THE DESIGN OF CONTROL SYSTEMS FOR AUTOMATED TRANSPORT

BY

LAURENCE DOWNTON BURROW

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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 degredation 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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Preface

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 ½ 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.[1-6] More recent work has concentrated on less demanding projects, for example, thirty vehicles to control rather than two thousand, five kilometres of track rather than several hundred, vehicle headways of ½-1 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 automated systems requires that the entire system design is carefully 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 unforseen 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 maintainance, 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 proceedure. 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.

Specification	(1.	Definition of objectives
	(2.	Formulation of measures of effectiveness
Search for an optimal solution	(3.	Generation of alternatives
	(4.	Evaluation of alternatives

	(5.	Selection
Finalising	(	
	(6.	Documentation

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 effectivness, 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.

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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.(13-17)

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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 maintainance 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.(Dia 1)

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 occuring 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 maintainance, 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.

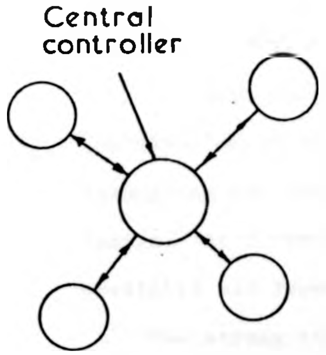
<u>Hierarchical Distributed Systems</u>. - A hierarchy is a multilayer control organisation. It can be considered as a filter,

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.(Dia 3) 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.

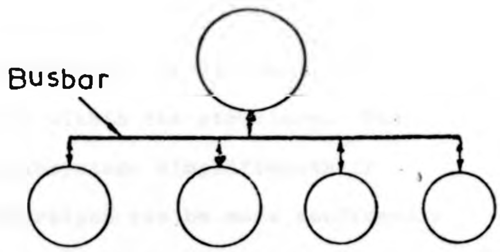
Information is only selectively directed up a hierarchy. Consequently not all the system information is available everywhere in the network. Information of marginal value from elsewhere in the system cannot be used. This has several consequences.[2, 4-9]

- 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.

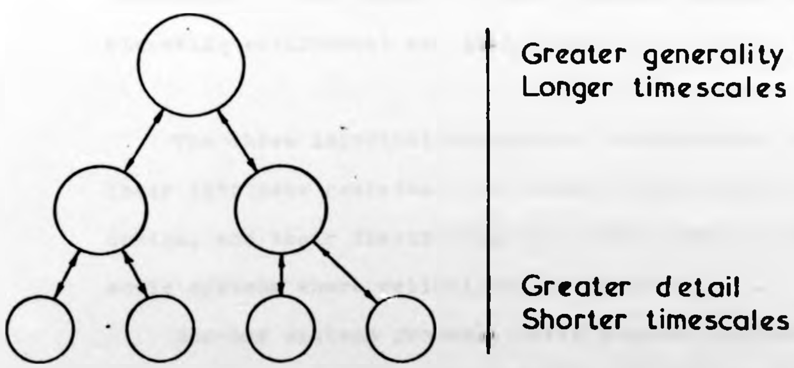
- The ultimate performance of a hierarchical system may be less than an equivalent centralised system.



DIA. 1 Centralised network



DIA. 2 Decentralised busbar network



DIA. 3 Decentralised hierarchical network

* 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 propogate. 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.[2] 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 independantly 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.

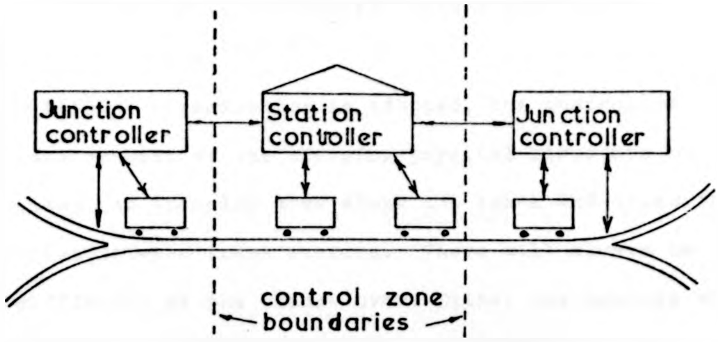
A transport network will be physically distributed over a large area. The computing power required to carry out the necessary control will demand the use of several inter-connected computers carrying out specific tasks. The additional considerations of designability and reliability encourage the use 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: -

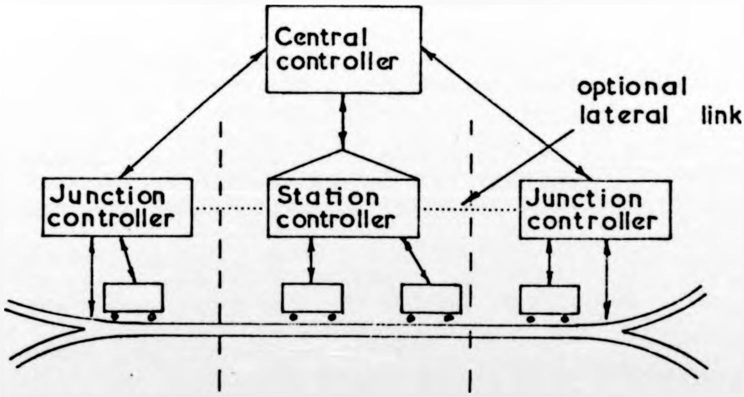
* Two tier localised control:- Local controllers, attached to the junctions and stations, supervise their adjacent track sectors. Vehicles are handed on from one sector to the next. Information about the vehicle (eg, destination and status) may be carried by the vehicle (which is then interrogated by each local controller, or may be transfered 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 (eg, dispatching and routing, optimisation). (Dia 5)

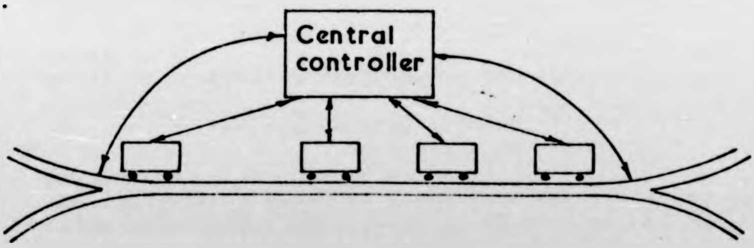
* Two tier centralised control:- All control is located at one place from which commands are dispatched to



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 proceedures 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 refri gerators, 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]

<u>The Fail-operational Approach</u> - 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, eg, 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 degredation 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 degredation 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.

2.2 The Definition of the Fail-Soft Characteristic

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:-

PERFORMANCE = (VALUE OF SYSTEM) - (COST OF SYSTEM)

[or SURPLUS = BENEFIT - COST]

The way the surplus, value and cost are distributed between the user and the operator is not important to the argu ments 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.

$$S = \sum_{\text{all states}} \bar{S}_i P_i \qquad \text{- - - - - 1}$$

where

S - expected value of surplus

$\bar{S}_i$ - mean value of surplus when in state i

P_i - probability of being in state i

Alternatively, equation 1 can be stated:-

$$S = So - \sum_{\text{all incidents}} R_k C_k$$

$$S = S_o - C \qquad \text{- - - - - 2}$$

where

S_o - 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_o at the expense of a larger loss term C 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

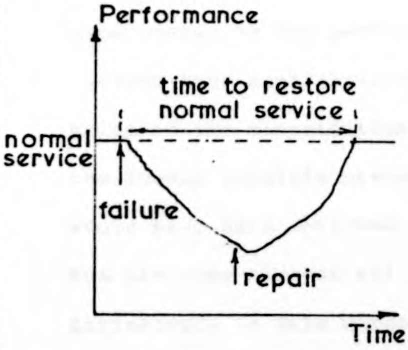
$$\text{DISRUPTION} = \int (\text{DEGREE})\, dt$$

over the incident duration

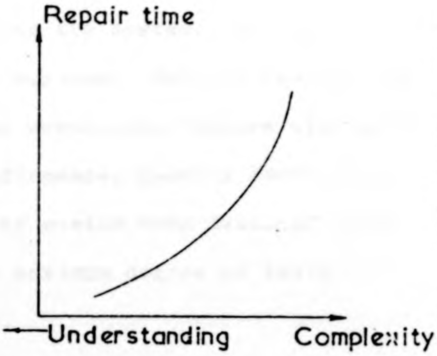
Degree is therefore (Δcost + Δbenefit) per unit time

The Δ cost term is the cost of the incident incurred by the operator for repair and replacement.

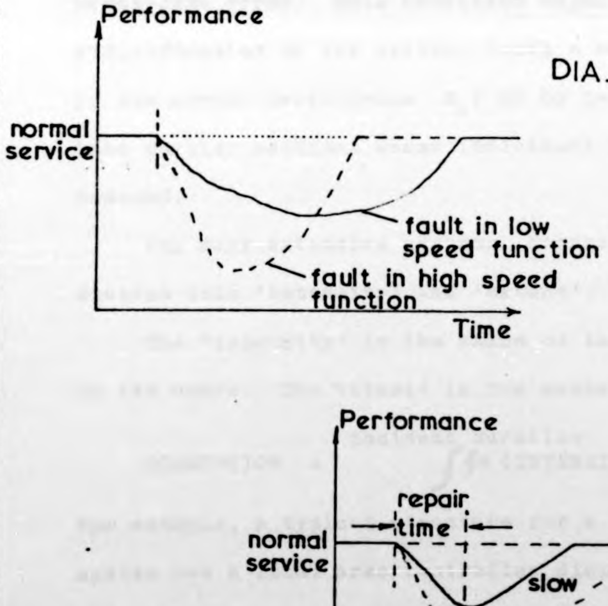
The Δ benefit term is the loss of service resulting from the incident. It is assumed to be much bigger than Δ cost and therefore more important. In the discussions which follow only the Δ benefit term is considered.



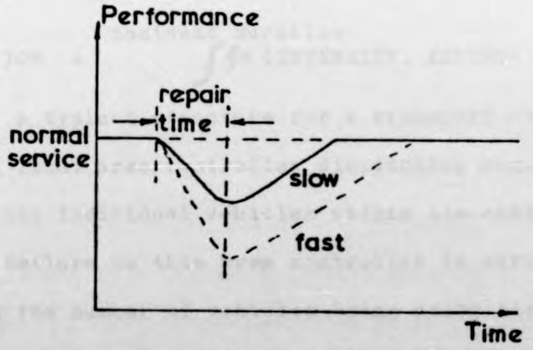
DIA.7 System performance following a fault



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 anywnere 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_o) 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:-

$$\text{DISRUPTION} = \int^{\text{incident duration}} fn\,(\text{INTENSITY, EXTENT})\ dt$$

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 ie, 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 introduced 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.

2.6 Types of Fault

A failure is an event, after whose occurrence the output state of a device shifts outside permissable 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 maintainance and operating proceedures), 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 propogate 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, ie, the transfer function [G] with m components is the same as the transfer function with one component.

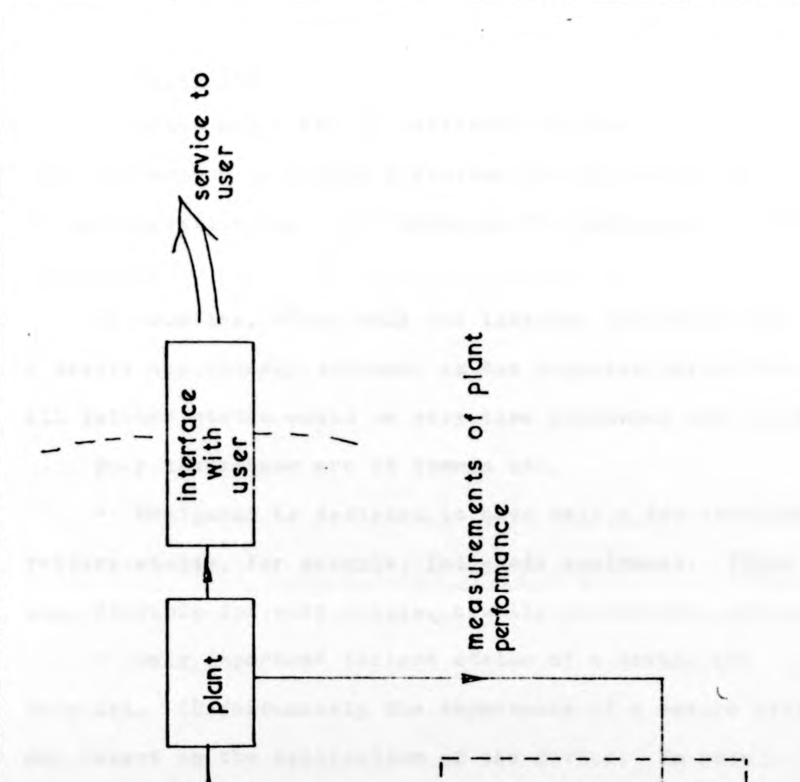
$$G_m(s) = G_{m-1}(s) = G_1(s)$$

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]

<u>Closed-loop</u> - 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 propogate 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 practice, limitations in both the function and the monitor ensure that they are not. As a measure of this, two parameters 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).[13-15] 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:

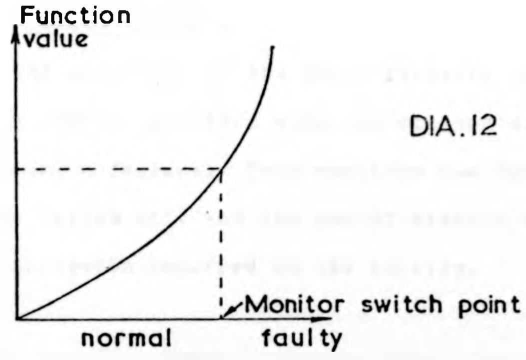
- The same process on the same hardware at different times (time redundancy to detect intermittent faults).
- The same process on different hardware at the same time (hardware redundancy to detect hardware faults).
- The same process based on different algorithms in the same hardware (software redundancy 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.

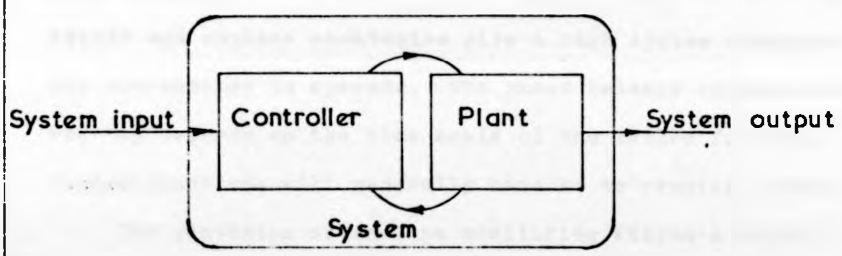
Redundancy is the only means of simultaneously achieving high coverage and minimum restrictiveness. Redundancy is expensive and because of the necessary comparison operation, speed of operation is limited to that of the slowest processor.

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]

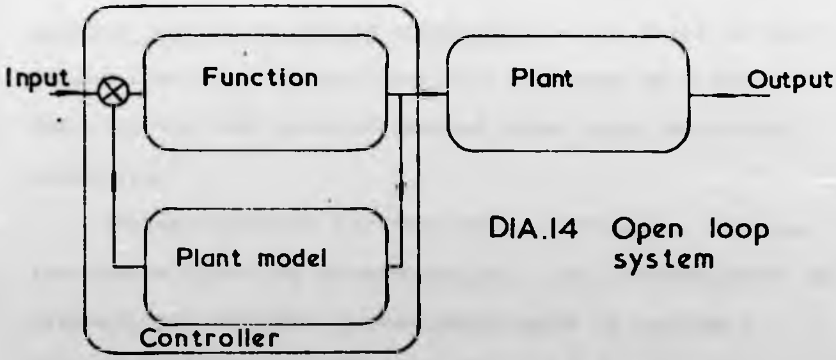
Error Detection Using Information Redundancy - Using coding, redundancy can be incorporated into data signals. Many sophisticated error detection and correction codes have been devised which are effective for a wide range of possible fault situations. They are used in communication links and data storage/retrieval 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]



DIA.12 The monitor



DIA.13 The controller and plant



DIA.14 Open loop system

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 maintainance men improves system reliability and makes better use of test equipment, so reducing costs that way.(8)

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, maintainance 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)

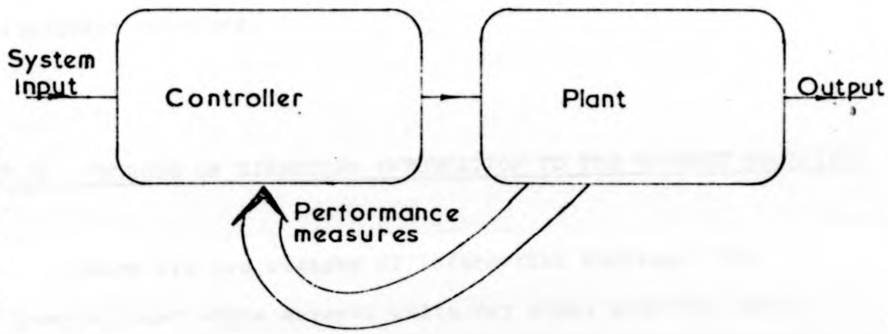
In closed-loop systems the controller may not necessarily hold a conceptual plant model. However the use of a plant model by the controller improves its ability to compensate for disturbances and enables optimum seeking methods to proceed faster. Such an arrangement is commonly called feed-forward control 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)

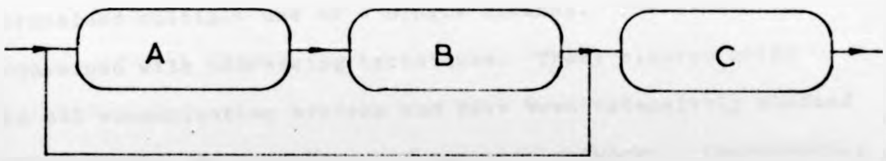
Fault-Control - Fault-control systems are usually closed-loop. Measures of actual system states are compared with predicted values of the states. The detection of abnormal discrepancies initiates standby strategies designed to counteract the effects of the failure. (See Chapter 2)

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

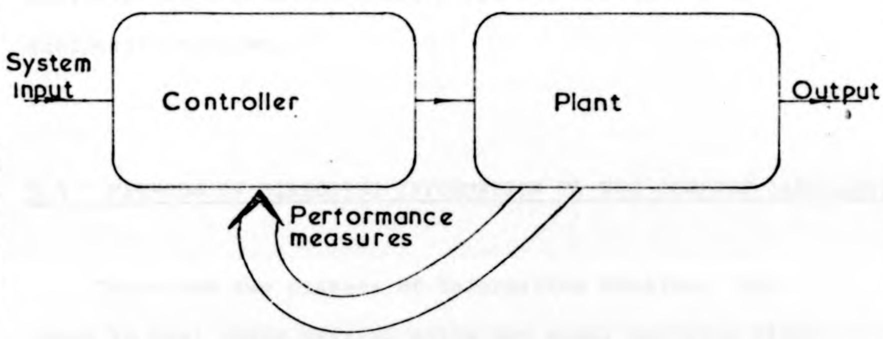
Within a closed-loop system, elements may be operating locally in an open-loop manner.(Dia 16) If measurement activities are moved further downstream, they will monitor a wider range of system states. A single transducer will tap information output by several preceeding elements. However the information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



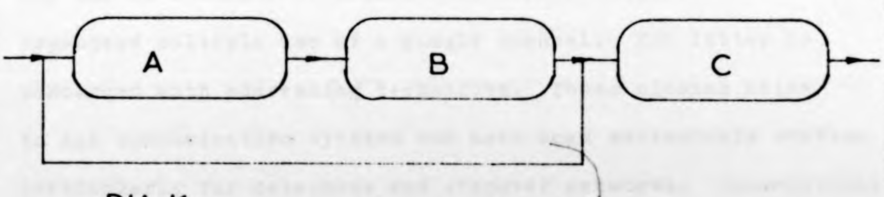
DIA.15 Closed loop system



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.

3.5 METHODS OF DIRECTING INFORMATION TO THE CORRECT 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.

3.6 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 prearranged 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 (eg 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.

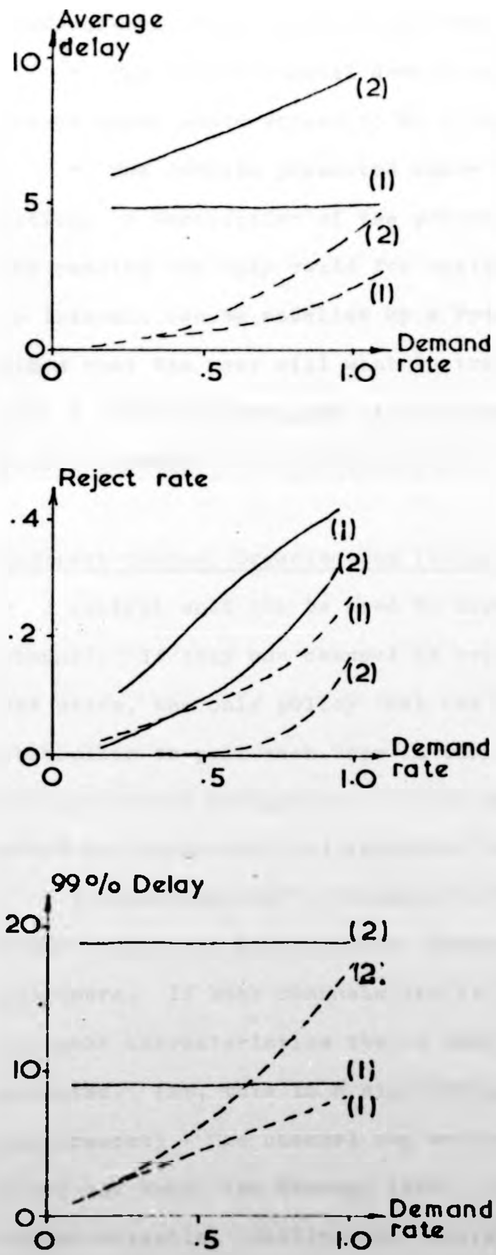
The use of stop-start codes to define the message boundaries allows vehicles, with no information to output, to use the channel less. The start of each transmission relies upon the end of the previous one. If one user fails to transmit, backup proceedures are required to restart transmission.

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



DIAS. 17–19

Characteristics of a single shared communication link operated cyclically or asynchronously

KEY:

- - - Asynchronous

——— Cyclic

(1), (2) The no. 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.

<u>Indirect Channel Organisation (Using a Central Controller)</u> - 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.

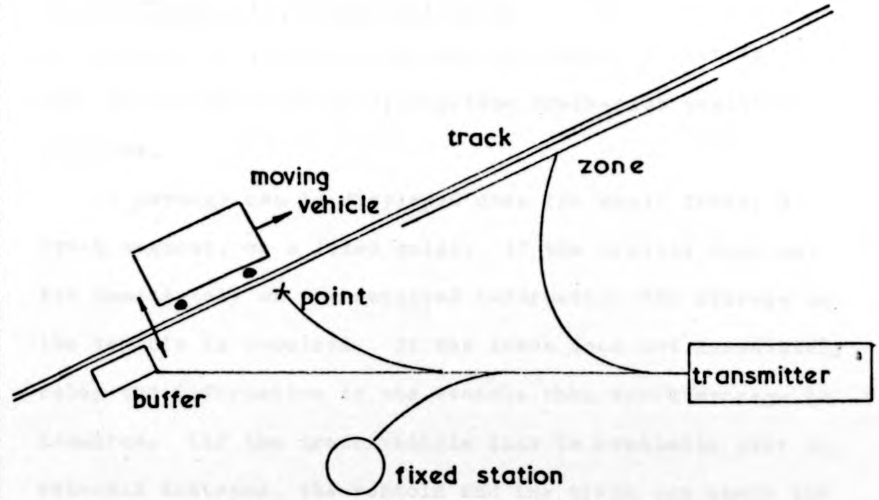
Against these benefits must be balanced the alternative gains that would have been achieved by operating each of the two channels independently for the same link. This provides lower delays and reject rates as a consequence of the lower usage of each channel.

3.7 Addressing

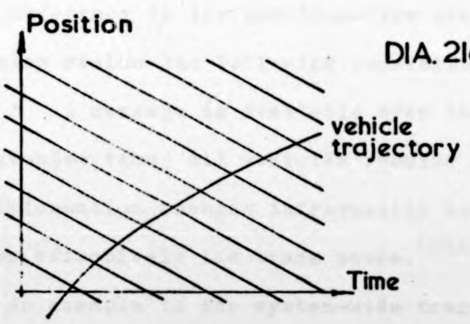
The successful transmission of information from one place to another in a system requires routing to the correct location, and timing to ensure that it will be received.

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]

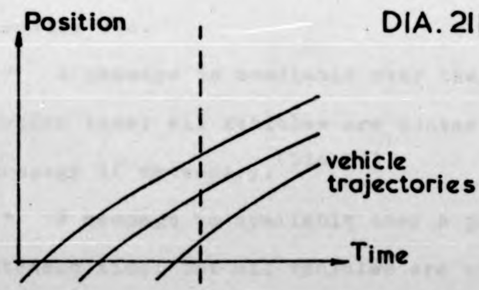
Communication systems linking fixed points have been extensively studied, particularly with respect to distributed computing systems, telephones etc. The extra refinement necessary to communicate correctly and efficiently with moving vehicles is the main concern of this paper.



DIA. 20 Types of transmission to a vehicle



DIA. 21a A message is recieved 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).

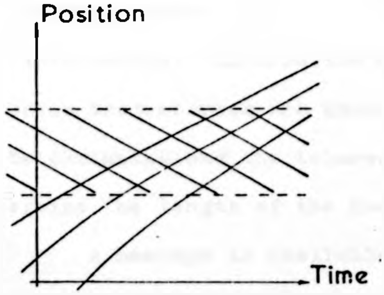
Reference to the position-time trajectories of the vehicles yields the following possibilities.

- 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)

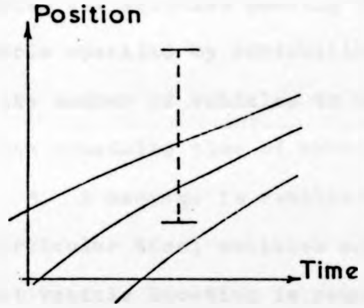
An example is the system-wide transmission of system status, signals such as, normal or emergency, service option, fare scale, etc.

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

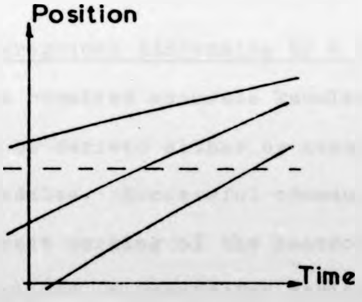
- A message is available over a portion of track for an extended time; not all vehicles are contacted, only those passing that portion of track.(Dia 23)



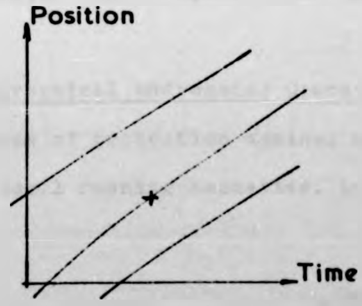
DIA. 21c Message displayed over a portion of track for an extended time



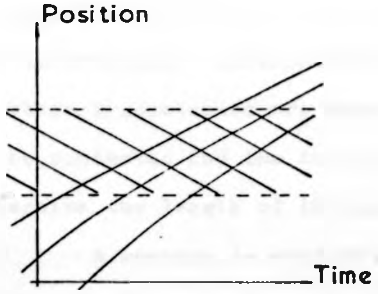
DIA. 21d Message displayed over a track zone at a fixed time



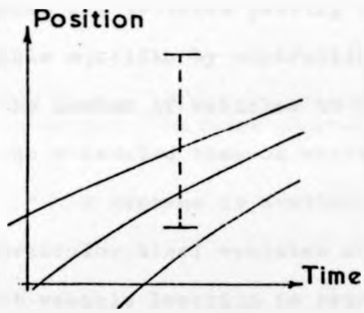
DIA. 21e Message displayed at a fixed position for an extended time



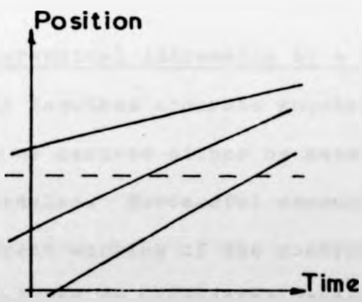
DIA. 21f Message displayed at fixed position and time



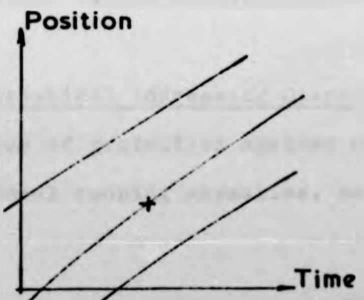
DIA. 21c Message displayed over a portion of track for an extended time



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

- 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)

<u>Geographical Addressing by a Centralised Unit</u> - 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.

<u>Geographical Addressing Operated by the Vehicle</u> - 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]

3.6 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. Conversly 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 useable 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 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 band-width. With the latter, in which position increments are counted, memory is required, signals are of narrow band-width, 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 by 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.

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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

Force = Mass x 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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6 Black I G et al
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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 (½ - 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 accessability 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.[1]

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 accleration and jerk considered for automated transport are:-

Limit with seated passengers - accn $2m/s^2$ jerk $2m/s^3$

Limit with standing passengers - " $1.2m/s^2$ " $1.2m/s^3$

with emergency deceleration rates of twice the normal rate. This compares with

Normal accn	1 - 2 m/s^2	-	lifts
	1 - 1.6 m/s^2	-	metros
Emergency	2.5 - 3 m/s^2	-	lifts
Decelerations	1.4- 3.6 m/s^2	-	metros
Jerk	.5- .7 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 2m at a speed of 12 m/s with a jerk constraint of 1.2 m/s^3 requires 45 m of track. A bend taken at the same speed must have an approximate radius of 130 m. (Dia 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.

<u>Journey Time</u> - 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.

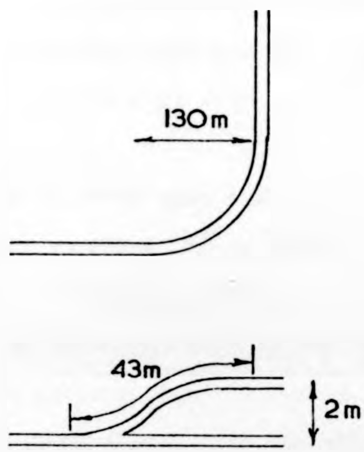
$$T_j = T_w + T_s + T_v$$

where

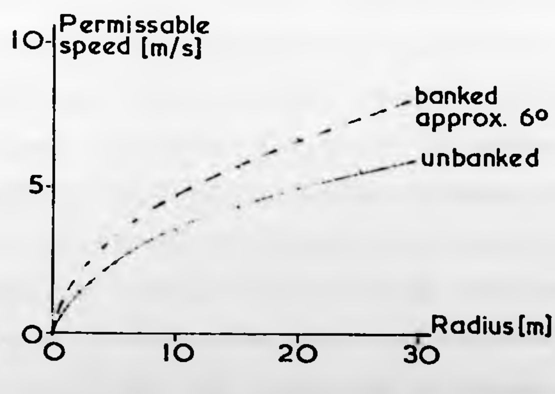
- T_w - walk time to and from the station
- T_s - station wait time
- T_v - in-vehicle time.

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.



DIA. 22 Typical dimensions for full speed curve or turnout



DIA.23 Maximum bend radius when subject to a lateral accn. limit of $1.2 m/s^2$ (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.(8)

In-vehicle time has three components:-

Tv - Tb + Tc + Td

where

Tb - base trip time

Tc - speed change delay

Td - 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.[9 - 11] 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 28 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.[1]

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 - 30% 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).[16] 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 occured. 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 Probabalistic 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 maintainance 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.[1,6,18]

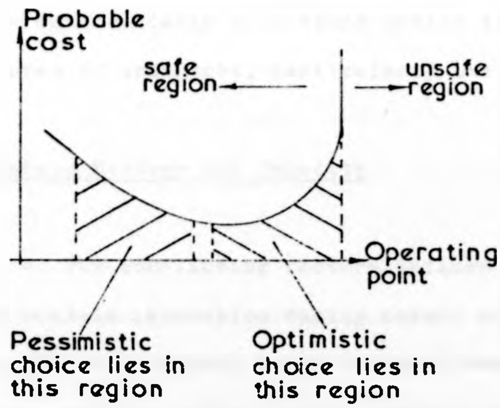
The probabalistic (or fail-soft) design process yields the second and more controversial approach to safety. Referring to Chapter 2, section 2.2, equation 2, the cost term C is chosen to maximise S for a given budget. This means choosing an optimal balance between the frequency term Rk (which depends on the reliabilities of components) and the incident cost Ck (which depends on system design). For unsafe failures (that is, failures that cause human injury or death), the incident cost Ck 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



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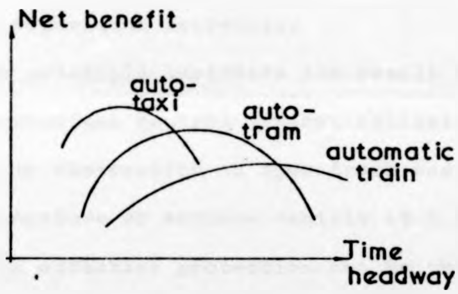

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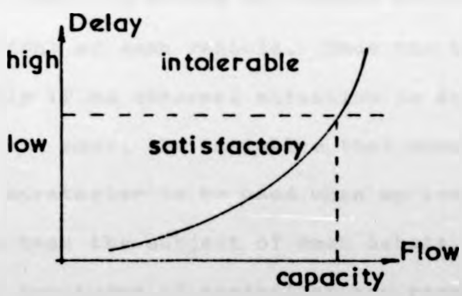

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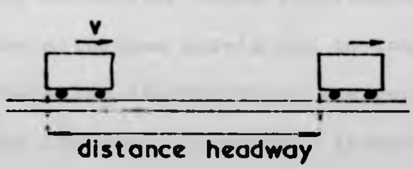


DIA.27

can draw substantially on current design techniques for other modes of transport, particularly the motor car.[6,20,21]

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 proceedures 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 - $\dfrac{1}{\text{Flow}}$

Minimum time headway - $\dfrac{1}{\text{Capacity}}$

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.

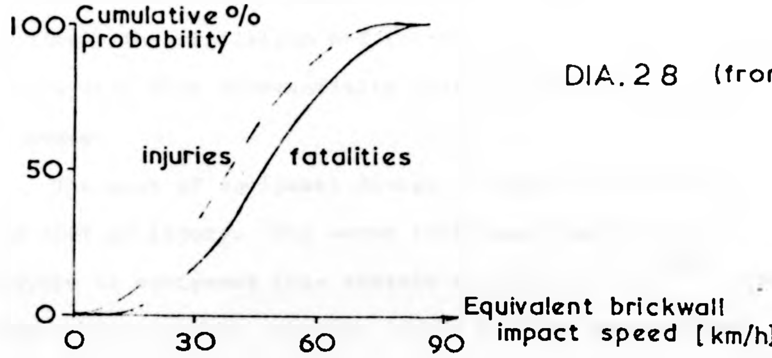
Probabilistic Approach - A number of costs have to be considered when choosing the size of the emergency headway.

* 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:-

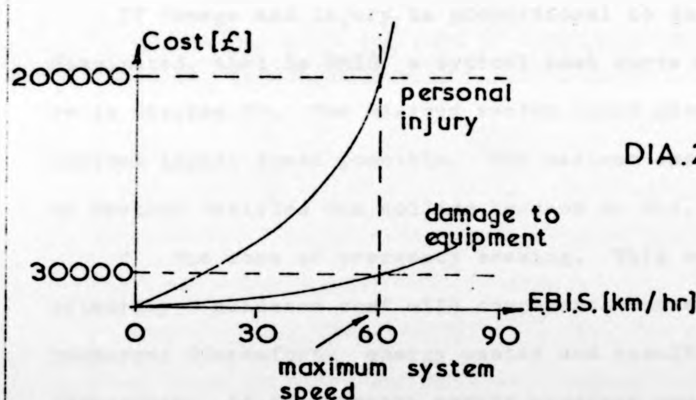
Collision with an immovable object	EBIS	=	velocity of vehicle at impact
Collision with another free-moving vehicle	EBIS	=	.5 x relative speed at impact
Collision with another vehicle with its brakes applied	EBIS	=	.7 x relative speed at impact

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). (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)



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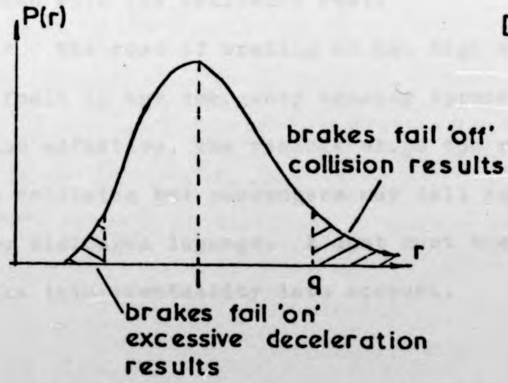
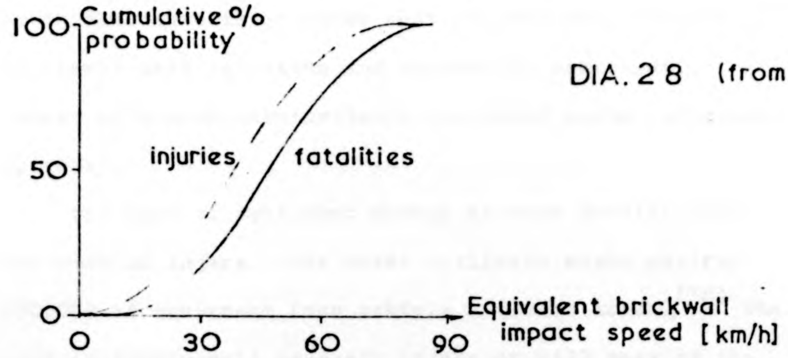


DIA. 30 Distribution of stopping distance about normal



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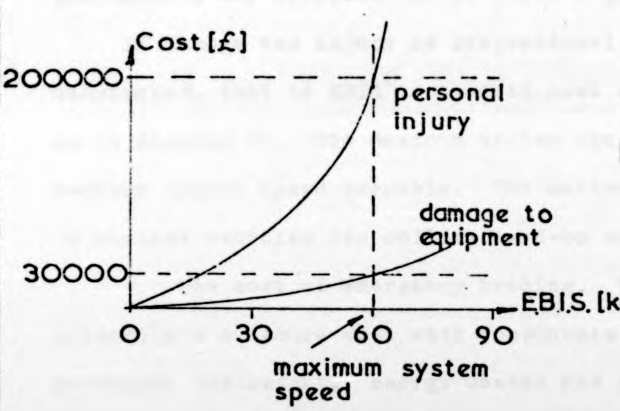

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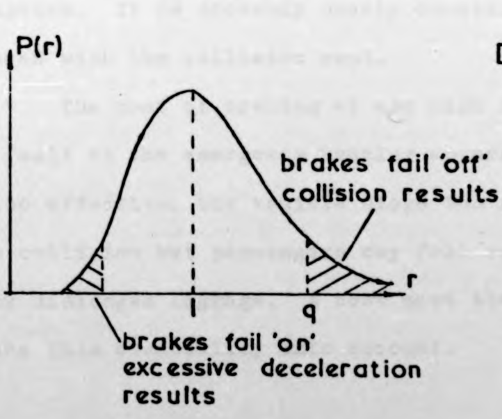


DIA.30 Distribution of stopping distance about normal

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 $EBIS^2$ a typical cost curve would look as in Diagram 29. The maximum system 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 * 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 $r < q$ EBIS = 0

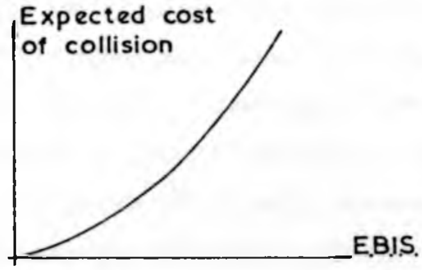
For $r \gg q$ EBIS = f(r,q) where f( ) is monotonically increasing and depends on initial velocity and the behaviour of the vehicle ahead.

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.

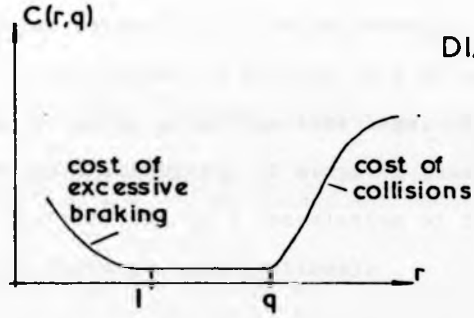
Thus, given that an emergency stop is required, a cost can be associated with a decision to make emergency headway equal to the nominal stopping distance (q=1). The cost is reduced if the headway is made larger (q > 1). For all possible choices of emergency headway a cost can be calculated

$$\text{Cost}(q) = \int_{\text{all } r} P(r)\; C(r,q)\; dr$$

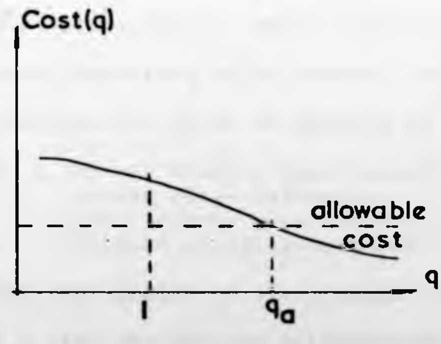
This is shown in Diagram 33.



