, 2), J=1, 25)
    N=0
  4 CONTINUE
    WRITE(*, 108)(ISAVE(J, 1), J=1, N)
    WRITE(*, 108)(ISAVE(J, 2), J=1, N)
    N=0
  3 CONTINUE
104 FORMAT(X, 25I4)
  WRITE(108, 102)
  WRITE(108, 105)
105 FORMAT(X, 120I4)
  RETURN
10 CONTINUE
C TRANSLATE TRACE NUMBER (IUNH) INTO ARRAY LOCATION.
  DO 20 J=1,100
20 IF (ITRANS(J) EQ IVNE) GOTO 30
  CONTINUE
  LV=0
  IF (IVEHA(J, 4) EQ 0) GOTO 50
  LV=ISIGN(ITRANS(IABS(IVEHA(J, 4)))*IVEHA(J, 4))
50 CONTINUE
WRITE(108,103) TRANS(J), (IVEHA(J,K), K=1,7), HDWYS(J), (IVEHA(J,K), K=8,3), LV
RETURN
100 FORMAT(/X,'TIME',F10.3,'30X','DATA','60X','LINKS')
101 FORMAT(1HO,'N6',5X,'ACCR',9X,'VEL',8X,'POSN',6X,'T/TIME',6X,'A/TI
EME',4X,'NODE VEL',3X,'INT SPEED',5X,'HEADWAY',10X,'IN',3X,'NOW',3X
&,'OUT',X,'TABLE')
102 FORMAT(1HO)
103 FORMAT(X,I3,F9.3,F12.3,F8.16)
END
C CHECKS IF ANY VEHICLE IS AT A CONTROL POINT.
C
SUBROUTINE CRLCHK
COMMON /CONST1,SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWSIDE
&CSPEEDS,PEND(I),SPEEDL,XYTAB(20),ASPACE(4),PROB(4,4)
&CRL(I),CONST1,CONST2,ACCJK,DELT,HEIGHT,WIDTH
COMMON /CONST2/IBUF(20),LENF(20),JNEY(4,5),NLINKS,NIN,NDUT
&MARK10,ICODE(20),ICRL(I),JPRINT,JPLT,JPICT,JFLOW,JPARAM,JMAG
COMM N /VAR/ TIME,TSTOP,VEHA(100),TIME1(4),HDWS(100),SFACT
&IVEHAI100*,LINKP(20),LICE,NCRL(I),20
&TIME,TPRINT,NPLT,NPICT,NFLO,PARAM,INAG,ITRAN(100),ITRP
&HALC(21)
&HALC(21)
&HALC(14)
&HALC(21)
&HALC(15)
&HALC(13)
K=0
C DO FOR EACH LINK FRONT AND BACK QUEUE POINTERS.
DO 1 I=1,NLINKS
  NO=NCRL(I)
  JJ=LINKP(I,2)
  IF (MARK(I,J)=1) GOTO 5
  POBN=VEHA(J,1)
  IF (IVEHA(J,6)*GT.0) GOTO 3
  NDUN=K+1
  NDUM=K+NE
  DO 2 JJ=NDUN,NDUM
    NSTAT=ICRL(JJ)
  C LOOK AT EACH VEHICLE ON LINK.
C IF AT CONTROL POINT CALL CONTROL.
  IF (POBN.LT.CRL(JJ)) OR POBN.GT.CRL(JJ)+VL GOTO 2
  CALL CONTROL (J,POBN,NSTAT)
  CONTINUE
  IF (IVEHA(J,3)*EQ.1) GOTO 3
  S=PEND(I)=ABS(VEHA(J,2)*VEHA(J,2)+VEHA(J,2)+VEHA(J,6)+VEHA(J,6))/(2*ACCNML)
1 CONTINUE
2 CONTINUE
3 CONTINUE
C CHECKS THE TIME SPACINGS OF VEHICLES THROUGH A NODE.
C VEHICLES ON DIFFERENT ROUTES MUST BE SEPARATED BY CROSSING HEADWAY
C ELSE FOLLOWING:

SUBROUTINE NODCHK(I,J)
COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
&CSPEED,PEND(20),SPEEDL(20),XYTAB(20),ASPACE(4),PROB(4),4
&CR(20),COMMON/CONST2/BUF(20),LEN(20),JNE(4),4,5),NLINKS,NIN,NOUT
&HAR(10),ICODE(20),ICRL(20),JPRINT,JPLBT,JPICT,JFLW,JPARAM,JMAG
COMMON /VAR/ TIME,TSTOP,VEHA(100*8),TINEN(4),HDWYS(100),SFAC
&XVEHA(100*4),LINKP(20*2),LLINCR(20)
&TIME,NPRINT,NPLBT,JPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
&TNODE(10),NODE(10),LASTRT
&BAL2(14)
&LAL3(21)
&BAL6(5)
&L,NUMBER(2)
GOTO 2

C
ENTRY INOD
LASTRT=0
RETURN
2 NODEP=LEN(I,J)
NUMBER(I)=NODEP
CALL PRINT1('VEHICLE PASSING NODE 'TIME,I,J)
IF (LASTRT.EQ.0) GOTO 1
LASTRT=NODEP
LASTRT=NODEP
NEKTRT=NLINK(I)*100+1
THDWEY=VEHA(I,6)/2*ACCEG+VL/VEHA(I,6)
THDWEY=THDWEY+FCHDWY
IF (NEKTRT.EQ.LASTRT) THDWEY=THDWEY+FFHDWY
IF (LASTRT.THYST*TIME+5) CALL PRINT1('VEHICLE TIME INFRINGED AT NODE 'TIME,I,J)
1 TNODE(NODEP)=TIME
C ENTER A NEW VEHICLE INTO A VEHICLE QUEUE AT ENTRANCE.

C SUBROUTINE ENTRY(I,J)
COMMON /CONSTM,SPNML,ACCML,ACC,RO,N,L,FFHDWY,FCHD,WY,SIDE
&CBPEND,SPendl20,SPendl20,YTAB,SHD,7,ASPACE(4),PMB(4,4)
&CA(20),CONST1,CONST2,ACC,DEL,T,HEIGHT,WIDTH
COMMON /CONST2/,IBUF(20),LEN(20),JNEY(4,4,5),INLINKS,NINT,NEUT
&MAR(10),ICODE(20),ICRL(20),JPRINT,JPLT,JPCT,JFLWJ,PARAM,PMAG
COMMON /VAR/,TIME,TSTOP,VEHA(100,1),TEN(4),HDWY(100),SFAC
&IHEA(100),IIE(20),LI,NCRL(20)
&LTIME,NPRINT,NPLT,JPCT,NFLO,J,PARAM,PMAG,ITRAN(100),ITR
&BAL1(21)
&BAL2(14)
&BAL3(21)
&BAL6(5)
&BAL17(3)
C INITIALISE ARRAY CONSTANTS.
SPNML=SPEND(1)
VEHA(J,1)=0
VEHA(J,2)=SPNML
VEHA(J,5)=TIME
VEHA(J,3)=0
VEHA(J,4)=0
VEHA(J,6)=CBPEND
VEHA(J,7)=SPNML
VEHA(J,8)=0
IVEHA(J,1)=1
IVEHA(J,2)=1
CALL RANDOM(LI,LI,RAND)
SET=0
C SELECT ROUTE ACCORDING TO PROBABILITIES.
DO 1 K=1,4
SET=PMB(K,1)+SET
IF (RAND*LI*SET) GOTO 2
1 CONTINUE
2 IVEHA(J,4)=1
C RESET POINTER
    IVEHA(J+3)=K+NIN
    LINKP(I+2)=MARK(I+LINKP(I+2),1)
    ITTRANS(J)=ITRP
    ITRP=ITRP+1
    IF (ITRP+EQ+101) ITRP=1
    RETURN
END
SUBROUTINE ECHECK(NUM)
COMMON /CONST1,SPNL,ACCNL,ACCEMG,VL,FFHDWY,FCHDWAY,SIDEA
& CSPEED,PEND(20),SPEDEL(20),XTAB(20,7),ASPACE(4),PRB(4,4)
& CR(20),CONST1,CONST2,ACJ,K,DELT,HIGHT,WIDTH
COMMON /CONST2/, IBUF(20), LENLI(20), JUNEY(4,4,5), NLINKS,NIN,NCUT
&MARI(10),  ICOL(20), TCR(20), JPRINT, JPLT, JPICT, JFLOW,JPARAM,JMAG
COMMON /VAR/, TIME,TSTOP, VEMA(100,8), TIMEN(4), MDWSI(100), SFACT
& IVEH(100,4), LINKP(120,2), LINCRL(20)
& ITIME,NPRINT,NPLT,NPICT,NFLOW, NPARAM,NMAG, ITRANS(100), ITRP
& BAL1(121)
& BAL2(14)
& BAL3(21)
& BAL4(5)
& BAL17(3)
DO 1 I=1, NLINKS
J=LINKP(I,1)
JCHECK=MARK(I,J,-1)
IF (JCHECK.EQ.0) LINKP(I,2) GOTO 1
EMHDWY=EVAH(J,2) + EVAH(J,2)/2*ACCEMG+VL
HDWY=EMHDWY+FFHDWY
HDWY(J)=HDWY
IF (J+NEIVEH(J,3)) GOTO R
IF (NUM.EQ.1) GOTO 7
GOTO 3
1 CONTINUE
NEXTL=NLINK(J)
K=LINKP(NEXTL,2)
IF (MARK(NEXTL,K,1) .NE. LINKP(NEXTL,1)) GOTO 9
IF (NUM.EQ.1) GOTO 7
GOTO 3
R CONTINUE
POSN2=VEHA(J,3)
POSN1=VEHA(K,3)+PEND(I)
GOTO 4
5 POSN1=VEHA(K,3)
    POSN2=VEHA(J,3)
6 EMHDWY=VEHA(J,2)+VEHA(J,2)/(2*ACCEMG)+VL
    IF (NUM*ED=1) GOTO 6
    IF (POSN1=POSN2+GE*EMHDWY) GOTO 3
    CALL PRINT1("EMERGENCY HEADWAY INFRINGED AT " TIME,I,J)
    HDYB(I,1)=HDYB(I,1)+1
    VEHAI(J,1)=ACCEMG
3 IF (J=EO=LINKP(I,2)) GOTO 1
    K=J
    J=MARK(I,J)
    GOTO 5
1 CONTINUE
RETURN
C CALCULATE ACCELERATION ACCORDING TO HEADWAY LAWS
6 HDWY=EMHDWY+FDHDWY
    HDYB(I,1)=HDWY
    VREL=VEHA(K,2)-VEHA(J,2)
    SEP=POSN1-POSN2
    VELT=VREL*CONST2
    IF (VREL*GT.0) VELT=0
    ACCN=(SEP-HDWY)/HDWY*CONST1+VELT
    GOTO 10
7 ACCN=ACCNML
10 ACCN=ACCN
    IF (ABS(ACCN)*GT.0*(ACCNML)) ACCN=SIGN(ACCNML,ACCN)
    IF (VEHA(J,7)=VEHA(J,2)) 13,14,15
12 ACCN=ACCNML
    GOTO 16
14 ACCN=0
    GOTO 16
15 ACCN=ACCNML
16 ACCN=MIN(ACCN,ACCN)
    VEHAI(J,1)=AJERK(VEHA(J,1),ACCN)
    GOTO 3
END
C
GENERATE TIME HEADWAYS ACCORDING TO DISTRIBUTION.
C
FUNCTION SPACE(I)
C
ENTRY SPACES(I)
COMMON /CONST1/SPNML, ACCENGL, ACCENGR, VL, FFHDWY, FCHD, SIDEA,
& CBSPED, PEND(20), SPEDDL(20), XTAB(20), 7, ASPACE(4), PRBB(4, 4),
& CR1(20), CONST1, CONST2, ACCJK, DELTA, HIEGHT, WIDTH,
& COMMON /CONST2/ IBUF(20), LEND(20), JNEY(4, 4), 5, NLINKS, NIN, NOUT,
& HARI(10), IC60E(20), ICRL(20), JPRINT, JPLT, JPICT, JFLOW, JPARAM, Jmag,
& COMMON /VAR/ TIME, TSTOP, VEHG(100), 8, TIMEN(4), HDWYS(100), SFCT,
& TVEH(100), L, LINKP(20, 20), L, ICRL(20), 5, ITIME, NPRINT, NPICT, NFLOW, NPARAM, NMAG, ITANS(100), ITRP,
& BALT(21),
& BAL2(14),
& BAL3(21),
& HDWY=II(4),
& BAL17(3),
IF (I=EQ.0) GOTO 4
I=0
2 CALL RANDOM(II(I), II(I), RN)
II=II+1
II(II) II=12
GOTO 1
3 IF (RN GT ASPACE(I)) GOTO 3
GOTO 2
3 GAP=II*HDWY/10,
IF (GAP LT HDWY) GAP=HDWY
SPACE=GAP (VEHG(1, 3), GOTO 2
RETURN
4 CONTINUE = NEXTL
DO 1 II=1, 14, 14II
II(I) II=100+1
1 CALL RANDOM(II(II), II(III), RN)
HDWY=(SPNML/2 & ACCENGL) * VL, SPNML = FFHDWY
RETURN
1 X=II
9 END
C TRANSFER VEHICLES FOR ONE LINK QUEUE TO THE NEXT WHEN A NODE C IS PASSED.