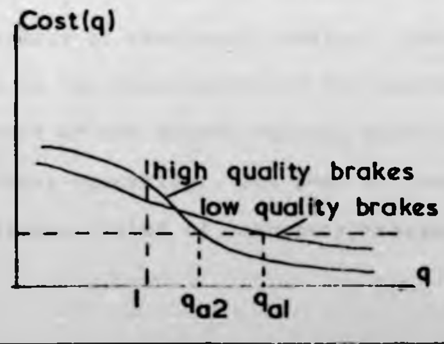
DIA. 31



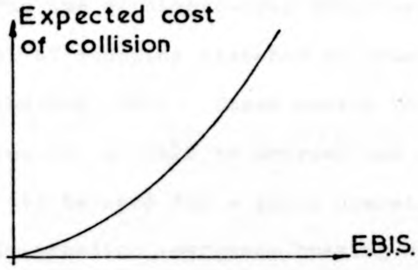
DIA.32 Cost of stopping as a function of r



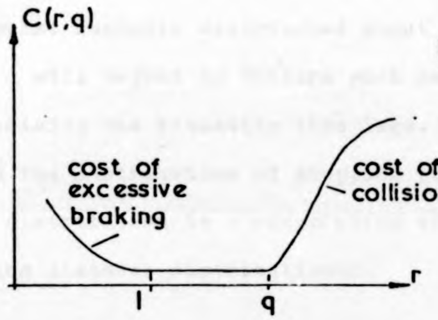
DIA.33 Cost of using a headway q



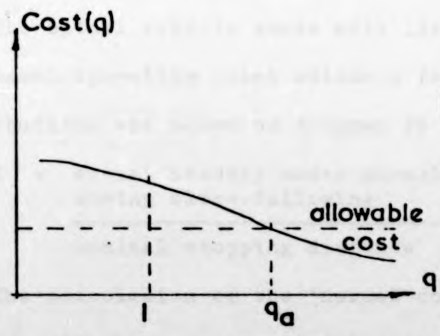
DIA.34 Comparative operating costs of two sorts of brakes



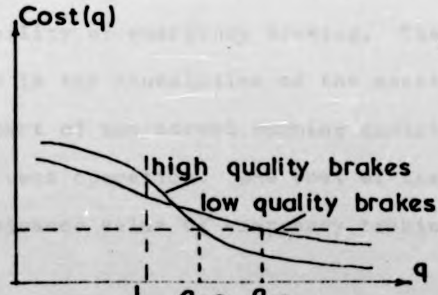
DIA. 31



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

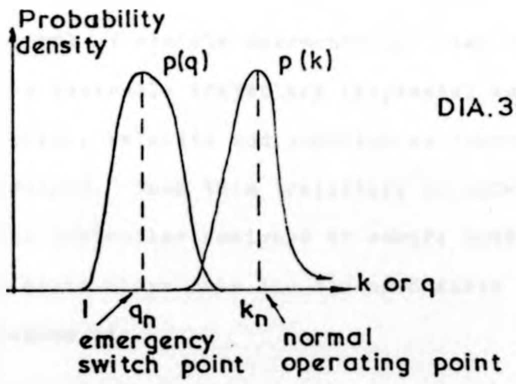
The use of closed-loop emergency braking gives a better control of stopping distance so reducing the spread of the distribution P(r). Consequently the cost (q) as a function of q will be sharper and enable a smaller value of q to be used for a given operating cost. (Dia 34)

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).

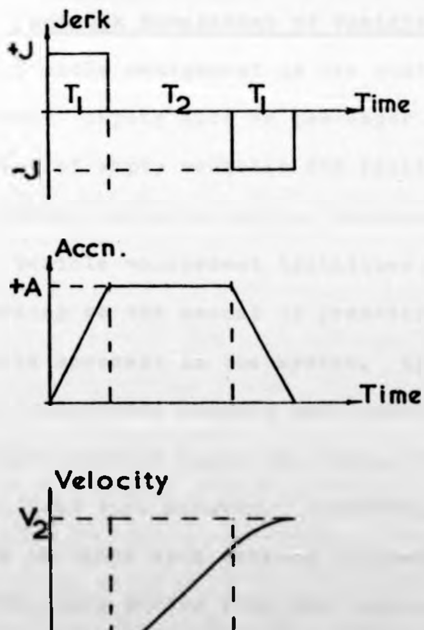
The actual vehicle state will lie in the vicinity of the normal operating point unless a failure occurs. The distributions are shown on diagram 35 where

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

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.



DIA.35



DIAS.36–38 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 1

Technique	Station	Track	Junction
1 - Neverstop	S	S	S
2 - Synchronous Slot	A	S	S
3 - Quasi-synchronous slot	A	S	A
4 - Asynchronous	A	A	A

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]

<u>Synchronous-Slot Control</u> - 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. (Speed = marker spacing x 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 degredation 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)

<u>Asynchronous Control</u> - 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 preceeding 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

$$\left| \frac{V_{n+1}(jw)}{V_n(jw)} \right| \leqslant 1 \quad \text{for all } w$$

this condition is satisfied,[38] where

V_n - velocity of N^{th} vehicle

V_{n+1} - velocity of $N+1^{th}$ vehicle

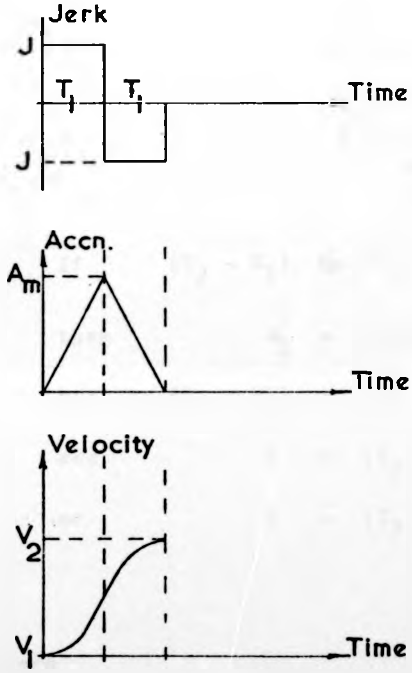
If this condition is not satisfied any disturbances become multiplied by the cascaded control action of the following vehicles so that the last vehicle undergoes large fluctuations in speed etc.

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.

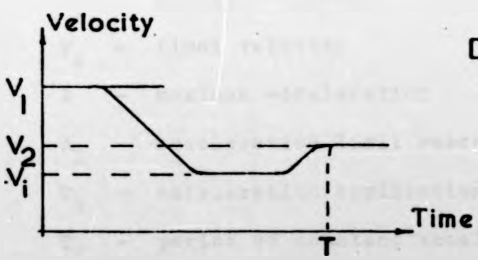
4.9 Performance Characteristics of Fleet Management Techniques

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.



DIAS.39-41 The trapezoidal manoeuvre: full accn. not reached



DIA.42 Velocity profile of headway changing manoeuvre

If $(V_2 - V_1) > AT_1$ ie, maximum acceleration is realised

then $T_1 = \frac{A}{J}$

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

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

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

If $(V_2 - V_1) \leq AT_1$ ie, maximum acceleration is not reached

then $A_L = T_1 J$

and $(V_2 - V_1) = JT_1^2$

and $D = (V_2 + V_1)T_1$

or $D = (V_2 + V_1)\frac{(V_2 - V_1)^{½}}{J}$

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

<u>Headway Changing Manoeuvre</u> - 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

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

where

$$z = T - \left(\frac{\tau_1 + \tau_2}{1} \right)$$

$$Y = \tau_1 V_1 + \tau_2 V_2$$

$$\tau_1 = \frac{a}{J}$$

$$\tau_2 = \frac{a_2}{J}$$

J = jerk limit used

a_1 = acceleration reached in stage 1

a_2 = acceleration limit reached in stage 3

Standard Emergency Headway - 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 x emergency headway where K is a safety factor.

This specification yields an emergency distance headway

$$H_e(v) = \frac{V^2}{2.ae} + L$$

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.

$$C(v) = \frac{V}{H_D(v)} = \frac{1}{H_T(v)} = \frac{1}{\left(\frac{V}{2ae} + \frac{L}{V}\right) K}$$

where

$H_T(v)$ - 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 = vehicle length x K

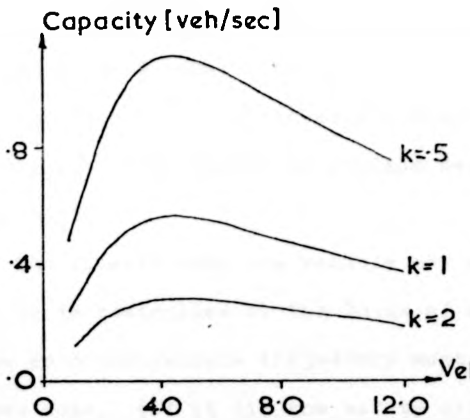
$$V_{sat} = \sqrt{2ae.L}$$

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.

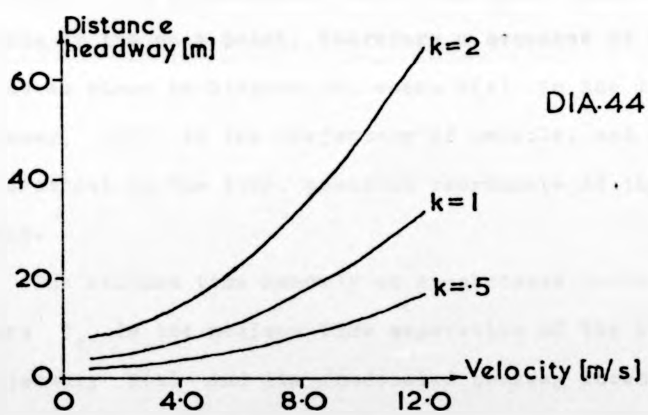
4.10 Synchronous Control

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)

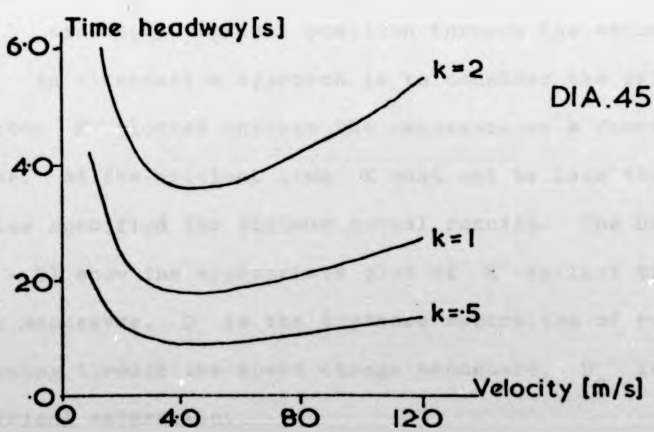
If speed changes are required anywhere on synchronous track, for example because of small track radii at corners, or station turnouts, the time headway between vehicles must be increased from the constant speed minimum. The increased



DIA.43 Capacity of constant speed track



DIA.44 Distance headway as a function of speed



DIA.45 Time headway as a function of speed

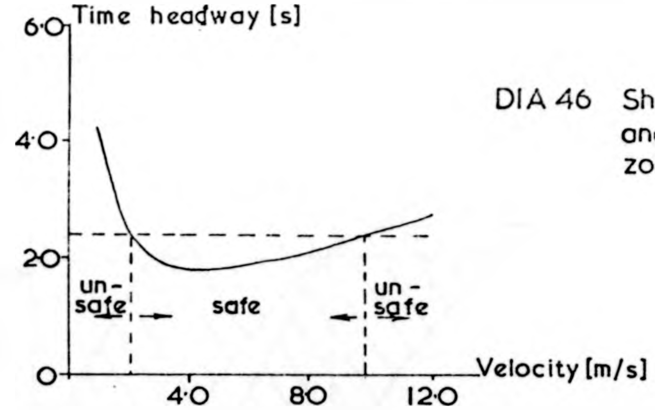
headway is necessary because vehicles close up as they go through a speed reduction.

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

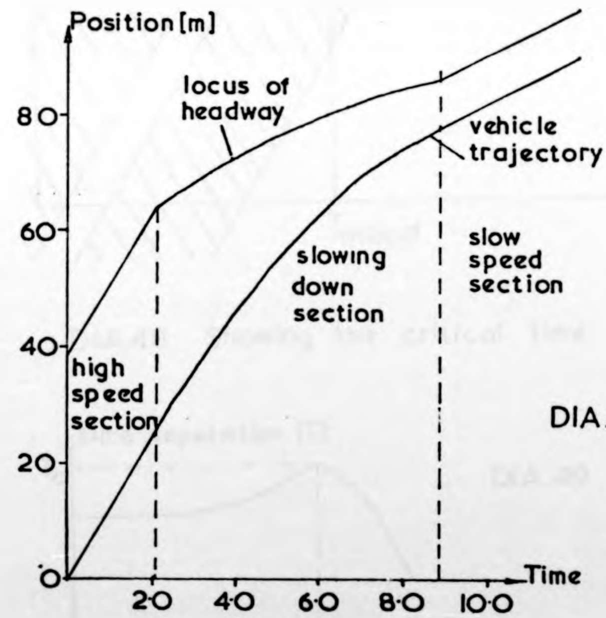
The closest that the vehicle may approach a previous vehicle is controlled by the locus of the minimum headway, since no other vehicle trajectory must pass through the shaded zone. (If it did the safety criteria would be violated). On synchronous track, the speed reduction always starts at the same point, therefore a sequence of vehicles looks as shown in Diagram 48, where H(t) is the locus of headway, S(t) is the trajectory of vehicle, and ^{t}critical, ^{P}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.

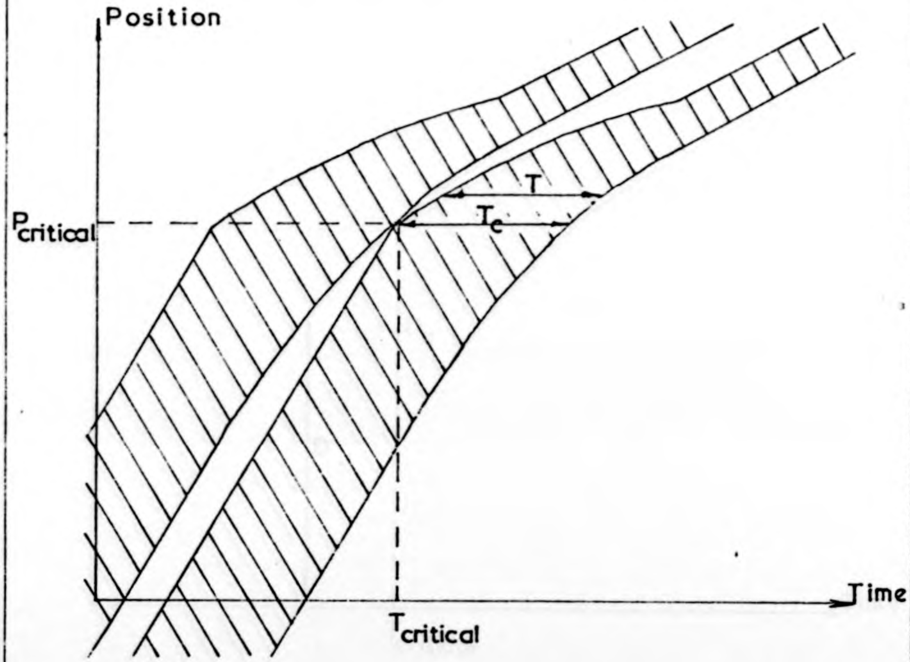
An alternative approach is to consider the safety factor K plotted through the manoeuvre as a function of time. At the critical time K must not be less than the value specified for minimum normal running. The Diagrams 50 - 51 show the appropriate plot of K against time through the manoeuvre. D is the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



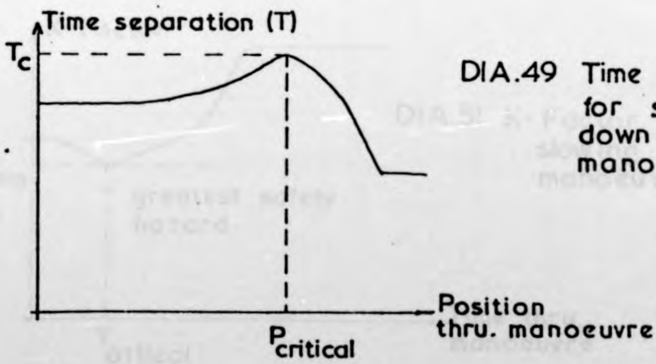
DIA 46 Showing safe and unsafe zones



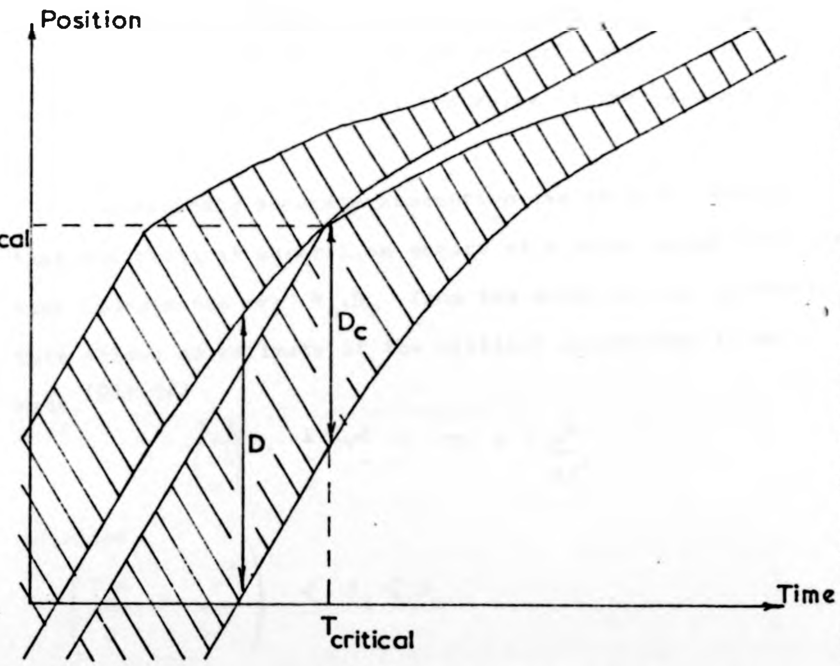
DIA.47 Slowing down manoeuvre



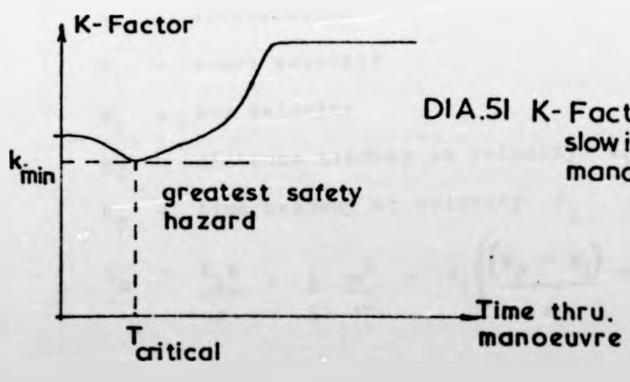
DIA.48 Showing the critical time separation



DIA.49 Time separation for slowing down manoeuvre



DIA.50 Showing the critical spacing separation



DIA.51 K-Factor for slowing down manoeuvre

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

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)

$$T_c = -\left(\frac{V_1}{a}\right) - \frac{1}{a} \quad V_1^2 + 2H_d \, a + \frac{a^4}{3J^2}$$

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

$$S_m - \frac{V_1 a}{J} + \frac{1}{6}\frac{a^3}{J^2} + V_1\left(\frac{(V_2 - V_1)}{a} - \frac{a}{J}\right) + \tfrac{1}{2}\left(a \, \frac{(V_2 - V_1)}{a} - \frac{a}{J}\right)^2$$

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 ver 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.

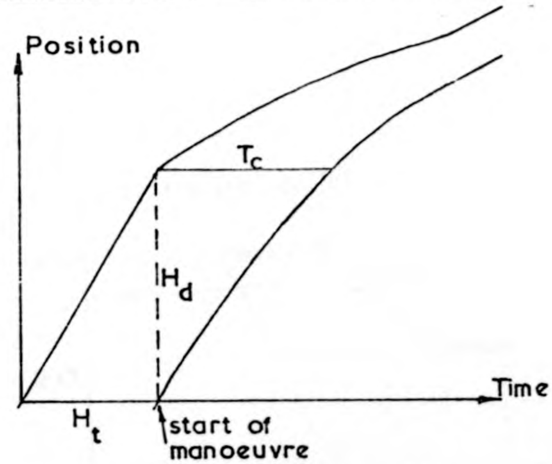
Diagram 53 shows the variation in the capacity of a speed change manoeuvre according to initial speed. (For a final speed satisfying Note i above)

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.

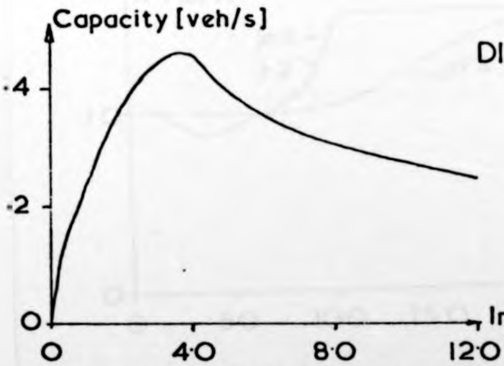
Diagrams 55,56 show the effect of limiting jerk on the time separation and safety factor curves plotted as functions of distance and time respectively.

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)).

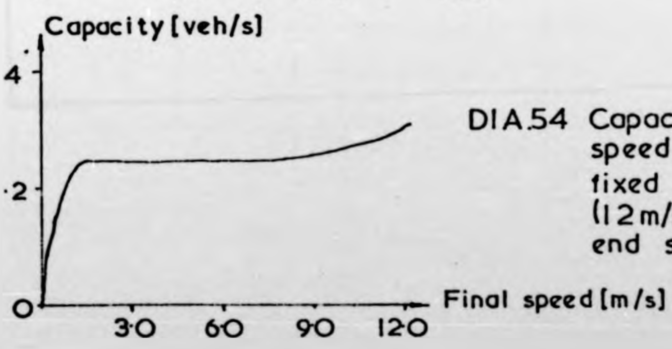
Diagram 58 shows the same curves but for a speed-up manoeuvre from a variable start speed (V_1) to a fixed final speed (V_2).



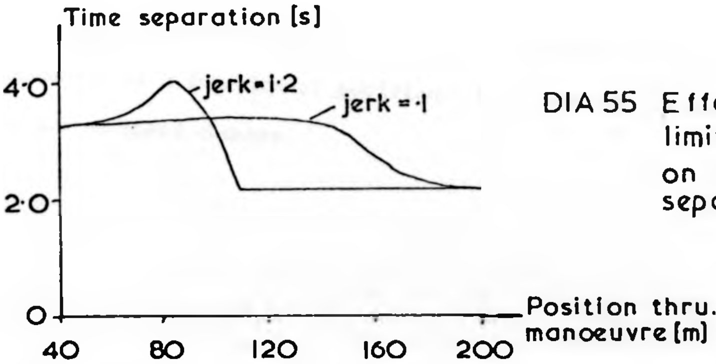
DIA.52 Showing point used to estimate the capacity of a speed change



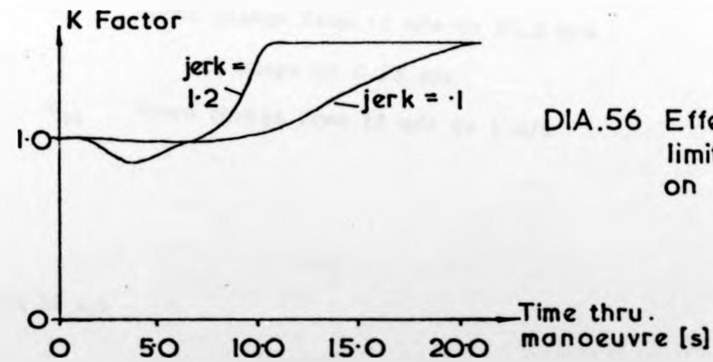
DIA.53 Capacity of a speed change - fixed end speed (4·0 m/s) variable start speed



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

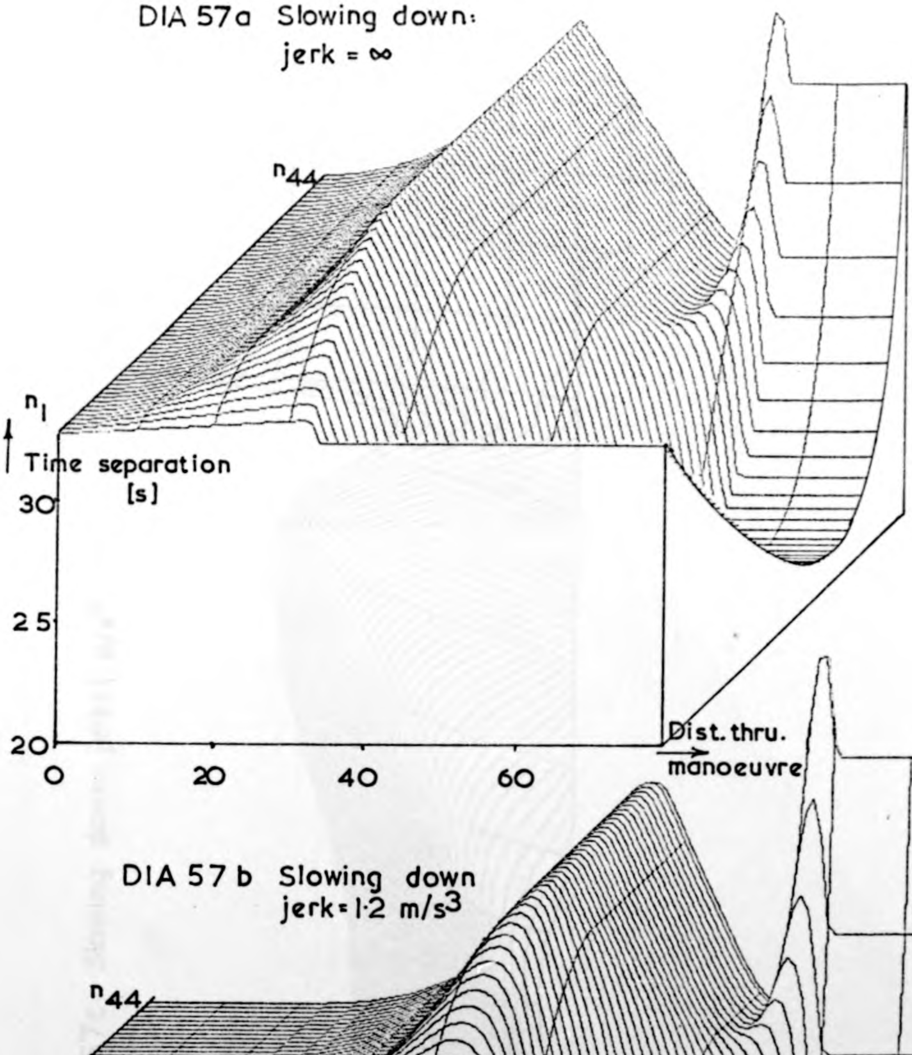
n_{44} Speed change from 12 m/s to 1 m/s

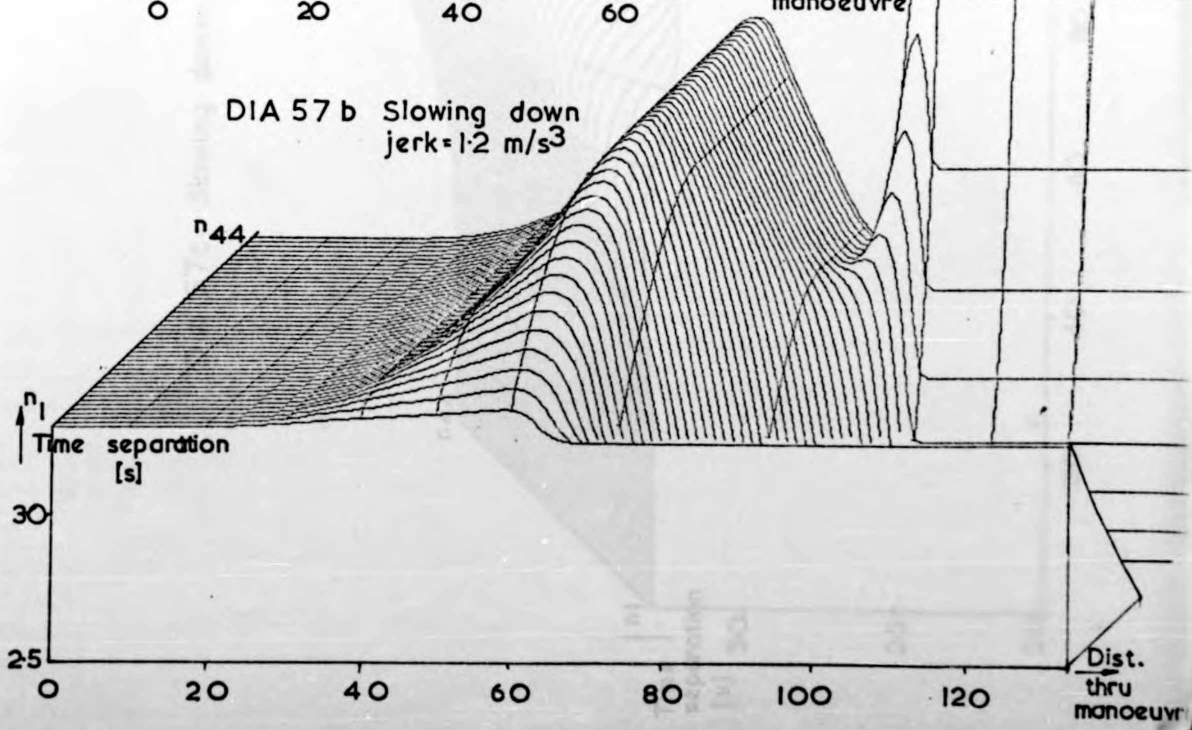
Diagram 58 a,b

n_1 Speed change from 1 m/s to 12 m/s

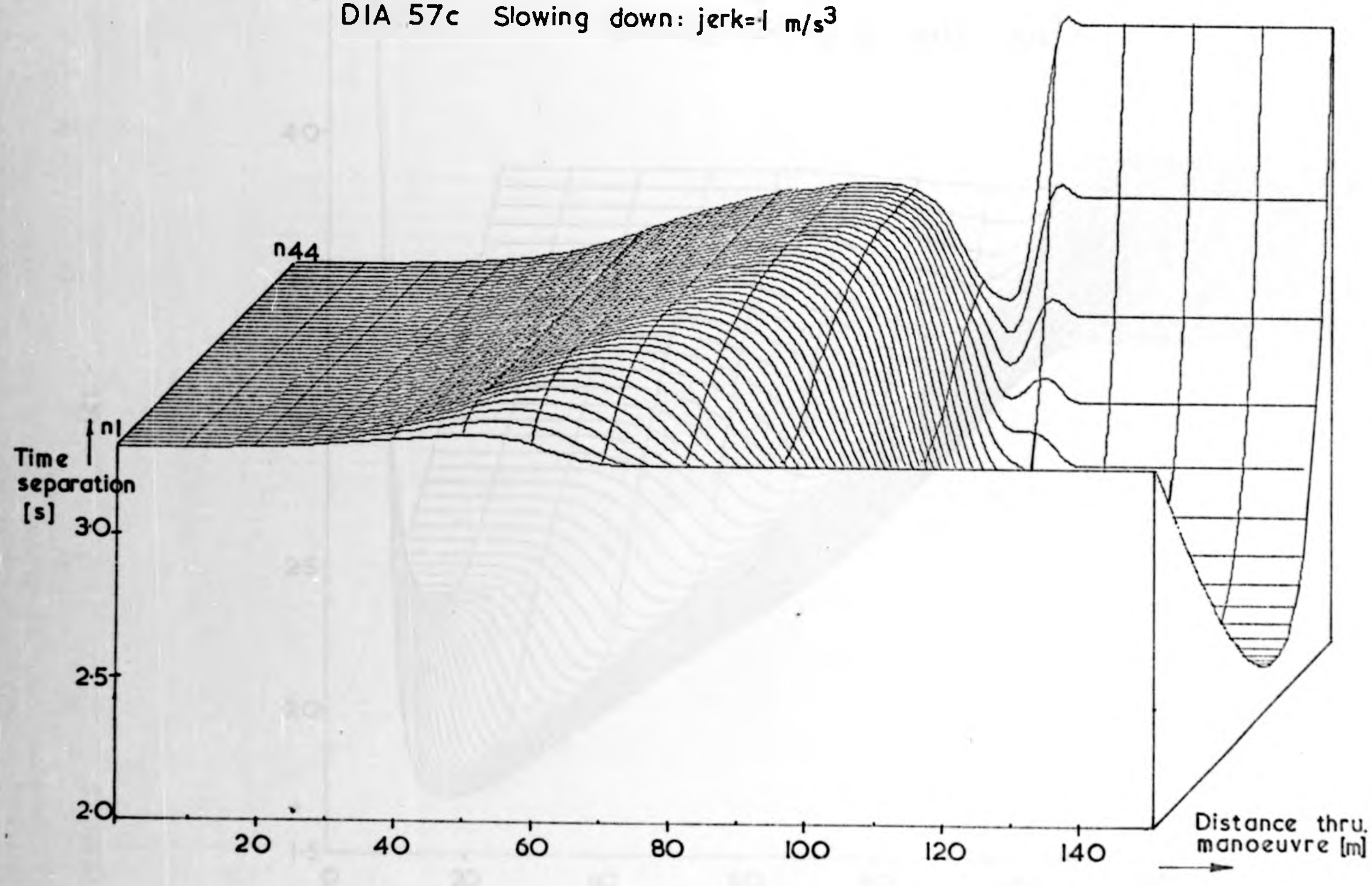
in steps of 0.25 m/s

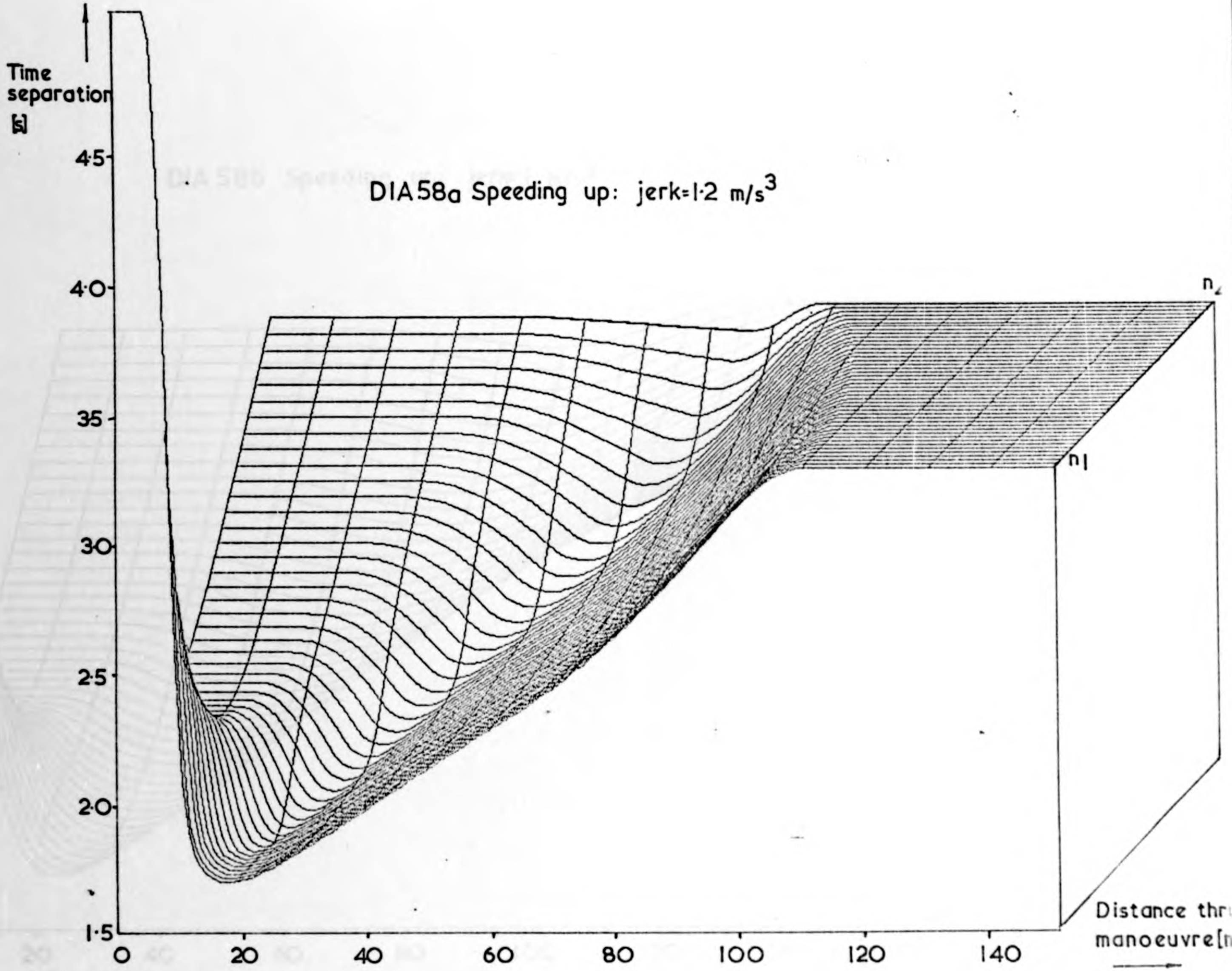
n_{44} Speed change from 11.5 m/s to 12 m/s


DIA 57a Slowing down:
jerk = ∞
n44
n1
Time separation
[s]
30
25
20
0
20
40
60
Dist. thru.
manoeuvre

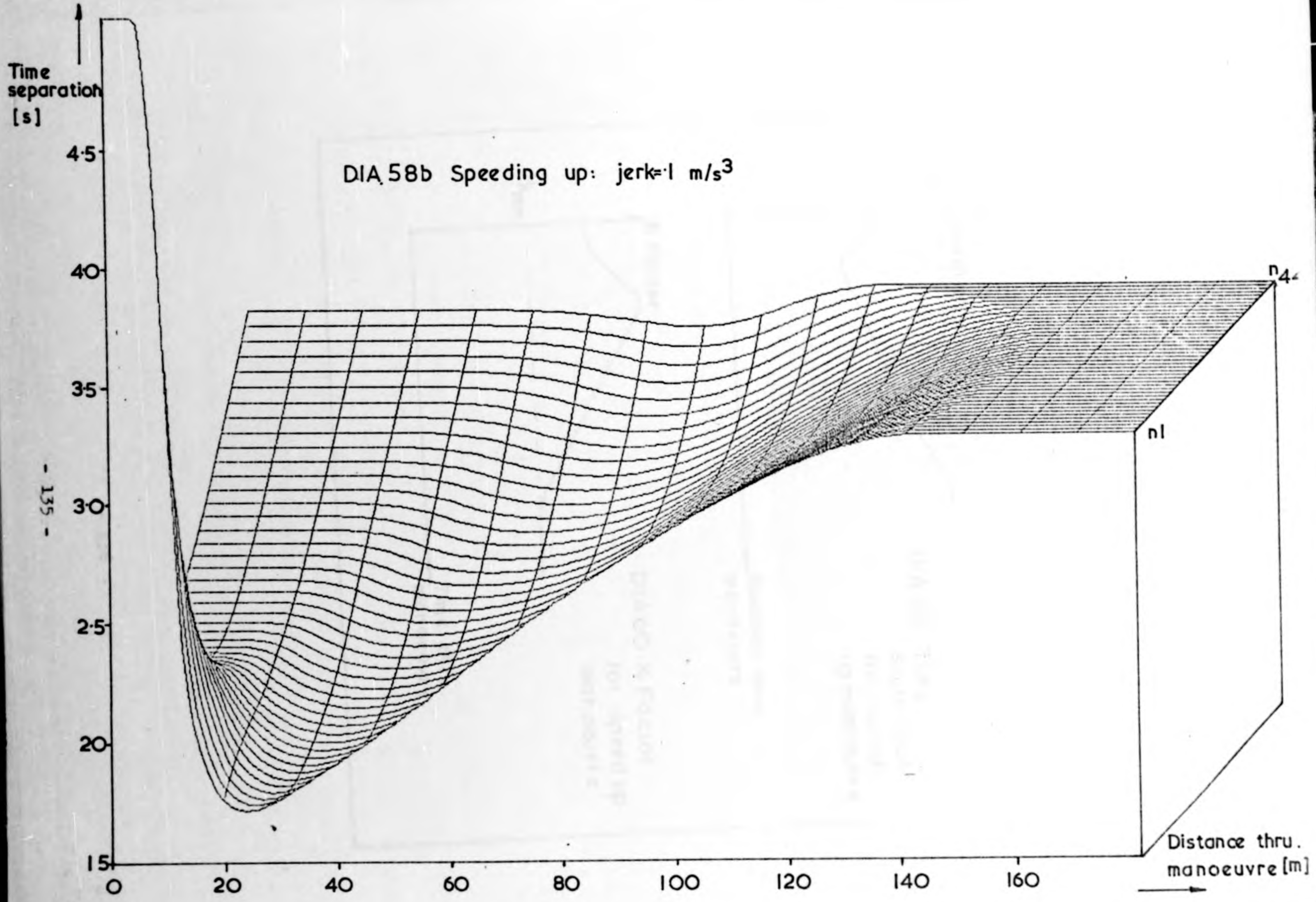

DIA 57 b Slowing down
jerk = 1·2 m/s3
n44
n1
Time separation
[s]
30
2·5
0
20
40
60
80
100
120
Dist.
thru
manoeuvr

DIA 57c Slowing down: jerk=1 m/s^3

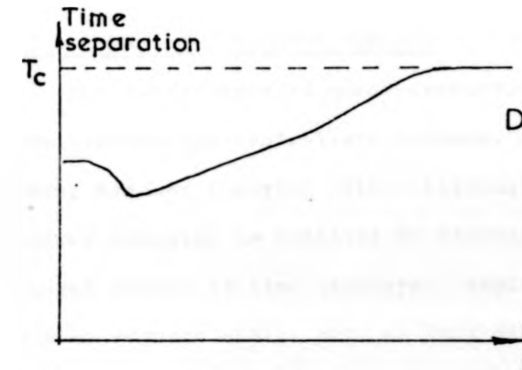




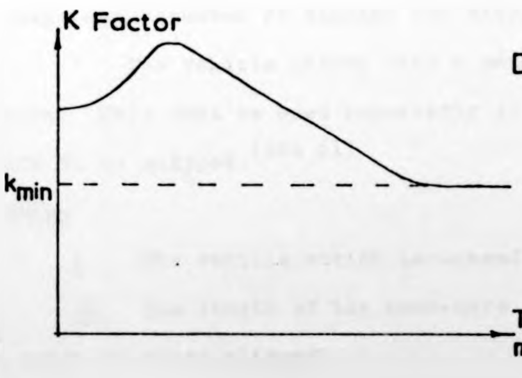
DIA58a Speeding up: jerk=1·2 m/s^3



DIA 58b Speeding up: jerk=·1 m/s³



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

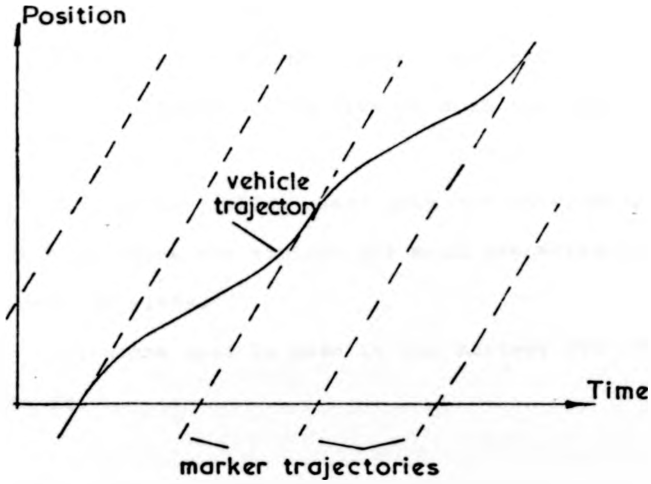
i The vehicle motion is uncomfortable

ii The length of the manoeuvre zone depends on the number of slots slipped

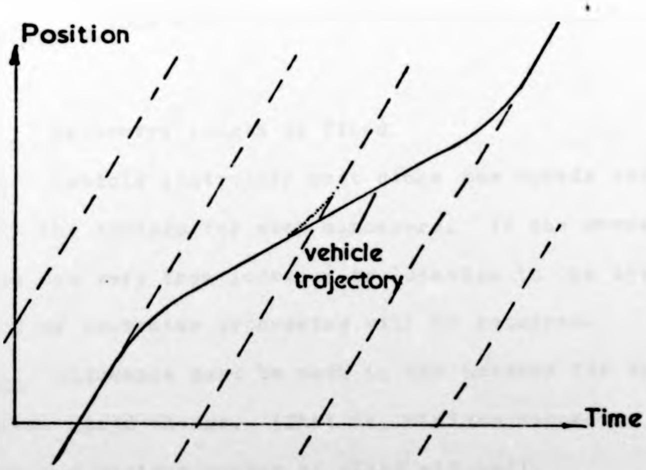
iii Simple vehicle control

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)

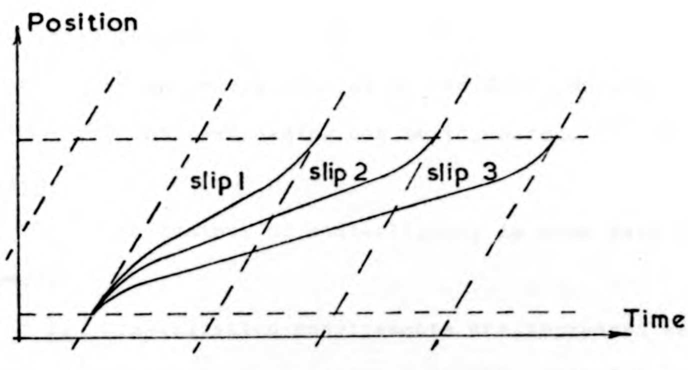
Notes

i   Manoeuvre length is fixed

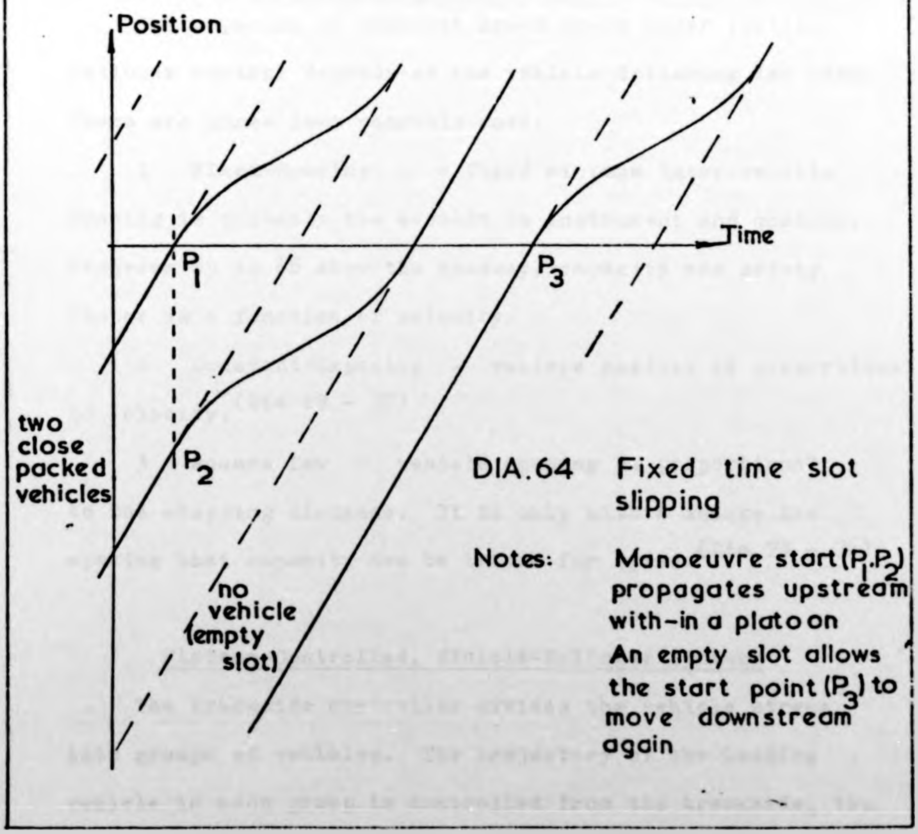
ii   vehicle controller must store the speeds and probably the timings for each manoeuvre. If the manoeuvre distance can vary from location to location in the system, on-board or trackside processing will be required.