SUBROUTINE ASVEH
  COMMON /CONST1/SPML,ACCML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
  &CSPACE,PEND(20),SPEEDL(20),YTAB(20,7),ASPACE(4),PRB(10,10)
  &CRL(20),CONST1,CONST2,ACCJK,DELT,HEIGHT,WIDTH
  COMMON /CONST2/IBUF(20),LENX(20,3),JNEY(4,5),NLINKS,NIN,NEUT
  &NMARK,ICODE(20),ICRL(20),JPRINT,JPLOT,JPIC,NTIME,FLOW,JPARAM,JMAG
  COMMON /VAR/TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SFACT
  &IEMH,T(20,2),LCR(20)
  &ITIME,NPRINT,PHLE,IPIC,NFLOW,JPARAM,NMAG,IITRAN(100),ITRP
  &BAL1(21)
  &BAL2(14)
  &BAL3(21)
  &BAL4(15)
  &BAL5(3)
  C FOR EACH LINK:
  DO 1 I=1,NLINKS
       J=LINKF(I,1)
       C NO VEHICLES?
       IF (MARK(I,J)=0) GOTO 1
       C ANY VEHICLES PASSED?
       IF (VEHA(I,J) .LT. PEND(J)) GOTO 1
       C FIND THE NEXT LINK
       NEXTL=LINKF(J,1)
       IF (I.EQ.IEVA(I,J)) GOTO 2
       CALL NODCHR(I,J)
       IEVA(I,J)=NEXTL
       IPL=LINKF(NEXTL,2)
       IP=MARK(NEXTL,IPL,1)
       DO 3 K=1,6
           IF (K.LE.6) GOTO 9
           VHEA(I,J)=0.

1 CONTINUE
C ADD VEHICLE TO NEXT LINK QUEUE AND REMOVE FROM OLD LINK QUEUE.
C INTEGRATE VEHICLES FORWARD ONE INCREMENT.

SUBROUTINE VMOVE
COMMON /CONST1/SPNML,ACCMGL,ACCEMG,VL,FFHMLY,FFHMY,SIDEA
& CSPEED, PEND(20), SPEEDL(20), XTAB(20,2), ASPACE(1), PROB(2,2)
& CRL(20), CONST2, ACCJ, DELT, HIEGHT, WIDTH
COMMON /CONST2/ IBUF(20), LEIND(20,3), JNEY(2,2,5), NLINKS, NIN, NOUT
& MAR(10), ICODE(20), ICRL(20), JPRINT, JPLT, JPCT, JFLOW, JPARAM, JMG
COMMON /VAR/ TIME, TSTEP, VEHAI(100,8), TMIN(4), HDWSY(100), SFAC T
& IVEHA(100,4), L1NK(20), L12, NCRL(20)
& ITIME, NPRINT, NPLT, NPCT, NFLOW, NPARAM, NMAG, ITRANS(100), ITRP
& BAI1(21)
& BAI2(21)
& BAI3(21)
& BAI6(5)
& BAI7(3)
DO 1 I=1,NLINKS
J=LINKP(I,1)
1 IF (MARK(J,J)=1) EQ, LINKP(J,2) GOTO 1
2 DP=VEHA(J,2)*DELT+VEHA(J,1)*DELT/2,
VEHA(J,3)=VEHA(J,3)+DP
VEHA(J,8)=VEHA(J,8)+DP
VEHA(J,2)=VEHA(J,3)+VEHA(J,1)*DELT
IF (VEHA(J,2),LT,0) VEHA(J,2)=0
IF (VEHA(J,2)*GT,*SPEEDL(I)) VEHA(J,2)=SPEEDL(I)
IF (J,EQ, LINKP(I,2)) GOTO 1
J=MARK(I,J+1)
GOTO 2
1 CONTINUE
RETURN
END
C C Generates random numbers with equal probability between 0 and 1
C
SUBROUTINE RANDOM(IY,YFL)
IY=IY+4656613E-9
IF (IY>=6) THEN
   YFL=IY
RETURN
END
C GENERATES RANDOM NUMBERS WITH EQUAL PROBABILITY BETWEEN 0 AND 1

C

SUBROUTINE RANDOM(IH,YI,YFL)
IY=IY*65536
IF (IY)<65536 THEN RETURN
YFL=(YFL*2147483647)+YI
RETURN
END
C JERK LIMITS ANY CHANGE IN ACCELERATION.

FUNCTION AJERK(ACCN1, ACCN2)
COMM /CONST1/BPNML/ACCMX/ACCEMG/VL/FFHDSY/FCHDWS/FSIDE
&CBPSH/PEND(20)/SPEED(20)/XTBR(20)/ASPC(4)/PRBR(4,4)
&CLCR(s)/CONS1/CONS2/ACCJK/DLT/HIGHT/WIDTH
COMM /CONS2/IRED(20)/LENH(20)/JNE4(4,4,5)/NFILES/NM, NOUT
&HAR(10)/ICRDL(20)/ICRCL(20)/PRINT/JPRINT/JPICT/JFLOW/JPARAM/JMAG
COMM /VAR/TIME/TSTEP/VEMA(100)/TIM1/4/HDWY(100)/SFQ
&JTFMA/100/10/LINKP(20)/LJ=NCRL(20)
&JTIME/PRINT/NPRINT/NPICT/NFLOW/NPARA/NMAG/TRANS(100)/ITR
&BAL1(121)
&BAL2(114)
&BAL3(21)
&BAL6(5)
&BAL7(3)
ADIFFM=ACCJK*DELT
DELACC=ACCN2-ACCN1
AJERK=ACCN2
IF (AB(DDELACC))*GT*ADIFFM) AJERK=SIGN(ADIFFM, DELACC)*ACCN1
RETURN
END
C SEND DATA TO BRANCH TO CLOCK SUBROUTINE IN FOCAL.

SUBROUTINE CLOCK(ISUB)

COMMON /VREAD/ IBC, IST, L, IM, IBUF(10)
COMMON /CONST1/ FILL(236)
COMMON /CONST2/ FILL1(219)
COMMON /VAR/ TIME
EQUIVALENCE (FILL(236),DELT)
EQUIVALENCE (FILL1(219),JPICT)
DIMENSION IA(5), IJ(5)
ISIGN=0
IF (ISUB EQ 3) then
   ISIGN=64
3 CALL LDWD2(0)
   CALL LDWD2(RO)
   CALL LDWD21(1)
   CALL WDBEND
1 ITIME=JPICT*DELT*10
   ITIME=TIME*10
   ITIME=ITIME*ITIME
   IF (ITIME*LT*0) ITIME=100000+ITIME
C SEND CLOCK DATA TO RESET PICTURE CLOCK.
   DO 2 I=1,5
      ITIME=ITIME/10
      ITIMEV=ITIME/10
      IA(I)=ITIMEB=ITIME*10+16
      IJ(I)=ITIMEU=ITIME+10+32+ISIGN
      ITIME=ITIME
      ITIMEU=ITIME
   CALL LDWD2(IJ(I))
   CALL LDWD2(JJ(I))
   CALL LDWD21(0)
   CALL WDBEND
   IF (ISUB.LT.0) RETURN
C CHECK FOR TIMING CHARACTER FROM GT40.
5 CALL CHECK(L,IM,IST,IBC)
IF (IAND(IST,1) iEQ 1) GOTO 5

IST=0
IBYTE=0
CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
IST=0
IBC=2
C SET UP 2 CHARACTER ASYNCHRONOUS READ
CALL BCREAD(L,IBC,IST)
RETURN
END

LOGICAL SEND
IF (MVARL) RETURN
FLAG=0
C BRANCH IF NOT MATCHED BY MVAR
IF (MVAR) GOTO A
C DO FOR EACH LINE
DO 7 I=1,IP
6 IF (MVAR.LT.I) EXIT
CALL MVAR
C SEND LINK NUMBER
CALL LOCED
CALG LOW
PLAS=1
10 CONTINUE
IPS=ILNK1+31*PLAST+FACT*K+5
C SET ZERO FLAG
IF (IPS=ILNK1.IPS.IPS) 10
IF (MVAR.K IBC+1) GOTO 10
IPS=IPRD+30*4094*IPS
C DRAWING MOVING VEHICLE PICTURE ON GT40.

C SUBROUTINE VEHPIE
COMMON /CONST1/BNML, ACALML, ACCEMG, VY, FFHDMY, FCHDMY, NMARK
& CBSPED, PEND(20), SPFDL, YTAB(20), ASPACE(4), PNAME(4,4)
& CR(20), CNAME, CONST2, ACCJ, DELT, MIGHT, WIDTH
C COMMON /CONESP/, IBUF(20), LEND(20,3), JKEY(4,4,10), NMARK, NMARK, NMARK
COMMON /VAR/ TIME, TSTOP, VEH(100,8), TIMEM, HDWYS(100), SDUM
& YVEHA(100,4), LINK(20,2), LT, NCRL(20)
& TIME, NPRINT, NPLT, NPICT, NFLW, NPARA, NMARK, NMARK, NMARK, NMARK
& BAL(1:21)
& BAL(1:14)
& BAL(1:21)
& BAL(1:5)
& BAL(1:3)
LOGICAL SEND
IP = MARK(4) NE 0 RETURN
FLAG = 0
C BRANCH IF MAGNIFIED PICTURE.
IF (MARK(1) NE 0) GOTO 1
C DO FOR EACH LINK.
DO 2 I = 1, NMARK
J = LINK(I, 2)
8 IF (MARK(I, 1) EQ LINK(I, J)) GOTO 2
C SEND LINK NUMBER.
CALL LDMD(0)
CALL LDMD(11)
PLABI = 0
10 CONTINUE
IPBS = YVEHA(I, 3) + PLASI + SFCT + 5
C SET ZERO FLAG.
IF (IPBS EQ 0) IPBS = 1024 + 1
IF (HDWYS(I, J) LE 0) GOTO 100
IPBS = IPBS + ISIGN(4096, IPBS)
C NDWS NEGATIVE WHEN EMERGENCY HEADWAYS INFRINGED
  HDWS(J)=HDWS(J)
100 CALL LDWD2(IP05)
21 PLAST=VEHA(J,3)
   IF (VEHA(J,3)+HDWS(J)>PEND(I)) GOTO 4
22 NEXTL=NLINK(J)
   IF (I=EQ*VEHA(J,3)) GOTO 5
C SPECIAL CASES WHEN VEHICLE HEADWAY OVERLAPS INTO ANOTHER LINK,
C WHEN VEHICLE EN LAST LINK,
C NO
INDWY=VEHA(J,3)+HDWS(J)=PEND(I)*SFAC=1
33 CALL LDWD2(0)
   CALL LDWD1(NEXTL)
   GOTO 40
C 5 INDWY=PEND(I)=VEHA(J,3)*SFAC=1
   PLAST=PEND(I)
   GOTO 40
4 INDWY=HDWS(J)*SFAC=1
   PLAST=PLAST+HDWS(J)
40 IF (INDWY*EQ+0) INDWY=1024+1
C SEND HEADWAY
   CALL LDWD2(INDWY)
   IF (J=EQ*LINKP(I,1)) GOTO 2
C TAKE J=MARK(I,J)=1
   GOTO 10
2 CONTINUE
   CALL LDWD1(0)
   CALL LDWD2(0)
C SEND PICTURE
   CALL HDSEND
C ADD RETURN ENTRY PSTOP
C STOP PICTURE DISPLAY AND BRANCH TO DIALOGUE IN GT=0
500 CALL LDWD2(0)
   CALL LDWD2(10)
   CALL LDWD2(11)
   CALL HDSEND
   RETURN
C DO FOR EACH LINK.
   1 DO 20 I=1+PLINKS
      DO 20 K=1+20
   21 IF (ABS(LINKST(K)) EQ 1) GOTO 22
      GOTO 20
   22 IPLAST=0
   23 IF (LINKST(K) LT 0) IPLAST=IPST(K)
   24 SEND=FALSE
   25 J=LINKP(I+2)
C END VEHICLES
   38 IF (MARK(I,J) EQ LINKP(I+1)) GOTO 20
   39 IMDWY=ABS(MDWY(J)) * SFACT + 1 + 5
   40 IPSB=VEHA(I,J) * SFACT + 5
C BRANCH IF PART OF LINK SEEN IS FIRST PART OF VEHICLE SEEN?
   41 IF (LINKST(K) LT 0) GOTO 23
   42 IF (IPSB GT IPST(K)) GOTO 24
   43 IF (IPSB + IMDWY LT IPST(K)) GOTO 25
   44 IF (IPSB + IMDWY GT IPST(K) + SFACT) GOTO 30
   45 IMDWY=IPST(K) - IPSB
   46 IPLAST=IPSB
   47 IPST=IPST(IPST)
   48 IF (SEND) GOTO 26
C TRANSMIT LINK NUMBER.
   49 CALL LDW20(0)
   50 CALL LDW1(K)
   51 SEND=TRUE
   52 IF (IPSB EQ 0) IPSB=1024+1
   53 IF (IMDWY EQ 0) IMDWY=1024+1
   54 IF (HDWY(J) GE 0) GOTO 200
C ADD FLAGS FOR ZERO AND EMERGENCY BRAKING.
   55 IPSB=IPSB + ISIGN((0), IPSB)
   56 HDWY(J)=MDWY(J)
   57 200 CONTINUE
   58 CALL LDW20(IPSB)
   59 IF (FLAG EQ 0) GOTO 1
C SEND NEW LINK NUMBER IF VEHICLE OVERLAPS INTO NEXT LINK.
   60 CALL LDW20(0)
CALL LDWD1(L1)
   FLAG=0
16 CONTINUE
   CALL LDWD2(INWDY)
   GOTO 24
C COME HERE IF PART OF LINK SEEN IS LAST PART.
23 IF (IPSB*INWDY*LT*IPST(K)) GOTO 24
   IF (IPSB*GT*IPST(K)) GOTO 27
   INWDY=IPSB*INWDY*IPST(K)
   IPLAST=IPLAST+INWDY
   IPSI=0
   GOTO 11
27 IF (IPSB*INWDY*GT*PEND(I)*SFCT) GOTO 30
   IPSI=IPPS*IPLAST
   IPLAST=IPPS*INWDY
   GOTO 11
30 NEXTL=NLINK(J)
C VEHICLE SYMBOL OVERLAPS NEXT LINK:
   IPSI=IPPS*IPLAST
   IPLAST=IPPS+INWDY
   INWDY=IPPS+INWDY*PEND(I)*SFCT
C FIND IF NEXT LINK IS DISPLAYED:
   DO 12 L=1,20
12 IF (LAB*LINKST(L)) EQ*NEXTL) GOTO 13
13 FLAG=1
   GOTO 11
C IF J=EQ*LINKPI(I,J)) GOTO 20
26 IF (J*EQ*LINKPI(I,J)) GOTO 20
   J=MARK(I,J)=11
   GOTO 38
20 CONTINUE
C TERMINATE PICTURE:
   CALL LDWD11D0)
   CALL LDWD2(0)
   CALL WDSEND
   RETURN
END
C SEND STANDARD PICTURE TABLE TO GTAPI

SUBROUTINE PICT
COMMON /CNST1, SPML, ACCML, ACCMG, VL, FFHDWY, FCHDWA, SIEDE
& GBPEED, PEND(20), SPFDL(20), XYTAB(20, 7), ASPACE(4), PROB(4, 4)
& CRL(20), CNST2, ACCUX, DELT, HIEGT, WIDTH
& COMMON /CNST2, IBUF(20), LEND(20, 3), JNEY(4, 4, 5), NLINKS, NIN, NOUT
& IMAR(10), ICODE(20), ICRL(20), JPRINT, JPLOT, JPICT, JFLOW, JPARAM, JMAX
COMMON /VAR1, TIME, TSTOP, VHEA(100, 8), TIMEN(4), HDWS(100), SDUM
& IVEHA(100, 4), LINKP(20, 2), LI, NCRL(20)
& ITIME, NPRINT, NPICT, NFLD, NPARAM, NMAX, ITRANS(100), ITRP
& DB(121)
& DB(120)
& DB(121)
& DB(120)
& DB(17)
TO COMMON /VREAD, IBC, ISTL1, IM, IBUF(10)
COMMON /WRTT, SETTIM, ISTEP, IKNOW, IFLG, TSAVE, IPRT
& ITRACE, ILINK, IVO
& ITMU
& ISTOP
COMMON /CNST3, LINKST(20), IPST(20), SFCT
IF IMAR(4) NE 0 RETURN
C RESET LINKSTORE.
DO 31 I=1,5
31 LINKBT(1)=0
C CALCULATE SCALE FACTOR.
SFCT = MIN1((400 - HIEGT, 1000 / WIDTH)
C SET UP GTAPI READY FOR TABLE.
CALL TAB0(NLINKS)
DO 1 I=1, NLINKS
C SEND LINK NUMBER.
CALL LDW(20)
CALL LDW(I)
IX=SFCT*XYTAB(I, 1)+.5
IY=SFCT*XYTAB(I, 2)+.5
RADIUS=XYTAB(I,7)
L=1
IF (RADIUS) 2,11,4
L=L+1
RADIUS=RADIUS
C CALCULATE NUMBER OF SEGMENTS IN CURVED LINK
THI=ATAN2( XYTAB(I,2)-XYTAB(I,6), XYTAB(I,1)-XYTAB(I,5))
THETAM=PEND(I)/RADIUS
NINTP=6+THETAM/3+142+5
IDATA=BFACK*PEND(I)/NINTP+5
C SEND SEGMENT LENGTH AND X AND Y CO-ORDINATES
CALL LDWI1(IDATA)
CALL LDWI1(IK)
CALL LDWI1(IY)
IF (RADIUS) 10,3,10
IDATA=BFACK*PEND(I)
GOTO 12
10 KK=NINTP+1
DO 7 J=1,KK
THETA=THETAM+J/NINTP
IX = (XYTAB(I,5)+RADIUS*COS(THETA+THI))*SFACK+5
IY = (XYTAB(I,6)+RADIUS*SIN(THETA+THI))*SFACK+5
C SEND INTERMEDIATE X,Y CO-ORDINATES
CALL LDWI1(IK)
CALL LDWI1(IY)
7 CONTINUE
3 IX=XYTAB(I,3)*SFACK+5
IY=XYTAB(I,4)*SFACK+5
C SEND END X,Y CO-ORDINATES
CALL LDWI1(IK)
CALL LDWI1(IY)
1 CONTINUE
C END OF DATA
CALL LDWI2(0)
CALL LDWI1(0)
CALL WEND
IF (ISTEP+NE+0) GOTO 21
RADIUS=XYTAB(I,7)
    L=1
    IF (RADIUS) 2,11,4
2 L=1
    RADIUS=RADIUS
C CALCULATE NUMBER OF SEGMENTS IN CURVED LINK
4 THI=ATAN2(XYTAB(I,2)-XYTAB(I+6),XYTAB(I,1)-XYTAB(I,5))
    THETAM=PEND(I)/RADIUS
    NINTP=6*THETAM/3+12*5
    IDATA=SFACTPEND(I)/NINTP+5
C SEND SEGMENT LENGTH AND X AND Y CO-ORDINATES.
12 CALL LDW1(IDATA)
    CALL LDW1(IY)
    GO TO 12
10 KK=NINTP+1
    DO 7 J=1,KK
        THETA=THETAM*J/NINTP
        IX =(XYTAB(I,5)+RADIUS*COS(THETA+THI))*SFACTP+5
        IY =(XYTAB(I,6)+RADIUS*SIN(THETA+THI))*SFACTP+5
C SEND INTERMEDIATE X,Y CO-ORDINATES.
        CALL LDW1(IY)
        CONTINUE
7 CONTINUE
3 IX=XYTAB(I,3)*SFACTP+5
    IY=XYTAB(I,4)*SFACTP+5
C SEND X,Y CO-ORDINATES.
        CALL LDW1(IY)
    CONTINUE
C END OF DATA.
    CALL LDW2(I0)
    CALL LDW3(I0)
    CALL WDBEND
    IF (IBTEP.NE.0) GOTO 21
C CHECK IF TIMING CHARACTER FROM GT+G RECEIVED.
  20  CALL CHECK(L1,IM,IST,IBC)
      IF (IBC+LTE-1) GOTO 20
  21  CONTINUE?READY;BC=IST;CH=TRU+1;101
      RETURN;WRITE;GETTIME;STEP;INCH;INLG;TRAIN;IPR;
      END
  4  ING:
      COMMON /COMP/ LINKST(20),IFST(20),SPAC
      COMMON /ACGERM/ NODE,KEGEER(20),TDBE
      E/STKX;SCOTY
      COMMON /ACERI/ SPINL,ACCLNL,ACCMNL,SL,MOHXL,LYX,LX,TLX,ALX
      &EPSFREE;ENDDO;PTEDC(50),XMT,LYX,LYX,LYX,LYX,LYX,LYX,LYX
      &CRL20;ACERI,CONST,ACCLN,ACCMNL,SL,MOHXL,LYX,LX,TLX,ALX
      &MARX;IEST(20),ICRL(20),PRTX,TLOT,PICT,ELM,HAM,PARH,MTH
      COMMON /VARV/ TIME,TSTOP,VECAL1000,CH,TIMEMV,MC,TEMPB,100100
      &HVARA(100),11,1,INKR;30,1,1;1,INCR(20)
      &TIME,PRINT,NPLT,NPLT,NPLT,NPLT,PAMH,49,TIMHAV100011
      &BAL(1)
      &B=3,1
      &B=3,1
      &BSL=1
      &B=3,1
      &B=3,1
      &BAL-139
      DIMENSION VOLH(5,77)
      DIMENSION ACGERM(100)
      EQUIVALENCE(TDBE,ACGERM)
      DIMENSION ,INDEX(10),XNDES(10),XNODES(10)
      IF (MARX+HEX-O) RETURN
      C RECALCULATE SCALE FACTOR:
      SPAC=MINXI(760.*MIXON/11000./WIDTH)
      U=0
      DD 200 I=1,20
      614   LINKSTING
      DD 500 I=1,10
      560   INDES(1)=0
      C SET OF NEW REFERENCE POINT FROM NODE INPUT IN DIALOGUE:
      INDPT=1
SUBROUTINE NEWPIC
COMMON /VREAD/IRC,IST,ILP,IM,IBUF1(I0)
COMMON /WRT/ SETTIM,ISTEP,ITRAN,IFLG,TSAVE,IPRT
&/TRACE,ILINK,IVNO
&/ITMO
COMMON /CONST3/ LINKR(20),IPST(20),SFAC7
COMMON /CARRY/ NODE,STAGE,STORE
&/CSTX,CSTY
COMMON /CONST/SPNML,ACCMG,ACCEMG,VL,FFHDWY,FCHDXY,SIDEA
&/CSPEED,PEND(20),SPFEDL(20),XYTAB(20,7),SPACE(4),PROB(4,4)
&/CRL(20),CONST1,CONST2,ACCE,DELT,MIEGHT,WIDTH
COMMON /CONSP/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINX,NIN,NMUT
&/MAR(10),ICODE(20),ICRL(20),JPRINT,JPLST,JPCTF,FLW,JPARAM,JMag
COMMON /VAR/TIME,TSTOP,VHA(100,8),TIME(4),HDSYS(100),SNEM
&/VEMA100,E1,LINKP(20,2),LT,NCRL(20)
&/ITIME,NPRINT,NPLOT,NPCTF,FLW,NPARAM,NMAG,ITRAN(100),ITRP
&/BAL1(21)
&/BAL2(14)
&/BAL3(21)
&/BAL6(5)
&/BAL7(3)
DIMENSION SOLT(5,2,2)
DIMENSION ASL(20)
EQUIVALENCE(SL,S,LN)
DIMENSION IODES(10),XTDES(10),YMDES(10)
IF (MAR(4).NE.0) RETURN
C RECALCULATE SCALE FACTOR.
SFAC7=MIN(1760/MIEGHT,1000/WIDTH)
J=0
DB 565 I=1,20
565 LINKST(I)=0
DB 560 I=1,10
560 INODES(I)=0
C SET UP NEW REFERENCE POINT FROM NODE INPUT IN DIALOGUE.
INDPT=1
INODES(INDPT)=NODE
XNODES(INDPT)=SCSX
YNODES(INDPT)=SCSX

540 CONTINUE
XPC=XNODES(INDPT)
YPC=YNODES(INDPT)
DO 1 I=1,NLINKS
DO 500 J=1,RAK
500 IF (I.EQ.IABS(LINKST(I90))) GOTO 1
C ONLY LINKS ATTACHED TO REFERENCE NODE SELECTED.
IF (LENL(I3).EQ.NODE) GOTO 2
IF (LENL(I2).NE.NODE) GOTO 1
J=J+1
C LINKST NEGATIVE IF NODE IS AT START.
LINKST(J)=I
GOTO 3
2 J=J+1
LINKST(J)=I
CALL LDMD2(I)
C TRANSMIT NEW LINK NUMBER.
CALL LDMD1(I)
DO 11 II=1,20
11 ABSLN(II)=0
K=1
IF (LINKST(J).LT.0) K=3
CXNOD=XYTAB(I,K)*SFEXT
CYNOD=XYTAB(I,K+1)*SFEXT
XM=XPC=CXNOD
YM=YPC=CYNOD
SOLN(5+1,1)=XYTAB(I,K)*SFEXT+XM
SOLN(5+1,1)=XYTAB(I,K)*SFEXT+YM
L=1
C IS END OF LINK WITHIN PICTURE.
RADIUS=XYTAB(I,7)
IF (SOLN(5+1,1).GE.0 .AND. SOLN(5+1,1)+LE.1000 .AND. SOLN(5+1,2).GE.0
& .AND. SOLN(5+1,2)+LE.740) GOTO 100
IF (RADIUS) 45,6
C DETERMINE THE X, Y CO-ORDINATES WHERE LINK INTERSECTS
C PICTURE BOUNDARY.
5 DX=XYTAB(I+1)=XYTAB(I+3)
   DY=XYTAB(I+2)=XYTAB(I+4)
   IF (ABS(DX).*LT.*1) DX=0
   IF (ABS(DY).*LT.*1) DY=0
   IF (DX)78,7
7   IF (DY)910,9
 C SORT OUT VERTICAL AND HORIZONTAL LINKS.
8  SOLN(3111)=XPC
7   SOLN(4111)=XPC
   SOLN(4112)=760
   GOTO 12
10  SOLN(1112)=YPC
   SOLN(2111)=1000
   SOLN(2112)=YPC
   GOTO 12
9  GRAD=DY/DX
   C=XYTAB(I+2)*SFAC+YM=GRAD*(XYTAB(I+1)*SFAC+XM)
 C CALCULATE X,Y INTERSECTS FOR SLANTING STRAIGHT LINKS.
 DO 15 II=14
   IF (II*GE.*3) GOTO 13
   X=0
   IF (II*EQ.*2) X=1000
   Y=GRAD*X+C
   IF (Y*GE.*0.*AND.*Y*LE.*760) GOTO 14
   X=0
   Y=GRAD*X+Y
   GOTO 14
13   Y=0
   IF (II*EQ.*4) Y=760
   X=(Y*C)/GRAD
   IF (X*GE.*0.*AND.*X*LE.*1000) GOTO 14
   X=0
   Y=0
14  SOLN(II111)=X
   SOLN(II112)=Y
CONTINUE
DO 17 II=1,4
IF (SOLN(II,1,1)*EQ.0.*AND.SOLN(II,1,2)*EQ.0.)* GOTO 17
DELX1=(XYTAB(I,1)-XYTAB(I,3))*SFAC
DELX2=XC=SOLN(II,1,1)
IF (LINKST(J)*LT.0) DELX2=DELX2
IF (ISIGN(1,DELX1)*ISIGN(1,DELX2)) 18,19,18
SOLN(II,1,1)=0.*
SOLN(II,1,2)=0.*
GOTO 17
19 IJMIN=II
JMIN=1
CONTINUE
180 IX=SOLN(IJMIN,JMIN,1)+.5
IY=SOLN(IJMIN,JMIN,2)+.5
XFLT=FLOAT(IX)
YFLT=FLOAT(IY)
IDATA=IFIX(SIGRT((MULT=XPC)*(XFLT=XPC)+(YFLT=YPC))
IF (LINKST(J)*GT.0) GOTO 50
IPST(J)=PENDII*SFAC=IDATA*+5
GOTO 21
50 IPST(J)=IDATA
IX=XPC
IY=YPC
GOTO 21
4 L=1
RADIUS=RADIUS
6 RADIUS=RADIUS*SFAC
F=MULT*SFAC+XM
G=MULT*SFAC+YM
C CALCULATE INTERSECTION OF CURVED LINKS WITH PICTURE BOUNDARY.
DO 25 II=1,4
A=0
H=F
IF (II*EQ.2) A=1000.
IF (II*EQ.3) H=G
IF (II*EQ.4) A=760
ARG=RADIUS**2=(A-H)**2