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



DIA.63 Slot slipping with fixed manoeuvre zone



DIA.64 Fixed time slot slipping

Notes: Manoeuvre start (P_1.P_2) propagates upstream with-in 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-slipping 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.

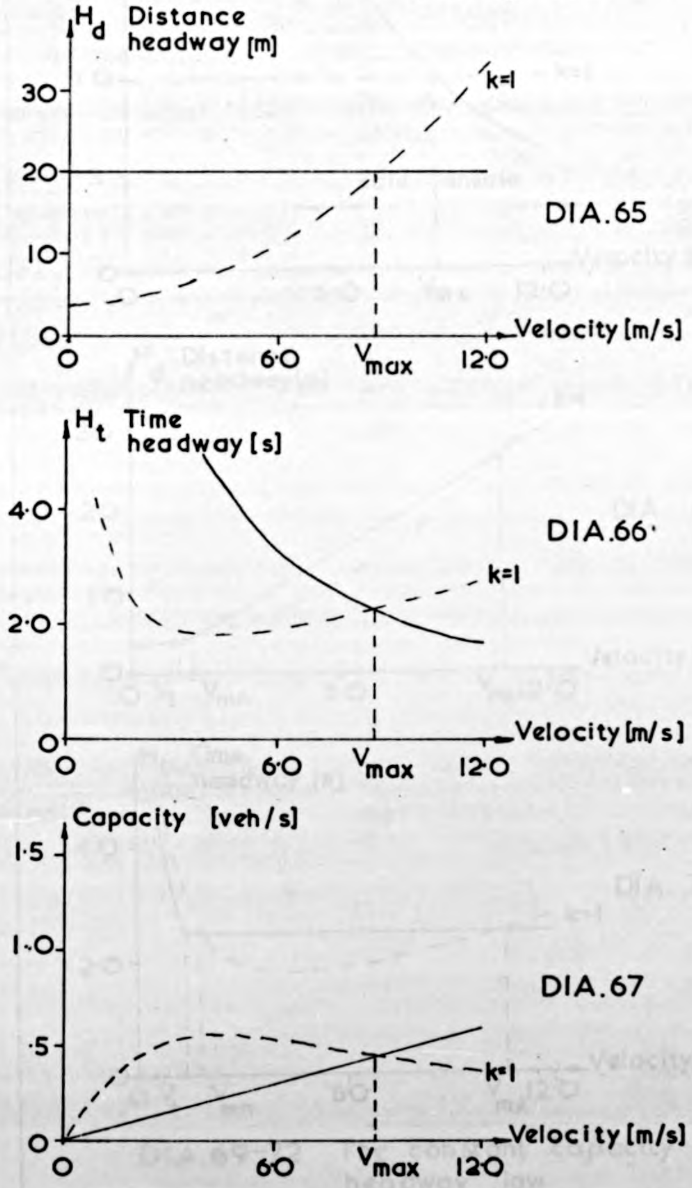
2 Constant-Capacity - vehicle headway is proportional to velocity.(Dia 69 - 72)

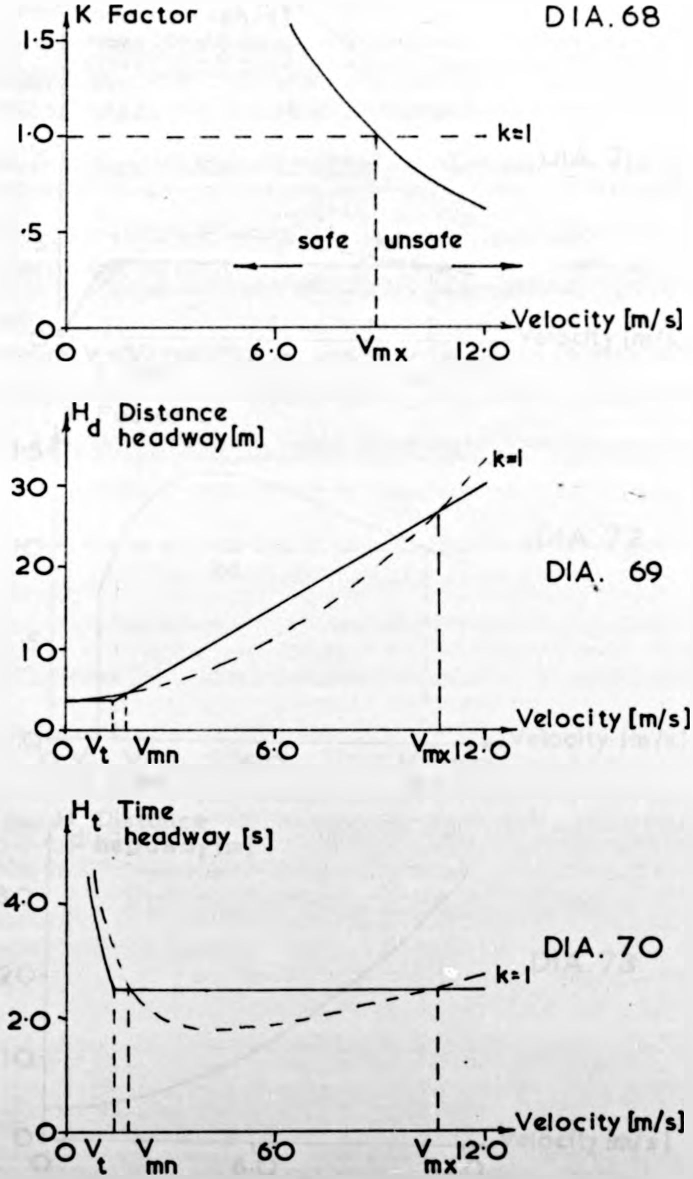
3 Square Law - vehicle spacing is proportional to the stopping distance. It is only with a square law spacing that capacity can be traded for speed.(Dia 73 - 76)

Platoon-Controlled, Vehicle-Follower Systems

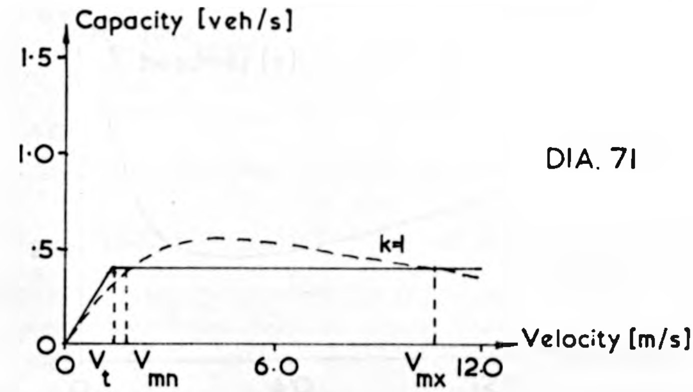
- The trackside controller divides the vehicle stream into groups of vehicles. The trajectory of the leading vehicle in each group is controlled from the trackside, the

DIAS. 65-68 The fixed spacing headway law

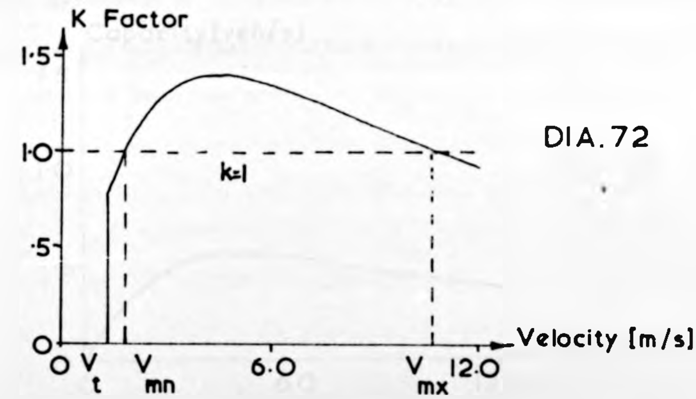




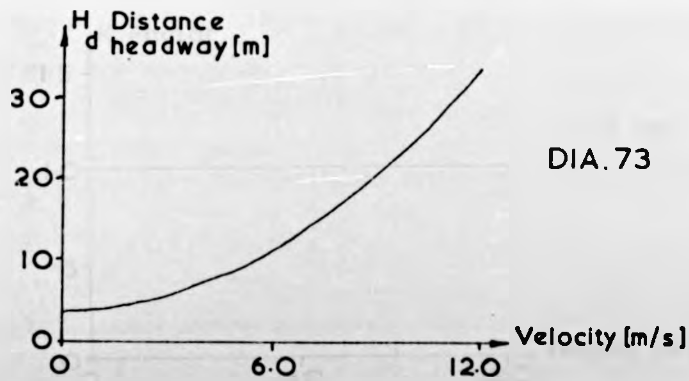
DIA.69–72 The constant capacity headway law
(V_t vehicles touch V_{mn} lowest safe speed)
(V_{mx} highest safe speed)



DIA. 71

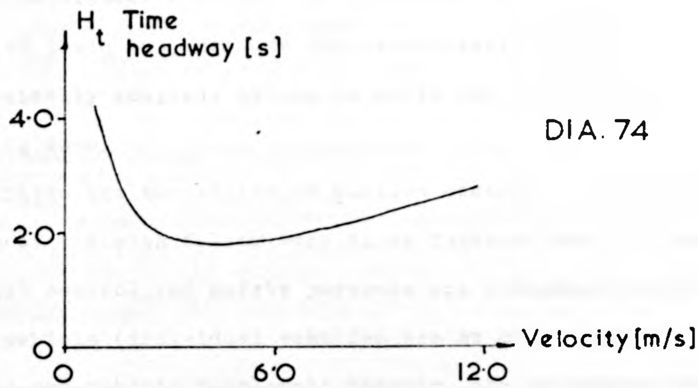


DIA. 72

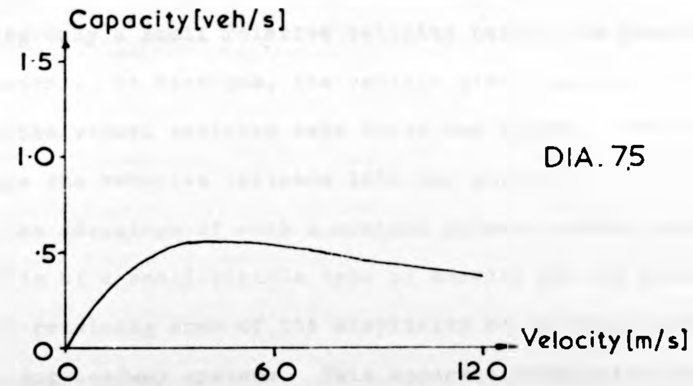


DIA. 73

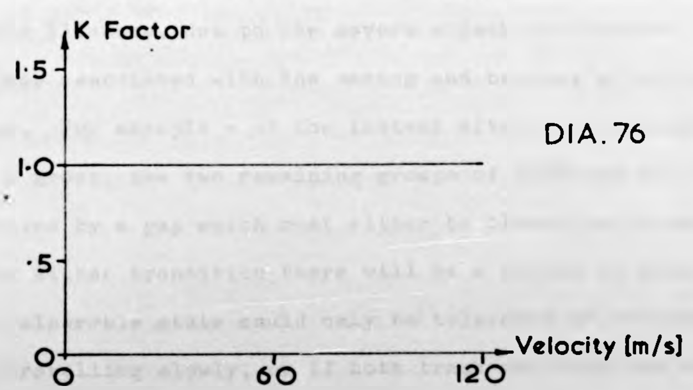
DIAS. 73–76 The stopping distance headway law



DIA. 74



DIA. 7.5



DIA. 76

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 probabalistic 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.

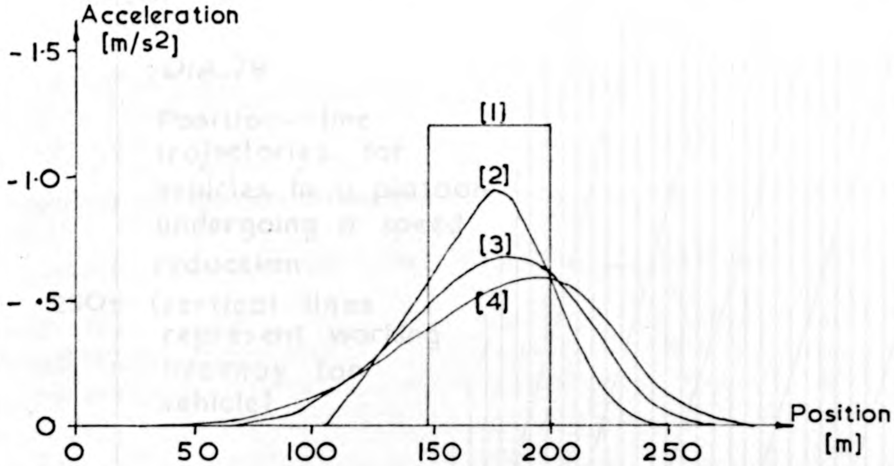
Notwithstanding the difficulties, two organisations have proposed using this form of control, FLYDA, and MATRA in their ARAMIS system. MATRA built a test track but it seems likely that they have now abandoned the enterprise.

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)

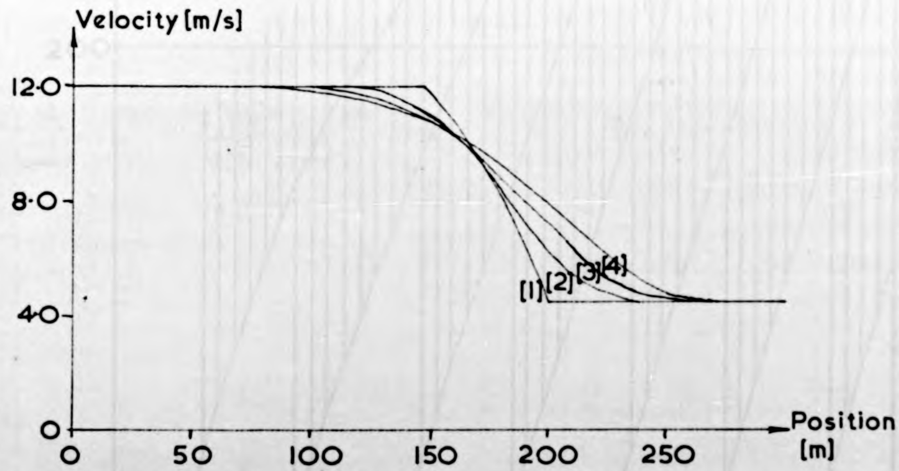
Consequently to change the speed of a platoon takes a long time and requires a considerable distance.

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.

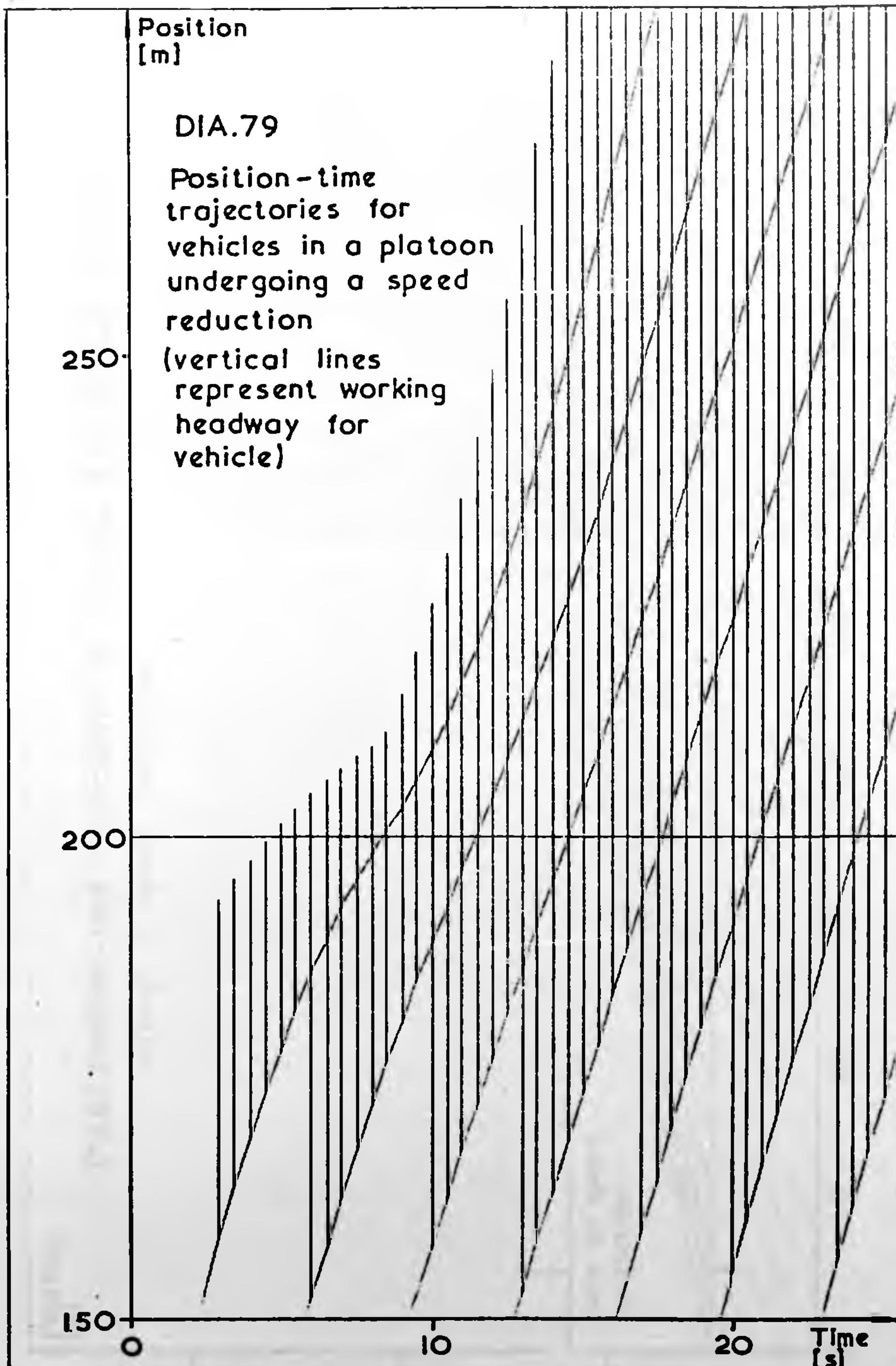
All vehicles in a platoon passing through a speed restriction and then returning to normal line speed experience the same delay as the front vehicle. However, the front vehicle must commence its manoeuvre some distance before the restriction in order that the last vehicle in the platoon

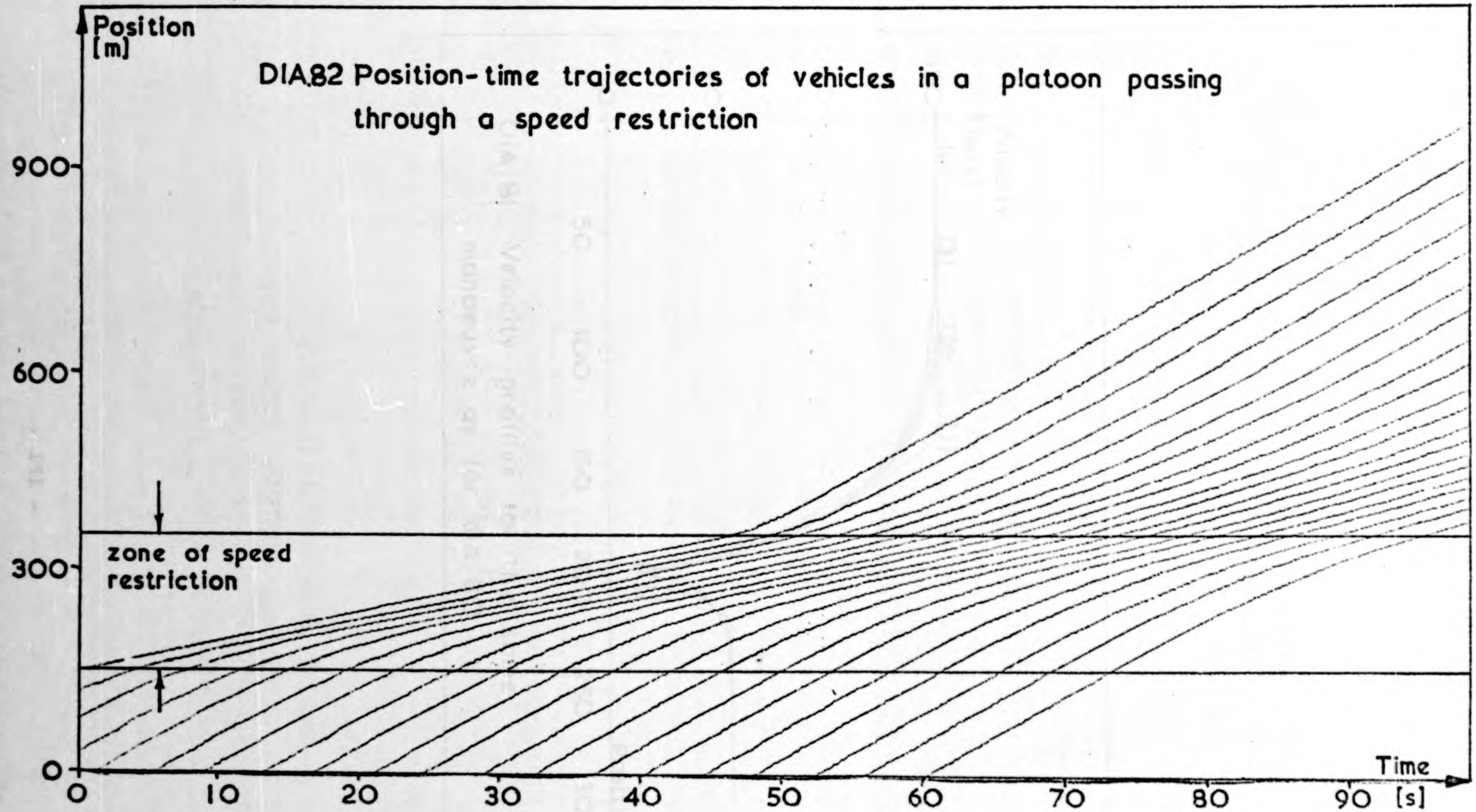


DIA.77 Acceleration profiles of vehicles in a platoon subject to a speed reduction
[1] etc. is position of vehicle in group
(1 is front)

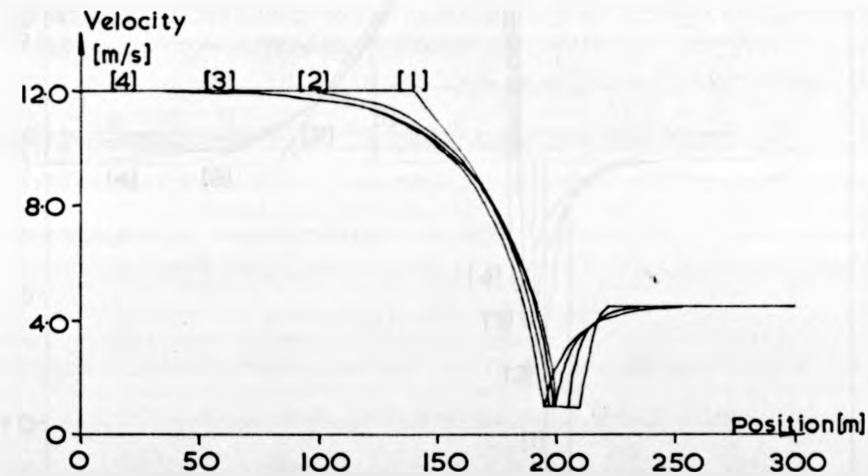


DIA.78 Velocity profiles for the same manoeuvre as for dia.77

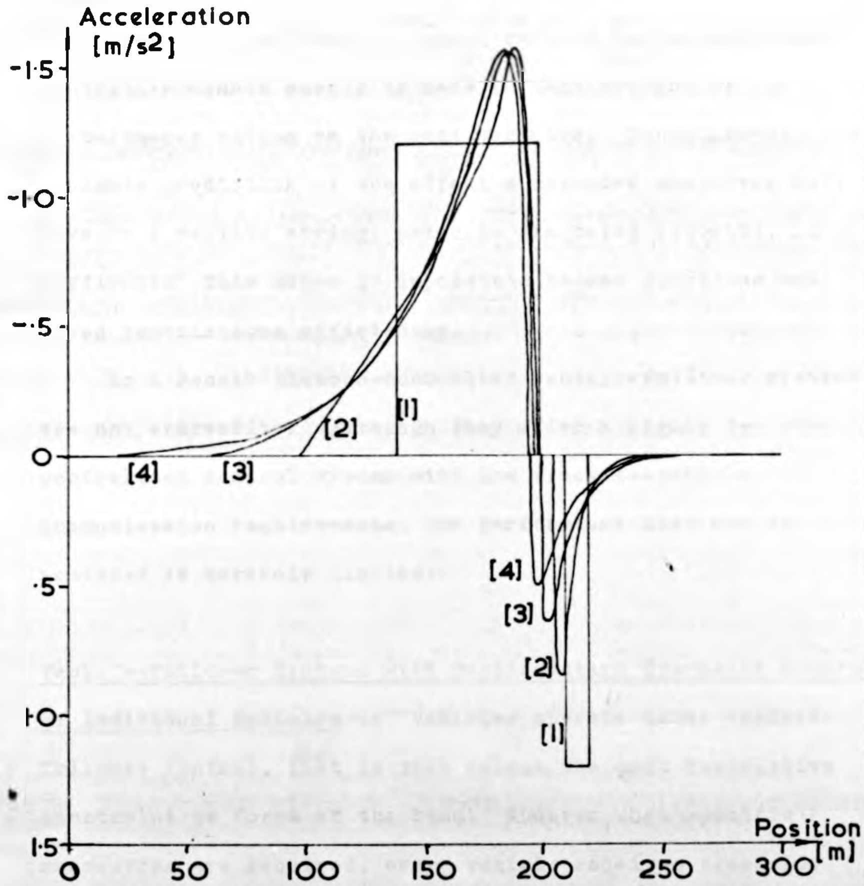

Position
[m]
DIA.79
Position-time trajectories for vehicles in a platoon undergoing a speed reduction
(vertical lines represent working headway for vehicle)
250
200
150
0
10
20
Time
[s]



DIA.82 Position-time trajectories of vehicles in a platoon passing through a speed restriction



DIA. 81 Velocity profiles for the same manoeuvre as for dia. 80



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.

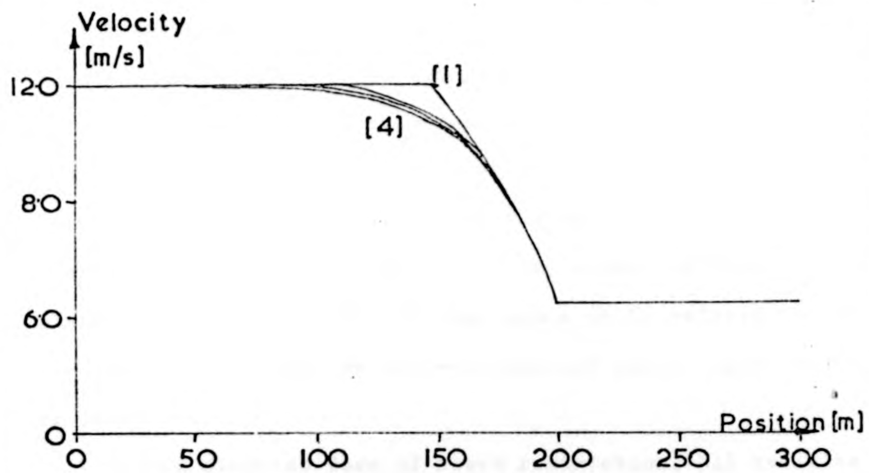
<u>Vehicle-Follower Systems with Supplementary Trackside Control of Individual Vehicles</u> - Vehicles operate under vehicle-follower control, that is they select the most restrictive constraint in force at the time. However when specific manoeuvres are required, every vehicle receives trackside control 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.

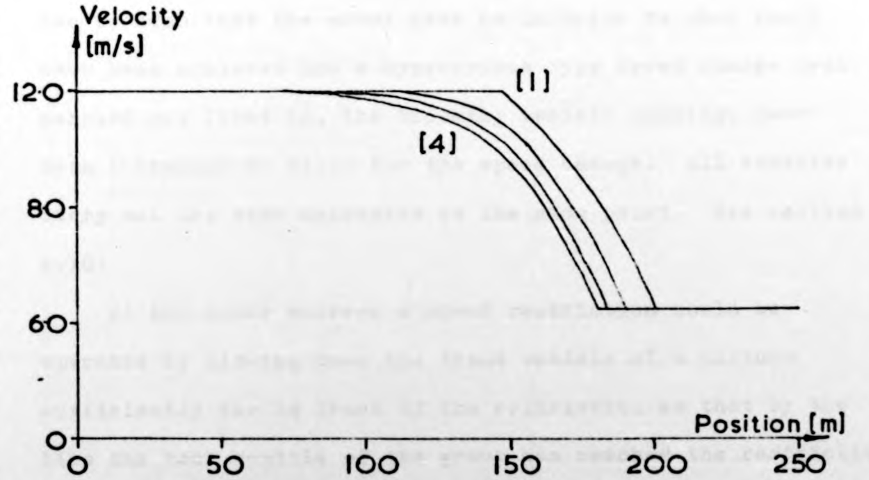
For a speed restriction, vehicles are required to be travelling at a set low speed after a certain point on the track has been passed. The front vehicle of a platoon can be commanded to follow the appropriate trapezoidal profile. Simultaneously the remaining vehicles in the platoon start to slow down 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.(Dia 63) 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



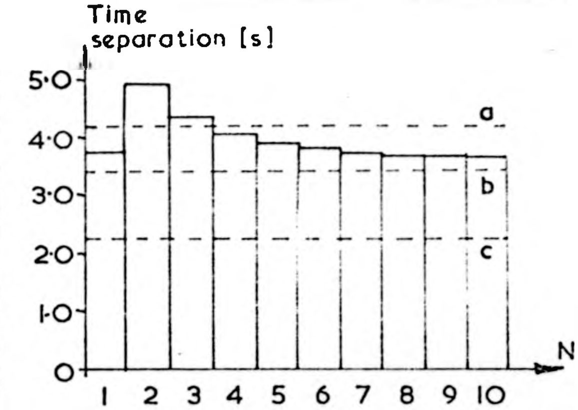
DIA.84 Velocity profiles of a platoon of vehicles passing through a simple speed restriction

of the speed restriction, slower vehicles will consequently be delayed by more than is necessary.(Dia 84)

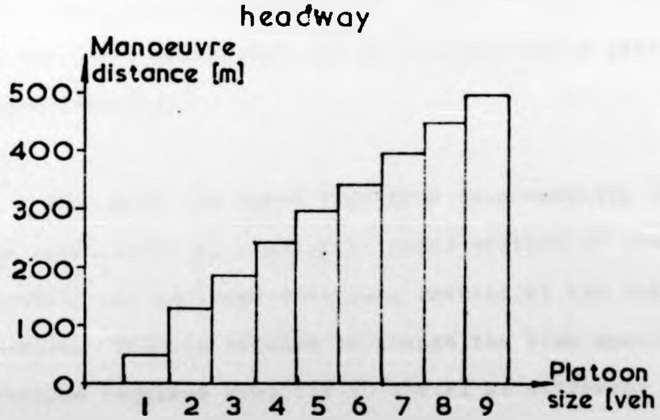
When a vehicle switches from a vehicle-follower trajectory to the trapezoidal trajectory the enforced slowing down introduces gaps into the vehicle platoon, that is, the platoon spreads out. The extent of this platoon elongation is of interest since it is related to the capacity that can be achieved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



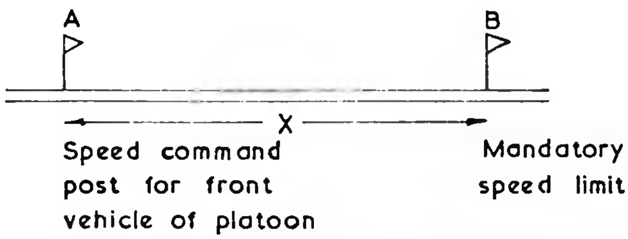
DIA.85 Time spacing between vehicles of a platoon after passing through a simple speed reduction from 12 to 4·5 m/s
N is the time separation between the n-1 and the n-th vehicle
a – is the synchronous headway appropriate to the speed change
b – is the high-speed, close-packed headway
c – is the low-speed, close-packed headway



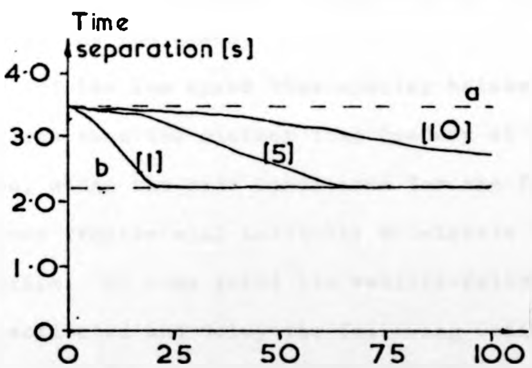
DIA 86 Manoeuvre distance as a function of platoon size for a speed change from 12 to 4·5 [m/s]

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 what ever 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).



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.

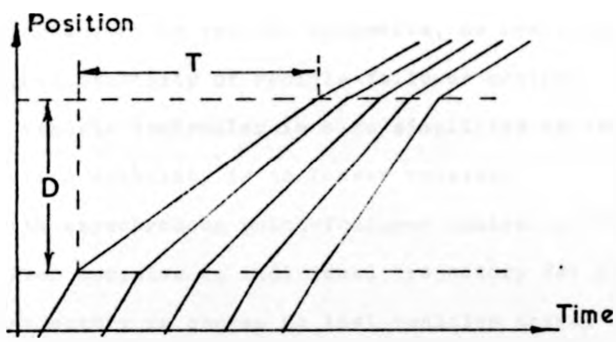
If the low speed time-spacing between the two vehicles is less than the minimum time headway at the higher speed then, under the same conditions for the front vehicle, the second vehicle will initially accelerate on a trapezoidal profile. At some point its vehicle-following control will be activated 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

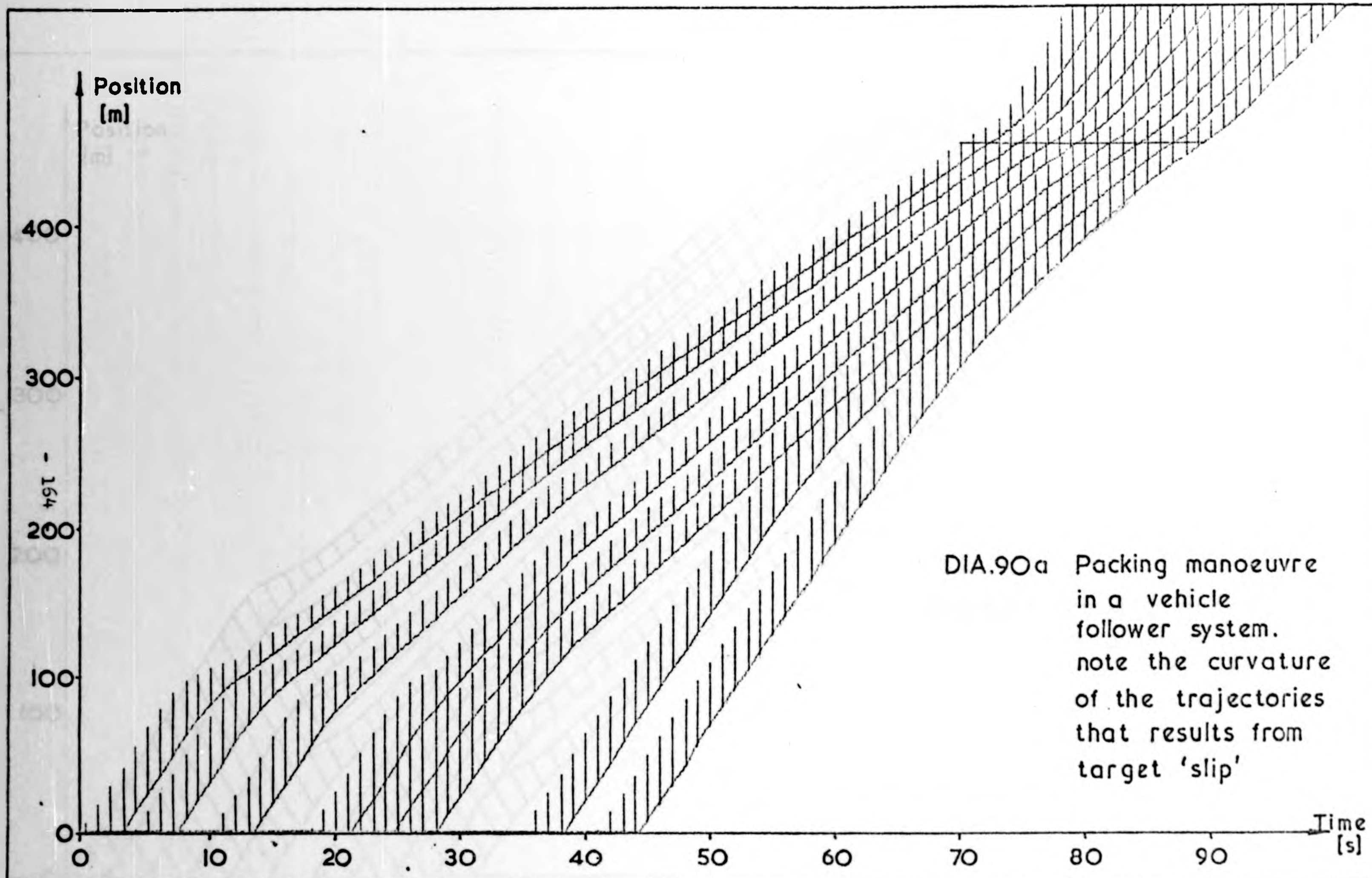
on junction control refer to Chapter 6). Diagram 9d shows the position-time curves of vehicles in a packing manoeuvre.

<u>Asynchronous Point-Follower Control</u> - 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.

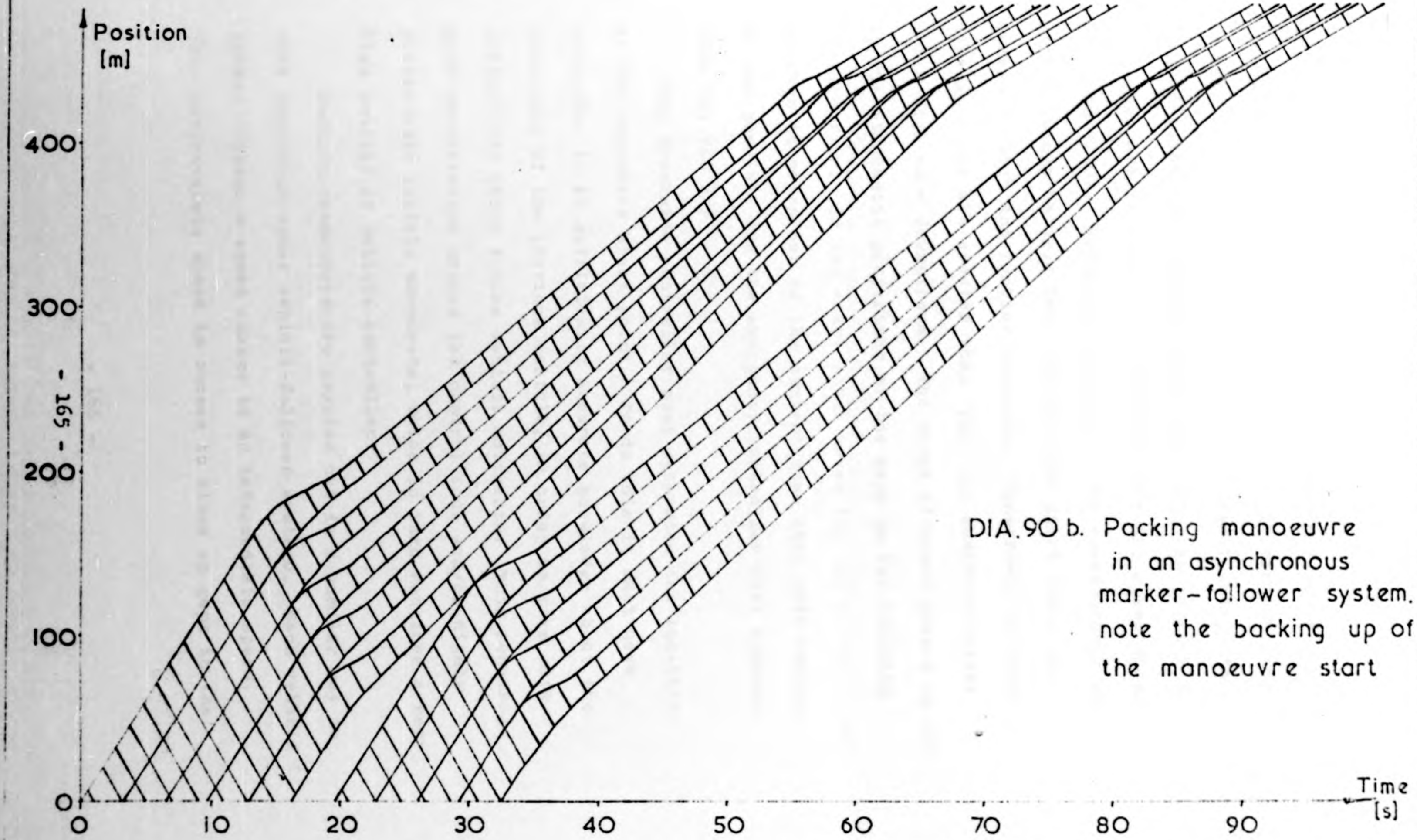
With asynchronous point-follower control a trackside controller computes an individual trajectory for each vehicle. This trajectory is chosen so that vehicles travel as close-packed as safety criteria allow. Thus unlike vehicle-follower systems, in which the vehicle-follower controller ensures the safe 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



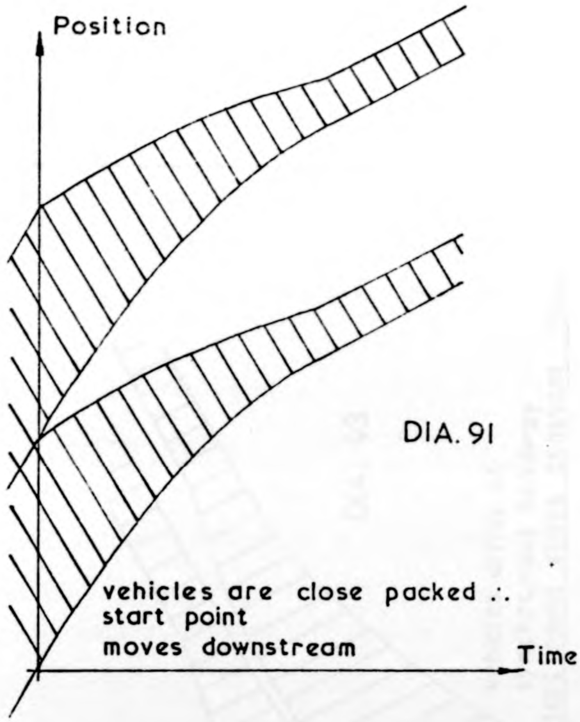
DIA.90a Packing manoeuvre in a vehicle follower system. note the curvature of the trajectories that results from target 'slip'



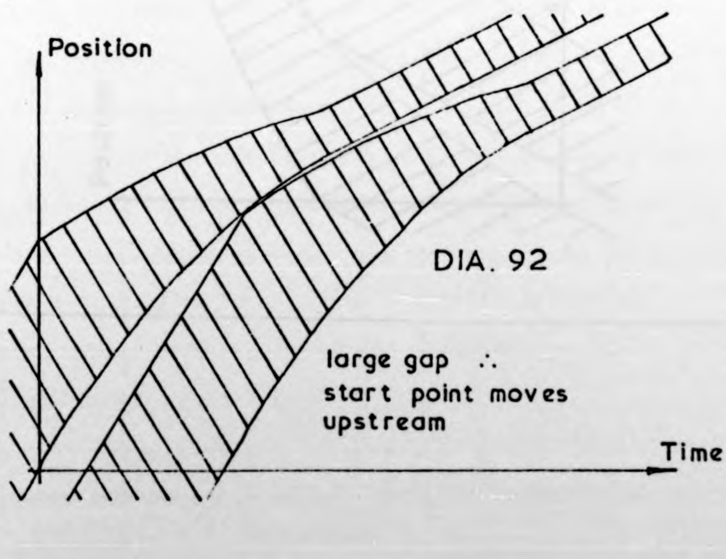
DIA. 90 b. Packing manoeuvre in an asynchronous marker-follower system. note the backing up of the manoeuvre start spacings of importance; the minimum time spacing of vehicles travelling at constant speed Tmin, and the minimum time spacing (Tsp) required for vehicles to travel safely through a fixed point speed change manoeuvre. Tsp is greater than Tmin because it includes a component for the speed change (Section 4.10). Vehicles arriving at the speed-change zone with spacings between Tmin and Tsp will start their manoeuvre further and further upstream. Conversely if their time spacings are greater than Tsp 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.

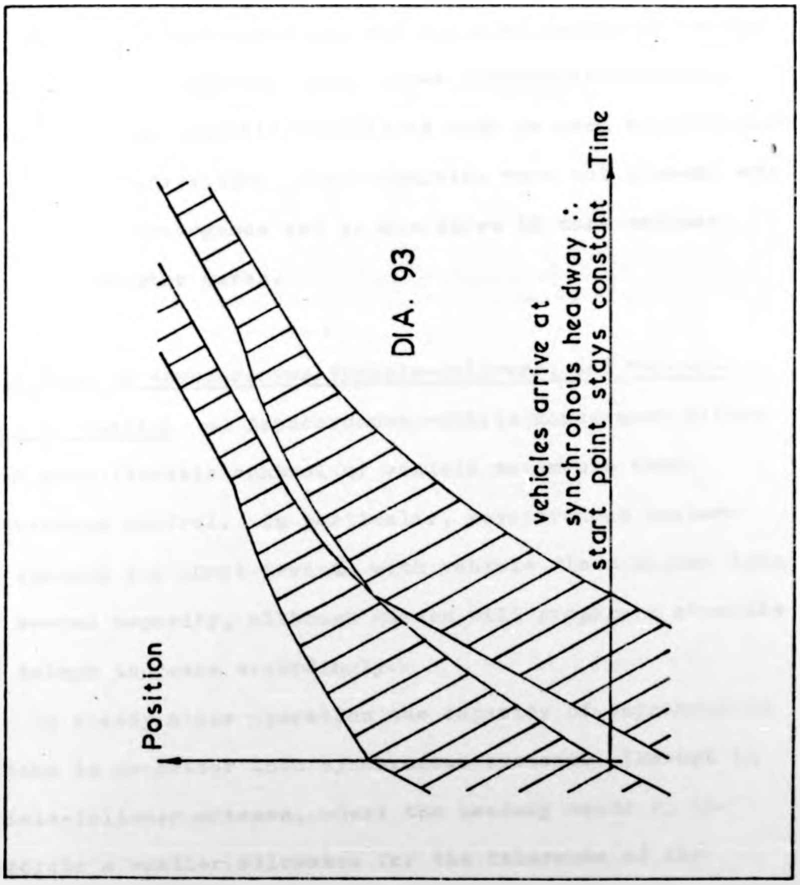
Packing manoeuvres are carried out in a similar way to that described under vehicle-follower systems. Each vehicle passes through a speed change to an intermediate speed. This intermediate speed is chosen to close up gaps in the

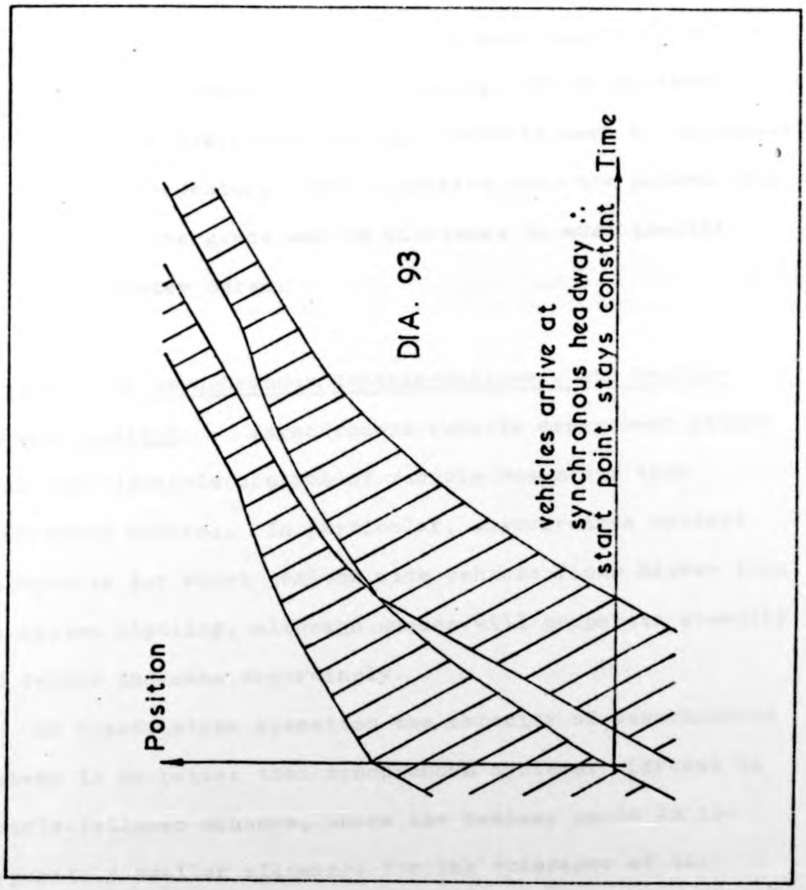

Position
vehicles are close packed ∴
start point
moves downstream
Time

DIA. 91


Position
large gap ∴
start point moves
upstream
Time

DIA. 92


Position
Time
DIA. 93
vehicles arrive at
synchronous headway ∴
start point stays constant


Position
Time
vehicles arrive at
synchronous headway ∴
start point stays constant

DIA. 93

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 90b)

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 amuch 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

$$M(t)\,\frac{dv}{dt} = -\,Fa(V,Vw) + F - Fr(v) - M(t)g\sin\theta - B$$

where

M(t) - mass of the vehicle which varies according to passenger loading

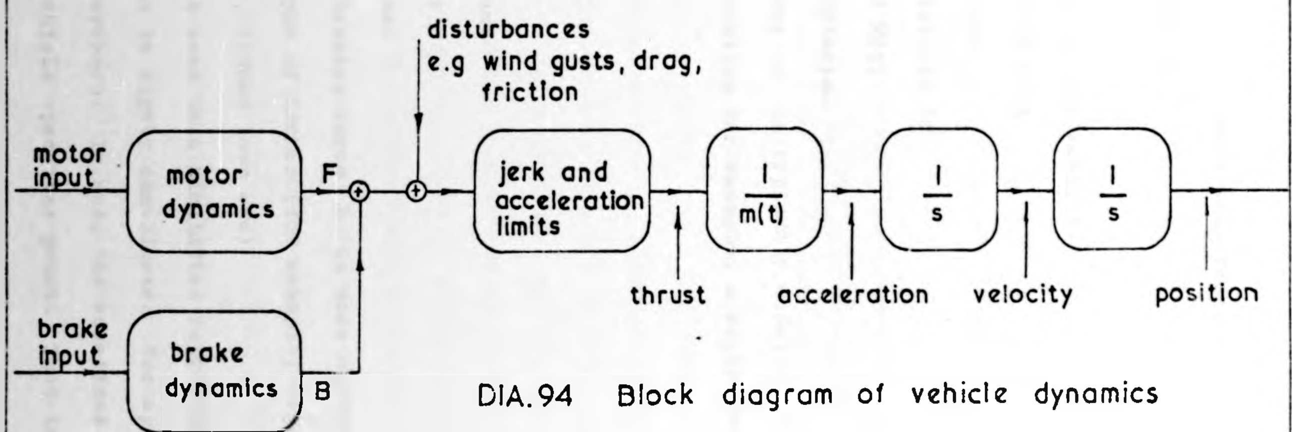
V - vehicle velocity

Vw - wind velocity (relative to the track)

F - propulsion force

θ - gradient of the track

B - braking force



DIA. 94 Block diagram of vehicle dynamics

Fa - aerodynamic drag force

Fr - rolling resistance

an approximation to the aerodynamic drag force is given by

$$Fa \doteq \tfrac{1}{2}\, pA\, Cd\, (V - Vw)^2$$

where

A - frontal area of the vehicle

Cd - coefficient of drag

p - density of air

and to the rolling resistance is

$$Fr \doteq (Cs + CrV)\, M(t)$$

where Cs and Cr 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

τ - 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, 56 - 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[55] 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.

1 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.[66] 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 Gourisnankar.[45] The latter proposes the use of jerk as a controlled variable and includes a $(jerk)^2$ 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[46] 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[48,49] and Hetrakul and Fortman.[47] They use modal control techniques to produce a controller requiring fewer communication 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 revue of early work is contained in Tabak.[65]

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[55] 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[59] 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.

3 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[38] has shown that string stability is ensured provided

$$G(jw) = \left| \frac{V_2(jw)}{V_1(jw)} \right| \leqslant 1 \quad \text{for all } w$$

where

$V_1(t)$ = velocity of front vehicle

$V_2(t)$ = 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.

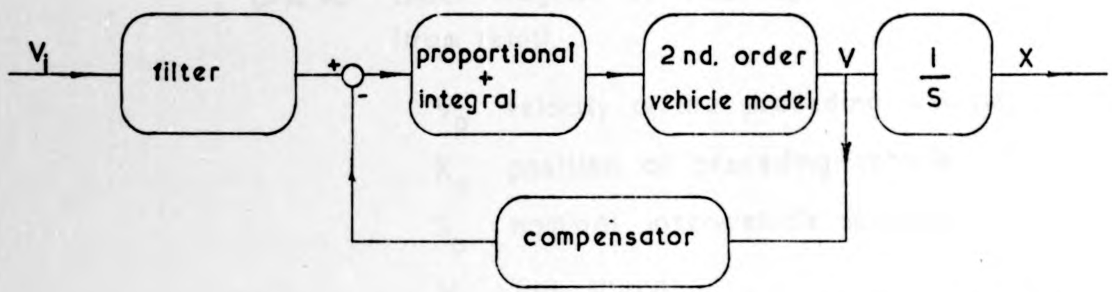
Secondly vehicle-follower controllers must be designed for two modes of operation, namely, for velocity control when the vehicle is travelling along open track and for headway regulation when the vehicle is following another vehicle at minimum headway. The transition between the two modes is usually 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 CABINENTAXI.[37] 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.

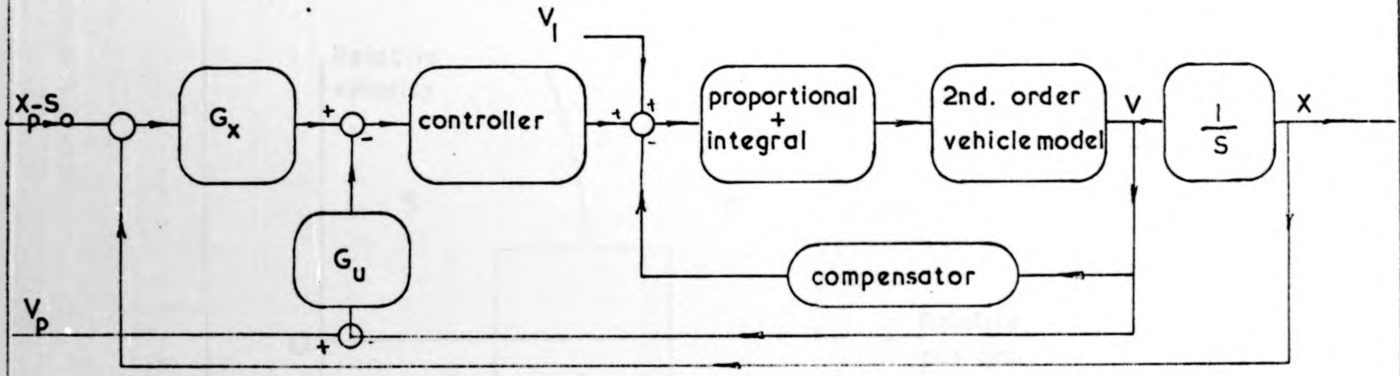
Hinmann and Pitts[67] describe a control scheme based on a fixed block technique for measuring vehicle spacing. They describe initially a simple logic scheme for extracting the spacing information from the received signal aspect. The measurement is sampled data, the sampling rate depends on the speed 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).[30]

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)



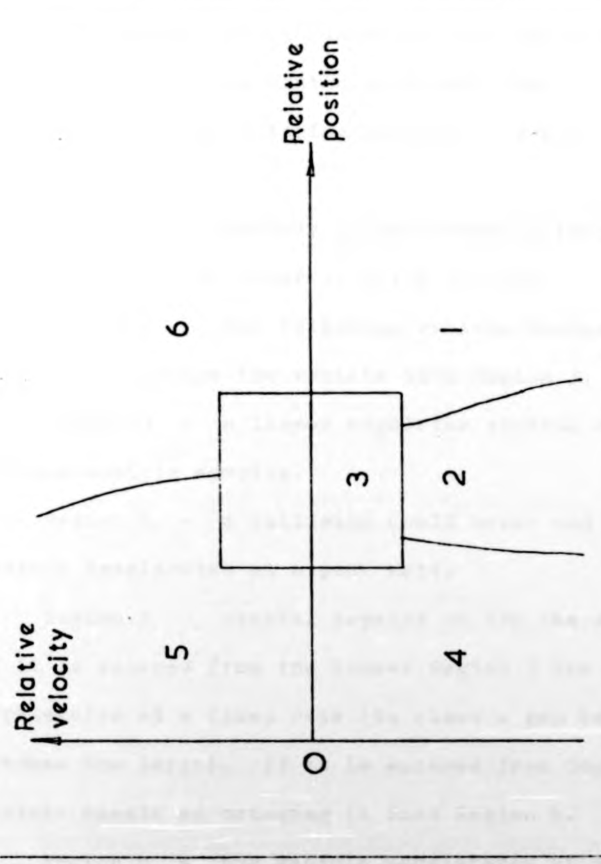
DIA.96 Block diagram of headway controller (from ref.61)

V_p velocity of the preceding vehicle

X_p position of preceding vehicle

S_o nominal inter-vehicle spacing

V_l line speed



DIA.97 Areas of phase plane (from ref.63)

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.(Dia 97) 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 degredation 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.

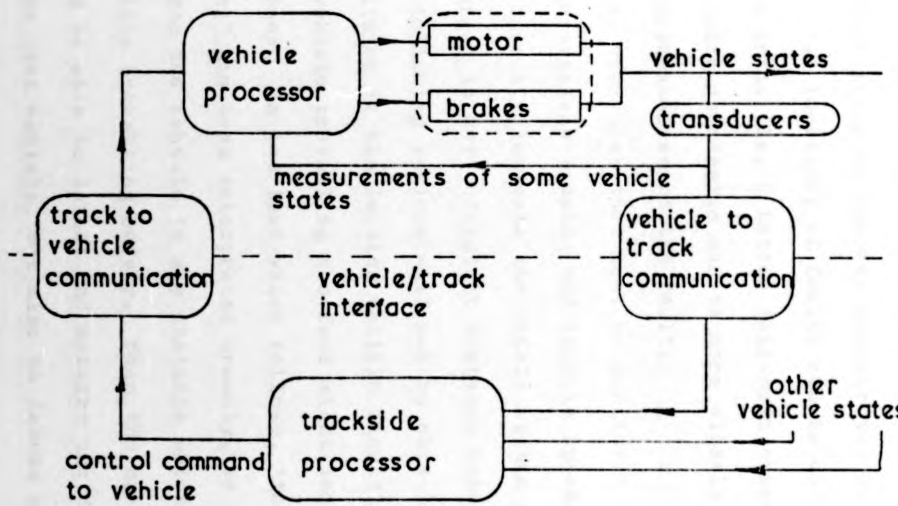
Reliability - If unsafe situations are to be avoided, the availability of the safety backup system must be sufficiently high for there to be a negligible probability of the normal and the backup system jointly failing. This can only be ensured if:-

* 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 excercised 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]

<u>Monitors</u> - 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, 'inter-vehicle 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.(10 - 12) 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 $^1/$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 then 5 - 6 seconds.

The choice of block-size is discussed at length by Pitts(12). Pitts (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.

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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[5] 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).

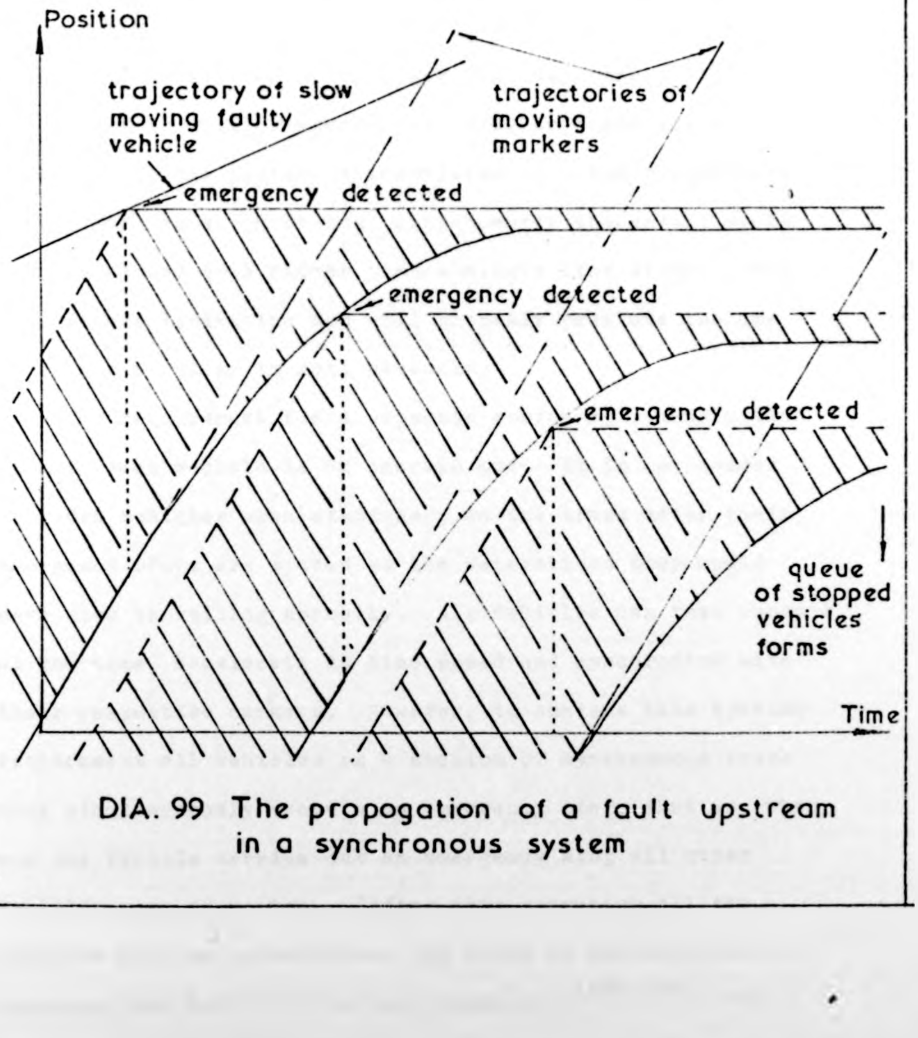
Restart of a vehicle-follower system is relatively simple. Once the faulty vehicle has been removed from the main-line the queue of vehicles can be released to continue their journey and no further trackside control is necessary.

Asynchronous point-follower schemes are more complex to control. Following the failure of one vehicle, the track-side 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.(Dia 99) 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.

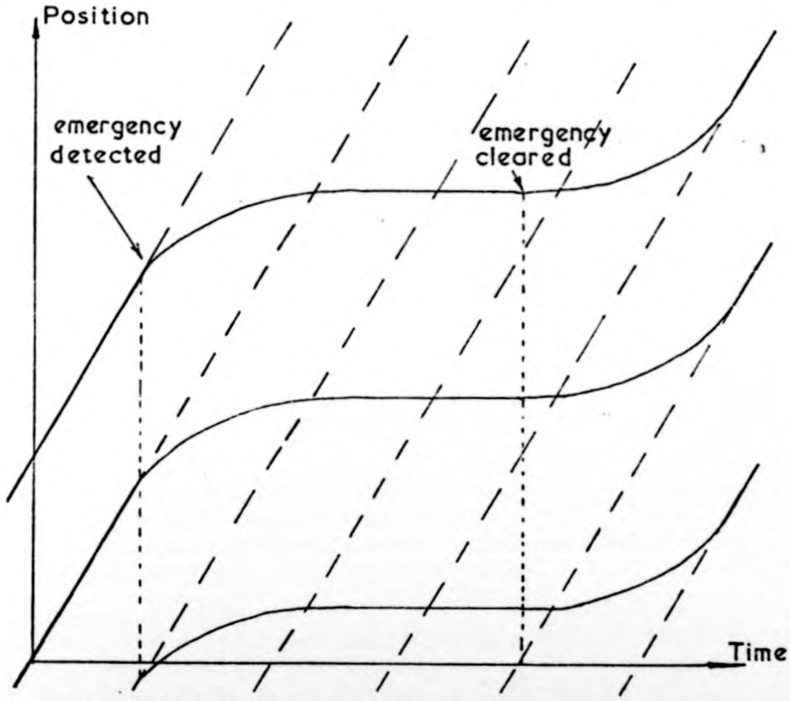
Some vehicles in the stopped queue will be close to the junction at the end of the link. These vehicles will not have synchronised with their markers before reaching the junction and must therefore continue straight on (even if this is not their intended route). Vehicles intending to merge into the faulty link probably will also have to be restricted.



DIA. 99 The propogation 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 from 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). (Dia 100) 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 Manoeuvres - 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 cross-overs 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.

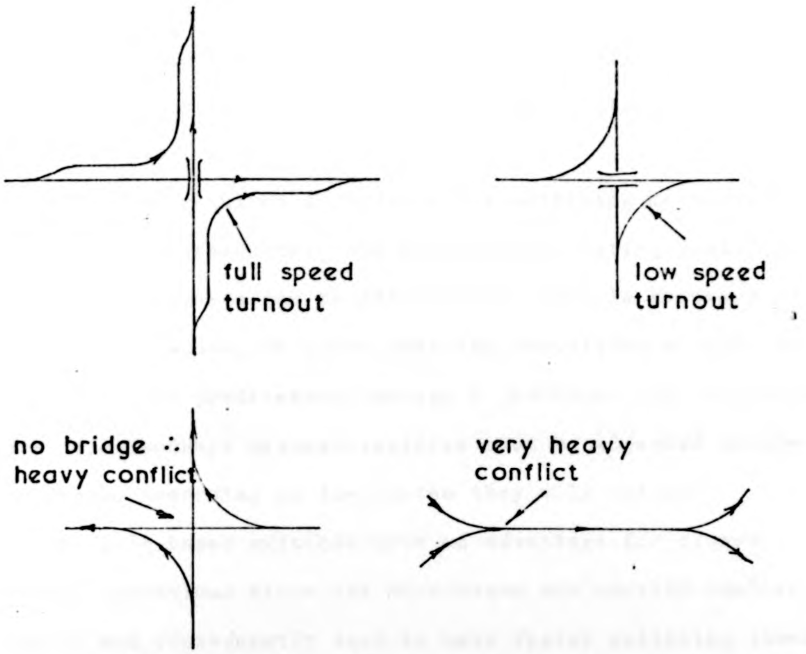
Proposers of automated transport schemes are usually more concerned with the simpler junctions between two uni-directional traffic streams, in which any crossovers are replaced with bridges.(Dia 101)

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



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.

<u>Intersections</u> - 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.

6.4 Quasi-Synchronous Control of Junctions

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. (Dia 102) This abort lane must reconnect with the main line at a point further downstream. If the abort lane is operated synchronously with the main line there is no guarantee that an unresolvable conflict will not arise again at the second merge although the probability of this happening will be very low. Only 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.[3] 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.

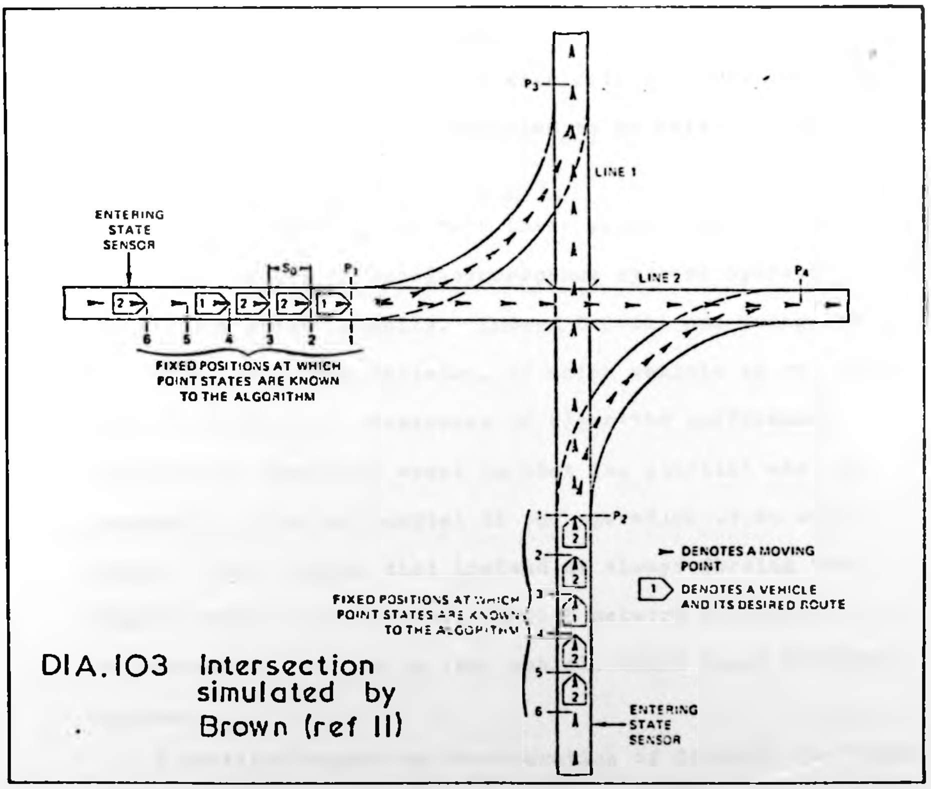
6 First-come first-served with simultaneous arrivals resolved by giving priority to the lane not served last.

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 procedes 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



DIA.103 Intersection simulated by Brown (ref 11)

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 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

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

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.

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

$$\text{Occ} = \frac{n\, H_t\, (v)}{T}$$

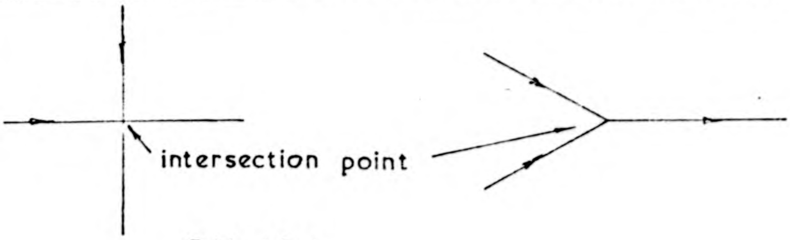
$$\text{Occ} = F\, H_t\, (v)$$

where the mean flow rate is

$$F = \frac{n}{T}$$

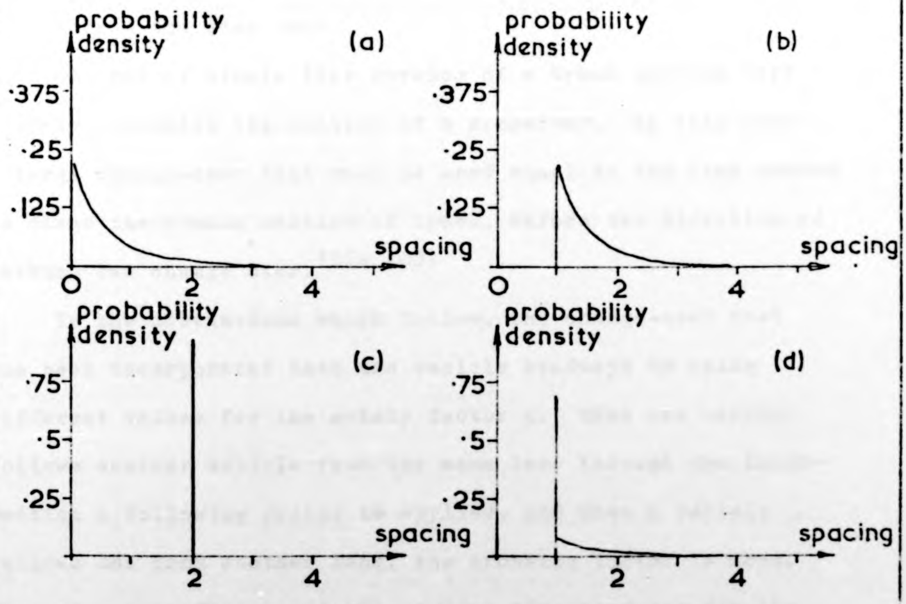
n - number of vehicles passing in time T.

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.

$$f = \left(\frac{v}{2ae} + \frac{L}{v}\right) \cdot Kf$$

$$C = \left(\frac{v}{2ae} + \frac{L}{v}\right) \cdot Kc$$

where

C - crossing time headway

f - following time headway

v - vehicle speed

Kf, Kc - safety factors - following and crossing respectively

L - vehicle length

ae - 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

$$Fs = \frac{n}{(n-1)f + c}$$

where

n - mean platoon size passing the intersection from either lane

Fs - maximum vehicle flow

The occupancy is therefore

Occ - F.(average headway)

$$Occ - F \cdot \frac{(n-1)f + c}{n}$$

As n increases from 1 Fs 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 (Vsat) 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.

<u>Slowing Down and Conflict Delay</u> - 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 realised 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.

4 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 $\frac{(A + B)!}{A!\ B!}$ 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 the 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 -

$Prob(H_t = t) = \lambda e^{-\lambda t}$ where λ = mean flow rate

3 Shifted negative exponential -

$Prob(H_t = t < Hmin) = 0$

$Prob(H_t = t \geq Hmin) = Qe^{-Q(t - Hmin)}$

4 Truncated negative exponential -

$Prob(H_t = Hmin) = \int_0^{Hmin} R\, e^{-Rt}\, dt$

$Prob(H_t = t > Hmin) = R\, e^{-Re}$ (Dia 106)

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]

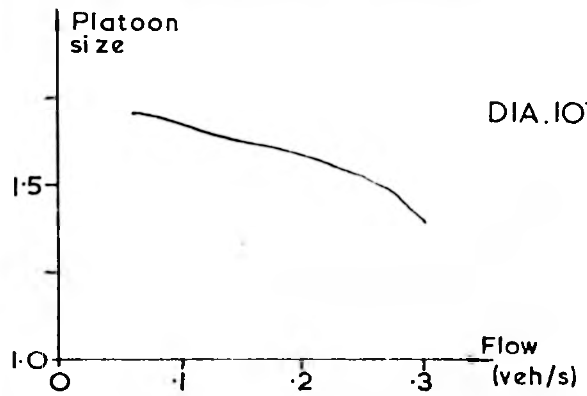
At high flow rates the truncated negative exponential looks like a fixed spacing and at low flows tends towards the negative exponential. Consequently, a mean platoon size that tends from 2 to 1 as the flows increase would be expected. Such a trend has been shown in simulation experiments.[Dia 107]

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]

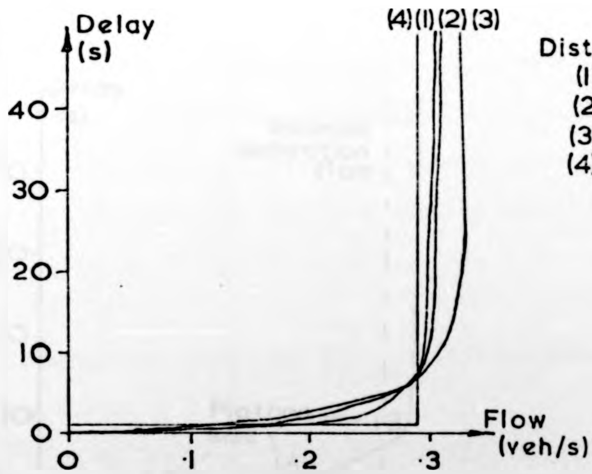
Conflict Delay

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,

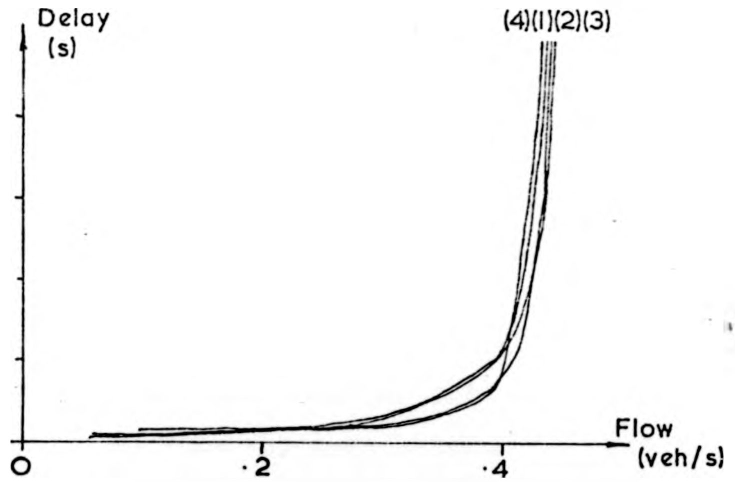


DIA.107 Platoon size for first-come first-served with truncated distribution

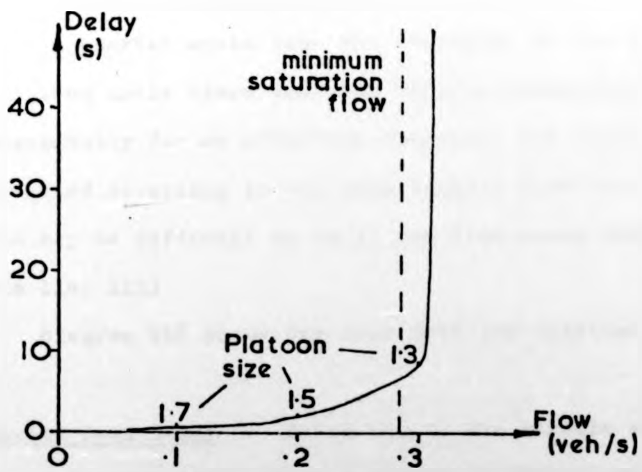


Distributions are:-
(1) Shifted -ve. exp.
(2) Truncated -ve. exp.
(3) -ve. exp.
(4) Uniform

DIA.108 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)

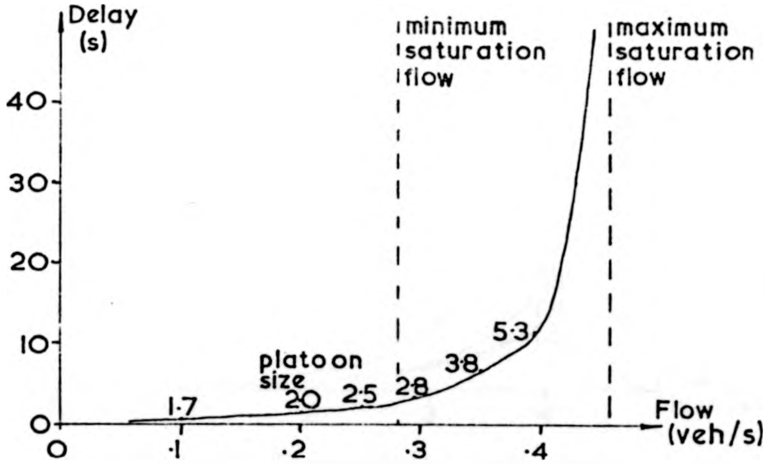
The 'hold' time is a parameter which can be varied according to flow so as to minimise the mean delay. However it does not vary much over the full range of flows. Consequently a single preset value could be used which will give a near optimum performance over the whole range of flows.(Dia 113)

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.

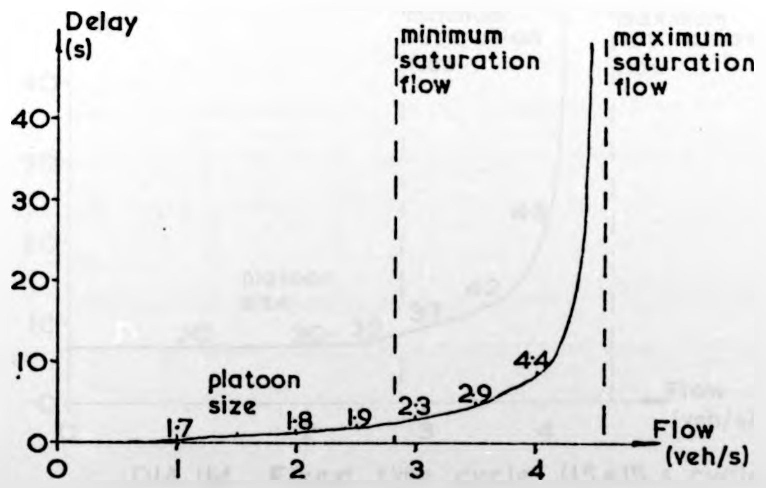
However, the mean delay experienced by vehicles is at least a quarter cycle time and therefore at low flow rates and with long cycle times vehicles will be unnecessarily delayed. Consequently for an efficient operation the cycle time must be varied according to the mean vehicle flow rate. In practice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

Diagram 116 shows the four policies together for comparison.