IF (ARG<=25,20,20)

20 IF (II+GE+3) GOTO 27
SOLN(II,2)=A
SOLN(II,1)=II+2
SOLN(II,1)=A
DO 28 JJ=1,2

28 CONTINUE
GOTO 25

27 SOLN(II,1)=II+2
SOLN(II,2)=A
SOLN(II,1)=II+2
SOLN(II,2)=A
DO 25 JJ=1,2

25 CONTINUE
THI=ATAN2(YPC-Q, XPC-F)
THEMIN=6.284
DB 31 II=1+1
DB 31 JJ=1+1

70 IF (SOLN(II,1)=GE+0. AND. SOLN(II,2)=GE+0.) GOTO 31
THE=THETI
L1=1
IF (LINKST(I)+LT+0) L1=0
IF (L+LT+0) L1=0
IF (THE+LT+0 AND L1+GT+C) THE=6.284+THE
IF (THE+GT+0 AND L1+LT+C) THE=THE=6.284
IF (ABS(THETI)+GT+THEMIN) GOTO 31
THE=THE
THEMIN=ABS(THETI)
IIMIN=II
JMIN=JJ
31 CONTINUE T(II+GT.0) GOTO 82
DO 32 II=1,2
DO 32 JJ=1,2
IF (II*EG+IIMIN*AND.+JJ*EG*JMIN) GOTO 32
SOLN(II,JJ)=0.
SOLN(IJ,II)=0.
32 CONTINUE LDNS=THEMIN*RADIUS
104 IF (LINKST(J)+GT.0) GOTO 10
IPST(J)=PEND(I)*SFACT=THEMIN*RADIUS++5
IX=SOLN(IIMIN,JMIN)++5
IY=SOLN(IIMIN,JMIN)++5
GOTO 41
40 IPST(J)=THEMIN*RADIUS++5
TEST0=0.
IX=XPC
IY=YPC
41 NINTP=6*THEMIN/3*142++5
IDATA=LONG/NINTP++5
21 CALL LDNC1(IDATA)
IF (IX*EG<0) IX=1
IF (IY*EG<0) IY=1
20 CALL LDNC1(IX)
CALL LDNC1(IY)
100 IF (RADIUS) 70,71,70
70 KK=NINTP+1
IF (KK*EG<0) GOTO 71
DO 80 JJ=1,KK
THETA=K*THEMIN*JJ/NINTP
IX=F+RADIUS*COS(THETA+THI+TEST0)++5
IY=0+RADIUS*SIN(THETA+THI+TEST0)++5
530 IF (IX*EG<0) IX=1
530 IF (IY*EG<0) IY=1
CALL LDNC1(IX)
CALL LDNC1(IY)
IIMIN=II
JMIN=JJ
31 CONTINUE
DO 32 II=1,4
DO 32 JJ=1,2
32 IF (II*EG*IIMIN*AND*JF*FG*JMIN) GOTO 39
BDLN(II, JJ, 1) = 0.
BDLN(II, JJ, 2) = 0.
33 CONTINUE
LNG=THEMIN*RADIUS
104 IF (LINKSET(J)+GT+0) GOTH 40
IPBT(J)=PEND(I)+SFAC=THEMIN*RADIUS+5
IX=BDLN(IIMIN, JJMIN, 1)+.5
JY=BDLN(IIMIN, JJMIN, 2)+.5
GOTO 41
40 IPBT(J)=THEMIN*RADIUS+5
THEBD=0.
IX=XPC
JY=YPC
41 NINTP=6*THEMIN/3+1+2+5
IDATA=LNG/NINTP+5
21 CALL LDWI1(IDATA)
IF (IX*EG+0) IX=1
IF (JY*EG+0) JY=1
22 CALL LDWI1(IX)
CALL LDWI1(JY)
IF (RADIUS) 70, 71, 70
70 KK=NINTP=1
IF (KK*EG+0) GOTE 71
DO 80 JJ=1, KK
THETA=THEMIN*JJ/NINTP
IX=F+RADIUS*COS(THETA+THI+THEST)*+5
JY=F+RADIUS*SIN(THETA+THI+THEST)*5
IF (IX*EG+0) IX=1
IF (JY*EG+0) JY=1
CALL LDWI1(IX)
CALL LDWI1(JY)
80 CONTINUE
81 IF (LINKST(J) .GT. 0) GOTO 82
   IX=XPC
   IY=YPC
   GOTO 89
82 IX=SOLN(IIMIN,JJMIN,1) +.5
   IY=SOLN(IIMIN,JJMIN,2) +.5
89 CONTINUE
   IF (IX .EQ. 0) IX=1
   IF (IY .EQ. 0) IY=1
   CALL LDWD1(IX)
   CALL LDWD1(IY)
   1 CONTINUE
      INDP1=INDPT+1
      NODE=INDESE(INDPT)
   IF (NODE .NE. 0) GOTO 540
   CALL LDWD1(0)
   CALL LDWD2(0)
   CALL TABLO(IJ)
   CALL WSEND
   IF (ISTEP .NE. 0) GOTO 210
200 CALL CHECK(LP,IM,IAT,IBC)
   IF (IBC .LT. 1) GOTO 200
210 CONTINUE
   RETURN
100 IIMIN=5
   JJMIN=1
   KP=2
   IF (LINKST(J) .LT. 0) KP=3
   IF (LEND(I*KP) .EQ. 0) GOTO 510
   DB 520 191=1.10
510 IF (INDESE(191) .EQ. 0) GOTO 530
520 IF (LEND(I*KP) .EQ. INDESE(191)) GOTO 510
530 INDESE(191)=LEND(I*KP)
   XNDESE(191)=SOLN(IIMIN,JJMIN,1)
   YNDESE(191)=SOLN(IIMIN,JJMIN,2)
510 CONTINUE
IF (RADIUS)1C1,180,103
101 L=1
RADIUS=RADIUS
103 RADIUS=RADIUS*SFAC
F=XYTAB(I*5)*SFAC*XY
G=XYTAB(I*6)*SFAC*XY
THI=ATAN2(G,XPC=F)
THE=ATAN2(SBLN(IIMIN,JMIN,2)+G,SBLN(IIMIN,JMIN,1)+F)
THE=THEI=THI
L1=1
IF (LINKST(I)+LT.0) L1=1
IF (L=LT.O) L1=L1
IF (THE*LT.0.2*AND+L1*GT+O) THE=6.284*THE
IF (THE*GT.0.2*AND+L1*LT+O) THE=THE=6.284
THEMIN=ABS(THE)
THESTO=THE
LONG=THEMIN*RADIUS
GOTO 104
END
CALL BREAD(1,1B,C,T)
100 CALL CHECK(1,1B,16,18)
IF (IAND(lST,6)) GOTO 500
1EV=O.
1ST+0.
CALL BMOVE(1,1B,F,IPO,TST)
ENCODE(1+10,165544,MI1,SFAC,IET)
111 FORMATT(1,1B,1,STF,1,165541,1,1B,11)
1ST=0.
C SEND COMMANDS TO GTO
CALL BWRITE(T,165544,0)+I,1ST
1ST=0.
C SET CS TO ASYNCHRONOUS READ
CALL BSET(I,17,0)
20 CONTINUE
970END
I=O
C READ TIMING CHARACTER FROM 970

SUBROUTINE TABLE(INL)
COMMON /READ/IBC,IST,L,IM,IBUF(10)
COMMON /CONST3/LINKS(20),IPST(20),SFACT
DIMENSION IMESS1(8),IMESS2(8),IMESS3(3)
DIMENSION IMESS4(6)
DATA ICR/'8Z0D0000000/
DATA IMESS1/'PICTURE TABLE READY TO SEND','8Z0D0000000/
DATA IMESS2/'TYPE CONTROL T A','8Z0D0000000/
DATA IMESS3/'G 111','8Z0D0000000/
IST=0
IBC=2
C PICTURE TABLE READY TO SEND TO GT40.
C SET GT40 TO RECEIVE, READ TIMING CHARACTER FROM GT40.
CALL BSET(L,132,0)
CALL BCWRITE(L,IMESS1,0,29,IST)
IST=0
CALL BCWRITE(L,IMESS2,0,29,IST)
IST=0
IBC=1
CALL BREAD(L,IBC,IST)
500 CALL CHECK(L,IM,IST,IBC)
IF (IAND(IST,81LE8) GTB 500)
IBYTE=0
IST=0
CALL BCMVE(L,IBUF,IBYTE,IBC,IST)
ENCODE(22,110,IMESS,N,NL,SFACT,ICR)
110 FORMAT('S N=','JS SF=','F7.3','1G','A1')
IST=0
C SEND COMMANDS TO GT40.
CALL BCWRITE(L,IMESS4,0,6,IST)
IST=0
C SET COC TO ASYNCHRONOUS READ.
CALL BCSET(L,19,0)
20 CONTINUE
IST=0
IBC=1
C READ TIMING CHARACTER FROM GT40.
CALL BCREAD(L,IBC,IST)
1  CALL CHECK(L,IM,IST,IBC)
   IF (LAN(DIST1) .EQ. 1) GOTO 1
   IST=0
   IBYTE=0
   CALL BCREADE(L,IBUF1,IBYTE,IBC,IST)
   IST=0
   IBYTE=0
   CALL BCREADE(L,IBUF1,IBYTE,IBC,IST)
   IST=0
   IBYTE=0
C SET UP 2 CHARACTER ASYNCHRONOUS READ
   CALL BCREAD(L,IBC,IST)
   CALL BCREAD(L,IBC,IST)
C PAUSE LIMITED TIME
   DO 455 I=1,20000
   455 CONTINUE
   RETURN
END
I SAVES PICTURE
I CLOCK DATA AS A BASE AND INCREMENT • TIME CALCULATED BY ADDING
I INCREMENT TO BASE EACH PICTURE CYCLE
I ARITHMETIC DONE IN BCD FOR SIMPLICITY (SINCE NO DECODING REQUIRED FOR
I PRINTING ON SCREEN)
I DATA IS MAX 5 BCD CHARACTERS • FOR EACH OF INCREMENT AND BASE TIME
I END WITH A ZERO CHARACTER
I BIT 4 = BIT INDICATES BASE NUMBER
I BIT 5 = BIT INDICATES NEGATIVE NUMBER
I FUNCTION CALL FUL
I
SP=16
R2=12
R1=11
R0=10
PC=7
RDONE=200
RBUF=175617
RCSR=17510
RDEC0=20
RN=100
RALL=160
R5=15
MIBRD=177600
==1524
DECO:
==+10*
TIME:
==+10*
BEGIN:
MOV #TIME,R0  ;SET UP INITIAL VALUES
MOV #DEC#R1
MOV R5,= (SP)
CON:
BIT #RDONE,RCR
BEG
MD,A RBUF,MP
BICB #MIBRD,R2
BEG
CLR R5
BIT #RDEC,R2
BEG LEMP
INC R5

LOOP1:
BIT #NEG,R2
BEQ POS
BIC #RALL,R2
NEG R2
BR LOOP2

POS:
BIC #RALL,R2

LOOP2:
TST R5
BEQ LTIME

LTIME:
MOV R2,(R1)+
BR CON

STOP:
MOV (SP)+,R5
UNSAVE REGISTER AND RETURN.