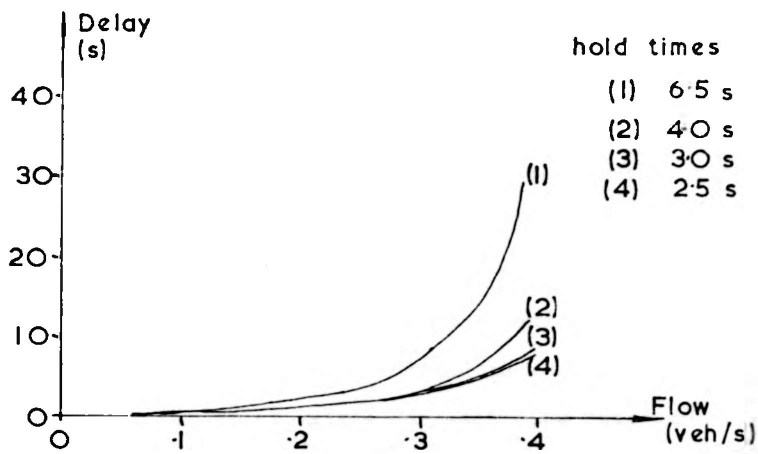
<u>Slowing Down Delay</u> - Delay due to the vehicle slowing down to the intersection target speed is simple to calculate. It is the difference between the time the vehicle actually takes to slow down, minus the time the vehicle would have taken to



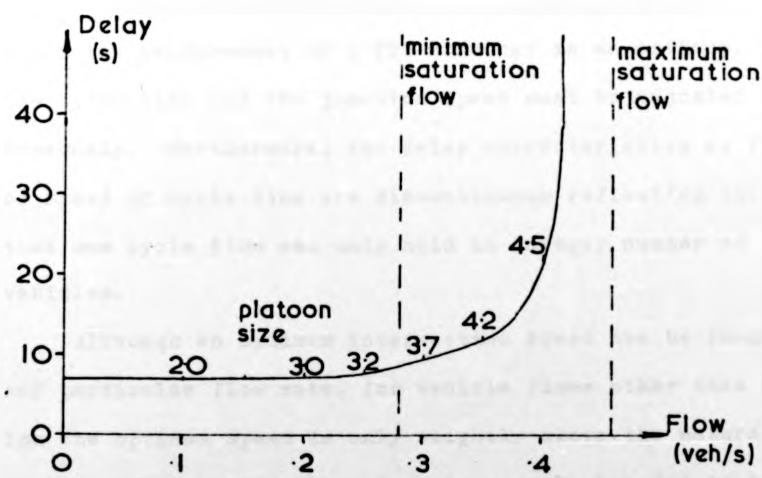
DIA.111 Alternate priority
conflict delay at junction
speed of 4·5 m/s



DIA.112 First-come first-served with hold
of 3·0 secs.
conflict delay at junction
speed of 4·5 m/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

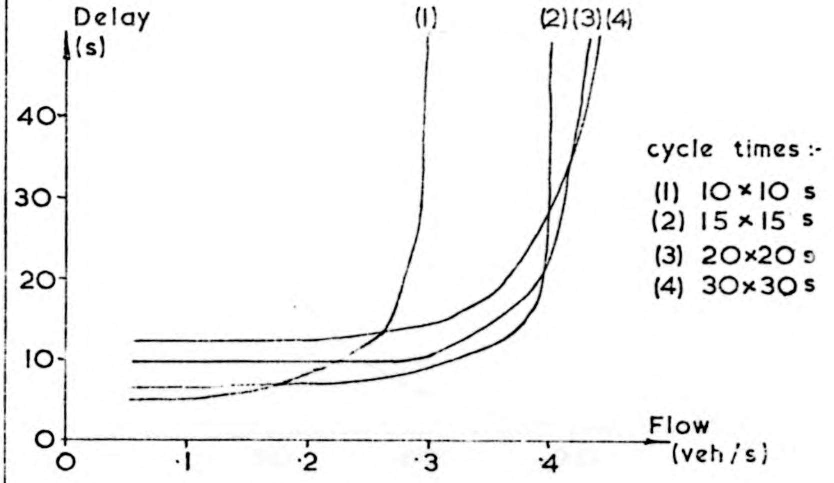
travel the same distance at full speed. The curve is shown on Diagram 117.

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.(Dia 116) However the delay incurred by slowing down to the intersection speed and speeding up after it increases as the intersection speed is reduced.

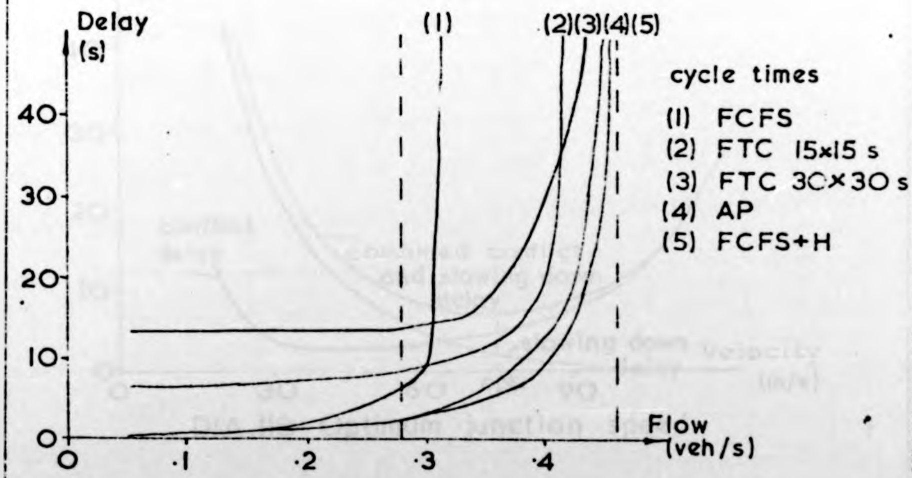
An optimum speed exists for each flow rate and merging strategy, at which the sum of the slowing down and conflicts delay is a minimum.(Dia 118) Diagram 119 shows the optimum flow delay curves for FCFS, FCFS + H and AP.

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.

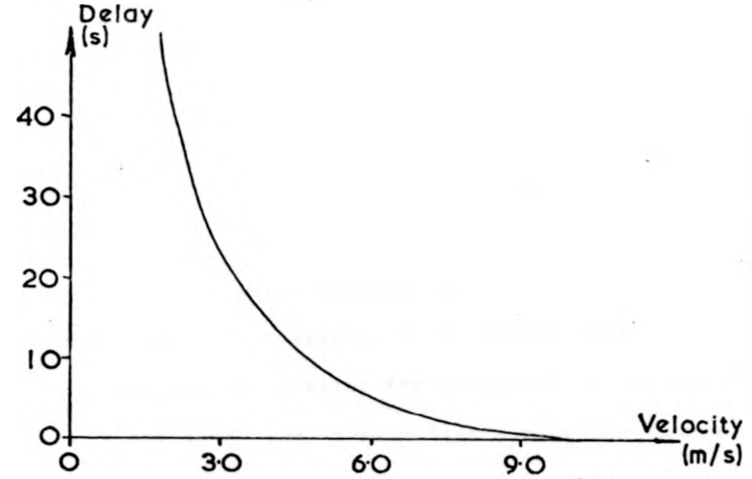
Although an optimum intersection speed can be found for any particular flow rate, for vehicle flows other than the very low the optimum speed is only slightly above the saturation speed. Consequently there is only a small benefit to be gained by varying the junction speed according to flow, and that with the penalty of increasing the complexity of junction controller.(Dia 122)



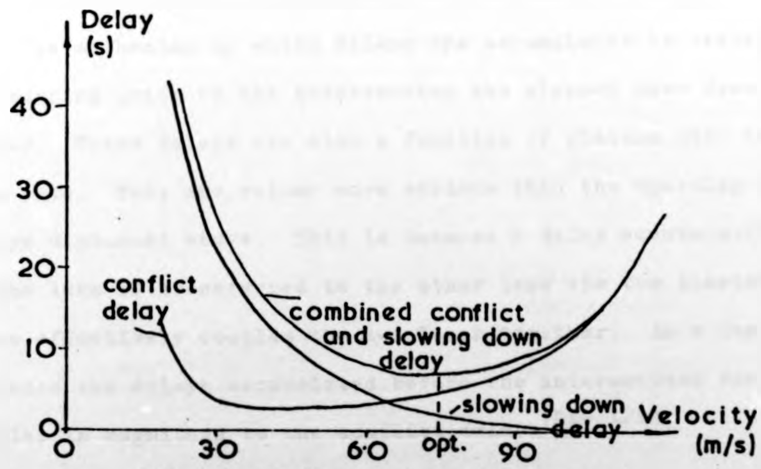
DIA.115 Fixed time cycle showing the effect of varying cycle time



DIA.116 Comparison of ordering policies conflict delay at junction speed of 4·5s



DIA. 117 Slowing down delay.

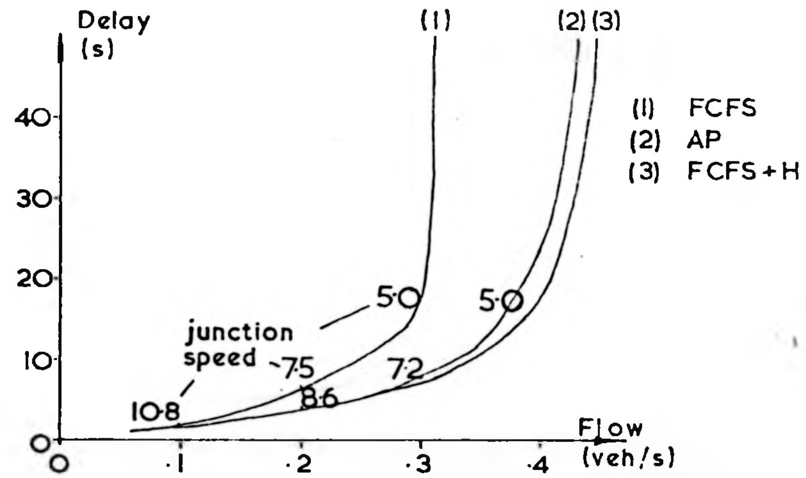


DIA. 118 Optimum junction speed

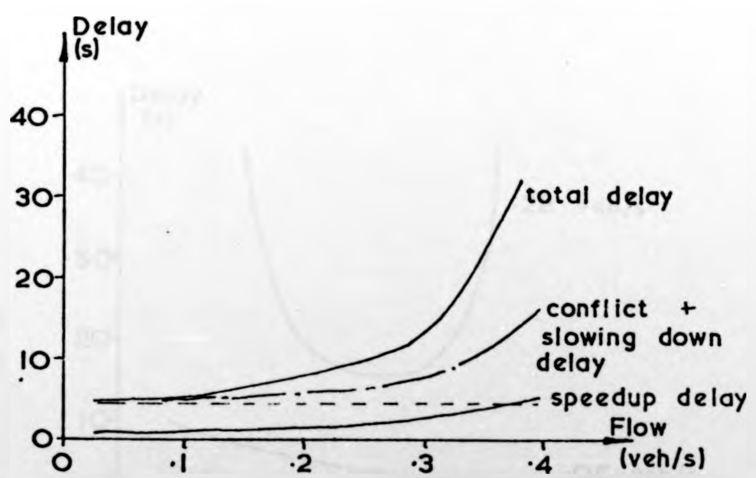
Manoeuvre Delays - Delays due to headway infringement can be divided into two parts. The part which is accumulated as a vehicle approaches an intersection and the part accumulated as the vehicle accelerates away from the intersection.

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)

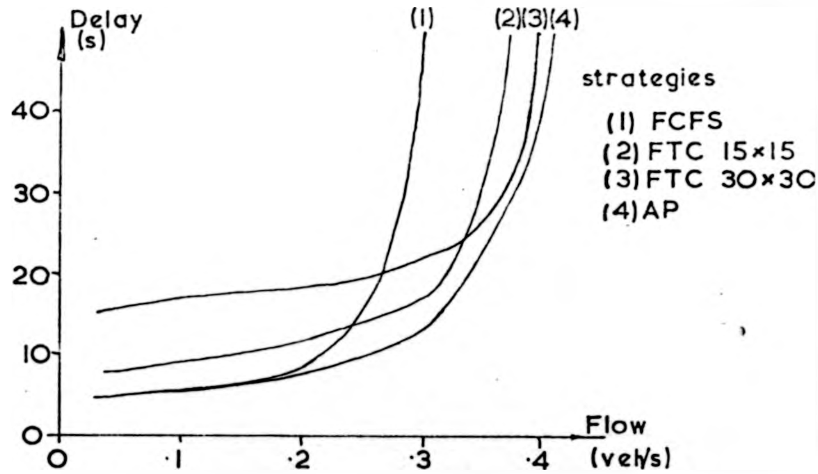
The mechanism by which delays are accumulated by vehicles manoeuvring prior to the intersection has already been described. These delays are also a function of platoon size and flow rate. They are rather more serious than the speeding up delays discussed above. This is because a delay accumulated on 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)



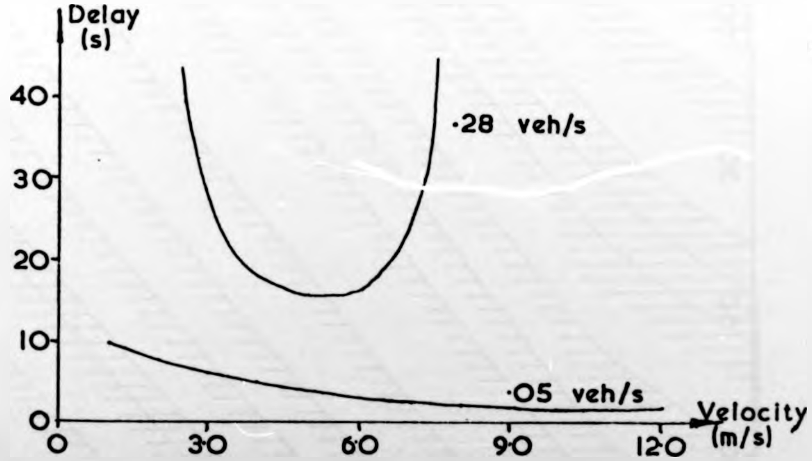
DIA.119 Ordering strategies with optimised junction speed



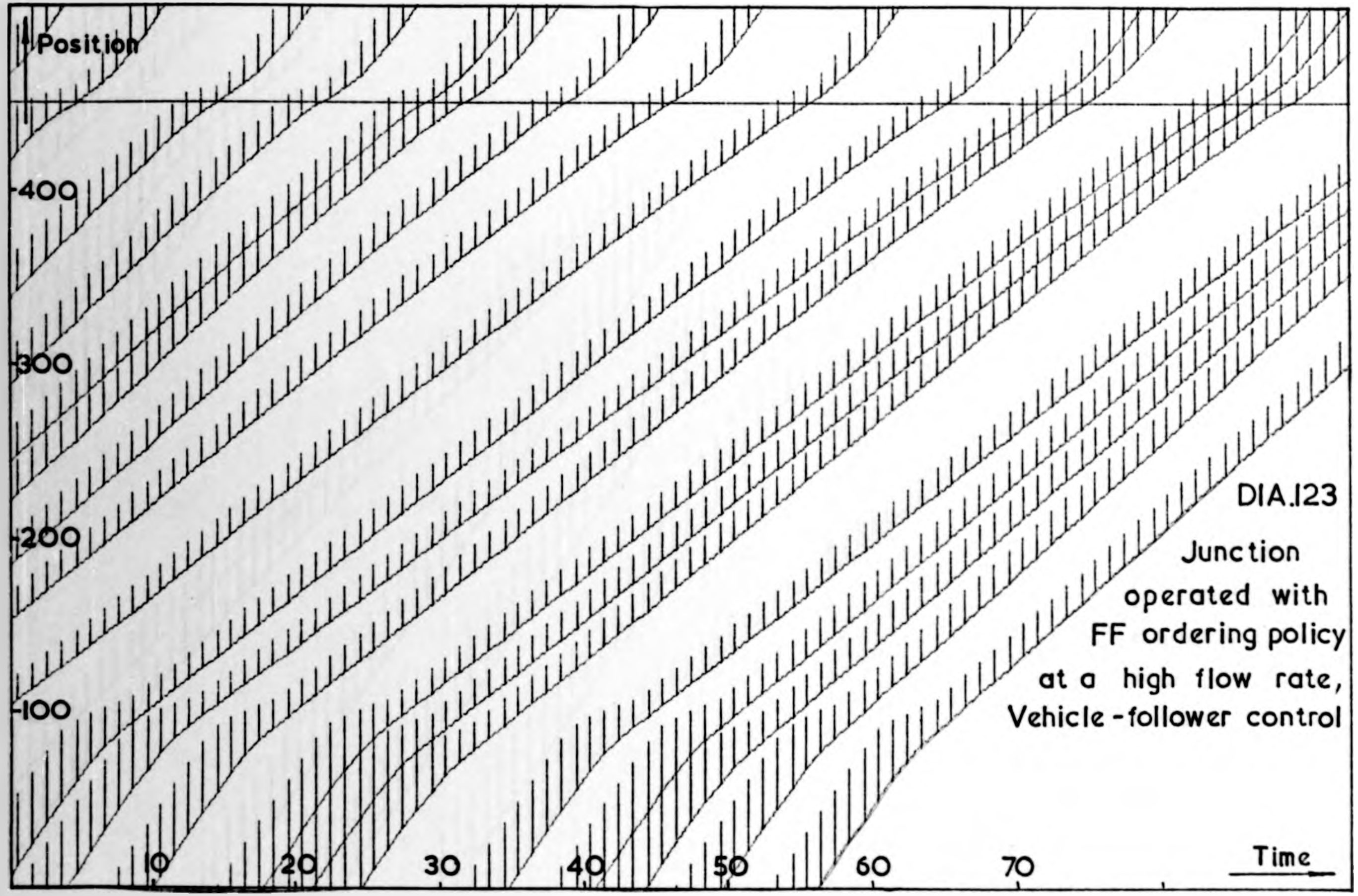
DIA.120 Alternate priority; showing the component delays

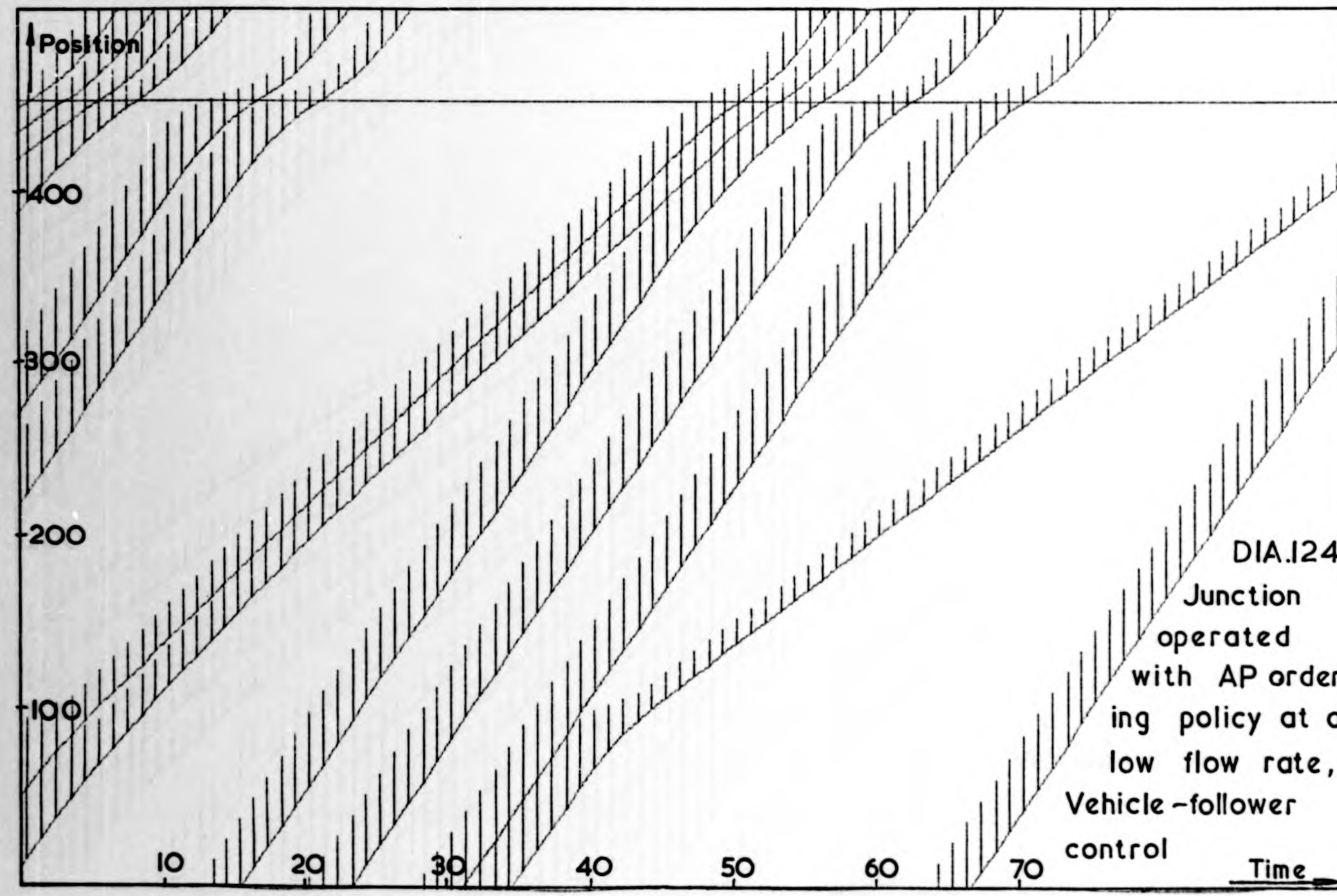


DIA.121 Complete flow delay characteristics of three ordering strategies

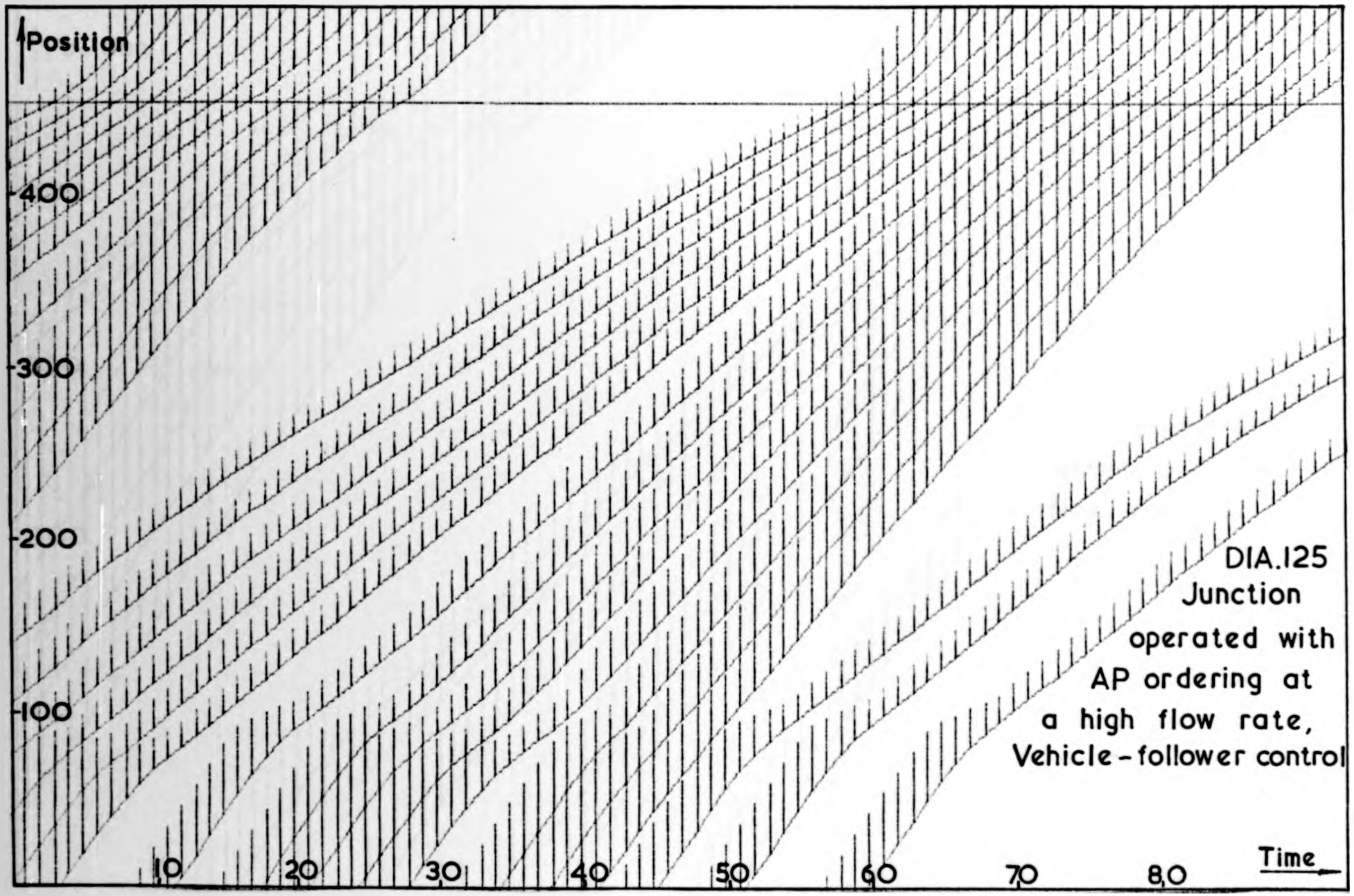


DIA.122 Effect of junction speed on delay characteristics of first-come first-served strategy

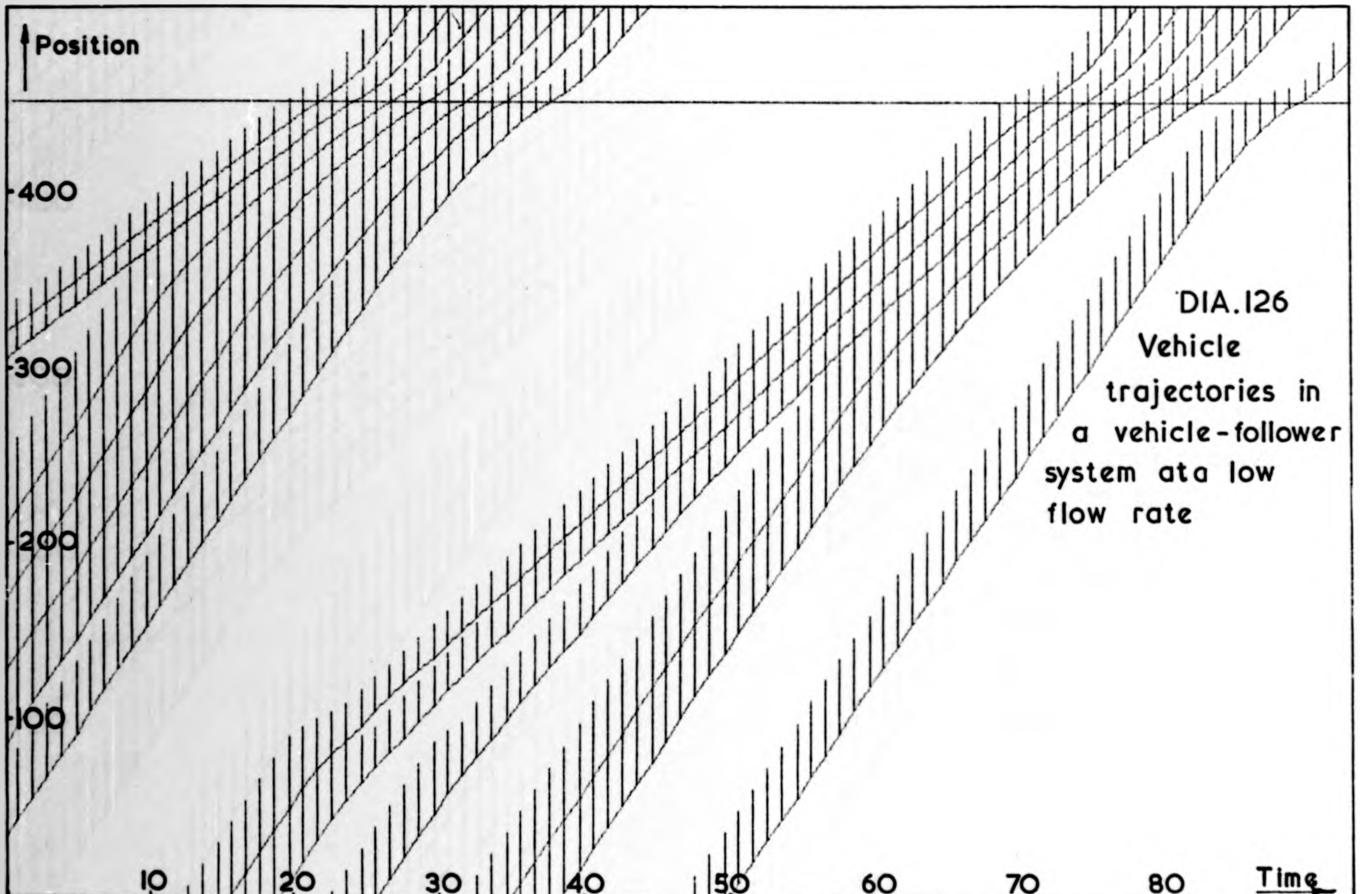

Position
-400
-300
-200
-100
10
20
30
40
50
60
70
Time
DIA.123
Junction
operated with
FF ordering policy
at a high flow rate,
Vehicle-follower control



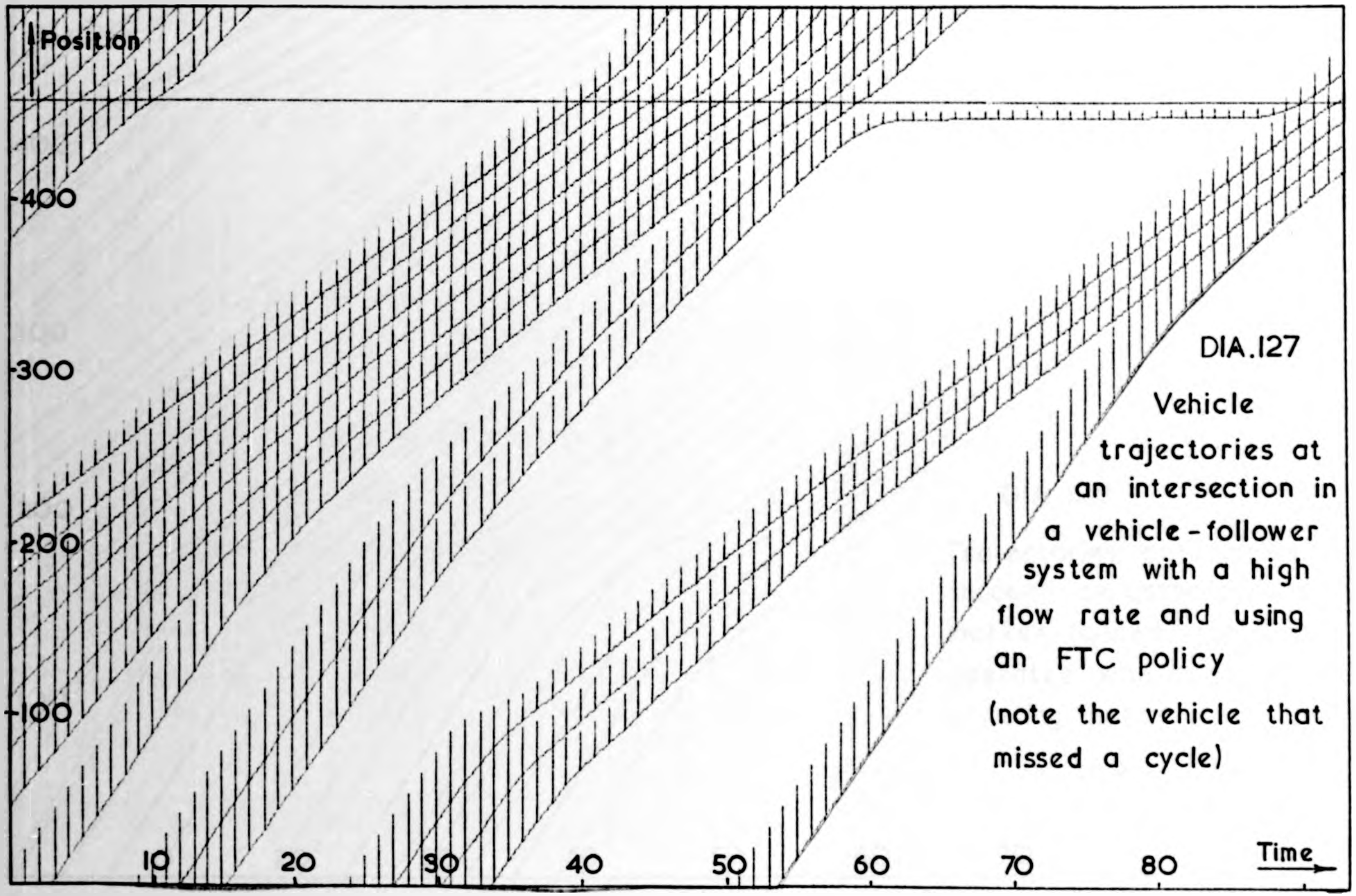
DIA.124 Junction operated with AP ordering policy at a low flow rate, Vehicle-follower control



DIA.125 Junction operated with AP ordering at a high flow rate, Vehicle-follower control



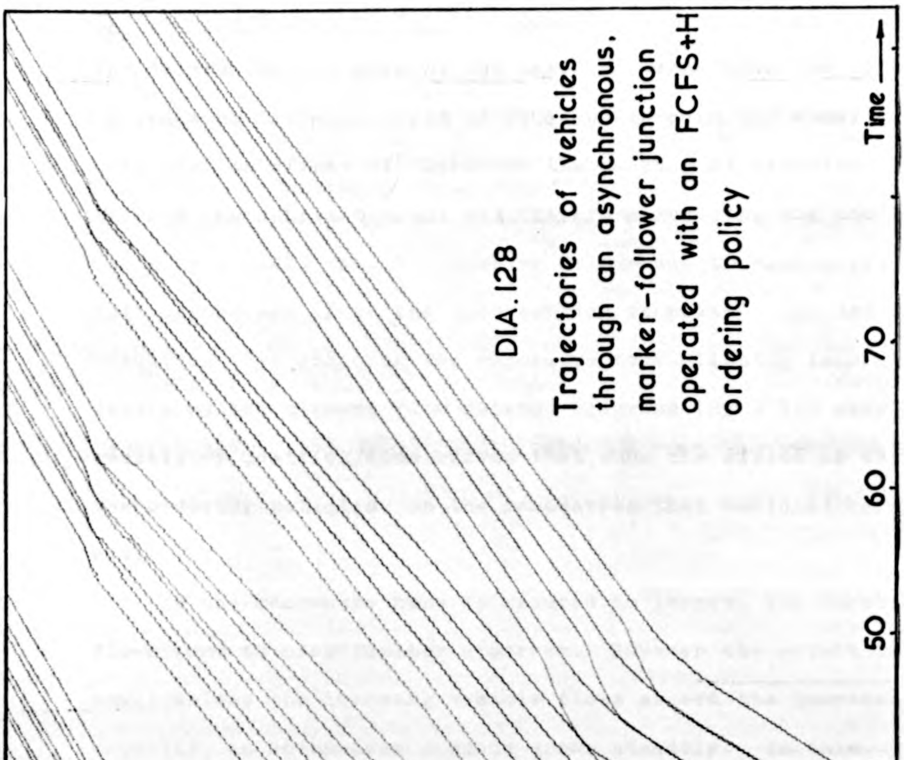
DIA. 126
Vehicle trajectories in a vehicle-follower system at a low flow rate



DIA.127

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

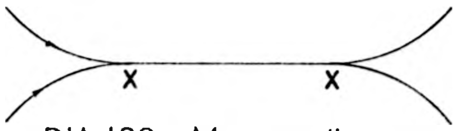
Trajectories of vehicles through an asynchronous, marker-follower junction operated with an FCFS+H ordering policy

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 125 - 128 show a variety of position/time curves that show the effect of varying the ordering policies, on the manoeuvres that vehicles carry out.

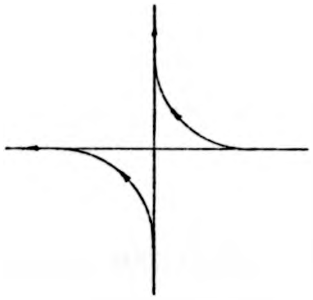
As the manoeuvre zone is reduced in length, the incoming flows tend to back further upstream. However the effect is small unless the incoming vehicle flows exceed the junction capacity, in which case a queue grows steadily. In this situation, the longer the manoeuvre zone, the longer can a junction tolerate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

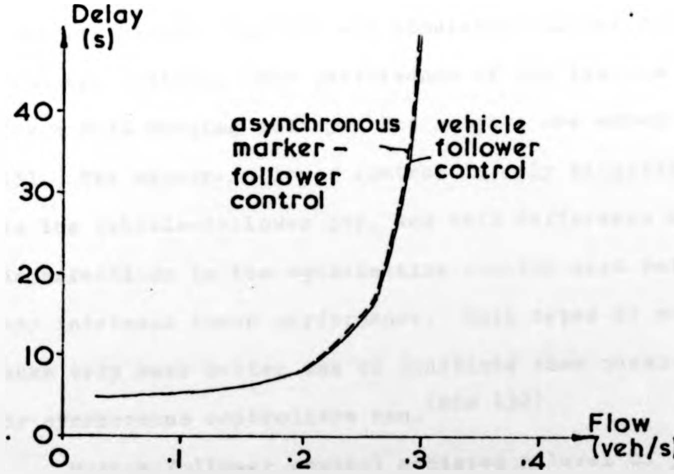
The simplest junction, a cross-over has a performance characteristic as shown in Diagram 121. The same characteristic will describe a merge-diverge junction, (Dia 129) if the extra delay incurred by running at the intersection speed along the common section x - x is added.



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

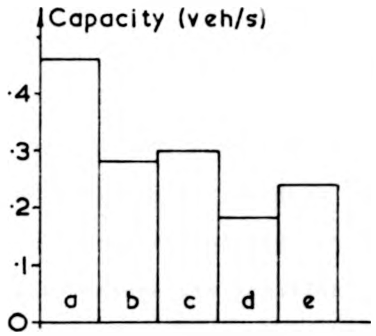
A crossing junction with low speed turns is similar to a cross-over with no turning, because all the conflict points must be considered as one, there being no room to manoeuvre between them.(Dia 130) However the time headways must be increased to take account of the transit time of the vehicle through 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.(Dia 132)

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

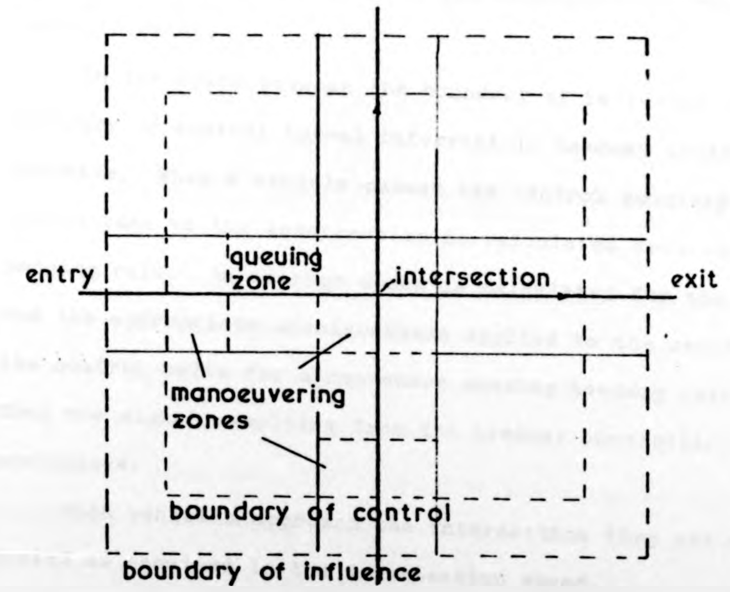
The junction is split into several regions. (Dia 133)

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

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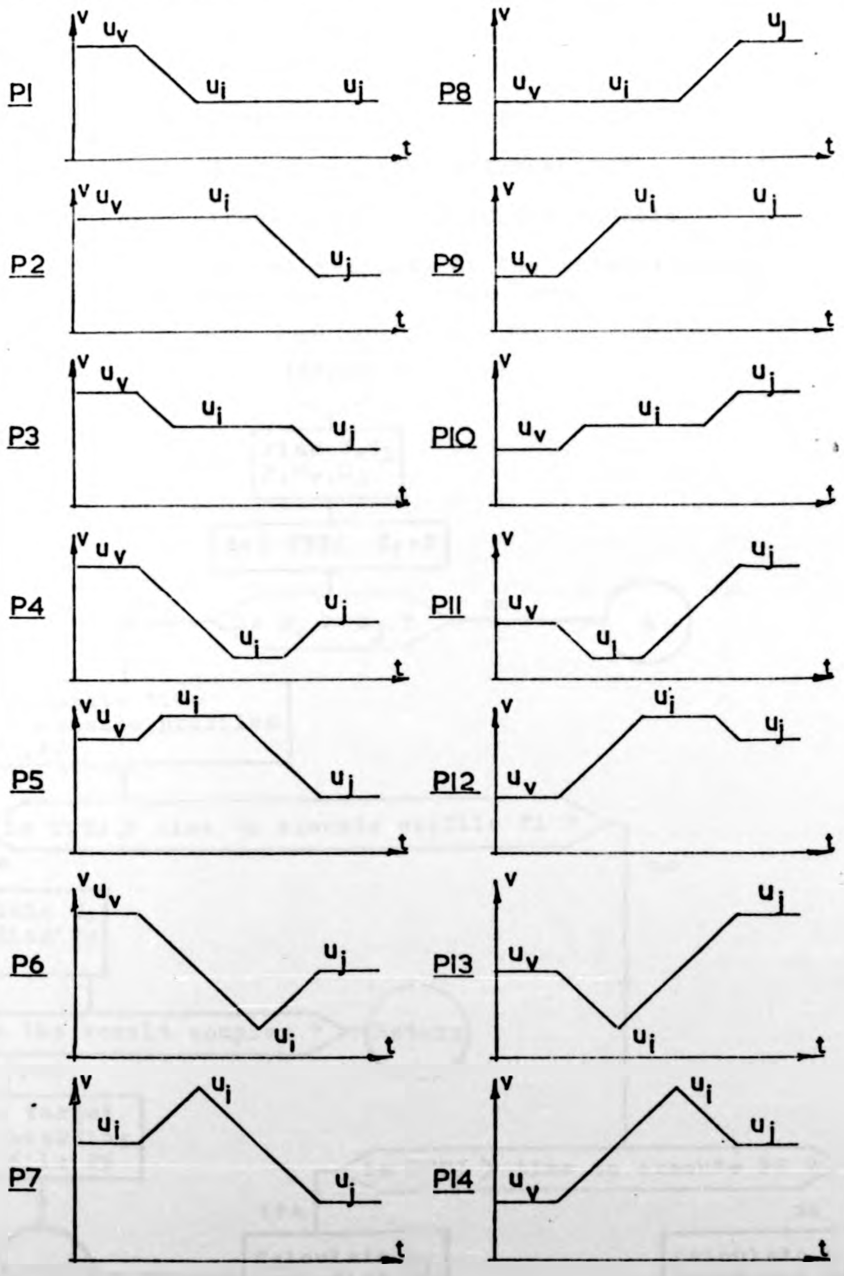
The amount of information transfer required for track-vehicle and vehicle-to-track communications is a particularly important parameter in the assessment of a control strategy. Within the simulation information transfer points are positioned on the track; the passing of a vehicle calls a servicing routine 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 o 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.

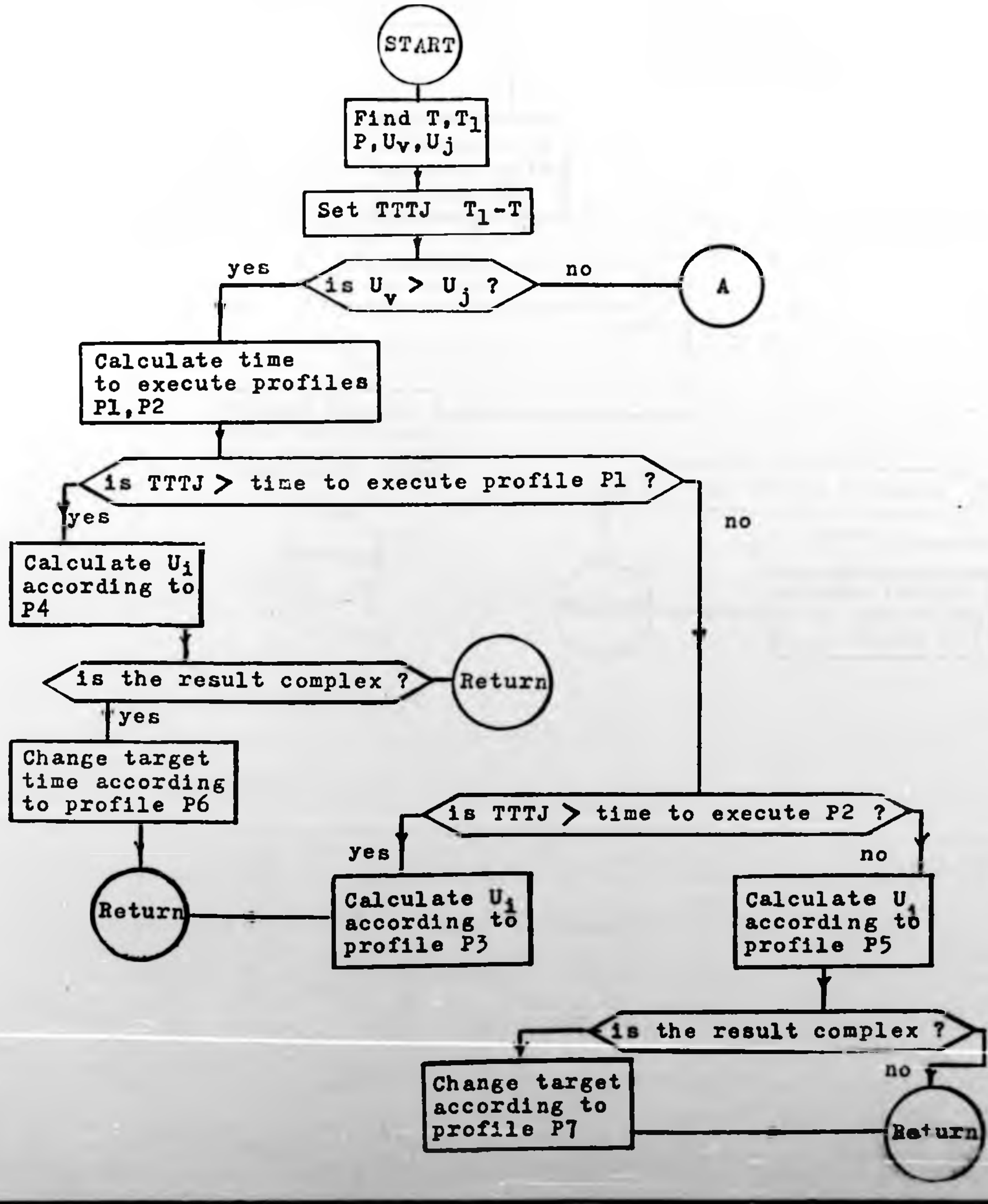
Control Routine - The main task of the control routine is to calculate the intermediate speed of the vehicle. In both the junction and the network simulation the same technique was used, - namely a simple logical selection of the appropriate velocity profile. (Dia 134, 135) For simplicity, jerk was not included in the calculations.



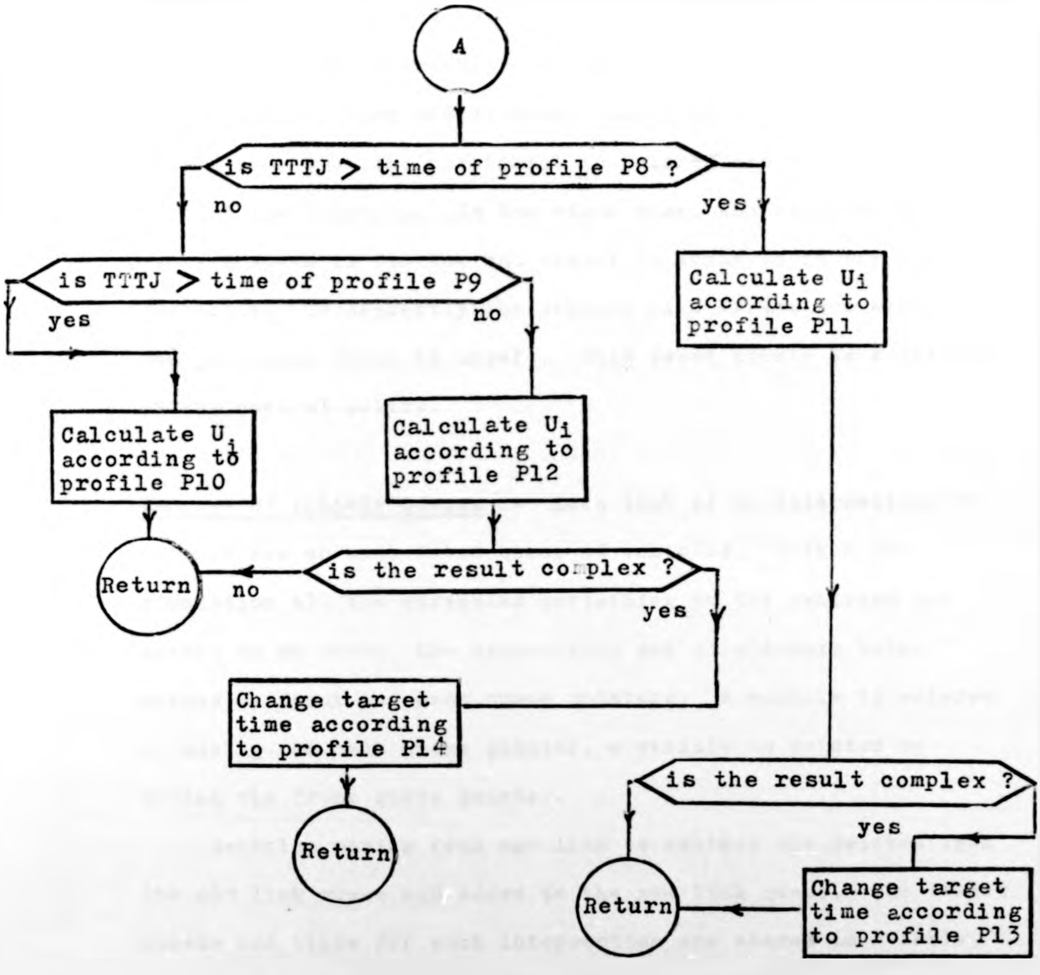
DIA.134 The set of velocity time profiles used in the calculation of the intermediate speed (see dia.135)

Dia. 135 flow chart of intermediate speed selection

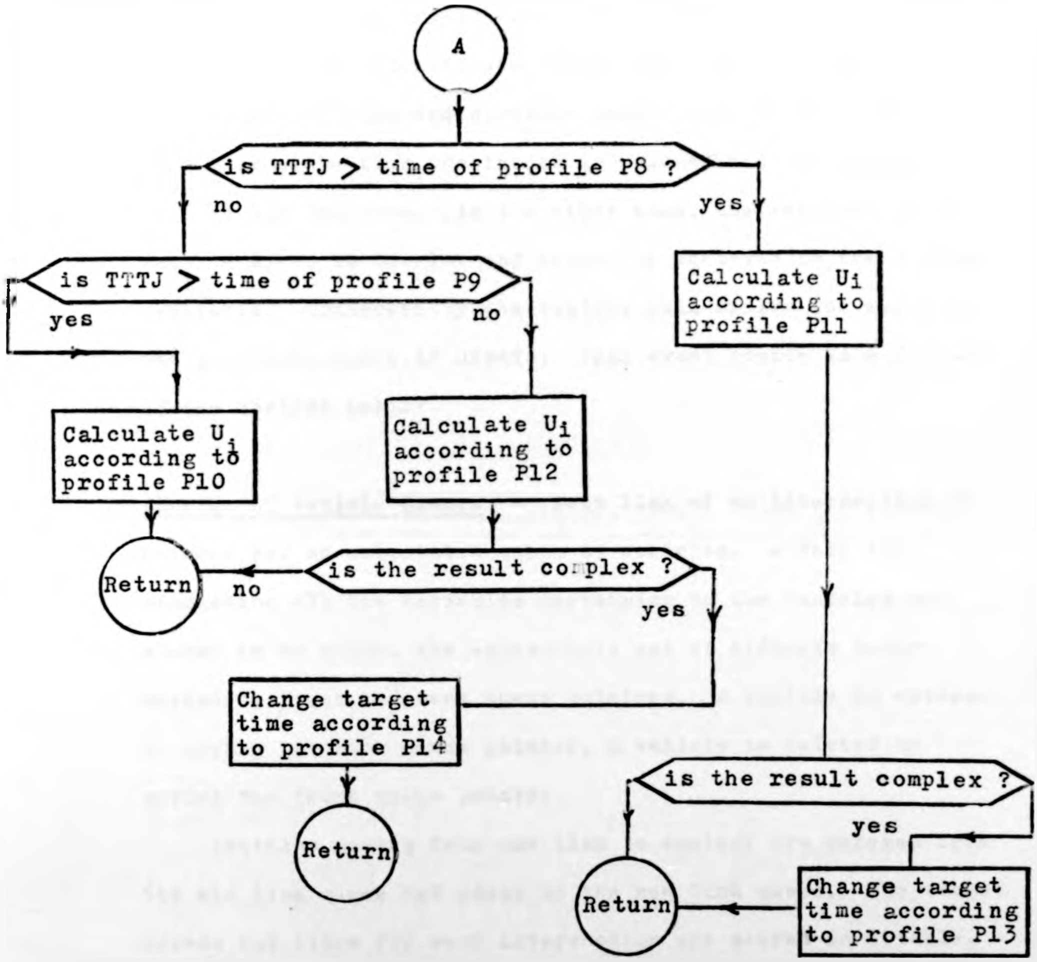
Where	T	-	Present time
	T_1	-	Target time at the intersection
	P	-	Distance to the intersection
	U_v	-	Present velocity of the vehicle
	U_j	-	Target velocity at the intersection



Dia.135 continuation of flow chart



Dia.135 continuation of flow chart



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)).

<u>Output of Information</u> - 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 unforseen 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.

<u>Moving Picture Display</u> - 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 ASCll 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)

$$Xp = Xn + \left[X_{n-1} - X_n\right] \times g$$

$$Yp = Yn + \left[Y_{n-1} - Y_n\right] \times g$$

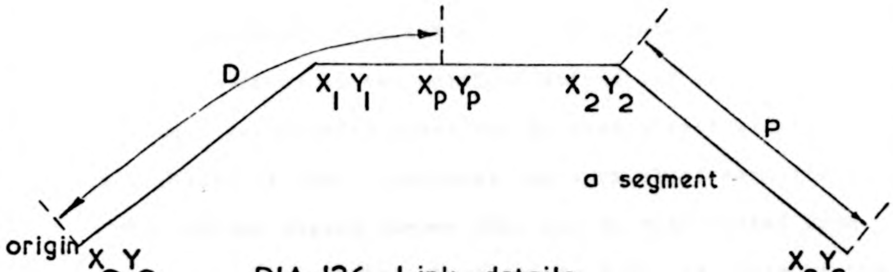
where

n - integer part of $\left[D/p\right]$

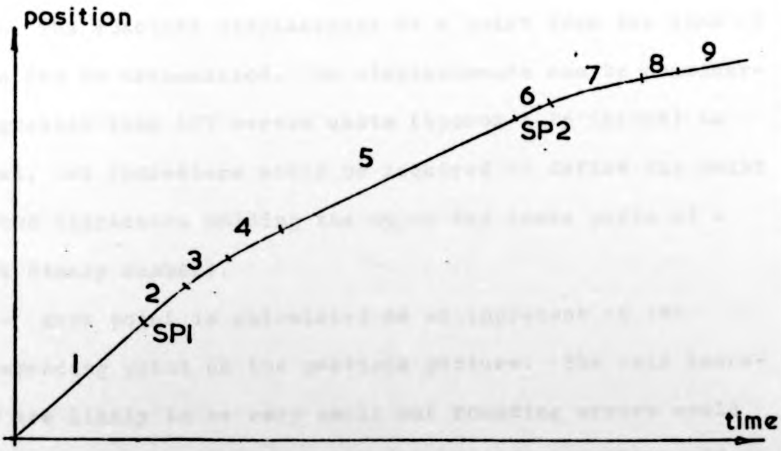
g - fractional part of $\left[D/p\right]$

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

X,Y - x y coordinates of link segment start

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

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- 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 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,(Dia 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.

	i	Constant line speed input
First speed change	ii	Constant jerk transition
	iii	Constant acceleration
	iv	Constant jerk
	v	Constant speed
Second speed change	vi	Constant jerk
	vii	Constant acceleration
	viii	Constant jerk
	ix	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 - 8 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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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.

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 Hulme) 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 probabalistic 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
C SIMULATION OF ASYNCHRONOUS COMMUNICATION LINK WITH CYCLIC STRATEGY.
C
C!FORTRANH G0,S
      DIMENSION DELSAV(1000),NSUM(50)
      DIMENSION TT(20)
      COMMON RLEVEL,TELT
      LOGICAL STOPNOW
      NAMELIST
      STOPNOW=.FALSE.
   21 CONTINUE
C INITIALISATION.
      TIMESS=1.
      NUSER=10
      TELT=.1
      TIMEWT=NUSER/10.
      DELSUM=0.
      PCU=.9
      IRC=0
      IUFC=0
      NOBUF=1
      NOBUF=2
      NCOUNT=0
      INPUT(105)
      IF (STOPNOW) STOP
C CALCULATE MESSAGE GENERATION RATE.
      RLEVEL=1.-(PCU*TELT)/NUSER
      BAL=RN(0)
      DO 10 I=1,NUSER
      BAL=RN(I)
   10 TT(I)=RN(I)
      TIMIDLE=0.
    6 CONTINUE
      DO 1 I=1,NUSER
C IF MESSAGE DEMAND AFTER SERVICE TIME.
      IF (TT(I).GT.TIMIDLE) GOTO 2
      ILAG=(TIMIDLE-TT(I))/NUSER
```

```
      ILAG=0
C CALCULATE NO. OF BUFFERS REQUIRED.
      IF (ILAG.LT.NOBUF) GOTO 3
C REJECT THESE MESSAGES AS EXCESS.
      IRC=IRC+1
      GOTO 4
C UNUSED MESSAGE SLOT COUNT.
    2 IUFC=IUFC+1
      TIMIDLE=TIMIDLE+1.
      GOTO 1
C INCREMENT NEXT TIME IDLE.
    3 DELSUM=DELSUM+TIMIDLE-TT(I)
      NCOUNT=NCOUNT+1
C SAVE.
      DELSAV(NCOUNT)=TIMIDLE-TT(I)
C TIME IDLE AT TIMIDLE.
      TIMIDLE=TIMIDLE+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)
    1 CONTINUE
      GOTO 6
    5 AVDEL=DELSUM/NCOUNT
      SDS=0.
      DO 12 I=1,50
   12 NSUM(I)=0
      ICOUNT=0
      DO 7 I=1,NCOUNT
      SDS=SDS+(DELSAV(I)-AVDEL)**2
      IPT=DELSAV(I)*10./NUSER
      IF (DELSAV(I).GT.FLOAT(NUSER)) ICOUNT=ICOUNT+1
      IPT=IPT+1
      IF (IPT.GT.50) IPT=50
      NSUM(IPT)=NSUM(IPT)+1
    7 CONTINUE
      ODR=FLOAT(ICOUNT)/FLOAT(NCOUNT)
```

```
C CALCULATE VARIABLES AND OUTPUT.
      DO 17 I=1,50
      NTOT=NTOT+NSUM(I)
      IF (NTOT.GE.NCOUNT*99/100) GOTO 8
   17 CONTINUE
    8 I=I-1
      DNN=I*TIMEWT
      OCC=NCOUNT*TIMESS*100./TIMIDLE
      SD=SQRT(SDS/NCOUNT)
      ARRU=FLOAT(IRC)/TIMIDLE
      DRU=FLOAT(NCOUNT+IRC)/TIMIDLE
      RR=ARRU/DRU
      OUTPUT(108)'      MEAN DELAY     STANDD DEV     % OCCPNCY      MESS LN
     COTH    NO OF USER     WAIT TIME      AV RJCT R/U    DMND RT/U     '
      WRITE(108,100) AVDEL,SD,OCC,TIMESS,NUSER,TIMEWT,ARRU,DRU
      OUTPUT(108) '      RJCT RATIO     OVRDLY RTIO    99% DELAY     '
      WRITE(108,197) RR,ODR,DNN
      IPT=50
      DO 71 J=1,10
      DO 73 I=1,50
   73 NSUM(I)=DELSAV(I+(J-1)*50)**.5
   71 CALL PRINTH(NSUM,IPT,TIMEWT)
      GOTO 21
  100 FORMAT(4F14.2,I14,F14.2,2F14.4)
  197 FORMAT(3F14.3)
      END
```

```
C
C GENERATE RANDOM ANNUAL RATE.
C
      FUNCTION RN(I)
      COMMON RLEVEL,TELT
      DIMENSION RNX(20)
      INTEGER RNX
      IF (I)1,1,2
    1 DO 3 II=1,20
    3 RNX(II)=II*50+1
      RETURN
    2 CONTINUE
      ICOUNT=0
    7 CONTINUE
S          LW,4        *I
S          LW,9        RNX-1,4
S          MI,9        65539
S          AND,9       =X'7FFFFFFF'
S          STW,9       RNX-1,4
           RN=RNX(I)
           RN=RN*.4656613E-9
      IF (RN.GE..5.AND.RN.LT.1.5-RLEVEL) GOTO 4
      ICOUNT=ICOUNT+1
      GOTO 7
    4 RN=FLOAT(ICOUNT)*TELT
      RETURN
      END
```

```
C
C OUTPUT HISTOGRAM OF DELAYS.
C
      SUBROUTINE PRINTH(NSUM,IPT,TIMEWT)
      DIMENSION NSUM(50),LINE(120)
      DATA IBLANK/' '/,IAST/'*'/
      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)=IAST
      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,F6.2,2X,120A1)
      END
```

Measurement & Communication in Automated Transport

L Burrow & T Thomas

(oct '76)

Transport Research Group

England