RTS PC

*END 11330
; SAVES DATA FOR PICTURE OF NETWORK IN TABLE. DATA SENT AS:
; 00X = LINK NUMBER
; XX = LENGTH SEGMENT
; XX = X CO-ORDINATE (HIGH ORDER, LOW ORDER)
; XX = Y CO-ORDINATE (HIGH ORDER, LOW ORDER)
; 000 = END
; (BIT 13 SET INDICATES NEGATIVE VALUE)

;FUNCTION CALL FT:
RO=0
R1=1
R2=2
R3=3
R4=4
R5=5
SP=6
PC=7
BOTXX=1652
STACKC=1706
RDONE=000200
ERRORC=201
INB=100000
SIGN=020000
=2202
CSRR: 175610
BUFF: 175612
TABLE: "TAB: TABLE HOLD: DATA"
ADTAB: "TAB: ADDRESS OF EACH LINK START POINT"
ENTRY: MOV ADTAB,R5 "TABLE BASE TO R5"
MBVB @RBUF,R1
CLR R2 "INITIALISE"
MOV R4, (SP) "SAVE R4 ON STACK"
LOOPO: MOV #P,RO
MOV   #2,R1
LOOP1: BIT   @RDONE, @CSR
BEQ   LOOP1   LOOP FOR CHARACTER.
NOP   DEC R1   COUNT
MOVB   @BUF, BUFFER(R1)   SAVE CHARACTER IN LOCATION CLEAR 7TH BIT.
NOP   BNE   LOOP2   BRANCH IF CHARACTER NOT ZERO.
DEC   R0
LOOP2: TST   R1   BRANCH IF NOT RECEIVED A PAIR OF CHARACTERS.
TST   R0
BEQ   LOOP5   BRANCH IF 2 ZERO'S RECEIVED.
BR   LOOP4
LOOP3: TST   R2
BEQ   LOOP5   RECEIVE ANOTHER CHARACTER.
BICB   @200,BUFFER   BRANCH IF NOT ZERO.
MOV   @BUF, BUFFER   BRANCH IF NOT ZERO.
BNE   LOOP6
BIS   @INT, BUFFER   SET BIT 15 IN TABLE AS FLAG.
MOV   BUFFER, (R5)+
MOV   (SP)+, @R6   SHOWN WIN END OF LINK DATA.
RTS   PC   RETURN.
LOOP6: DEC   BUFFER   MULTIPLY BUFFER BY 2 TO TURN INTO
ABL   BUFFER, @R4   DISPLACEMENT FOR NEW LINK ADDRESS.
MOV   BUFFER, @R4
MOV   R5, @DATA(R4)
MOV   #1, R2
BR   LOOP0   NOW READY FOR NEW LINK DATA.
LOOP4: TST   R2
BNE LOOP7

MOV #2, R2

LOOP7:

ROL BUFFER
ROR BUFFER

TST R0, R1
NOP

BLT=5 LOOP9

BIT #2, BUFFER

TAP LOOP10

BIC #1, BUFFER
NEG BUFFER

NEG #10, BUFFER, (R5)
DEC #10, R2

NOP

BRNE=6 LOOP9

LOOP10:

RETUR FOR NEW VALUES.

BIS #5, INT BUFFER

MOV #1, BUFFER, (R5)

MOV #0, R2

NOP

BR=1000 LOOP9

END=8000, 11330

700: DC
R1=1
R2=2
R3=3
R4=4
R5=5
SP=6
PC=7

DATA=162
STACK=192

SAVE=0
DAY=1
X=0

0
ADD \$PBASE,Pt
MOV \$POINT,INST
MOVE ABSOLUTE POINT INTO PICTURE INSTRUCTION

ADD \#BASE,R1
MOV \$POINT,INST
MOVE ABSOLUTE POINT INTO PICTURE INSTRUCTION

ADD \$TAB(R5),R3
REGISTER.
XX:
YY:
INST:
START:

CLR x
CLR y
MOV R0,(SP)
MOV R1,(SP)
MOV R2,(SP)
MOV R5,(SP)
MOV R3,(SP)
MOV R4,(SP)

CMP -(SP)=%(SP)
FPP+PUT+STACK

EVAL

MOV SP,R1
CMP (R1)+(R1)+
MOV R4,(R1)+
MOV R3,(R1)+

NOP
FIN
DEC R1
ASL R1
MOV R1,SAVE

FPP+STACK
FMUL+IMMED
000003
000000
FIN
FPP+STACK

MOV SAVE,R6
NOP

CMP (SP)+(SP)+
ADD #BASE,R1
MOV #POINT,INST
MOV ADTAB(R5),R3

SAVE REGISTERS.
SAVE 1ST ARGUMENT.
EVALUATE 2ND ARGUMENT.
R4 & R3 CHANGED THEREFORE SAVE
AGAIN ON STACK IN CORRECT POSITION.
CALCULATE LINK NUMBER.

CONVERT LAC NUMBER INTO CORE LOCATION OFFSET
FROM PICTURE BASE.

MOVE ABSOLUTE POINT INTO PICTURE INSTRUCTION
REGISTER.
TST(R3)\*:

MOV (R3)\*XX
BIT \#PFIN\*XX
NOP
BEQ LOOP0
MOV (SP)\*R4
MOV (SP)\*R3
MOV (SP)\*R5
MOV (SP)\*R2
MOV (SP)\*R1
MOV (SP)\*RC
NOP
RTS PC

LOOP0:

MOV INST,(R1)\+
MOV (R3)\*YY
FADD+IMMED
000001
040000
MOV XX,RC
SUB X,RC
BGE LOOP1
NEG RC
BIS \#SIGN,RC
NOP

LOOP1:

BIS \#MBIT,RC
MOV RO,(R1)\+
MOV XX,XX
MOV YY,RO
SUB YY,RO
BGE LOOP2
NEG RC
BIS \#SIGN,RC

LOOP2:

MOV RO,(R1)\+
MOV YY,Y
MOV \#LONGV,INST
NOP
BR LOOP3

BR LOOP3

; FIND X CO-ORDINATE FROM TABLF.
; TEST BIT FOR END OF LINK DATA.
; RESTORE REGISTERS AND RETURN FROM SUBROUTINE.
; MOVE DISPLAY GRAPHICS INST INTO PICTURE FILE.
; FIND Y CO-ORDINATE FROM TABLF.
; FIND DATA INCREMENT.
; CONDITION BITS FOR DISPLAY DATA.
; SAVE X DATA IN PICTURE FILE.
; DO SIMILARLY FOR Y CO-ORDINATES.
; CHANGE PICTURE INSTRUCTION TO VECTOR INSTRUCTION.
FINT JCAICUATE ADDRESS OF
ADD #PBASER, R1
MDV R1, END(RO)
TGT RO
BEQ START
TGT = (RO)
MDV RO, = (SP)
MDV R1, = (SP)
EVAL
BR LOOP99
START:
MDV R3, = (SP)
MDV R#1, = (SP)
MDV LEC2, RS
BIS #2, &RCRP
MDV END, RO
ADD #12, RO
MDV RO, TBARF
ADD #4, RO
MDV #3, R1
TEXT0:
MDV TEXT(R1), (RO)
TGT = (R1)
TGT = (RO)
TST R1
BGE TEXT0
ADD #6, TBARF
BR COUNT1
NOP
G01:
CLR RO
CLR R1
G02:
ADD TIME(RO), R1
ADD R1, DEC0(RO)
CLR R1
MDV #100, = (SP)
TST DEC0(RO)
BLT GE3
CMP (SP), DEC0(RO)
BGT COUNT3
INC R1
COUNT4: SUB (SP), DEC R0
COUNT3: CMP (R0) + , (SP) +
COUNT1: CMP #8 , R0
BEQ COUNT1
BR G03
G03: DEC R1
NEG (SP)
BR COUNT4
G01: BIT #RDENE, #RCSR ; RECEIVE FIRST CHAR
BEQ G0
MOV8 @RBUF, BUFFER
BICB #HBIT, BUFFER
; ENSURE THAT THE EIGHTH BIT IS CLEAR
MOV8 BUFFER , R0
NOP
BEQ LOOP6
JMP LOOP20
LOOP6: MOV #1, R0 ; IZERO COUNT
MOV #2, R1 ; ICHAR COUNT
LOOP2: BIT #RDENE, #RCSR ; RECEIVE TWO CHAR
BEQ LOOP2 ; ICHECK FOR ZEROS
NOP
DEC R1
```assembly
MOVB @RBUF, BUFFER(R1) ; FIRST CHAR INTO HIORDER BIT
BICB @MBIT, BUFFER(R1) ; SECOND CHAR IN THE LOW ORDER BIT

BNE LOOP3
DEC RO

LOOP3:
TST R1 ; TEST FOR CONDITIONS
BNE LOOP2 ; ONE ZRO BUFFER=LINK NO
TST RO
NOP
BNE LOOP8 ; INC ZROs BUFFER=INC DATA

LOOP8:
BGT LOOP5 ; ALL ZROs PICTURE FINISH
CLR SUM
MOV #JINST1,(R5)+ ; R5 POINTS TO PICTURE END
MOV #JINST2,(R5)+
MOV END,(R5) ; INSERT JUMP INSTRUCTION
MOV LEC1,R5 ; INSERT JUMP ADDRESS
MOV LEC1,R5 ; JRSET R5
TST -(R5) ; IFIRST JMP ADDR LOCN
TST FLAG ; IWHICH PICT TO BUILD
BNE LOOP98 ; INC 1
MOV LEC1,R5 ; INM 2 MOV PICT INSTR ST ADD
INC FLAG ; INTO JMP
MOV LEC2,R5 ; JRSET
NOP
BR GE1

LOOP98:
MOV LEC2,R5 ; MOV PICT 2 ST ADD TO
DEC FLAG ; JMP 1
MOV LEC1,R5 ; JRSET R5
NOP
BR GE1

LOOP5:
MOV BUFFER,RO ; CONDITION INCREMENT DATA
ROLB RO
ROR RO
BIT #ZERO,RO
BEQ LOOP1
```
LOOP1: BIC #BYTE, R0
NOP BIT #STEP, R0 ;TEST STOP CONDITION
BEG LOOP7
BIT #SIGN, R0
BEG FINAL
JSR PC+CLC
BR GO

FINAL: MOV (SP)+R3
MOV (SP)+R4
RTS PC

LOOP7: BIT #COLLIDE, R0 ;CHECK COLLISION BIT
BEQ LOOP29
MOV #1, CTEST ;YES SET FLAG
BIC #COLLIDE, R0 ;CLEAR BIT
BIS #003400, POINT ;INTENSIFY VECTORS

LOOP29: BIT #SIGN, R0 ;TEST SIGN
BEQ LOOP0
BIC #SIGN, R0 ;CLEAR SIGN BIT
NEG R0 ;NEGATE
NOP
BR LOOP0

LOOP20: NOP
ADD R0, SUM ;FULL SUM FROM STORE
MOV SUM, R1
BNE LOOP43
CLR R3
BR LOOP40

LOOP43: MOV #15, R3

LOOP41: BIT #MSB, R1 ;NORMALISE R1 TO
BNE LOOP40 ;EXponent IN R3 &
ASL R1 ;Mantissa IN R1
DEC R3
BR LOOP41

LOOP40: SUB DATA, R3 ;SUM EXPONENTS
INC R3 ;EXPONENT OF DIVISION
NOP
MOV     DATAM, R0  ;SET UP REGISTERS FOR DIVIDE
MOV     R3 = (SP)  ;R1/R0=R2 SAVE R3
MOV     #040000, R3  ;+VE NORMALISED NOS USED
DIVIDE: CLR R2
LOOP62: SUB R0, R1
LOOP63: BLT LOOP61  ;IP4 HOLES LIKE DISPL R3 THESE 3 TIME RT NOT
BIS R3, R2
ASR R0
BEQ LOOP64
BR LOOP62
LOOP61: ASR R0  ;GO INTO PART BY 4 FOR DATA DISPL
BEQ LOOP64
ASR R0
ADD R0, R1
BR LOOP63
LOOP64: MOV (SP)+, R3  ;R2 HOLDS MANTISSA
NOP
CLR R0  ;RENEW JMPING NEXT TIME
TSI R3
BLT LOOP12
BEQ LOOP14
ASL R2
ASL R2
LOOP11: ROL R0
ASL R2
DEC R3
BNE LOOP11  ;CREATE INTEGER AND FRACTION IN R0 & R2 RESPECT
LOOP10: ROR R2
ROR R2
BR LOOP14  ;PREPARE THE NORMALISATION OF THE DIFFERENCE
LOOP12: NEG R3
LOOP13: ASR R2
DEC R3
BNE LOOP13
LOOP14: NOP
MOV R0, INTEG  ;R0 CONTAINS INTERER
LOOP46: CLR R3
ASL R2

LOOP71: ASR R1
ASL R2
BCC LOOP74
ADD R1,R3
BR LOOP71
IR3 CONTAINS MANTISSA RO THE EXPONENT

LOOP74: BNE LOOP71
SUB #15,R0
NEG R0
UNNORM: BEQ LOOP50
ASR R3
DEC R0
BR UNNORM

LOOP50: TST SIGN
BEQ LOOP51
NEG R3
ICARREC SIGN CONDITION

LOOP51: ADD STORE,R3
NOP
BR LOOP52

LOOP73: INC ENFLAG
BR LOOP34

LOOP72: DEC ENFLAG

LOOP34: MOV STORE,R3

LOOP52: TST VEHB
BEQ LOOP80
TST YES
BEQ LOOP1
MOV R3,(R5)+
MOV R3,LASTY
MOV POINT,(R5)+
MOV LASTX,R2
CALC COORD FOR
ADD #040000,R2
ADD #2,R3
MOV R2,(R5)+
MOV R3,(R5)+
ADD #2,R2

MOV R3,(R5)+
ADD #2,R2
SUB    #2, R3
MOV    R2, (R5)+
MOV    R3, (R5)+
SUB    #2, R2
SUB    #2, R3
MOV    R2, (R5)+
MOV    R3, (R5)+
ADD    #2, R3
MOV    R2, (R5)+
MOV    R3, (R5)+
DEC    VEHB
DEC    YYES
NOP
JMP    GO
LOOP81:
MOV    POINT$(R5)+, JX COORD
MOV    R3, LASTx  ;SAVE ABS POINT
SUB    #2, R3
BIS    #INTxR3
MOV    R3, (R5)+  ;INSERT
TST    CTEST  ;COLLISION
BEQ    LOOP87   ;INR
BIC    #003600, POINT  ;YES CHANGE INTENSITY
LOOP87:
INC    YYES
JMP    LOOP30
LOOP82:
MOV    R3, (SP)  ;SAVE ABS POINT ON STACK
TST    YYES  ;Y COORD ?
BEQ    LOOP82   ;INR
SUB    LASTyR3  ;YES CALC INCR
BGE    LOOP53   ;YES
NEG    R3  ;SORT OUT SIGN BIT
BIS    #SIGNxR3
LOOP53:
MOV    R3, (R5)+  ;MOVE INTO DISPLAY FILE
DEC    YYES
INC    VEHB  ;CHANGE FLAGS
MOV    (SP)+, LASTy  ;SAVE ABS POSITION
NOP
TST    CTEST
BNE LOOP55
JMP GE

LOOP55: BIS #002600, POINT
CLR CTEST
NOP
JMP GE

LOOP56: SUB LASTX-R3     I=1-CALC X INC
BEQ LOOP54
NEG R3       I=START OUT SIGN
BIS #PSIGN,R3

LOOP54: BIS #INT,R3      I=SET INTENSITY BIT
MOV #LNGV,(R5)+
MOV R3,(R5)+      1X CMRD
INC YYES
MOV (SP)+1,LASTX; SAVE ABS POINT
NOP
JMP LOOP30

LOOP41: MOV BUFFER,R4
MOV BUFFER,R4     I=START NEW LINE
DEC R4
ASL R4           I=1-CALC LINK OFFSET
MOV ADTAB(R4),R3
MOV (R3)+,R1     I=R1 HOLDS DATA DIST BTWN INTERP PTS
MOV #15>R0

LOOP67: BIT #MSB,R1     I=NORMALISE DATA
BNE LOOP68
ASL R1
DEC RC
BR LOOP67

LOOP68: NOP
MOV R1,DATAK
MOV RC,DATAK
TST VEH
BNE LOOP56
MOV #LNGV,(R5)+
MOV (R3)+,R1
SUB LASTX,R1
C FOCAL PROGRAM TO DISPLAY MOVING PICTURES.
C C:FOCAL=11 LF8CA=1

1.10 X FX(=1,.1,75610,2) ; DISABLE FOCAL INTERRUPT.
C SEND TIMING CHARACTER AND RECEIVE DATA TABLE.
1.15 D HIT ***;FX, FX(=1) R
1.20 X FDIS(0,0,0,0) S L=FSET(1,0,0,0);D 3;G 1,I
1.30 D HIT ***;FX, FULLiT ***;F SIC 1,7;G 1,85
B SIG 1,7
1.40 F I=1,NIS L=FR(L;I)
C DISPLAY LINKS.
1.50 X FDIS(0,0,0,0) S L=FSET(1,0,0,0);S L=FSKP(L;850)
C SET UP SKIPS, ONE PICTURE IS PRODUCED, ONE DISPLAYED. THESE ARE SWITCHED.
C WHEN BUILD COMPLETED AND THEN NEXT PICTURE IS BUILT.
1.60 X FS KP(850);T = SECS*
C DRAW MOVING PICTURE.
1.80 O HIT ***;FX, FULLiT
C EXIT FOR COMMUNICATION.
1.85 D HIT ***;FX, FX(=.5,500,850)
1.90 D FS KP(850);X FX(=1,175610,66);T ***;I 5;G

2.10 T = TYPE CONTROL F*;F I=1,1000;
2.20 X FX(=1,175610,66);X FS KP(900);G

3.10 D Q=51;5 P=ARIS L=FTXT(L;OM,0E,0T,0R,0E,0S)
C WRITE SCALING LABEL ON SCREEN.
3.20 D L=FTPL(L;100,10);S L=FVEC(L,.0=10)
3.30 F I=1,3;D &
3.40 F I=0,3;S L=FPT(L;100)+(3*1);SF=1,0,0);S L=FTXT(L;P);S Q=50=I
3.50 R

4.10 D L=FVEC(L,.10*SF,0);S L=FFRC(L,.0=10)
4.20 D L=FMBVR(L,0,.10);R
C SIMULATES INTERSECTION WITH ASYNCHRONOUS MARKER FOLLOWER TYPE CONTROL.
C
C NOTE THAT ONLY THE POSITION CURVE OF THE PREVIOUS VEHICLE AND HEADWAY
C CURVE OF THE PRESENT VEHICLE ARE STORED, ONE FOR EACH LANE.
C
CIFORTRAN 90<.S
INTEGER BUF(3)
DIMENSION IA(50)
DIMENSION IMESS(20)
DIMENSION IBUF(2), NIV(1)
INTEGER VI
LOGICAL NOTFRE
LOGICAL STOPN0W
DIMENSION Del(2)
DIMENSION FTIME(2)
DIMENSION CONPT(5), V1(10, 4), ACCN(10, 4), T0(10, 4), AJERK(10, 4)
& SINC(10, 4), HI(10, 4), COEFF(5, 10, 4), S1(10, 4), T1(10, 4)
DIMENSION IFCOUNT(2), SAVING(2)
DIMENSION ACoeff(200), FRINGE(10, 4), ISTACK(20)
REAL KON
COMMON /PLAT/ TBLCK, BOUNDH, BOUNDL, START, QTIME, ENDTIM
*+DEL
COMMON TSTART, TF1N, FLEVEL1, FLEVEL2
COMMON TFINC, TTD0T, HOLD
COMMON /SWAP/ NUM, IF, IB, IN, SPEEDI, STARTH1, STARTM2, STIME, FTIME
COMMON /CMAN/ ISTORE(4, 2), RSTORE(4, 2)
EQUIVALENCE (ACoeff(1), CEEFF(1, 1, 1))
LOGICAL KOBUT
LOGICAL ISBEGIN
LOGICAL FROMTK, BACKMK, SPEED8K
NAMELIST
ISFO=5
HOLD=2, 5
NOOUT=.FALSE.
TTDT=0
NIV(1)=0
In initialization and default values.
DEGREE = .5
Z=GA(3) 
ISBEGIN=TRUE

C INITIALISE POINTERS AND JERK VALUES.
START1=CONPT(2)
START2=CONPT(4)
TIME=0
F TIME=CONPT(1)/VELSTR
LANE=1
IF=1
I2=1
IN=1

SPEEDOK=FALSE
IF (NOOUT) GOTO 355
CALL CCLOCAL(L,AJERK,I1,IN)
CALL HTML

C SET UP FOR COMMUNICATION TO FOCAL PROGRAM, ROLLING GRAPH DISPLAY
C RUNNING ON GTO9.
C """"CALL BCSW(L,3,0)RECTRY SEGMENTS.
IST=1
IBC=0
CALL BCRED(L,IBC,IST)
GOTO 355

350 CONTINUE
IF COUNT(1)=0
IF COUNT(2)=0
SAFRING(1)=100
SAFRING(2)=100

C LENGTH.
IF (F TIME=TIME+TIME) GOTO 355
F TIME=TIME+TIME:
SPEED1=VELMAX

355 CONTINUE
C SET UP TRAJECTORY VELOCITIES.
V(1,IN)=VELSTR
V(2,IN)=VELSTR
V(3,IN)=SPEED1
V(4,IN)=SPEED1
V(9+IN)=VELEN
V(10+IN)=VELEN
C SET UP ACCELERATION AND JERK VALUES
DO 2 I=1,10
    ACC(I+IN)=0.
    TJ(I+IN)=0.
    AJERK(I+IN)=0.
    SINC(I+IN)=0.
2 CONTINUE
DO 1 I=1,2
    T=I*(T-1)*4
    DV=V(5+I+IN)-V(2+I+IN)
    AJERK(2+I+IN)=SIGN(AJERK*DV)
    AJERK(4+I+IN)=AJERK(2+I+IN)
    DELT=SQRT(ABS(DV)/AJERK)
    ACCN(3+I+IN)=SIGN(MIN(AJERK*DELT,ACCNML)*DV)
    ACCN(4+I+IN)=ACCN(3+I+IN)
C TIME DURATION OF TRAJECTORY SEGMENTS
    TJ(8+I+IN)=ACCN(3+I+IN)/AJERK(2+I+IN)
    TJ(6+I+IN)=ACCN(3+I+IN)/AJERK(4+I+IN)
    TJ(3+I+IN)=V(5+I+IN)-V(2+I+IN)-AJERK(2+I+IN)*TJ(2+I+IN)*2/2-2+
&ACCN(3+I+IN)*TJ(4+I+IN)=AJERK(4+I+IN)*TJ(4+I+IN)*2/2+1/ACCN(3+I+
&I+IN)
    V(3+I+IN)=V(2+I+IN)+AJERK(2+I+IN)*TJ(2+I+IN)*2/2+
    V(4+I+IN)=V(5+I+IN)-ACCN(3+I+IN)*TJ(4+I+IN)-AJERK(4+I+IN)* TJ(4+I+
&I+IN)*2/2+
C LENGTH OF TRAJECTORY SEGMENTS
    SINC(3+I+IN)*V(1+I+IN)*TJ(2+I+IN)=AJERK(2+I+IN)*TJ(2+I+IN)*3/6+
    SINC(3+I+IN)*V(1+I+IN)*TJ(3+I+IN)=ACCN(3+I+IN)*TJ(3+I+IN)*2/2+
    SINC(4+I+IN)*V(4+I+IN)*TJ(4+I+IN)=ACCN(3+I+IN)*TJ(4+I+IN)*2/2++
&AJERK(4+I+IN)*TJ(4+I+IN)*3/6+
1 CONTINUE
330 CONTINUE
NSTFONE*FALSE.
FRONTOK*FALSE.
BACKOK*FALSE.
C POSITION OF TRAJECTORY SEGMENTS,
T7(IN)=T8(IN)=TJ(7,IN)
T6(IN)=T7(IN)=TJ(6,IN)

556 CONTINUE
DO 3 I=1,10
C HEADWAYS:
H(I,IN)=S(I,IN)+(V(I,IN)\*V(I,IN))\*AKINT+VL*KDN
3 CONTINUE
DO 557 I=1,9,4
SINC(I,IN)=S(I+1,IN)-S(I,IN)
TJ(I,IN)=T(I+1,IN)-T(I,IN)
557 CONTINUE
IF (*.NOT.*ISBEGIN) GOTO 444
C ONLY HERE FOR INITIAL VEHICLES:
THETA=0.
FACTOR=0.
NUM=1
IN=2+(LANE=1)*2
CALL SAVE(LANE)
FTIME1(LANE)=FTIME
IF (LANE=EG=2) GOTO 351
IN=3
IF=3
IB=4
LANE=2
STIME=0
FTIME=FTIME+TSTART
FSTIME=FTIME
GOTO 355
351 ISBEGIN=*.FALSE.*
GOTO 356
444 CONTINUE
ILIM1=1+(LANE=1)*100
ILIM2=100+(LANE=1)*100
DO 4 I=ILIM1,ILIM2
ACCEFF(I)=0.
4 CONTINUE
C CALCULATE COEFFICIENTS OF POLYNOMIALS DESCRIBING EACH SEGMENT
IF (I NE 11) GOTO 12