```
PCU=.8,
*
STOPNOW=T
*
C!OLOAD GO
C!ROV
```

(Appendix. 2)

Measurement & Communication in Automated Transport

L Burrow & T Thomas (oct '76)

Urban Transport Research Group

Warwick University, Coventry, CV4 7AL, England

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

Contents

1.A - Whole system features governing the communication and measurement facilities provided

1.A.1 - The degree of automation sought

1.A.2 - The structure of control systems and its influence on information requirements
- Centralized control
- Hierarchical control

1.A.3 - Communications involved in open loop control, closed loop control and fault monitoring
- Open loop
- Closed loop
- Fault control

1.B - Methods of directing information to the correct recipient

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
- Message addressing

1.C - Measurement of position and its time derivatives

1.C.1 - Measurement and communication

1.C.2 - Position

1.C.3 - Velocity

1.C.4 - Acceleration and Jerk

1.C.5 - Time

1.D - Modulation

1.D.1 - The need for modulation

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 obeys 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.A.2 The Structure of Control Systems and its Influence on on Information Requirements

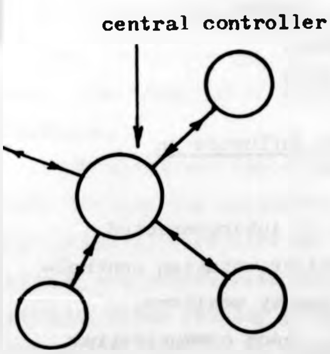
A transport control system is a structure of interconnected subsystems. These might include vehicle controller, station controllers, merge controllers, network controllers, safety monitors, passenger handling systems, power supplies etc., each communicating with some or all other units.

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.

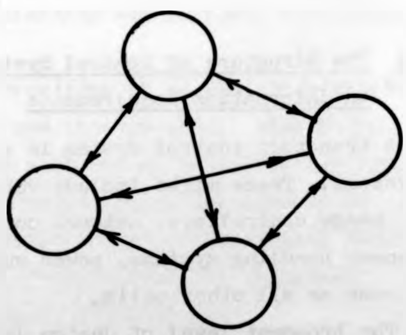
Control structures for an automatic transport system are usually either centralised or hierarchical. Other structures can be devised, for example, mesh structures in which every unit directly communicates with every other. Communication costs are very high and logical fault detection is almost impossible.

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 vunerable to damage and subsequent disruption. However better control may be possible as all the system information is available for processing.



*centralised structure



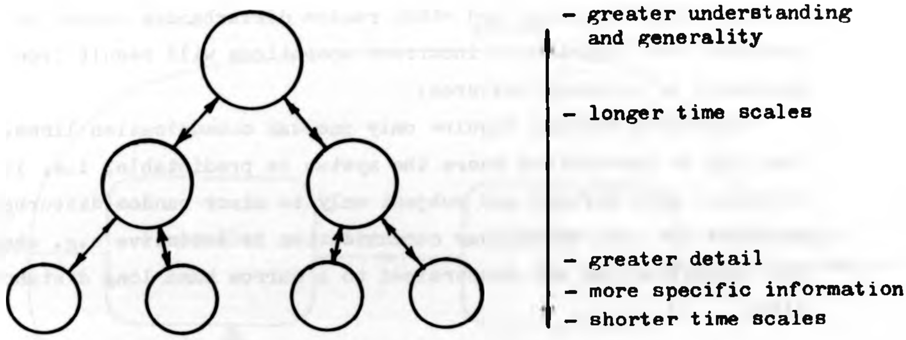
*mesh structure

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.

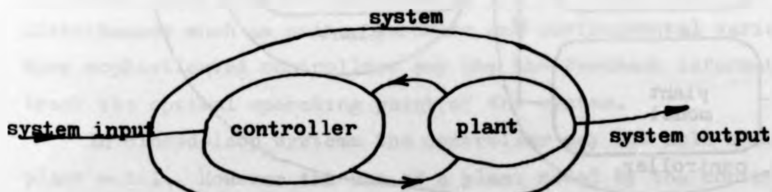
The use of hierarchical structures with decision units physically distributed throughout the network reduces the demand for communication links, so reducing costs. The disruption caused by faults is diminished and the modular nature of such systems simplifies the detection and repair of faults. (Ref. 30, 96)



Hierarchical structure

1.A.3 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'.



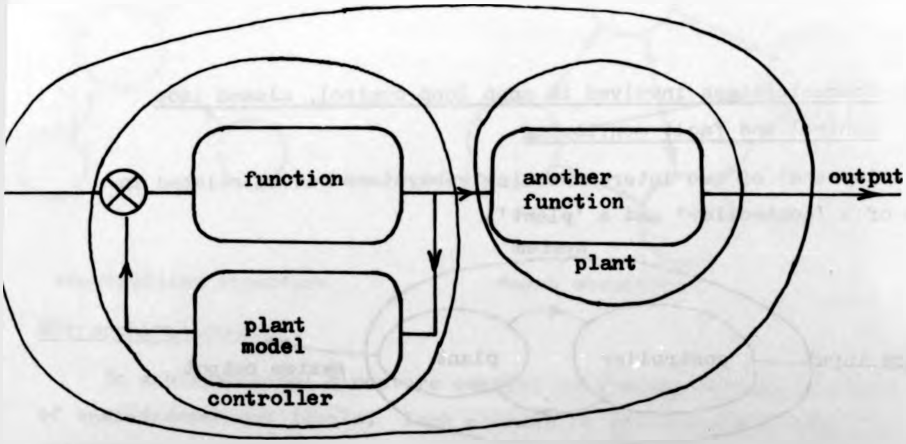
The role adopted by each subsystem depends on the primary direction of information flow. The 'controller' is the upstream element and supplies appropriate inputs to the 'plant' which responds with the 'system' output.

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.

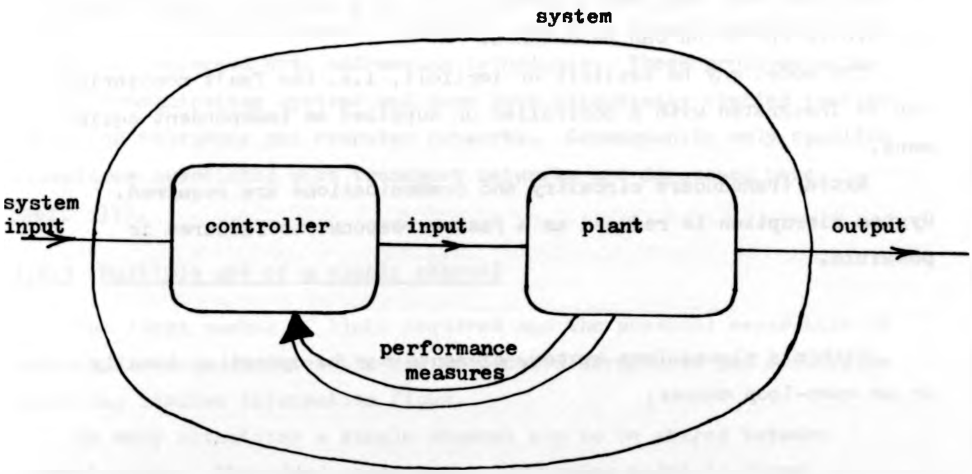
Open-loop systems require only one-way communication links. They may be appropriate where the system is predictable, i.e. it is reliable, well defined and subject only to minor random disturbances, or where the cost of two-way communication is excessive e.g. where the communications are constrained to a narrow band, long distance link.



Open loop system

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.

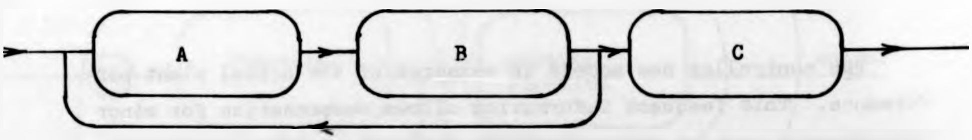
ault control

Fault control systems are always closed-loop. Measures of actual ystem states are compared with predicted values of the state. The etection of abnormal discrepancies initiates standby strategies esigned to counteract the effects of the failure. The identification f a system fault requires a system model as a reference against which he system operation can be checked.

The model may be explicit or implicit, i.e. the fault monitoring an be integrated with a controller or supplied as independent equip- ent.

Extra transducers circuitry and communications are required. ystem disruption is reduced as a faster response to failures is ossible.

Within a closed-loop system, elements may be operating locally n an open-loop manner.



Jnit B is part of a closed-loop but is itself operating open-loop. C is part of the system and 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 preceeding 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.

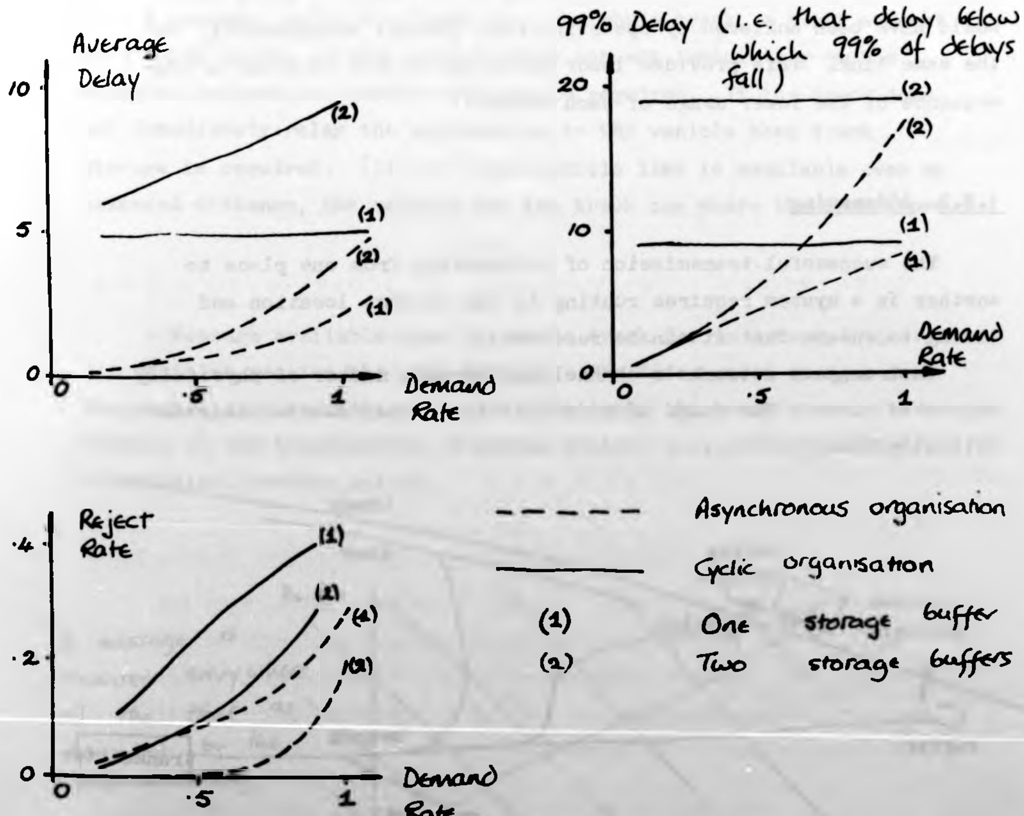
Direct channel organisation needs little equipment. Demand responsive systems give no indication of failed users, a check which is possible in a fixed sequence system.

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)



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).

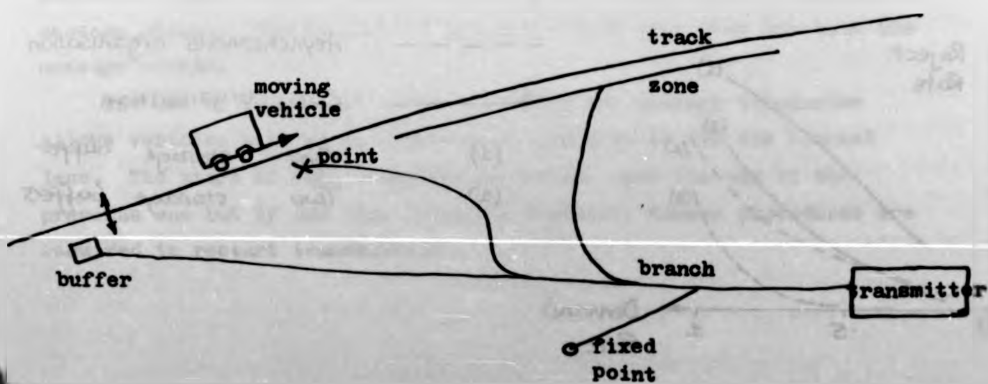
One channel can be designated an addressing line, the other, the message line. These channels could be interchangeable enabling some degree of standby service to be provided in the event of a failure.

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.

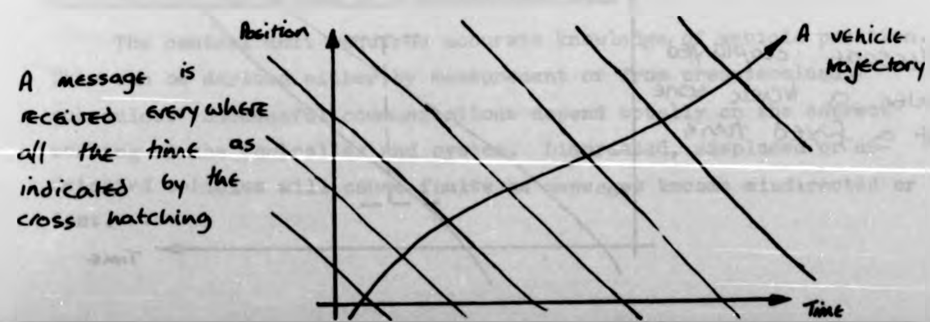
The geographical addressing problem

Information must be directed to intercept the intended vehicle, i.e. it must be available at an appropriate track-side position and time.

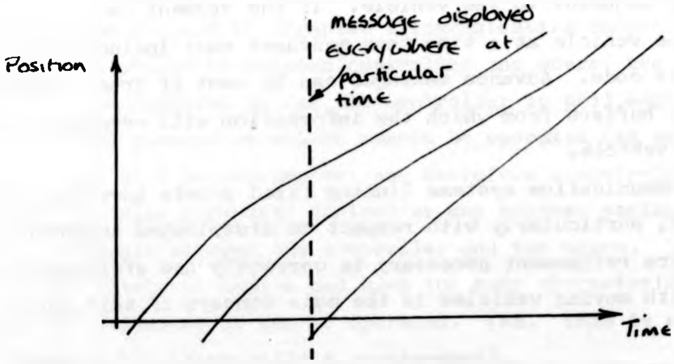
Reference to time-position trajectories of the vehicles yields the following possibilities.

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.)

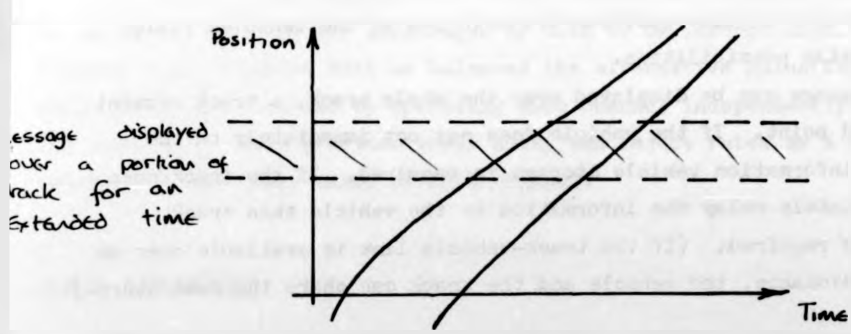
- Message available over the whole track for an extended time: All vehicles receive the same message. The information changes infrequently and transmitter may be effectively the track store. An example is the transmission of system status, i.e. normal/emergency, fare policy, service option.



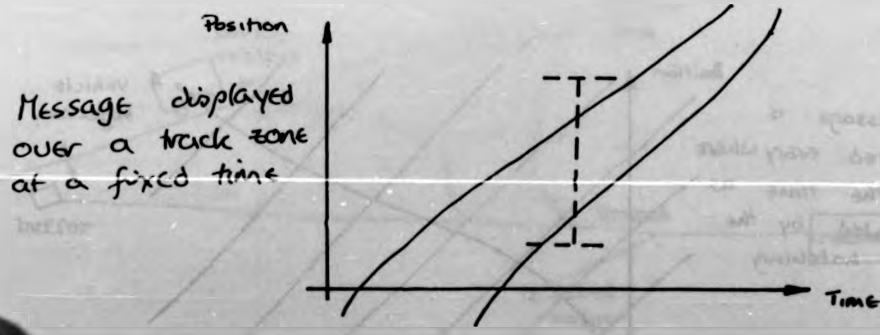
- Message available over the whole track at a particular time: All vehicles are contacted. Vehicles store message if necessary.



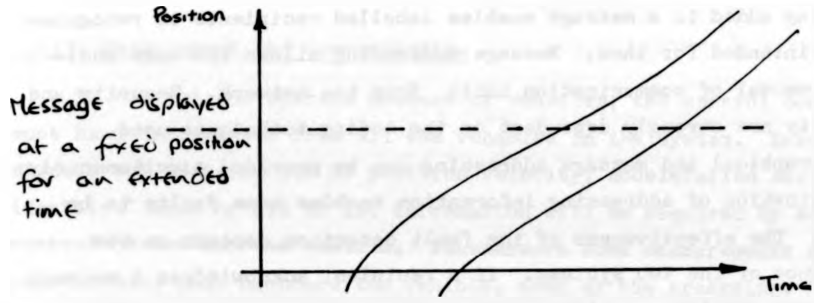
- Message available over a portion of the track for an extended time: Not all vehicles are contacted, only those passing that portion of the track.



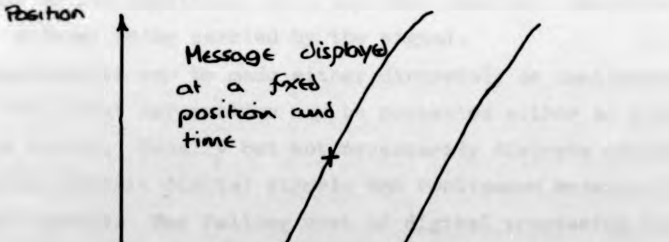
- Message available over a portion of the track at a particular time: Only vehicles within the zone receive the information. Information can be made vehicle specific if their trajectories are predetermined. The number of vehicles to be contacted and the tolerance on vehicle position determine the length 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.



<u>Geographical addressing by a centralised unit</u>

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.C 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.C.1 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 ixed point. They must be known sufficiently accurately to allow oth successful communications and safe manoeuvres.

Trackside position measurement systems will locate a vehicle to ie fixed resolution of the transducers. They are expensive unless recise measurements are only required at a few key points e.g. at unctions or station approaches.

On-vehicle position measurement requires instrumentation in each ehicle. Measures made locally on the vehicle must be periodically pdated to the track standard to remove any accumulated errors. The requency of this resetting depends on the transducer and the maximum llowable error.

Position measurement techniques are either

bsolute - in which the full precision of the device is used all the time. memory is required but signals are of wide bandwidth. They are used enerally for short range measurement.

ncremental - in which position increments are counted. Memory is equired, signals are narrow bandwidth but the measurement is subject accumulated error, similar to drift in analogue systems. Such schemes re generally used for long range measurement.

.C.3 Velocity

Analogue signals proportional to speed are given by dopplar shift ethods or those relying on electromagnetic induction. The rate of hange of a position measurement can be used as a velocity signal. he output is likely to be noisy and restricted in bandwidth.

Position based speed measurements can be made by timing between wo markers yielding a discrete measure, or by measuring the frequency f markers, yielding a continuous measure. The first is more appropiate where markers are widely spaced, the second requires close spaced arkers. Both are ineffective at low or zero speeds.

.C.4 Acceleration and ierk

A signal proportional to acceleration is generated using the relaionship force = mass x acceleration. The component of lateral

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1.C.5 T

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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.D. 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.D.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.

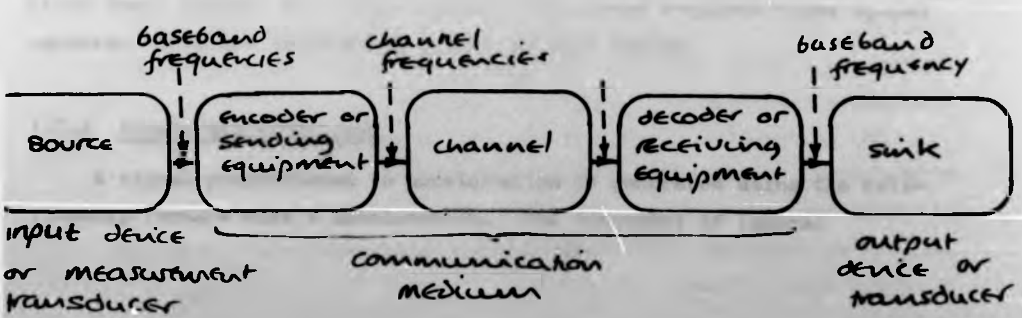
Digital signals occur where the information transmitted is defined by a sequence of signal levels, each drawn from a limited set of possible levels. The digital signals most commonly used are binary and have two levels corresponding to 0 and 1.

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) $f_n = 2 \times$ 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

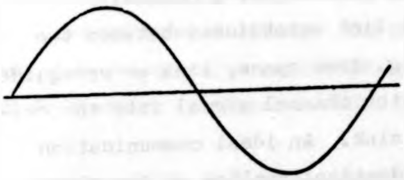
Modulation is achieved by having the source signal vary some physical characteristic of a carrier wave. This carrier may be a continuous sinewave or a train of identical pulses occuring at a constant rate.

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.

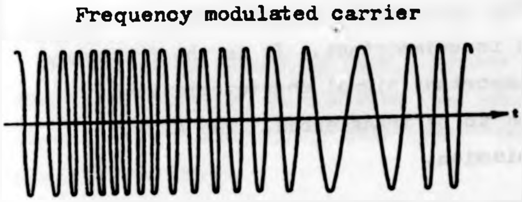
Angle modulation - where the source signal varies the phase of the carrier.

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.

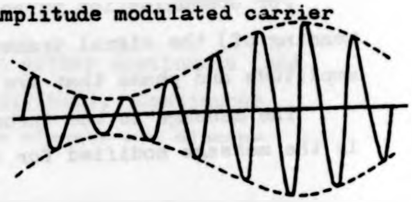


Modulating wave form

Frequency modulated carrier



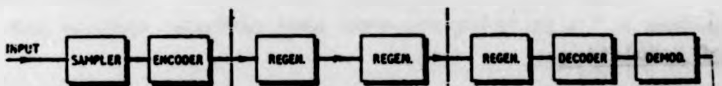
Amplitude modulated carrier



The use of pulse waveforms gives rise to a wide range of possibilities of which pulse amplitude, frequency and position are the more common.

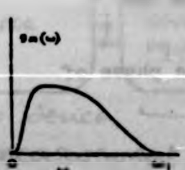
The combination of pulse waveforms and coding techniques yields pulse code modulation.

Pulse code modulation transmission



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 synchronisation 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 side band modulation requires the least equipment. The ; of suppressed carrier techniques enhances the signal to noise ratio the cost of greater complexity. Single side band transmissions iimise the bandwidth required to transmit a signal but at the expense reduced noise immunity and extra cost.

Channels subject to fading (i.e. time varying attenuation) rerely distort A.M. signals. Provided adequate bandwidth is ailable frequency modulation can perform better. The use of wider idwidths with frequency modulation improves noise rejection and stortion.

Pulse code modulated signals require more bandwidth, but are 'ective in poor quality channels. Bandwidth and signal to noise ;io can be traded for error rates. Further improvements in the re- ability of data transmissions are achieved by introducing redundancy ;o the coding. This redundancy enables transmission errors to be tected and with more complex codes allows corrections to be made. iy different coding techniques exist each offering different trade- 's between noise rejection and bandwidth.

<u>ltiplexing</u>

It is often useful to arrange a number of channels to simultaneously are a single communication link by the use of multiplexing. There are o methods

<u>equency multiplexing</u> - where each channel is allocated a frequency band acked in the frequency spectrum.

<u>me division multiplexing</u> - where synchronised switches at each end of communication facility enable samples to be transmitted in turn from ch channel to the receiving end.

Basic analogue systems are cheaper than the digital equivalent. wever where more elaborate signal processing is required costs tend favour digital systems, particularly as digital techniques have

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been much developed in recent years and costs are falling rapidly.

Every conversion from analogue to digital and digital to analogue 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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- Communications

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- Area position
- Continuous position
- Relative position
- Velocity
- Relative velocity
- Acceleration

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  4. Coaxial tube
  5. Treadle

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7. Mechanical lever

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10. Capacitance probe
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21. Linear cam
22. Linear digitiser
23. Integration
24. Wheel revolution counter
25. Incremental methods
26. Dead reckoning
27. Combinations of techniques yielding better precision

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32. Differencing
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58. Inductive loops

59. Waveguides

60. Free space radio

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.

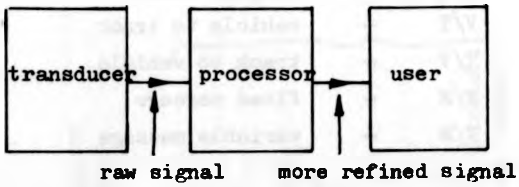
Within each of these groups measurements may be either

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



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.A.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

Point position Techniques	Application						Ref.	Comments
	Mess.		Communication					
	T/B	V/B	V/T	T/V	F/M	V/M		

Point position Techniques	Application: Meas. $^T/_B$	Meas. $^V/_B$	Communication $^V/_T$	Communication $^T/_V$	Communication $^F/_M$	Communication $^V/_M$	Ref.	Comments	
Pneumatic tube	w						1		
Hydraulic tube	e						2		All devices rely on mechanical contact and are subject to wear and reliability problems
Tiboelectric sensor	e						3	vehicle detectors only	
Coaxial sensor	e						4		
Treadle	w						5		
Contacting	e	e	e	e	e	e	6	track marker or vehicle detector can be used for communications	
Mechanical	w	e	f	f	f	f	7		
Strain gauged bar	f						8		
Seismic	f						9	i) vehicle detector only	Non-contacting devices.
Capacitance	e						10	ii) the M.G.V.D. has possible applications as a speed sensor	
Magnetometer	e						11		
Magnetic gradient vehicle detector (M.G.V.D.)	e						12		No wear problems but more expensive capital and installation costs
Magnetic	w	w	e	e	e	e	13	i) track marker or vehicle detector. All forms of fixed point communication	
Transverse or reflected beamed energy (radio, light, sound and radiation)	w	e	e	e	e	e	14	ii) Radiation energy is safety hazard	

Area Position Techniques	T/B	V/B	V/T	T/V	F/M	V/M	Ref.	Comments
Inductive loop	w	w	w	w	w	w	15	- very versatile and widely used
Track circuit	w	w		w	w	w	16	- widely used in railways for vehicle detection and short message transfers to vehicle
Check-in, check-out	w	w					17	- uses any form of vehicle detector
Continuous position								
Free space techniques (Propagation time, signal strength, direction finding radar)	w	w	e	e	e	e	18	- much developed for ship and aircraft navigation very poor accuracy in urban environments
Guided radio techniques (Propagation time, signal strength)	e	e	e	e	e	e	19	- fixed route operations only. Cannot be made failsafe. This constrains their application. Can be used for position, relative position velocity and relative velocity measurements
Linear synchro	e	f	f	f	f	f	20	} more commonly encountered as rotary instruments for measuring shaft rotation
Linear cam	f	f	u	u	u	u	21	
Linear digitiser	f	f	u	u	u	u	22	
Integration	f	w					23	} long term systematic errors. However simple and widely used where accuracy is less important or can be controlled.
Wheel revolution count		w					24	
Incremental measures	w	w					25	
Dead reckoning	f	w					26	

	Application: Meas.		Communication					
Continuous position	T/U	V/B	V/T	T/U	F/M	V/M	Ref.	Comments

	Application							
	Meas.		Communication					
Continuous position	T/B	V/B	V/T	T/U	F/M	V/M	Ref.	Comments
Combinational techniques	e	e					27	These combine systems to provide better accuracy
Relative position techniques								
Mechanical probe	u	f	u	u	u	u	28	Very fragile device
Capacitive inductive magnetic probe	u	f	u	u	u	u	29	Feasible for short distance ranging
Fixed block methods	u	w	w	w	w	w	30	Measures separation in units of block length. Can be manipulated from the track side to vary control action.
Poupe's coded track (oct)	u	f					31	
Differencing	f	f					32	Requires simultaneous absolute position measures. Only track based method.
Free space systems	u	e	f	f	f	f	33	See appropriate section in continuous position techniques
Guided radio systems	u	e	f	f	f	f	34	
Velocity								
Frequency rate	e	e					35	Requires track markers. Both give an estimate of speed which lags the actual speed.
Time interval	e	e					36	
Correlation	e	e					37	Widely used in industrial applications

Velocity	Meas. T/B	V/B	Communication				Ref.	Comments
'Flicker Rate'	f	f					38	Simple method involving correlation
Inductive	e	e					39	Principle widely used in rotary equipment
Dopplar	e	e					40	Frequently used to measure velocity in other applications
M.C.V.D.	f	u					41	Use of device has been proposed
Integration	e	e					42	Long term errors accumulate
Differentiation	f	f					43	Subject to noise and resolution problems
Relative velocity								
Dopplar	u	f	f	f	f	f	44	
Differencing	f	f					45	
Differentiation	f	f					46	
Free space	u	f	f	f	f	f	47	
Guided radio	u	f	f	f	f	f	48	
Acceleration								
Accelerometers		w					49	Acceleration is difficult to measure accurately
Differentiation	f	e					50	

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, 69, 88, 89, 98, 126)

1) Pneumatic Tube

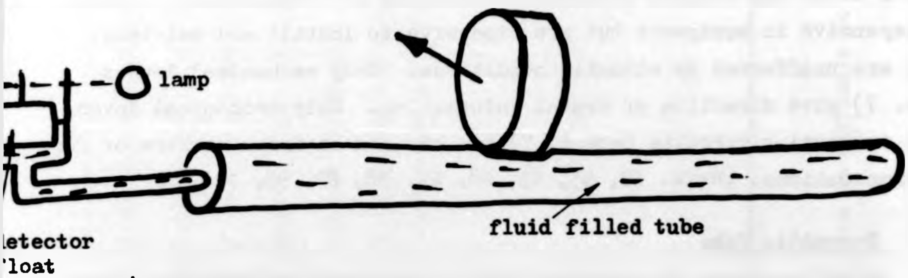
Wheel pressure of a passing vehicle on a soft walled tube, sends a pressure impulse to a pressure sensitive switch at one end. Pneumatic tube vehicle detectors have been extensively used for vehicle actuated traffic lights. They are now being superceded by inductive loop (see no. 15) and magnetometer 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) <u>Hydraulic tube</u>

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)



3) <u>Triboelectric sensor</u>

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.

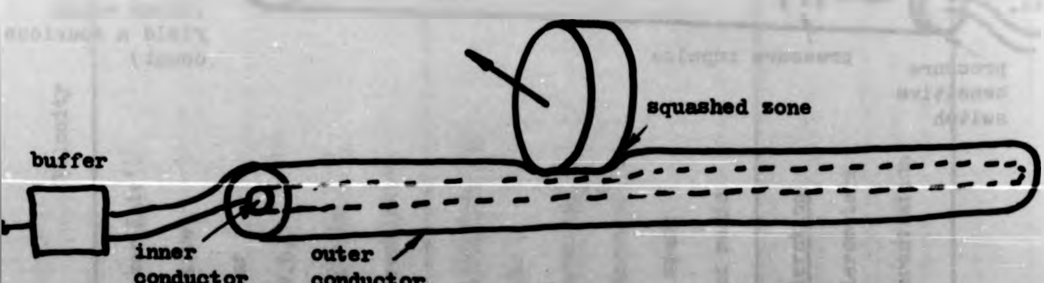
- As the device has a very high impedance, impedance matching and amplification are required to extract the signal.
- Was devised as an improvement on the pneumatic detector (no. 1)

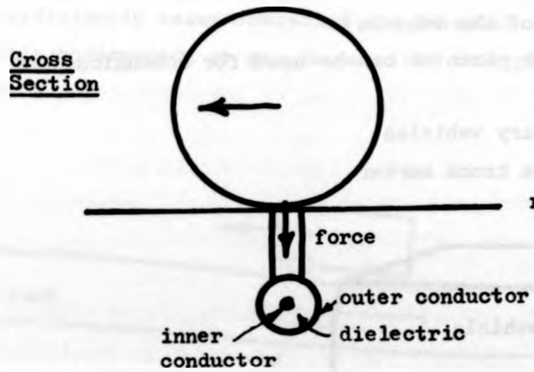
It has similar characteristics to the pneumatic detector (no. 1) but is less vunerable to damage.

4) <u>Coaxial cable sensor</u>

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)

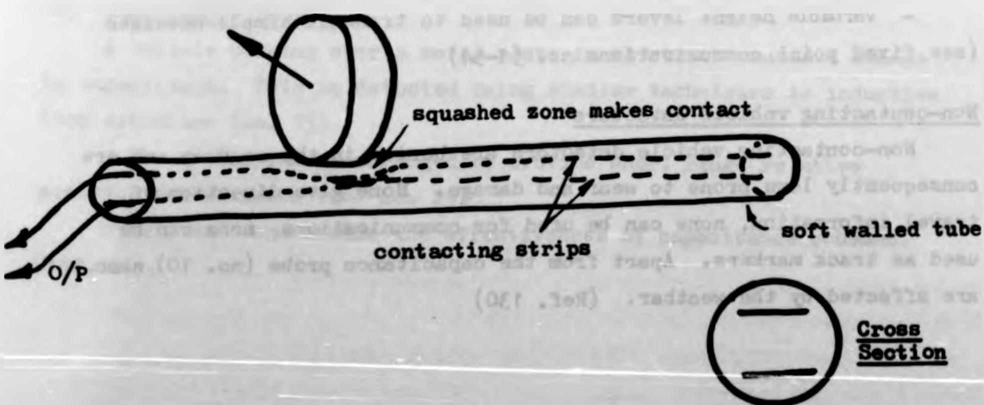




5) <u>Treadle</u>

Wheel pressure on normally separated contacting strips, usually carried in a flexible tube, closes an electrical contact.

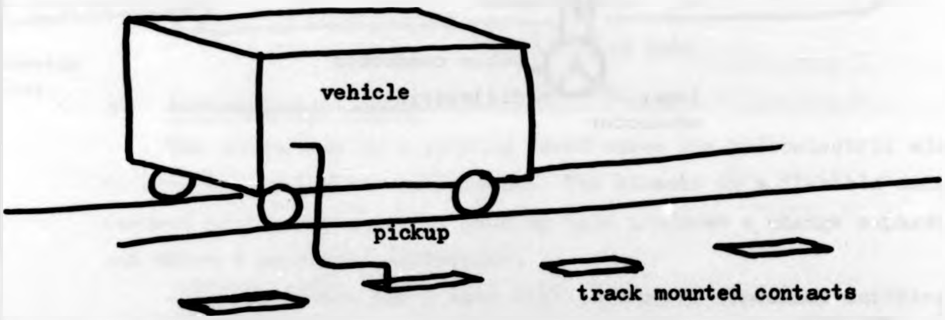
- Slow vehicles or stopped vehicles on the device are detected.
- Other characteristics are similar to the pneumatic detector.



6) <u>Contacting circuits</u>

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) <u>Mechanical lever</u>

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)

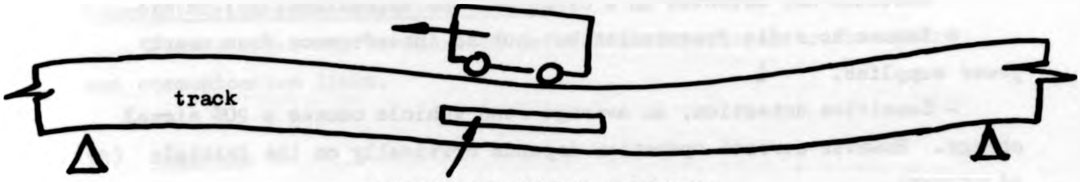
<u>Non-contacting vehicle detectors</u>

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 registers deflection as vehicle passes

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

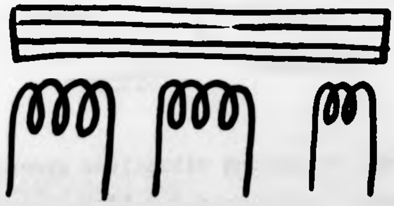
A vehicle passing over a metal plate in the track causes a change in capacitance. This is detected using similar techniques to inductive loop detectors (no. 15)

- 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.

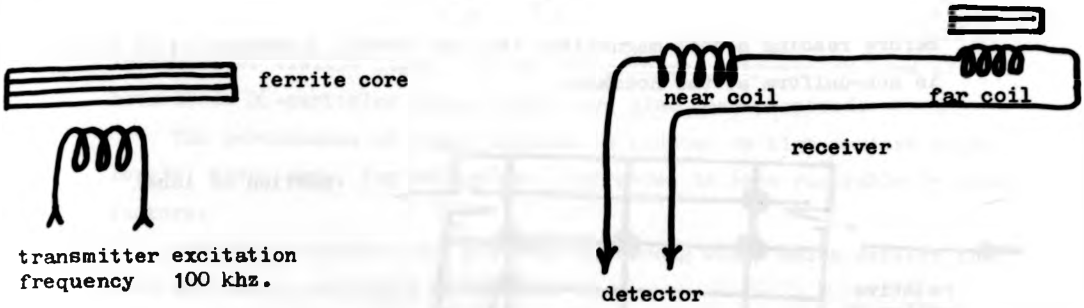
- Detector is small (typically 6cm long by 2cm diameter).
- Vehicles are detected in a circular zone approximately 1.5m dia.
- Immune to radio frequencies but not to interference from nearby power supplies.
- Sensitive detection, an average road vehicle causes a 20% signal change. However correct operation depends critically on the initial adjustment.



12) **Magnetic gradient vehicle detector (MGVD)**

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.



(Ref. 99)

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 45cm long by 6cm diameter giving a 1.2m diameter detection zone.

(b) Magnetic vehicle detector/track marker/communication link

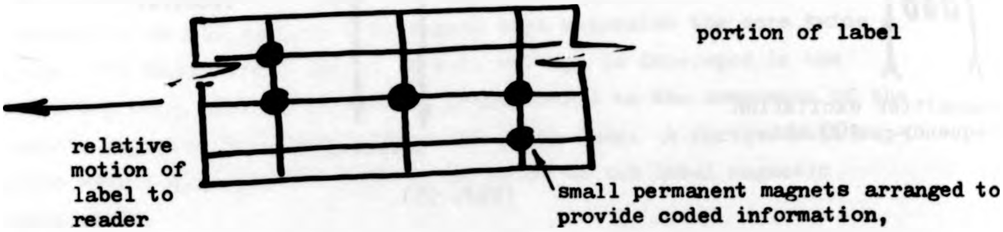
Vehicle mounted magnets are detected at the track using magnetically biased relays which change state when the local field reaches a threshold. Alternatively a detector coil as described in (a) above may be used.

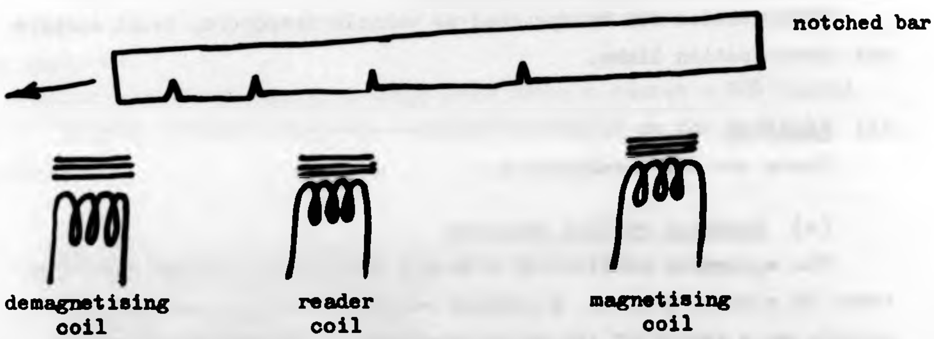
Communication link

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 magnetises 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) <u>Beamed Radiation</u>

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. α-particles and β-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 vunerable to such factors.

Ultrasonic systems are affected by strong winds which deflect the beam and heavy rain which attenuates it.

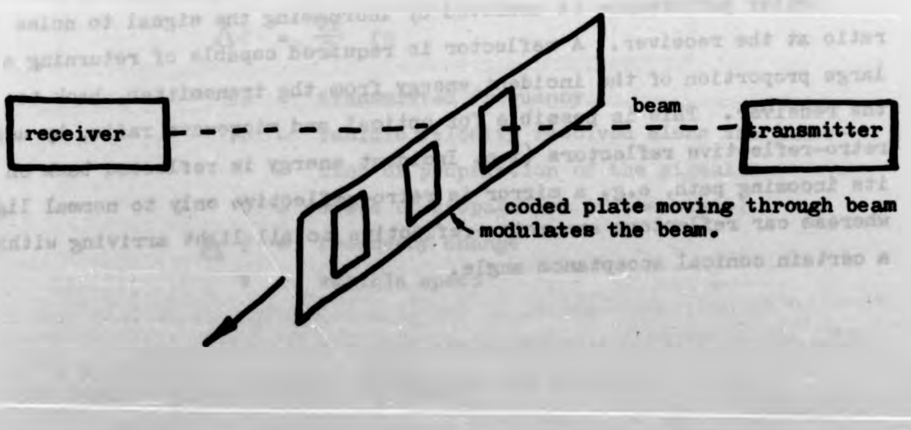
Microwave radio systems are unaffected by environmental factors but are more expensive.

α -particles and β -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.

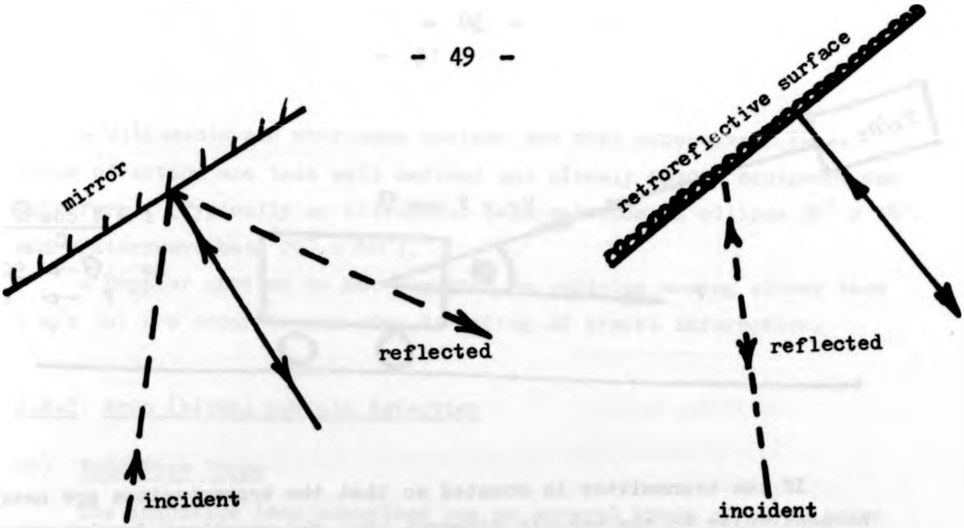
1) A carrier signal is transmitted continuously. The receipt of the echoed signal indicates vehicle presence. There is no discrimination between echoes resulting from the vehicle and those from nearby structures or between the transmitted signal and others at the same frequencies.

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 car 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)

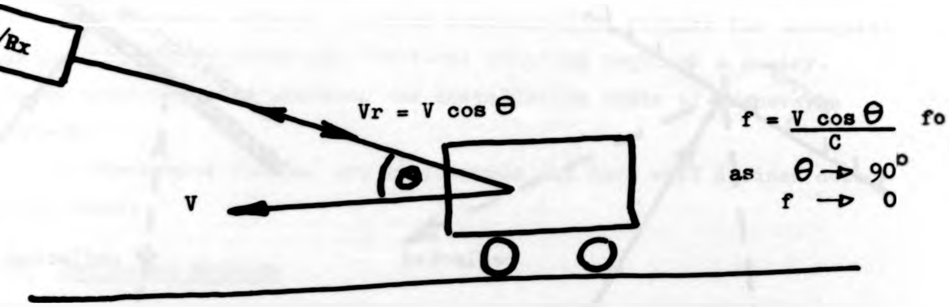
Only echoes corresponding to ranges in a certain band are accepted, thus discriminating between vehicle echoes and others.

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) Dopplar method - A continuous carrier wave is transmitted. Signals reflected back from moving objects are frequency shifted (i.e. the dopplar shift) by an amount proportional to the vehicle speed, according to the relationship

$$\Delta f = \frac{V_r}{C} f_o$$

fo = transmitted frequency
Vr = vehicle velocity resolved along the direction of propagation of the signal
C = speed of propagation of the signal
Δ f = frequency change
V = vehicle speed

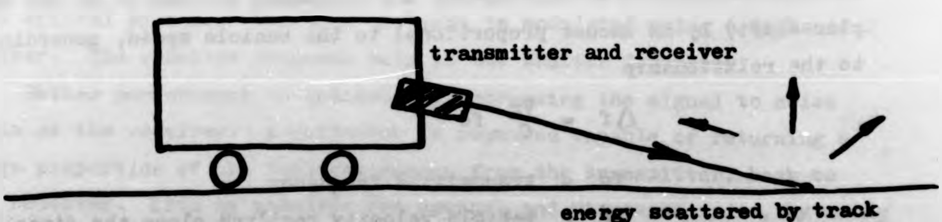


If the transmitter is mounted so that the transmissions are nearly perpendicular to the vehicle movement then the resultant dopplar shift will be small as the vehicle passes in range of the transmitter, regardless of vehicle speed.

<u>Dopplar used for speed measurement</u>

A beam directed longitudinally down the track such that $\Theta \rightarrow 0$ allows vehicle speed to be deduced from the dopplar 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.



<u>Communications</u>

See fixed point communications section 2.C.1.

<u>Characteristics of reflected energy methods</u>

- As only one mounting is required and alignment is less critical then 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° x 18° and a microwave beam 20° x 60°).

- Dopplar 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.

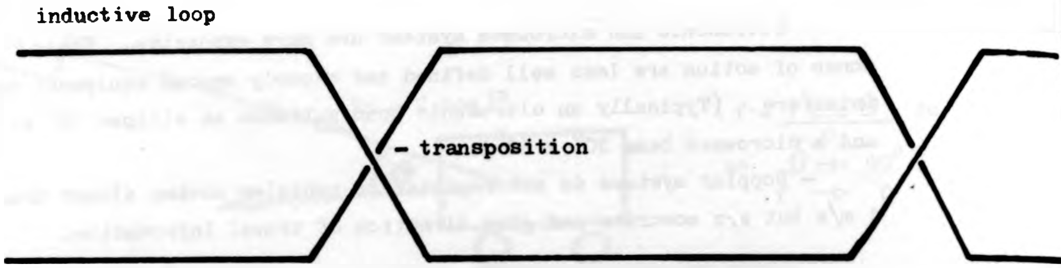
2) Communications

The mutual inductance between a vehicle mounted coil and the track coil allows the two-way transmission of modulated A.C. signals (see area communications section 2.C.2 no: 58).

3) Track marker

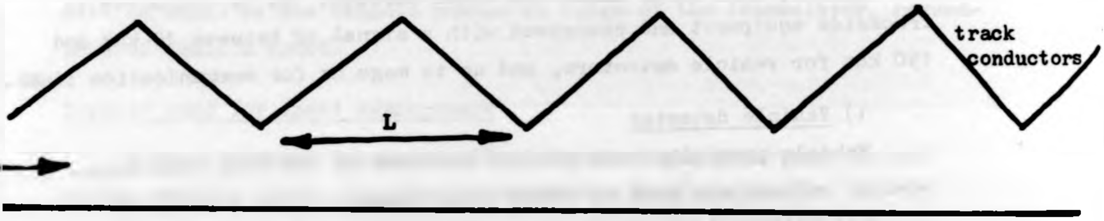
(a) A vehicle mounted loop antenna receiving transmissions from a small track loop yields a track marker device.

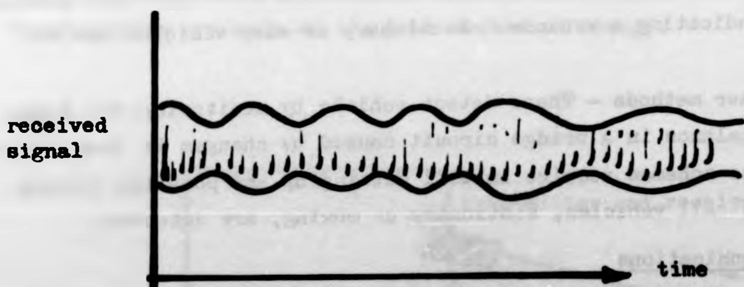
(b) A transposed inductive loop will introduce a 180° phase change in the received signal as the antenna crosses the transposition. This can be detected as a track marker.



4) Other devices

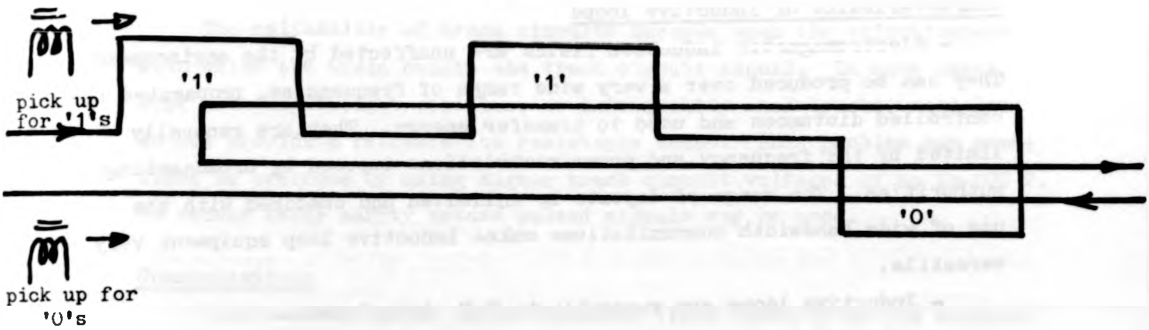
(a) If one of the two conductors is laid in a triangular form, an approximately sinusiod modulated signal is received by the vehicle.



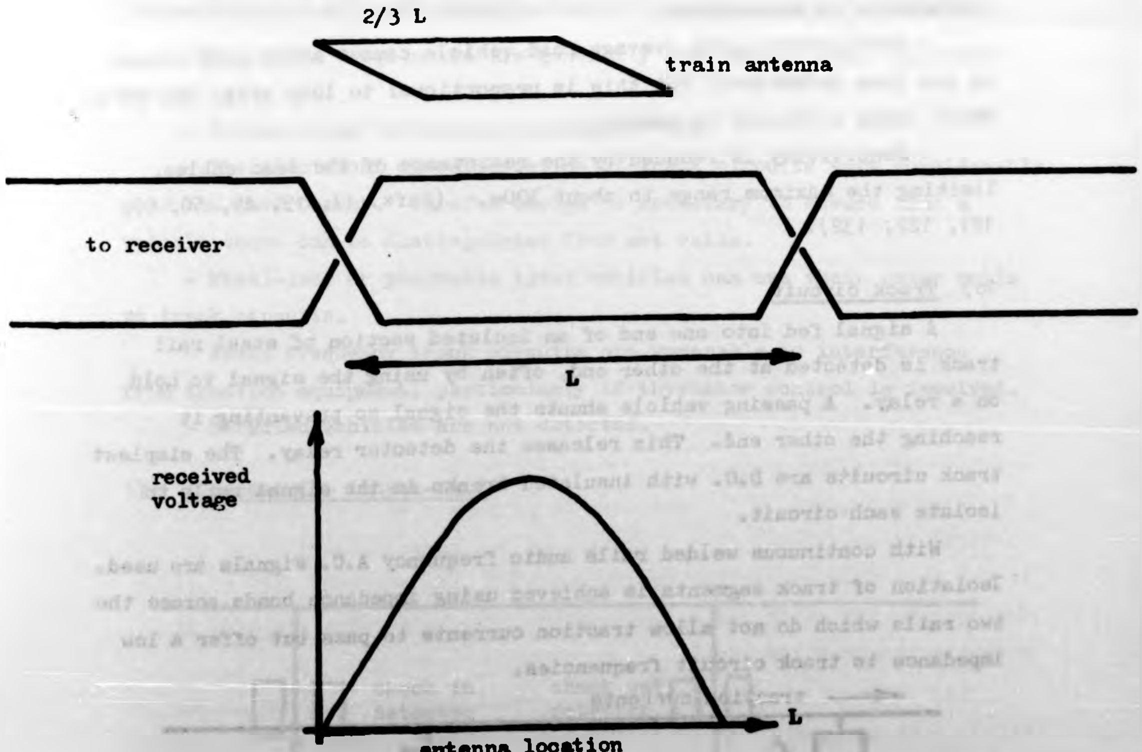


The modulation frequency = speed/L. The arrangement can be used either to provide a speed signal (with fixed L) or to encode track information read by the vehicle (with variable L) (see section 2.C.3 fixed point communications).

(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 vunerable 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 vunerable to damage and place constraints on maintenance.

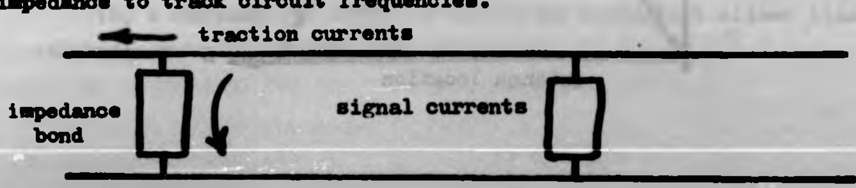
- Sensitivity - the average road vehicle causes about a 2% change in the loop inductance, but this is proportional to loop area, and makes small loops difficult to design.

- 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.

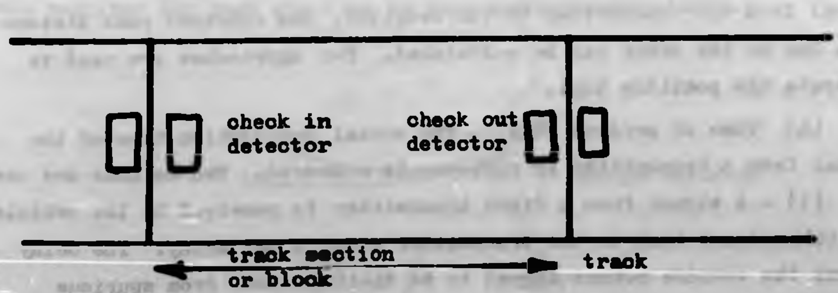
Communications

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 vunerable 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.

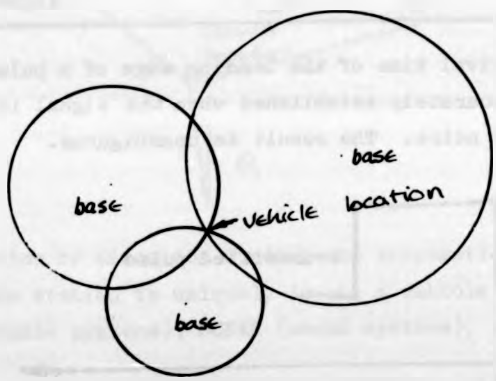
(a) Time of arrival (TOA) - The actual propagation time of the signal from a transmitter to receiver is measured. Two methods are used.

(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

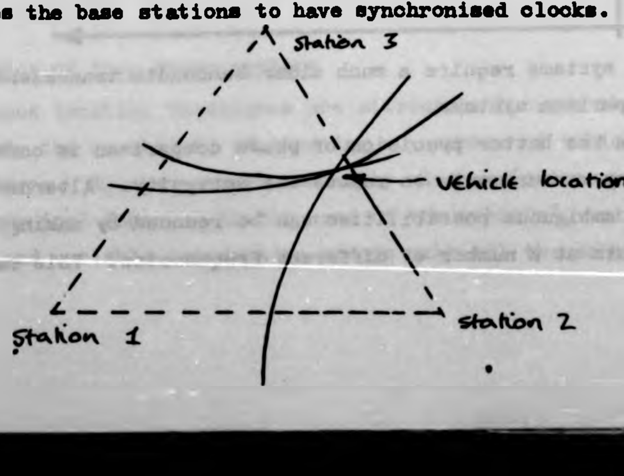
reflections. In environments where these spurious reflections are negligible the signal reflected from the vehicle structure can be used as the vehicle return signal. No active vehicle participation is required but range is limited, (see reflected beamed signals no. 14, and fixed point communications section 2.C.1).

(2) Both the vehicle and the fixed transmitter station are equipped with synchronized 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

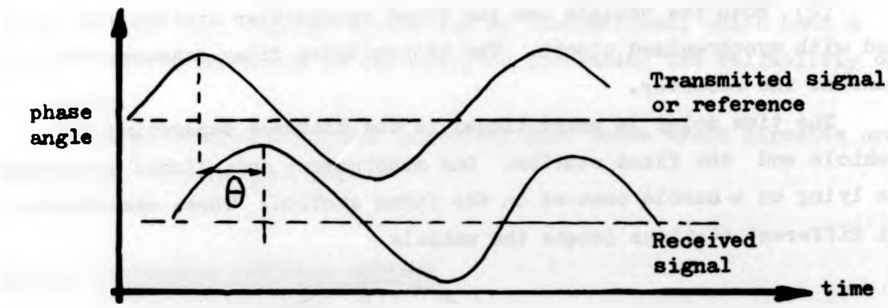