11 CONTINUE

10 IF (J # I) GOTO 11

100 IF (K = K + 2) GOTO 120

110 IF (J = J + 1) GOTO 130

120 IF (J = J + 1) GOTO 110

130 IF (J = J + 1) GOTO 110

C FINDING THE ORDERED TRAJECTORY BREAK POINTS.
230 GOTO 130
140 CONTINUE
   VAR=1
   GOTO 1000
1001 CONTINUE
10 DO 145 M=1,2
110 FRINGEM=1000.
120 IF (M.EQ.2) GOTO 147
130 IF (FRONTBK) GOTO 145
   I=0
140 BACF
   J=0 IF TAB FAR.
   K=0 IF (I.EQ.1)
   K=K+1
155 IF (J.EQ.5.AND.M.EQ.1) GOTO 170
160 IF (J.EQ.10.AND.M.EQ.2) GOTO 170
170 IF (K.EQ.21) GOTO 170
180 IF (I.EQ.1).AND.(J.EQ.1) GOTO 150
190 IF (FRINGE(J,I).GE.FRINGEM) GOTO 155
   FRINGEM=FRINGE(J,I)
   GOTO 155
150 I=I+1
200 IF (FRINGE(I).GE.FRINGEM) GOTO 155
210 IF (M.EQ.2.AND.J.EQ.6) GOTO 155
220 FRINGEM = FRINGE(I)
   GOTO 155
230 IF (ABS(FRINGEM).GT.EPS) GOTO 180
240 IF (M.EQ.1) FRONTBK=.TRUE.
   IF (M.EQ.2) BACKBK=.TRUE.
C FIND WORST INFRINGEMENTS DURING FRON Y AND BACK SPEED
C CHANGE MANEUVERS:
180 IF (M.EQ.1) STARTM1=STARTM1+FRINGEM
   IF (M.EQ.2).AND.(STARTM1.EQ.0) GOTO 473
230 IF (M.EQ.2) STARTM2=STARTM2+FRINGEM
   IF (FRINGEM.GT.MAXFRINGE(M)) GOTO 232
   IFCOUNT(M)=IFCOUNT(M)+1
   GOTO 233
232 IF COUNT(N) = 0
233 SAFRING(M) = FRINGEM
    GOTO 145
145 IF (BACKOK) GOTO 145
    K = K - 1
    GOTO 155
473 BACKOK = *TRUE*
145 CONTINUE
C START POINT FIRST MANEUVER:
    IF (START1 > CONPT(1)) GOTO 220
    ITT1 = 1
C BACKED UP TOO FAR:
    WRITE(108, 1810) ITT1, LANE, NUM
1810 FORMAT(X, X, X, I1, I1, I1, I1, I2, I2, I4)
    STOP
220 IF (START1 < CONPT(2)) GOTO 225
    START1 = CONPT(2)
    FRONTOK = *TRUE*
225 CONTINUE
    IF (IFCOUNT(2) < 2) GOTO 234
C START POINT FOR SECOND MANEUVER:
    IF (START2 > CONPT(3)) GOTO 270
    ITT2 = 3
C BACKED UP TOO FAR:
    WRITE(108, 1810) ITT2, LANE, NUM
    STOP
234 CONTINUE
C ITERATION FAILS TO FIND A START POINT FOR SECOND MANEUVER:
C THEREFORE CHANGE TARGET TIME AND START AGAIN:
    IF COUNT(3) = 0
    START2 = CONPT(4)
    FACTOR = FACTOR + 1
    GOTO 330
270 IF (START2 < CONPT(4)) GOTO 280
    START2 = CONPT(4)
    BACKOK = *TRUE*
280 CONTINUE
C HAVE SATISFACTORY FRONT AND RACK START POINTS BEEN FOUND? IF NOT
C RE-ITERATE SOLUTION:
  IF (NOT (FRONTOK AND BACKOK)) GOTO 330
  DISTI=6/18=5/18
  IF (DISTI+GT0) GOTO 300
C DISTANCE AVAILABLE FOR MANEUVER IS INADEQUATE. THIS IS A FAULT:
  WRITE (108*184*1) LANE, NUM
  1820 FORMAT (1=VE DIST1 ,11,1 V ' ,I4)
  STOP
  DISTI=0.
  300 TIMEI=T(6/18)=T(5/18)
  IF (TIMEI+GE+0) GOTO 31C
C TIME AVAILABLE FOR MANEUVER IS INADEQUATE. MAKE TARGET TIME LATER
  C AND RE-ITERATE:
  WRITE (108*184D) LANE, NUM
  1840 FORMAT (1=VE TIME L',11,1 V ' ,I4)
  FTIME=FTIME=TIMEI
  FTIME=FTIME
  GOTO 330
  310 IF (SPEEDOK) GOTO 320
  SPEED=DISTI/TIMEI
  IF (ABS (SPEED) = (SPEED)LT EPS2) SPEEDOK=TRUE*
C CALCULATE NEW INTERMEDIATE SPEED:
  SPEEDI=SPEED+ (SPEED-SPEEC1)*CONSTIT
  INIT=INIT+1
  IF (INIT=GT 10) SPEEDOK=TRUE*
C RETURN TO RE-ITERATE:
  GOTO 350
  320 CONTINUE
C FINAL TRAJECTORY FOUND:
  PDEL(LANE)=PDEL(LANE)+TSTART+FTIME+FTIME1(LANE)
  IF (PDEL(LANE)+LT 0+) PDEL(LANE)=0*
C CALCULATE DELAY, S.D. FVC:
  DELAY=TIME+TIME+PDEL(LANE)=TH
  FTIME1(LANE)=FTIME
  FLOW=NUM/FTIME
ISUM=ISUM+1
DESI=DESI*DESI*DESI
DELS=DELS*DELS*DELS
DELAYA=DELS/ISUM
FLOMA=ISUM/STIME
VARI=DESI/ISUM-DELAYA*DELAYA
VARI=STRT(VARI)
FRINMIN=1000.
DB 492 I=1,10
DB 492 J=1,2
IQ=IB
IF (J*EQ*2) IQ=IB
IF (FRINGE(I,J,T*T,FRTNMIN) GOTO 492
FRINGE=FRINGE(I,J)
492 CONTINUE
IF (SPEDE*LE*VELMAX) GOTO 390
DISP=DISTI/VELMAX*TIME
C CHECK THAT INTERMEDIATE SPEED IS WITHIN ALLOWED TRACK LIMITS.
FTIME=FTIME+DISP
FTIME=FTIME
SPEEDI=VELMAX
GOTO 350
390 CONTINUE
IF (ISUM=NEHUM) GOTO 391
STOPNBW==TRUE,
WRITE(108,907) FLOMA,DELAYA,VARI,OCPP
WRITE(108,908) IA
928 FORMAT(2);WRITE(108,908)
STOP
391 CONTINUE
IPPT=STARTM/125
IF (IPPT*LT*1) IPPT=1
IF (IPPT*GT*50) IPPT=50
C HISTOGRAM ARRAY SAVING THE START POINTS OF FRONT SPEED CHANGE MANEUVERSE.
IA(IPPT)=IA(IPPT)+1
OCPP=TTOT/FTIME
CALL PLOT(#EFF,T,IB,IF,LNAE)
VAR=2
GOTO 1000
1002 CONTINUE
INBIT=0
C CHANGE OVER POINTERS:
IB=IB+1(LANE=1)++
IF=IF+1(LANE=1)++
IN=IB
SPEEDOK=FALSE
NUM=NUM+1
THETA=0
FACTOR=0
356 CONTINUE
SAVE=STIME
CALL SAVE(LANE)
C FIND NEW LANE:
CALL NEWLANE(LANE,SAVE)
CALL UNSAVE(LANE)
SAVE=STIME
GOTO 350
1000 CONTINUE
IF (NBOUT) GOTO 114
C HAB TIMING CHARACTERS FROM PECAL PLOTTING ROUTINE BEEN RECEIVED?
801 CALL CHECK(L,IM,IST,IBC)
IF (IAND(IST,1)EQ1) GOTO 801
IST=0
IBYTE=0
CALL BMOVE(L,IBUF,IBYTE,IBC,IST)
C IV1 IS DECODED INTO FLAGS INDICATING WHICH OPTION HAS
C BEEN SELECTED FROM GT40. (IV1(1=7))
DECIDE(IBC,1802,IBUF,N) IV1
1802 FORMAT(11)
803 CONTINUE
CALL BCSET(L,132,0)
JEX=7
IV2=IV1
802 IF (IV2=2**IEX+LT*O) GOTE 806
   IV2=IV2-2**IEX
   NIV(IEX+1)=1
   GOTO 804
804 IEX=IEX+1
   IF (IEX*NE=1) GOTO 802
   IF (NIV(7)*EQ.1) STBF
   IF (NIV(6)*EQ.1) GOTE 1015
   IF (NIV(3)*EQ.0) GOTE 1014
   CALL BCSET(L=132,0)
   ICC=1
C READ DIMENSION CHARACTER IF GRAPH TO BE PLOTTED.
   CALL RD(ICC,V1)
   IBBO=(IVAR=1)+(LANE=1)*2+NUM*4
C SEND CODE NUMBER INDICATING WHICH LANE DATA TO BE SENT FOR, AND
C IF ITERATION OR FINAL TRAJECTORY,
   CALL BINEIC(ISFG,BUF,IBBO)
   CALL WTNL(ISFG,BUF)
   DB 978 I=1,10
   ICC=1
   CALL RD(ICC,V1)
C GT40 MAY REFUSE THE DATA BY SENDING A NON BLANK CHARACTER.
   IF (ICH(V1+1)*NE=2*40) GOTE 1004
   ISFG=5
C SEND DATA TO DRAW GRAPH ON GT40.
   VI=I(IN)+12+5
      CALL BINEIC(ISFG,BUF,VI)
   CALL WTNL(ISFG,BUF)
   ICC=1
   CALL RD(ICC,V1)
   ISFG=5
   VI=I(IN)+1+5
      CALL BINEIC(ISFG,BUF,VI)
   CALL WTNL(ISFG,BUF)
   ICC=1
   CALL RD(ICC,V1)
ISFG=5
V1=H(1,IN)+1.4*5
CALL BINDEC(ISFG,BUF,V1)
CALL WTNL(ISFG,BUF)
978 CONTINUE
1004 CONTINUE
1014 CONTINUE
    CALL BCSET(L,3,0)
    IST=0
    IBC=8
    CALL BCREAD(L,IBC,IST)
1114 CONTINUE
    IF (NIV(1)+EQ+1+AND+NIV(2)+EQ+1) GOTO 1012
    IF (NIV(2)+EQ+0) GOTO 1012
C OUTPUT ALL DATA PERTAINING TO TRAJECTORIES.
    WRITE(108,902) LANE,NUM
    OUTPUT(108)*TIME*
    WRITE(108,900)T
    OUTPUT(108)*POSITION
    WRITE(108,900)S
    OUTPUT(108)*HEADWAY
    WRITE(108,900)M
    OUTPUT(108)*VELOCITY
    WRITE(108,900)V
    OUTPUT(108)*FRINGE
    WRITE(108,900)FRINGE
    WRITE(108,902)
1012 CONTINUE
    IF (NIV(1)+EQ+1+AND+NIV(2)+EQ+1+AND+VAR+EQ+1) GOTO 1011
    IF (NIV(1)+EQ+0) GOTO 1011
1013 CONTINUE
C OUTPUT ANY SUMMARY DATA.
    WRITE(108,901) LANE,NUM,STARTM1,STARTM2,STIME,FTIME,FSTIME,SPEEDI
&      DELAY,DELAYA,VARI,FRINMIN,ACC
    IF (STOPNOW) STOP
1011 CONTINUE
    GOTO (1001,1002) VAR
1015 ICC=80
C READ MESSAGE FROM GT40 AND PRINT ON LINE PRINTER.
   CALL RDNL(ICC,IMESS)
   ICC=(ICC/4)+1
   WRITE(108,908) (IMESS(I),I=1,ICC)
908 FORMAT(X,20A4)
   CALL BCBSET(L,3,0)
   I=0
   IBC=8
   CALL BCREAD(L,IBC,IST)
   GOTO 801
900 FORMAT(X,10F10.3,3(/X,1CF10.3))
901 FORMAT(X,'L',I1,'X','V','I4','X','C1','X','C2','F6+1','X','F6+1','X,'
   D','F6+1','X','F6+1','X','(1,F6+1)'','X','I SP','F5+1','X','F6+1,'D','
   F6+2','X','F6+2','X','VAR','F6+2','X','F6+2','X','IM','F6+2','X','F6+2 ','
   BC','F4+3')
902 FORMAT(/X,'L',I1,'X','V','I4')
903 FORMAT(X,'START SPEED END SPEED MAX SPEED NML ACCN ENGR A'
   'LCCN VEM LENGTH')
904 FORMAT(X,'6F12.2')
905 FORMAT(3X,'CENTREL PTS 1=5,44X,'LEVELS 1=3,25X,'DEGREES')
906 FORMAT(X,'9F12.3')
907 FORMAT(X,'FLEW',F8+3,2X,'DELAY',F8+3,'S D',F8+3,'O CC',F8+3)
END
C GENERATE HEADWAY TO NEXT VEHICLE
C RANDOM NUMBER GENERATOR
C
SUBROUTINE RANDOM(IX,IY,YFL)
   IX=IX+95539
   IF(IY)5,6,5
   IY=IY+2147483647+1
   YFL=IY
   YFL=YFL+4656613E+9
   RETURN
5  CONTINUE
   IY=0
   CALL RANDOM(IY,IY,YFL)
   RETURN
END
C
C GENERATE HEADWAY TO NEXT VEHICLE.
C
FUNCTION GAP(I)
COMMON TSTART,TFIN,FLEVEL1,FLEVEL2
DIMENSION II(2),NE,I(LANE),S(LANE)
GOTO(1,2,3)I
3 I(1)=1
NE=OPEN(I(2),TSTART,START1,START2,SLINE,TIME)
CALL RANDOM(I(1),II(1),RN) (PREL12)
CALL RANDOM(I(2),II(2),RN)
GAP=0.
STC=TSTART+RN
RETURN
2 CONTINUE
1 IC=0
4 CALL RANDOM(I(1),II(1),RN) TO 5
IC=IC+1
IF (RN<TSTART)GO TO 4
GAP=FLOAT(IC)*TSTART/10.
IF (GAP<TSTART)GAP=TSTART
RETURN
END
PAGE=101
GOTO 3
7 LANES
IF I(LANE)=1 BEGIN 7
TURNSKIP
IF I(LANE)<LEAVE TIME=TFIN
IF I(LANE)<LEAVE S(LANE)=REORDER(6,LANE)
3 SPLIT_FWD
RETURN
END
SUBROUTINE NEWLANE(LANE,SAVET)
COMMON TSTART,TFIN,FLEVEL1,FLEVEL2
COMMON TFINC,TTOT,HOLD
COMMON /SWAP/NUM,IF,IB,IN,SPEEDI,STARTM1,STARTM2,STIME,FTIME
BEGIN1=RSTORE(4,1)
BEGIN2=RSTORE(4,2)
LSAVE=LANE
IF (LSAVE.EQ.2) GOTO 1
IF (BEGIN1.GT.SAVET+HOLD) GOTO 2
IF (BEGIN1.GT.BEGINP+50.) GOTO 2
TUSE=TFIN
LANE=1
GOTO 3
1 IF (BEGIN2.GT.SAVET+HOLD) GOTO 2
IF (BEGIN2.GT.BEGINP+50.) GOTO 2
LANE=2
TUSE=TFIN
GOTO 3
2 LANE=2
IF (BEGIN1.LT.BEGIN2) LANE=1
TUSE=TFIN
IF (LANE.NE.LSAVE) TUSE=TFINC
IF (LANE.NE.LSAVE) BEGINP=RSTORE(4,LANE)
3 FTIME=FTIME+TUSE
TTOT=TTOT+TUSE
RETURN
END
SUBROUTINE UNSAVE(LANE)
COMMON /SWAP/NUM,IF,IN,SPEEDI,STARTM1,STARTM2,STIME,FTIME
COMMON /CHAN/ ISTORE(1,2),RSTORE(4,2)
NUM=ISTORE(1,LANE)
IF=ISTORE(2,LANE)
IN=ISTORE(3,LANE)
SPEEDI=RSTORE(1,LANE)
STARTM1=RSTORE(2,LANE)
STARTM2=RSTORE(3,LANE)
STIME=RSTORE(4,LANE)
RETURN
END
SUBROUTINE SAVE(LANE)
COMMON /SWAP/NUM,IF,IB,IN,SPEEDI,STARTM1,STARTM2,STIME,FTIME
COMMON /CHAN/ ISTORE(4,2),RSTORE(4,2)
STIME=STIME+GAP(LANE)
ISTORE(1,LANE)=NUM
ISTORE(2,LANE)=IF
ISTORE(3,LANE)=IB
ISTORE(4,LANE)=IN
RSTORE(1,LANE)=SPEEDI
RSTORE(2,LANE)=STARTM1
RSTORE(3,LANE)=STARTM2
RSTORE(4,LANE)=STIME
RETURN
END
C SEND AXES TO PLOTTER FOR HARD COPY GRAPH PLOT.

SUBROUTINE AC
COMMON /PLAT/, TBLCK, BOUNDH, BOUNDL, START, QTIME, ENDTIM
* DDEL
DIMENSION MESS(3)
SCALE= TBLCK/10
SCALEP=(BOUNDH-BOUNDL)/R
CALL OFFSET(QTIME, SCALE, BOUNDL, SCALEP)
CALL PLOT(Q***,5,*,3)
CALL PLOT(QTIME, BOUNDL,12)
START=QTIME
ENTRY AXIS
CALL PLOT(START, BOUNDL,13)
DO 6 K=1,10 OLOR=START,BOUNDL GOTO 1
X=K*10*START
CALL PLOT(X, BOUNDL,12)
ENCOD(127, MESS, IRC, X)
7 FORMAT(F4,1)
CALL WHERE(1, Y, FCYR)
CALL PLOT(1,0,15,2 0)
CALL SYMBOL(1, =15,1, MESS, 0,IRC)
6 CALL PLOT(1, Y1,3)
START1=X
CALL PLOT(START1, BOUNDL,13)
CALL PLOT(START, BOUNDL,12)
START=START1
RETURN
END
50, DT, ENDTIM) GOTO 5
1K, (DT, BOUNDL, GOTO 6
GOTO 7
IF (T<DT, START) CALL AXIS
120=1
1M0=13
TS=DT, IRC)
P=CONFF (1, IRC)
C DRAW TRAJECTORY OF LAST VEHICLE AND HEADWAY PROFILE OF PRESENT VEHICLE.

SUBROUTINE PLAT(T,IB,IF,LANE)
COMMON /PLAT/TBLK,BOUND,BBOUNDL,START,GTIME,ENDT1M
*+DELT
DIMENSION COEFF(5,10,4),T(10,4)
IF (LANE.EQ.1) RETURN
ISEG=1
TS=T(1,1)
IMOD=13
P=COEFF(1,ISEG,IF)
CONTINUE
IF (TS.LT.GTIME.OR.TS.GT.ENDTIM) GOTO 1
IF (P.LT.BOUNDL.OR.P.GT.BOUNDR) GOTO 1
CALL PLOT(TS,P,IMOD)
TS=TS+DELT
IF (ISEG.EQ.10) GOTO 2
IF (TS.LT.T(1,ISEG+1,1)) GOTO 2
ISEG=ISEG+1
IF (ISEG.GT.10) ISEG=10
CONTINUE
DT=TS-T(1,ISEG,1)
P=COEFF(1,ISEG,IF)*DT+COEFF(3,ISEG,IF)*DT**2
#COEFF(4,ISEG,IF)*DT**3+COEFF(5,ISEG,IF)*DT**4
IMOD=12
GOTO 3
CONTINUE
IF (TS.GT.ENDTIM) GOTO 5
IF (P.GT.BOUNDR) GOTO 6
GOTO 7
CONTINUE
IF (TS.GT.START) CALL AXIS
ISEG=1
IMOD=13
TS=T(1,IB)
P=COEFF(1,ISEG,IB)
CONTINUE
IF (TS.LT.OSTIME.OR.TS.GT.ENTIM) GOTO 9
IF (P.LT.BOUNDL.OR.P.GT.BOUNDH) GOTO 9
CALL PLOT(TS,P,IMOD).
CONTINUE
TS=TS+DELT
IF (ISEG.EQ.10) GOTO 11
IF (TS.LT.T(ISEG+1,IB)) GOTO 11
ISEG=ISEG+1
IF (ISEG.GT.10) ISEG=10
DT=TS-T(ISEG,IB)
P=COEFF(1,ISEG,IB)+COEFF(2,ISEG,IB)*DT+COEFF(3,ISEG,IB)*DT**2
++COEFF(4,ISEG,IB)*DT**3+COEFF(5,ISEG,IB)*DT**4
IMOD=12
GOTO 8
CONTINUE
IF (TS.GT.ENTIM) GOTO 6
IF (P.GT.BOUNDH) RETURN
GOTO 10
CALL CLRFLT
RETURN
END
CIMACRSYM SI,GC,BA

DEF NMECHO
REF VDUDCB

NMECHO LI,1 X'20000'
STI,1 VDUDCB
B *15
END
DEF BCWRITE,BCREAD,BCSET,BCMOVE
REF CWRITE,CREAD,CSET,CMOVE

BCWRITE LI,12 CWRITE
B BCOC

BCREAD LI,12 CREAD
B BCOC

BCSET LI,12 CSET
B BCOC

BCMOVE LI,12 CMOVE

BCOC LD,4 14
CAL3,0 0
B *5,4
END
CCC: FOCAL = 11, LF0CA = A

C NECESSARY MODIFICATIONS TO FOCAL BINARY FOR SATISFACTORY
C COMMUNICATIONS TO SIGMA 5:
1.01 C PATCH 1044 D INTO 5252 (104475) NO;
1.02 C PATCH 1044 D INTO 5252 (104475) NO =
1.03 C PATCH 5376 INTO 2766 (3564) NO ECHO
C SENSE KEYS ON GT40 SELECT FUNCTION
1.04 C FO=SUMMARY ALL:FI=FULL DATA ALL:FO & F1=SUMMARY FINAL
1.05 C F2=GRAPHS;F3=FINAL ONLY;F4=LANE 1;F5=MESSAGE;F6=STOP
1.06 D 40:1 (1*P7(1)P9(1);)1;07;E1R S1D 210 42+1
C RETURN TO TELETYPES MODE (FW).
1.07 D MIX FW(1);1D

C INITIALISE POINTERS FOR ROLLING DISPLAY:
2.10 S L(1)=1;S L(2)=1;S L(3)=R5;S L(4)=R5;S L(5)=R5;S A=0;S Z=1
2.20 S 3:S CC=0;S AT=0;S SP=1;S ST=1;S EF=3;S EE=3;S PE=1
2.30 X FSKP(350,R5);S LG=R5;T *DON'T FORGET BGDCGC!*/.3*00;E H

C DELETE GRAPH AT EDGE OF DISPLAY TO ADD NEW GRAPH,
C RESCALE IF NECESSARY.
3.10 S PE=PE+1*S L(EE)=L(EE)+21*X FSKP(L(EF))=21*L(EE))
3.15 I (PC=CC)3;3;ID 21;ST=ST+2;ID 12;G 42+1
3.30 I (L(EE)=L(EF)=13;4);L(EF)=L(EE)+1;S EE=EF;S PE=PF
3.40 I (EE=EF)3.4;5;3.5;3.5
3.45 S 1*0;F LG=L(EF)+21;L(FF)=21;D 10
3.50 S 1*0;F LG=L(EF)+21;L(FF)=21;D 11
3.60 G 12;4

4.10 S DT(I)=TT(I)+TL;S TL=TT(I);S DP(I)=PP(I)+PL;S PL=PP(I)
4.20 S DH(I)=HH(I)+HL;S HL=HH(I)

C DRAW GRAPH VARIABLES TO SCRFFN UNITS:
5.10 I (I=15;76,5;76)1 (I=115,3,5;81) (I=215,6;5,9,5,9
5.30 S IT=FITRI(DT(I)+FSGN(DT(I)+5));S IP=FITRI(DP(I)+FSGN(DP(I)+5));
5.35 S LG=FVEC(LG,IT,IP);R
5.60 S IT=FITRI(DT(22-1)+FSGN(DT(22-1)+5));
5.61 S IP=FTR1(CH(22-I)=FSGN darken(22-I)*5);S LD=FVEC(LQ,IT,IP);R
5.76 S LQ=FSET(LQ,AT,0);R
5.80 S IP=FTR2(H1=FSGN(H1)*4);X FDIS(I=O);S LD=FMAY(LQ,C,IP);R
5.90 S IP=FTR2(H2=FSGN(H2)*5);X FDIS(I=O);S LD=FMAY(LQ,IP);R
10.10 X FDIS(O=3);O;R X FRETI(LQ,TS(PF)=TS(PE));O;S 1=I+1
11.x0 X FDIS(C=x3);O;R X FRETI(LQ,TS(PF)=TS(PE));O;S 1=I+1
12.x0 S CO=CO+1;S L(ES+1)=LFG
12.25 I (1=CO)2;S TL=TI(1)=ST
12.30 F I=1;I;S TI(1)=ST;S PP(I)=P(I)+PS;S HH(I)=M(I)+SP
12.35 S HH(I)=HH(I)+PP(I);F I=1;I;D 4
12.40 S TS(C)=TI(1)+I (100=TT(I)+TS(PE))(3+1)
12.45 I (L(ES+1)=L(5));I;D 5,12.x0;S FF=FF;S PF=CO
12.50 S LF=(L(E)=1);S AT=TR(CM)=TS(PE);F I=1;21;D 5
12.60 S TL=TS(C)+S PL=CO;S HH=0;I=1;I;D 13.x
12.70 A V1
C ASK FOR CODE CHARACTER FROM SIGMA 5
13.10 S VN=FTR1(V1=4);S LA=FTR1(V1=VN*4/LA*2);S IR=FTR1(V1=VN*4/LA*2)
13.x4 S LA=LA+1;S
C DECODE INTO PLOT ROUTINE IF REQUIRED; OTHERWISE SEND
C 11 TO SIGMA 5 TO CONTINUE SIMULATING
13.x5 T L(x+1)ON; LA*V N=x+3; CO; VN=x+1; X=x+30; IR=x+30; I=x+30
13.x6 I (PO(3)=IR)(13;17;13;17;13;5
13.x7 I (PO(3)=LA)+13;5;13;P;13;5
13.20 D 14;1;I (Z);I;Z;13;3;13;12+1
13.30 D 12;3;12;1;PO;35;S TS(CO)+TI(1);D O;5;6
13.x0 S Z=IR;G 42;1
13.50 T =1;G 42;1
14.x0 F I=1;1;A T(T);P(T);H(T)
C READ SENSE KEYS, DECODE IF CHANGED
40.x0 S A=FX(I=x77=S=1;11 I (IV=4;1;15,40;3,40;15
40.x5 S IV=AIS Ew7
40.20 I (FITR(A)=FITR(2-1)) 40.22 S A=FITR(A-FITR(2-1)):
C DECODE LOWEST 8 KEYS INTO P8(IN):
40.21 S P8(E)=1:G 40.25
40.22 S P8(E)=0
40.25 S E=E-1;I (=E) 40 +2, 40 +2;
40.30 R
42.05 T 1:0 H
C IF 7 SET WAIT:
42.10 D 40.11 (=P0(7)) 42 +1;I (=P0(5)) 42 +2;S PP=0
42.20 I (PP) 42 +3, 42 +3, 42 +1
C SEND CODED FLAGS TO SIGMA 5:
C IF ONLY LINE PRINTER OUTPUT NO FURTHER PARTICIPATION REQUIRED
C FROM GPU EXCEPT TO SEND CODED FLAGS:
42.30 T IV:
42.35 I (P0(5)) 42 +3, 42 +3, 42 +3;S PP=1:O S;I G 42 +9
42.36 I (P0(2)) 42 +1, 42 +1;D 12 ;7 ;I G 13 +1
C MESSAGE TYPED ON KEYBOARD IS TRANSMITTED TO SIGMA 5:
42.80 R
42.90 S ZZ=FCHR(FCHR(-1));I (7Z=13) 42 +9, 42 +9, 42 +9