(b) Time difference of arrival TDOA - The vehicle broadcasts a signal. Three fixed stations measure the arrival time of the signal. This is subtracted from the arrival time of the same signal at one of the other stations. The information locates the vehicle as lying on a hyperbolic curve symmetrical about the base line between two stations. TDOA requires the base stations to have synchronised clocks.

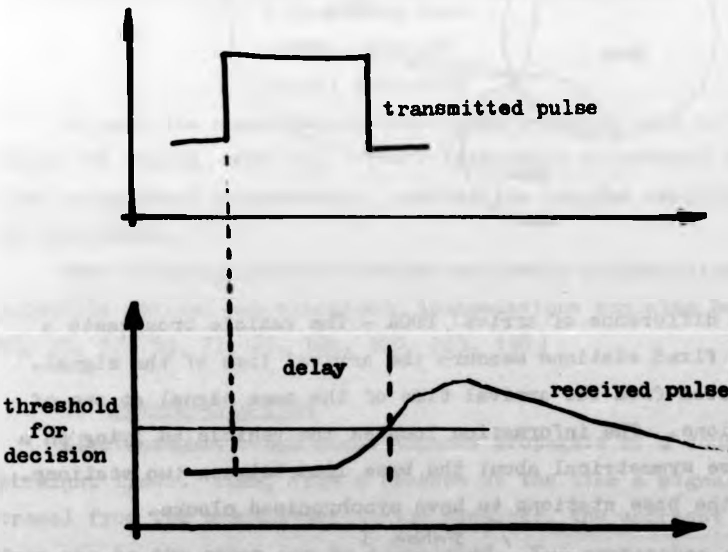


Methods used to measure the propagation time of signals

(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 $\longrightarrow \infty$



(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.

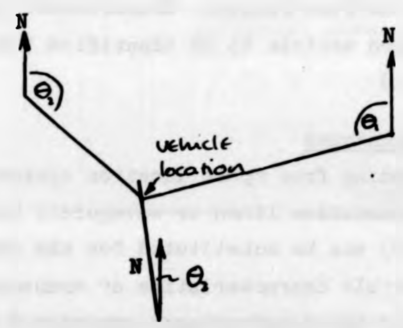
Often the better precision of phase comparison is combined with pulse delay measurements to remove the ambiguity. Alternatively the number of ambiguous possibilities can be reduced by making phase measurements at a number of different frequencies. This can yield very precise results in controlled environments and is the basis of land surveying using tellurometers etc.

2) Signal Strength

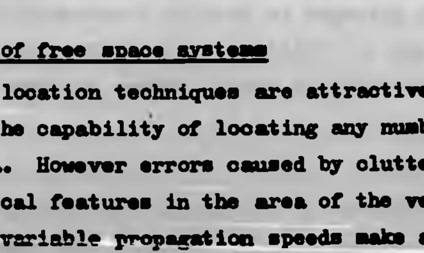
A number of remote stations measure the signal strength of a standardised vehicle transmission. Using previously plotted signal strength contour lines, the most likely vehicle location is determined.

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

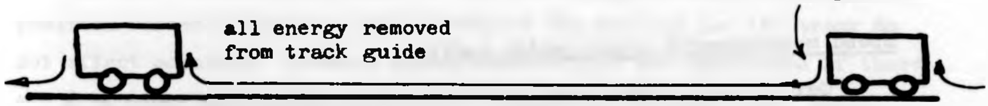
In all the preceding free space location systems, radio signals propagated along transmission lines or waveguides (see continuous communications nos. 57, 59) can be substituted for the free space radio link. The controlled and stable characteristics of transmission lines and waveguides removes most of 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

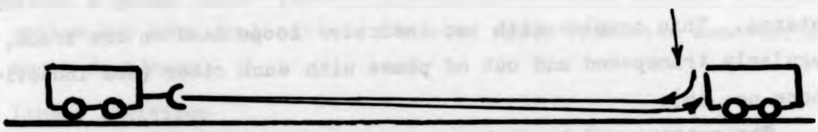
A particular feature of guided radio systems is the ability to couple energy into and out of the transmission line or waveguide and to propagate signals in one direction only down the line, without contacting or breaking the line or guide. This allows each of the techniques described above to be arranged 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

<u>Transmissive</u> -



<u>Reflective</u> -



1) <u>Propagation time</u>

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) <u>Signal strength</u>

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

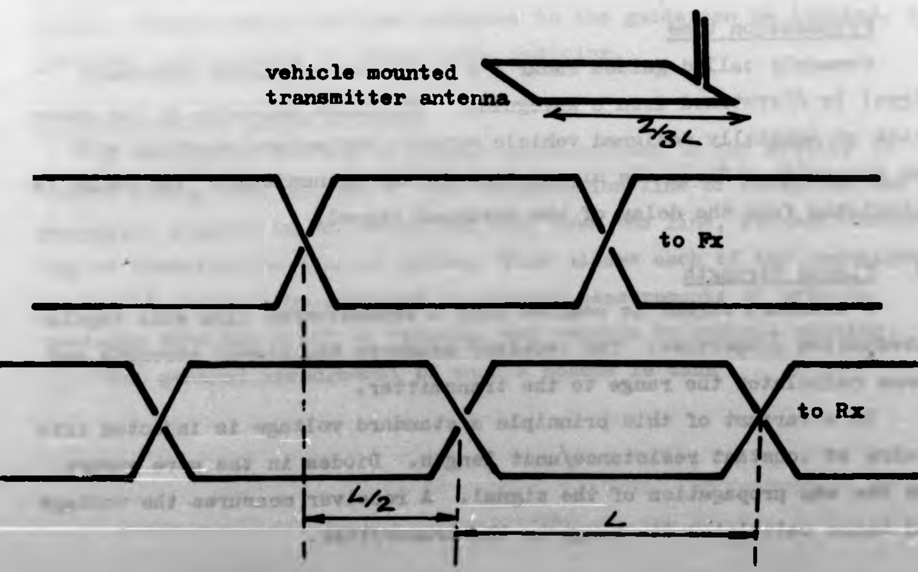
Guided radio techniques can be used to measure the speed of a vehicle. A signal reflected back from a moving vehicle will be dopplar shifted according to its speed (see Beamed Radiation no. 14).

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 x 2nL) n = , 0, 1, 2 .. This ambiguity is conveniently removed by counting the phase reversals of the received signal when the antenna passes the transpositions in the inductive loops.

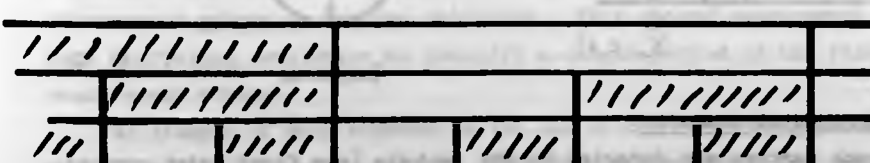
As only the relative phase of the two signals is used to calculate position variable coupling losses between the vehicle and the track do not affect accuracy. However significant errors are introduced if there are long transmission distances from vehicle to the receiver. These errors result from the unavoidable parameter differences of the two inductive loops.

21) <u>Linear Cam</u>

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) <u>Linear Digitiser</u>

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.



typical code structure

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 memorising each until the next is read. Any technique of fixed point communication (section 2.C.1) can be used to create such a structure, each change point being represented by a signpost holding the code for the next section.

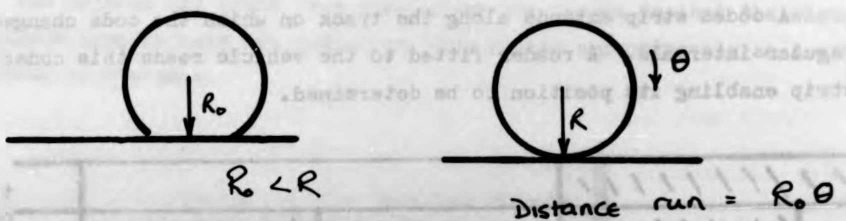
Digitisers are an absolute location system. An error at one point can be corrected at the next, and consequently systematic position errors do not build up.

23) <u>Integration</u>

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) <u>Wheel revolution counter</u>

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 5%.



25) <u>Incremental measures</u>

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

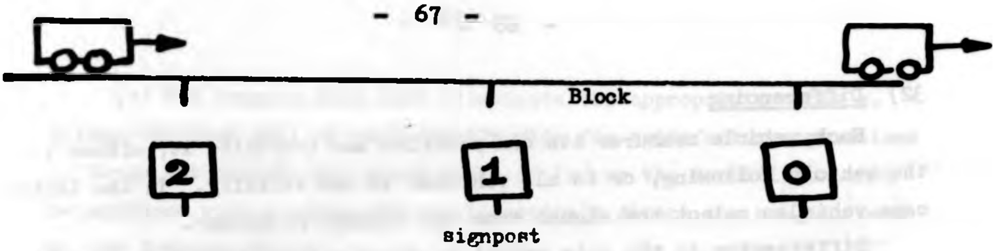
The proximity of another vehicle alters the capacitance measured by a probe on the front of the vehicle. The capacitance varies as a function of vehicle size and separation. Similar schemes can be devised using inductive loops or magnetic field detectors (see nos. 11, 13, 15).

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

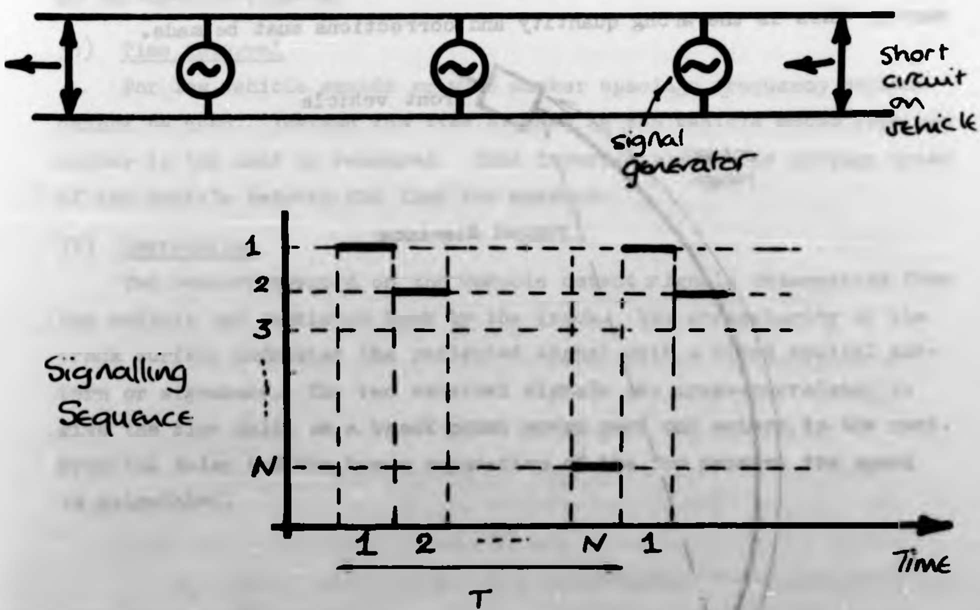
The track is divided into blocks (sections of track). A vehicle detected in one block causes coded messages to be displayed at each block upstream of the vehicle. A second vehicle following the first reads these messages and interprets them as the distance (in units of block length) separating the two 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 as 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.

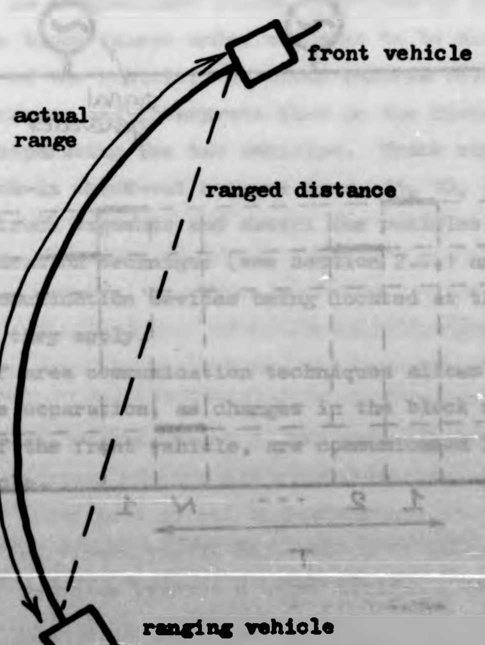
The same techniques can be applied to produce relative velocity signals.

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.



(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.3, no. 19.

2.B.5 Velocity Measurement

35) Frequency rate

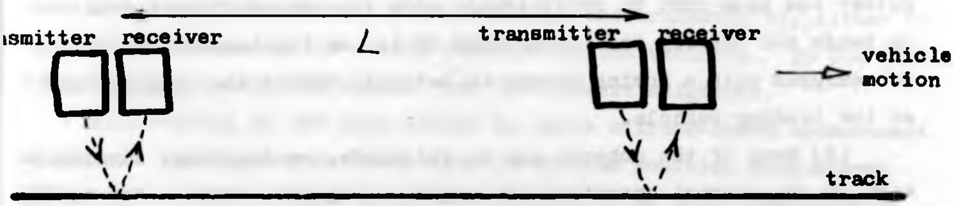
Regularly spaced track markers (see section 2.B.1, point position techniques) can be used to provide a vehicle based speed measurement. If the vehicle speed is sufficiently high and the markers closely spaced, the frequency that markers are passed yields a continuous measure of speed. The measurement 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.



(Refs. 46, 97)

38) <u>'Flicker' rate</u>

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

$$fo = \frac{\text{velocity x magnification factor}}{\text{line spacing}}$$

Due to the randomness of the surface the resulting signal is not a pure sine wave but has a power density spectrum spread around fo. 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) <u>Inductive tachometer</u>

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) <u>Dopplar methods</u>

See beamed radiation (no. 14) and free space or guided radio (nos. 18, 19).

41) <u>Magnetic gradient vehicle detector</u>

See M.G.V.D. no. 12.

42) <u>Integration</u>

Integration of acceleration yields speed (see no. 23).

43) <u>Differentiation</u>

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.

<u>2.B.6 Relative velocity measurements</u>

44) <u>Dopplar</u>

The relative velocity of two vehicles can be measured using Dopplar shift methods. (See beamed radiation, no. 14, free space systems no. 18 and guided radio no. 19).

45) <u>Differencing</u>

(See no. 32)

46) <u>Differentiation</u>

Relative position differentiated yields relative velocity (see no. 43).

47) <u>Free space systems</u>

(See no: 18)

48) <u>Guided radio systems</u>

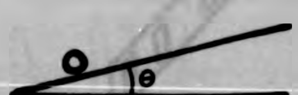
(See no: 19)

<u>2.B.7 Acceleration</u>

49) <u>Accelerometers</u>

All accelerometers apply the equation force/mass = acceleration

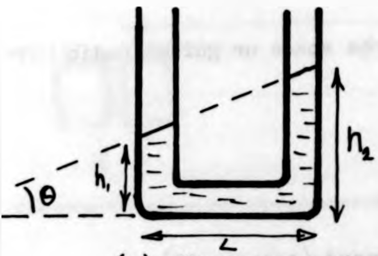
(a) Ball on an inclined plane.



The ball will roll up the plane if the acceleration $> g \tan \Theta$

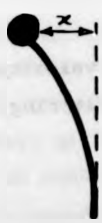
(g = acceleration due to gravity)

(b) Liquid in a U-tube



$$\text{acceleration} = \frac{g(h_2 - h_1)}{L}$$

(c) Mass on a spring



for small displacements

$x = k.M.a.$

M = mass

k = spring rate

a = acceleration

(d) Pendulum

$$\theta = \tan^{-1} \frac{a}{g}$$

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.

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)

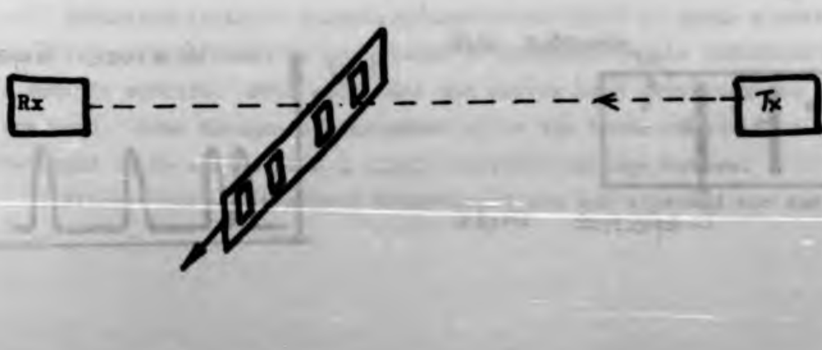
2.C.1 Point Communications

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, signposts, 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).

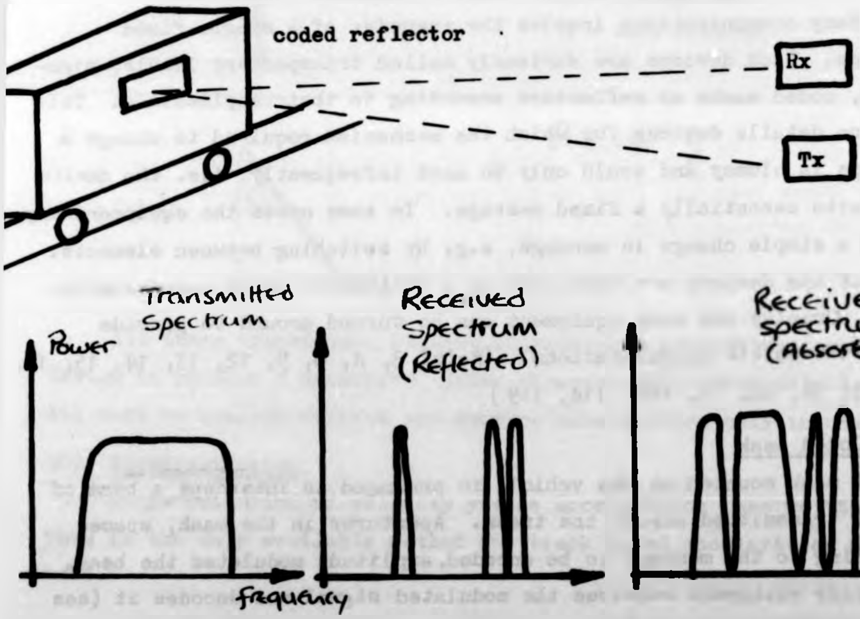


52) <u>Coded reflector</u>

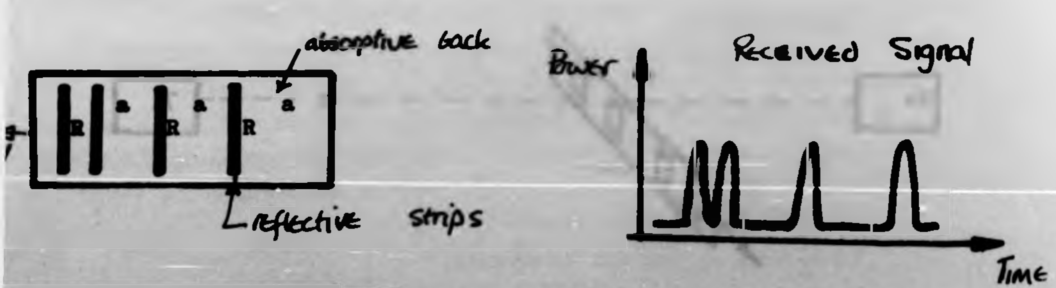
A vehicle mounted label reflects energy to a receiver when illuminated with an appropriate signal from a trackside transmitter (see beamed radiation no. 14).

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, 83, 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 trackside 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 khz 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 khz. 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 Ghz 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.A.1 BART (Bay Area Rapid Transit)

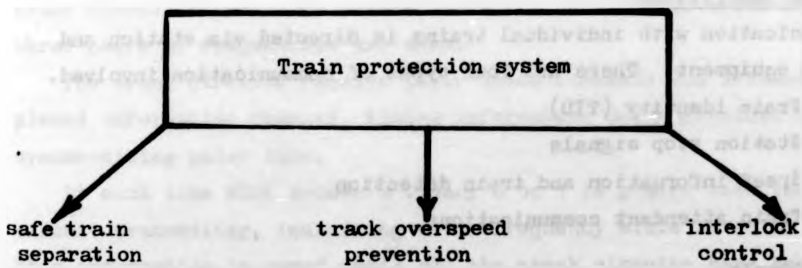
The Bay Area Rapid Transit is a computer supervised automatic rapid transit system in San Francisco. It features an extensive central control designed to optimise train running, and an innovative signalling system which is claimed to give a better, safer performance at a lower cost than could be attained using conventional techniques.

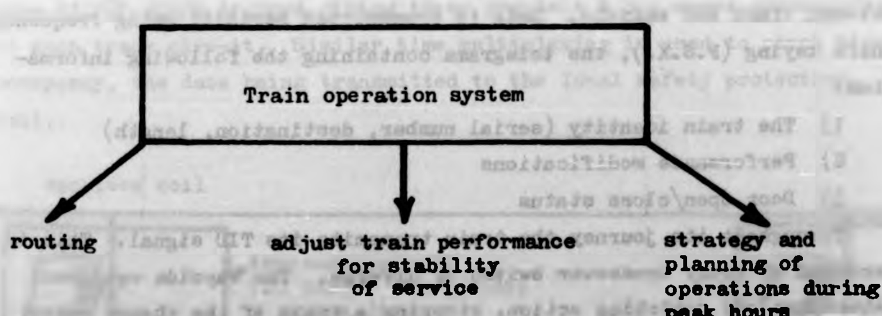
There are 120 km of track and 34 stations. Average journey speed is 80 km/h with a maximum speed of 130 km/h. Station stops are 20s and minimum headways are 90s.

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/close 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 cross-overs. 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.K. 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.

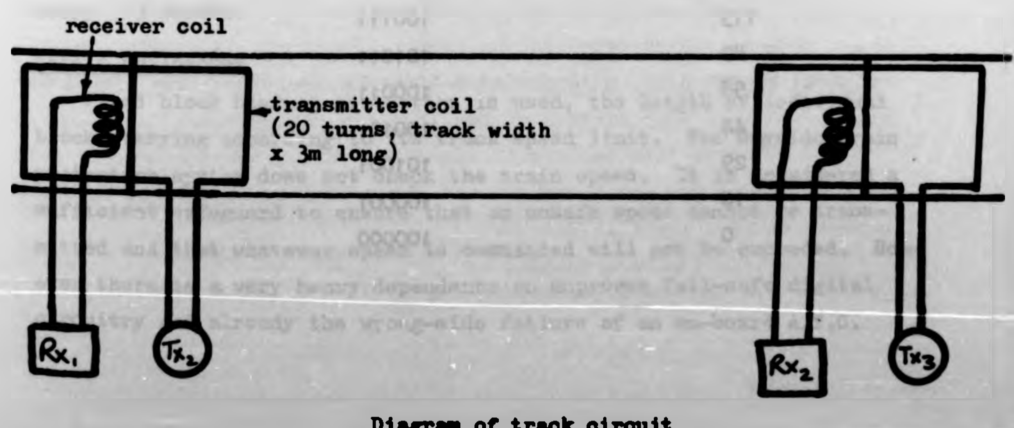
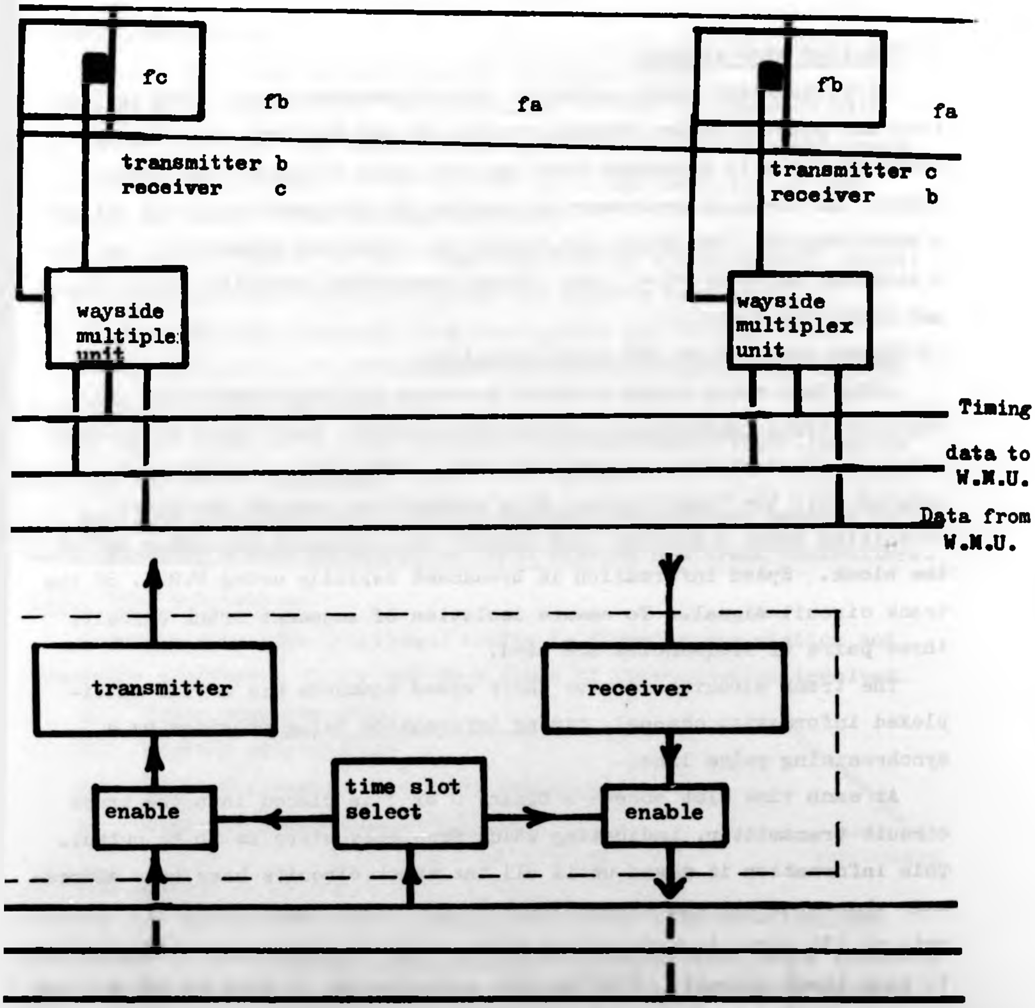


Diagram of track circuit



Wayside Multiplex Unit (W.M.U.)

Speed	Code
130 km/h	101111
113	100111
80	101011
58	100011
44	100101
29	101001
10	100001
0	100000

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 locked 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)

<u>3.A.2 Victoria Line</u>

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 cross-overs, 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.

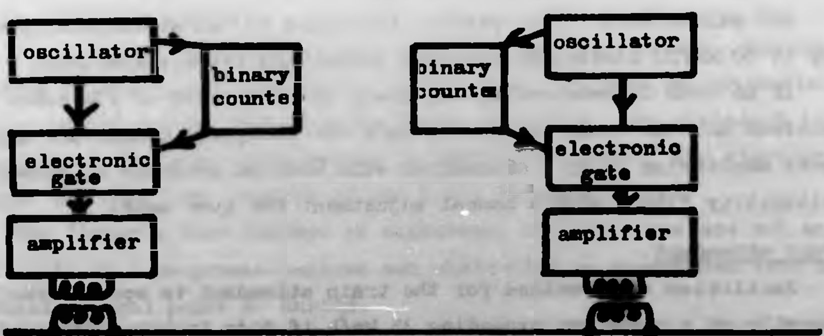
(b) Full duplex in-cab communication is provided called 'carrier-wave', which can be used at any time. A frequency modulated low frequency carrier signal is applied to the two conductor rails that carry the traction current. The track transmitter uses a frequency of 150 kHz.

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.

<u>The command system</u>

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.



Electrical circuits for command spots

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.

<u>Train identification</u>

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 28ms 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 proposed system contained 5.8 kms double guideway, six stations and 90 vehicles. The scale of the project has since been considerably reduced. The route is now 3.5 kms 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.

<u>Morgantown Control and Communications System (C & CS)</u>

The C & CS is divided into three functions:

(a) Central control and communications

(b) Station control and communications

(c) Guideway control and communications

(a) <u>Central control</u>

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) <u>Station control and communications (S.C.C.)</u>

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.

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) <u>London</u> (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.

<u>Operation</u>

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.

<u>Bristol</u>

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).

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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.

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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 " 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 " " "

$$T_1 = \frac{(V_i - V_1)}{a_1} + Q_1 \qquad \text{where } Q_1 = \left|\frac{a_1}{j_1}\right|$$

$$T_2 = \frac{(V_2 - V_i)}{a_2} + Q_2 \qquad \text{where } Q_2 = \left|\frac{a_2}{j_2}\right|$$

$$D_1 = \left(\frac{V_1 + V_i}{2}\right) . T_1$$

$$D_2 = \left(\frac{V_2 + V_i}{2}\right) . T_2$$

$$V_i = \frac{X - (D_1 + D_2)}{T - (T_1 + T_2)} \quad \text{.........} \quad (1)$$

$$(T_1 + T_2) = \frac{(V_i - V_1)a_2 + (V_2 - V_i)a_1 + a_1 a_2 (Q_1 + Q_2)}{a_1 a_2}$$

$$(D_1 + D_2) = \frac{1}{2a_1 a_2}\Big((V_i^2 - V_1^2)a_2 + (V_2^2 - V_i^2)a_1 + a_1 a_2 (Q_1 V_1 + Q_2 V_2)$$
$$+ a_1 a_2 (Q_1 + Q_2) V_i\Big)$$

From ① $V_i(T - (T_1 + T_2)) = X - (D_1 + D_2)$

$$LHS = TV_i - \frac{V_i}{a_1 a_2}\left[(V_i - V_1)a_2 + (V_2 - V_i)a_1 + a_1 a_2 (Q_1 + Q_2)\right]$$

$$RHS = X - \frac{1}{2a_1 a_2}\left[(V_i^2 - V_1^2)a_2 + (V_2^2 - V_i^2)a_1 + a_1 a_2 (Q_1 V_1 + Q_2 V_2) + a_1 a_2 (Q_1 + Q_2)V_i\right]$$

multiply by $2a_1a_2$ and collect terms

$$V_i^2(a_1 - a_2) + V_i\, 2\left(a_1 a_2 T + a_2 V_1 - a_1 V_2 - a_1 a_2 \left(\frac{Q_1 + Q_2}{2}\right)\right) + \left(a_1 a_2 (Q_1 V_1 + Q_2 V_2) - 2a_1 a_2 X - a_2 V_1^2 + a_1 V_2^2\right) = 0$$

using the standard solution for a quadratic equation and setting.

$$Z = T - \left[\frac{Q_1 + Q_2}{2}\right]$$

$$Y = Q_1 V_1 + Q_2 V_2$$

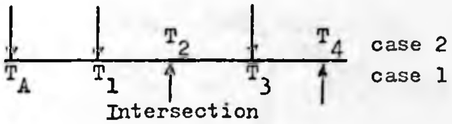
the final solution can be obtained after some algebraic manipulation. namely

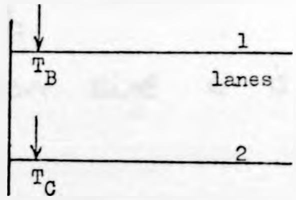
$$V_i = \frac{1}{(a_1 - a_2)}\left\{a_1 V_2 - a_2 V_1 - a_1 a_2 \left[Z \pm \left(Z^2 + \frac{1}{a_1 a_2}\left[(V_1 - V_2)^2 + \ldots\right.\right.\right.\right.$$

$$\left.\left.\left.\left.\ldots (a_2 - a_1)(Y - 2X) + 2(V_1 a_2 - V_2 a_1)Z\right]\right)^{1/2}\right\}$$

APPENDIX 4 Summary of lane change conditions for alternate priority

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.





Time diagrams

$T_1 = T_A + f$ f – following working time headway

$T_2 = T_A + c$ c – crossing working time headway

$T_3 = T_A + f + c$

$T_4 = T_A + 2c$

Diagram

The conditions for a change of lane allocation at the intersection may be summarised as follows.

1 <u>if</u> $T_B < T_1$
$T_C < T_2$

i.e. both vehicles will be delayed in both cases 1 and 2.

<u>then</u> vehicle B goes first, i.e. the lane allocation of the intersection will not change.

2(a) <u>if</u> $T_B > T_4$
$T_C < T_2$

<u>then</u> the lane allocation will change from 1 to 2, vehicle C will go first.

2(b) <u>if</u> $T_C > T_3$
$T_B < T_1$

<u>then</u> lane allocation will stay with lane 1, vehicle B will go first.

3 <u>if</u> $T_B > T_4$
$T_C > T_3$

<u>then</u> 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

$$p(t) = \lambda e^{-\lambda t}$$ is probability density that there is a gap of length t.

The probability of platoon size i is

$$P_i = \int_{t=0}^{\infty} P(i;t)\, p(t)\, dt$$

$$P(i;t) = \frac{k^i}{i!} e^{-k} \quad \text{where } k = \lambda t$$

$$dt = \frac{dk}{\lambda}$$

$$\therefore P_i = \int_{k=0}^{\infty} \frac{k^i}{i!} e^{-k} \lambda e^{-k} \frac{dk}{\lambda}$$

$$= \frac{1}{i!} \int_0^{\infty} k^i e^{-2k} dk$$

$$= \frac{1}{i!} \left[\frac{-1}{2} \left[k^i e^{-2k} \right]_0^{\infty} + \frac{i}{2} \int_0^{\infty} k^{i-1} e^{-2k} dk \right]$$

$$= \frac{1}{i!} \left[\frac{i}{2} \cdot \frac{i-1}{2} \cdots \frac{1}{2} \int_0^{\infty} e^{-2k} dk \right]$$

$$= \frac{1}{i!} \left[\frac{i!}{2^i} \cdot \frac{1}{2} \right] = \frac{1}{2^{i+1}}$$

$$\therefore P_0 = \tfrac{1}{2} \qquad P_1 = \tfrac{1}{4} \qquad P_2 = \tfrac{1}{8} \quad \text{etc}$$

If platoons of zero size are discounted then mean platoon size

$$= \sum_{i=1}^{\infty} i\, P_1^i \qquad \text{where } P_1' = \frac{P_1}{1-P_0}$$

$$= 2$$

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APPENDIX 7 Published papers

A number of papers have been published on the work reported in this thesis. They are as follows

1) L. Burrow and T. Thomas - - The performance of junction control strategies in a hierarchical urban transport system - ,I.E.E. conference 'Control aspects of new forms of guided land transport',London,28-30 aug,1974
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 polocies 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

Mr. Burrow and Dr. Thomas are members of the Inter University Institute for Engineering Control, Engineering Department, Warwick University.

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 close 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

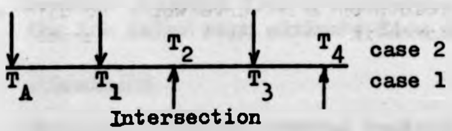
The comparison is carried out using the next vehicle in each lane to be allocated an intersection target.

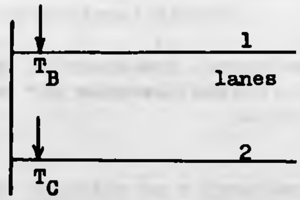
The total delay that would be incurred in each case is compared and the policy offering the lowest delay is the one adopted. This determines the next vehicle through the junction. The vehicle not allocated a target then participates in the next 'contest'.

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.





Time diagrams

$T_1 = T_A + f$ f – following working time headway

$T_2 = T_A + c$ c – crossing working time headway

$T_3 = T_A + f + c$

$T_4 = T_A + 2c$

Diagram

The conditions for a change of lane allocation at the intersection may be summarised as follows.

1 <u>if</u> $T_B < T_1$
$T_C < T_2$

i.e. both vehicles will be delayed in both cases 1 and 2.
<u>then</u> vehicle B goes first, i.e. the lane allocation of the intersection will not change.

2(a) <u>if</u> $T_B > T_4$
$T_C < T_2$

<u>then</u> the lane allocation will change from 1 to 2, vehicle C will go

first.

2(b) <u>if</u> $T_C > T_3$
$T_B < T_1$

<u>then</u> lane allocation will stay with lane 1, vehicle B will go first.

3 <u>if</u> $T_B > T_4$
$T_C > T_3$

<u>then</u> 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.
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)

<u>Conclusion</u>

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 be 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.

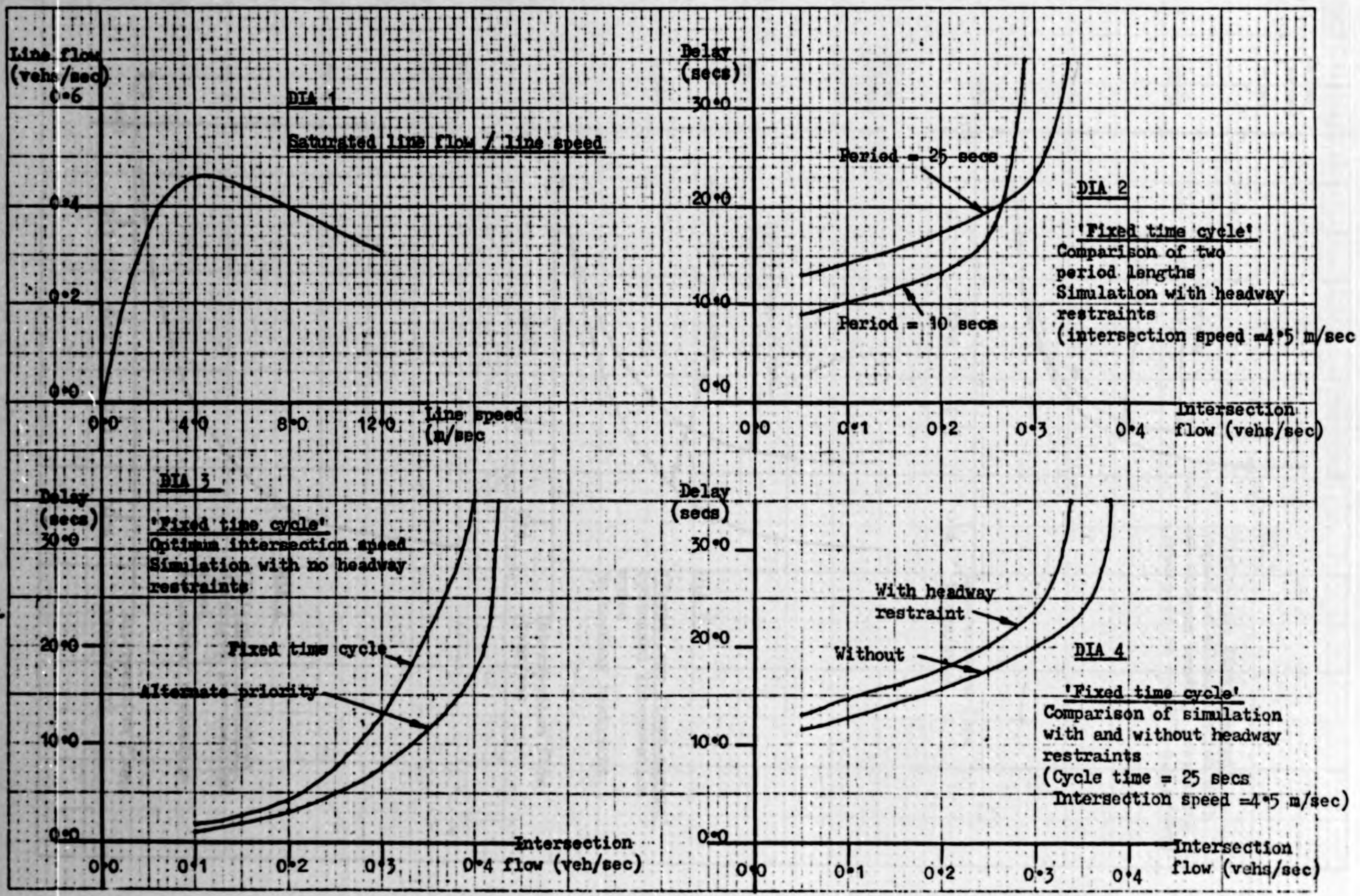
The 'alternate priority' policy generates platoons dependent upon the flow rate. This gives low delays at low flow rates but allows a high ultimate flow rate to be achieved.

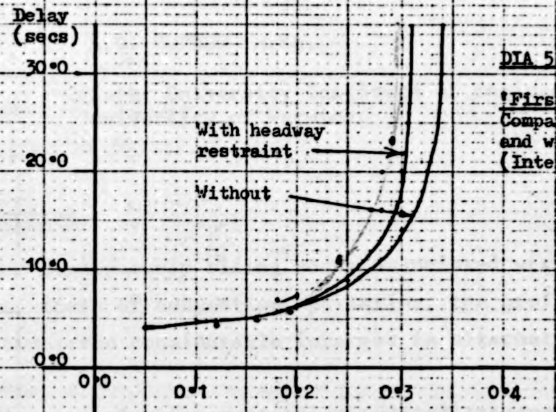
Appendix 1

The simulation parameters used were

Line speed	-	12.0 m/sec
Emergency deceleration	-	2.5 m/sec^2
Normal acceleration	-	1.25 m/sec^2
Following headway factor	-	1.2
Crossing headway factor	-	2.0
Vehicle length	-	4.0 m

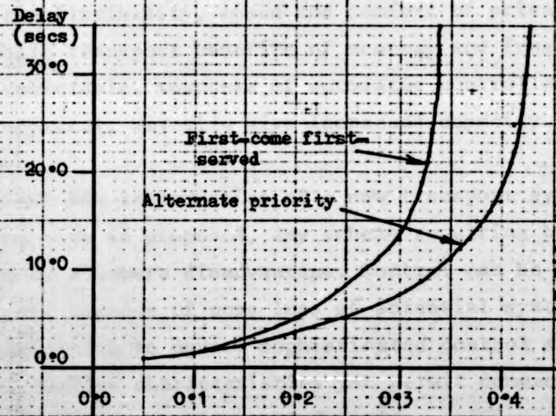
For the simulation including headway constraints control commenced 300 m before the intersection.


DIA 1
Saturated line flow / line speed
Line flow (vehs/sec)
0•6
0•4
0•2
0•0
0•0
4•0
8•0
12•0
Line speed (m/sec
DIA 2
'Fixed time cycle'
Comparison of two period lengths
Simulation with headway restraints
(intersection speed =4•5 m/sec
Delay (secs)
30•0
20•0
10•0
0•0
Period = 25 secs
Period = 10 secs
0•0
0•1
0•2
0•3
0•4
Intersection flow (vehs/sec)
DIA 3
'Fixed time cycle'
Optimum intersection speed
Simulation with no headway restraints
Delay (secs)
30•0
20•0
10•0
0•0
Fixed time cycle
Alternate priority
0•0
0•1
0•2
0•3
0•4
Intersection flow (veh/sec)
DIA 4
'Fixed time cycle'
Comparison of simulation with and without headway restraints
(Cycle time = 25 secs
Intersection speed =4•5 m/sec)
Delay (secs)
30•0
20•0
10•0
0•0
With headway restraint
Without
0•0
0•1
0•2
0•3
0•4
Intersection flow (vehs/sec)



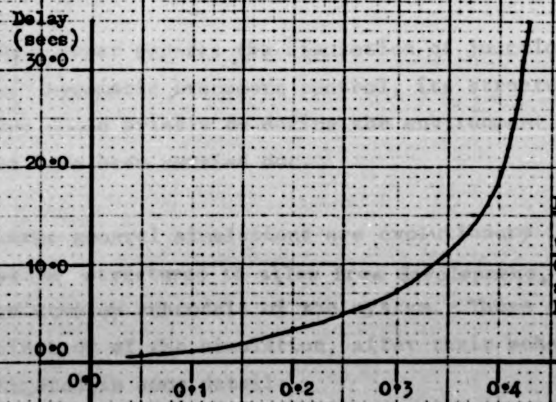
DIA 5

'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 restraints

THE SIMULATION OF JUNCTIONS IN AUTOMATIC URBAN TRANSPORT SYSTEMS USING INTERACTIVE GRAPHIC DISPLAYS

L.D. BURROW M.Sc.

Inter University Institute of Engineering Control
University of Warwick.

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 intro duced 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 emphasing 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.

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 independant 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 interdependant decisions involved.

(1) What future state is required of the vehicles?

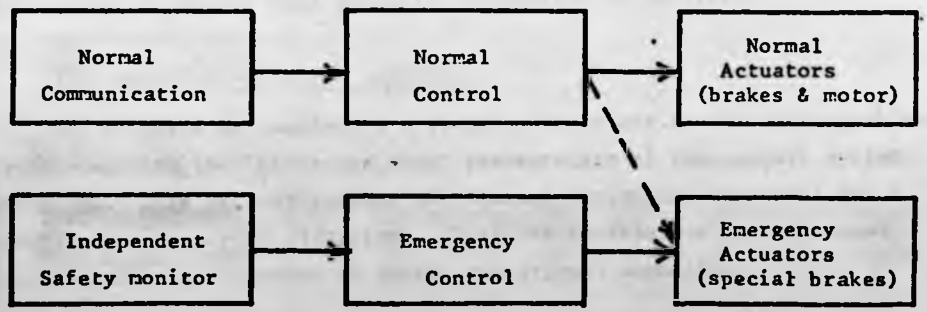
(2) What commands should be transmitted now to achieve that state?

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)



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, concommitant 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 unforseen 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 ba d, 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.

$$X_p = X_n + \left[X_{n-1} - X_n \right] \times g$$

$$Y_p = Y_n + \left[Y_{n-1} - Y_n \right] \times g$$

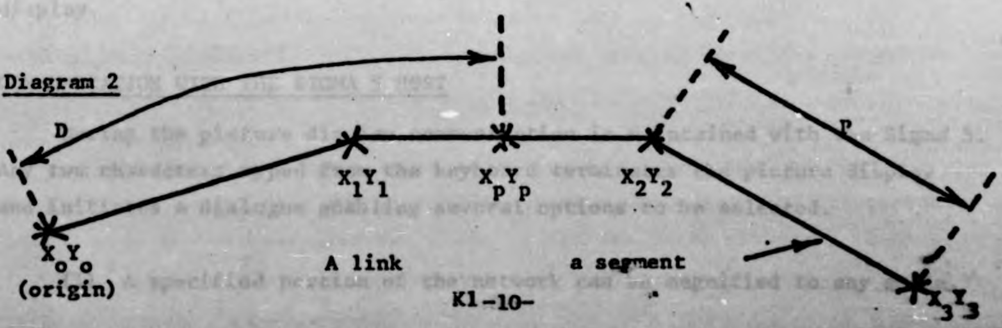
where n = integer part of $[D/P]$

g = fractional part of $[D/P]$

D = displacement of point from origin

P = length of one link segment

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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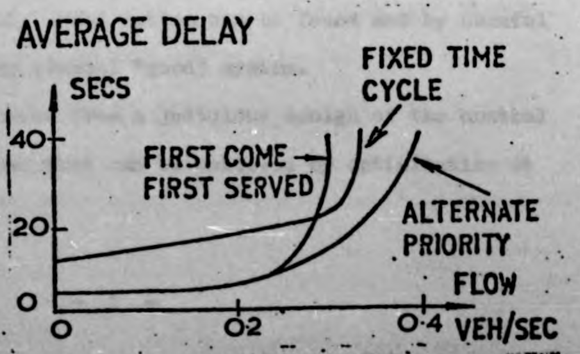
Diagram 3



UNIVERSITY OF WARWICK

Design of Control Systems in Automated Transport Systems

L. D. Burrow, M.Sc.,
Urban Transport Research
Group

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 these 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

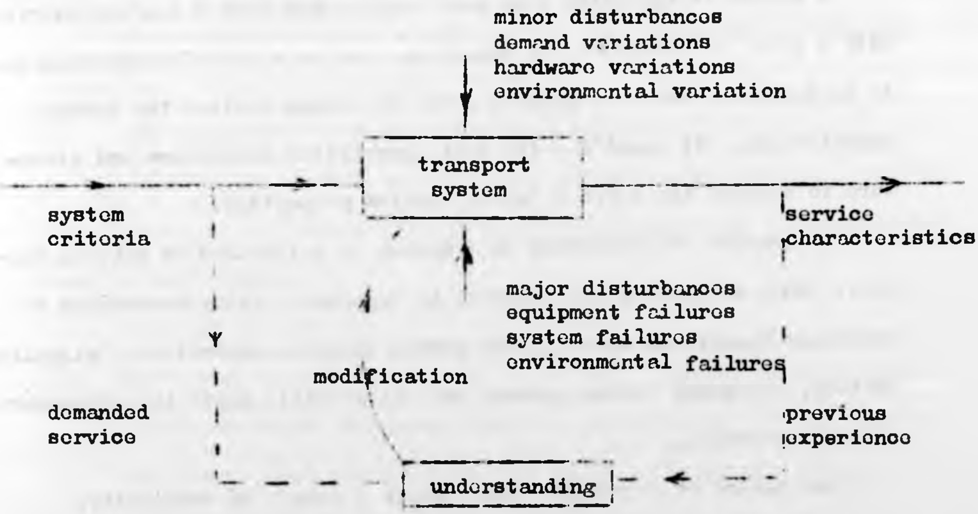
The process of optimisation is often presented as a highly exact process. Yet, if optimisation is taken in the general sense of meaning, the systematic approach to a situation, with a view to obtaining the best possible outcome, using what previous knowledge is available, then only in a few situations 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. Consqquently 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 centralized 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 vunerable 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:

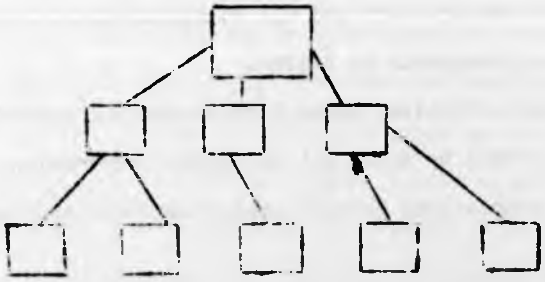
1) The system becomes more prone to software faults. An incomplete specification of subsystem states is more likely and may lead to undefined unsafe conditions. The greater number of subsystem states makes fault monitoring and rectification more difficult and costly.

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.



greater understanding
greater generality
longer time scales

greater detail
more specific information
shorter time scales

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 propogation 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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THE 'FAIL SOFT' DESIGN OF COMPLEX SYSTEMS

L.D. Burrow

Urban Transport Research Group, University of Warwick, UK

INTRODUCTION

Automation is increasingly being applied to large complex systems. Most of these systems are expensive to design, build and operate, their potential benefits are high but so also is the cost of their faulty running. Faults inevitably occur, more complex systems have correspondingly more faults. Contemporary automated systems are complex, they lack 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 may also prevent them being attained if the greater complexity leads to a reduction in system reliability. To maximise the operational effectiveness of the system the balance of system performance against system cost must take account of the effects of unreliability.

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 that 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 maintainance 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 Fault 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 conveniently splits into

1) 'Fail operational' design
2) 'Fail Soft' design

Both techniques are converned with the provision of flexibility in a system to make it less sensitive to the consequences of a failure. In both errors are detected and 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 degredation 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 degredation 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 subsystems.

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 degredation 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 subsystems
Duration	=	the time taken to restore the system to full operational effectiveness.

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 as to balance the cost of precautions against the potential disruption of an anticipated fault. A designer can only explicitly design for faults he has anticipated. His ability to forsee 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 to compensate for unexpected faults can only be taken at the time of failure. This on line 'design' action is carried out by the system operator involved with the fault. He is a part of the system and can be considered as a flexible, unspecialised, decision element. In many systems his role is the most

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 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 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. 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.

$$\text{Performance.} = \frac{\text{actual rate of profit generation}}{\text{maximum rate of profit generation}}$$

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 degredation 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 systems interface with its environment, 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) the processor can handle (analogue 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 route. 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
- Intensity of the fault
- Extent 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 distint 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 one-way communications, i.e. openloop operations. All of these policies reduce the potential performance of a system but improve their resistance to faults and therefore, may, with good designs improve, the operational performance of the system.

Time to restore service. Systems 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 effects 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 lower the delay a signal experiences the more up to date it will be and the more value it will have for control. The converse

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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 potential disruption is also a maximum, and 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. Alternatively 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 functional subsets 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 speed. All the system information is available everywhere so maximising the potential system performance. Centralised systems usually exploit the ability of digital machines to serve a large number of functions simultaneously by timesharing. Substantial numbers of high capacity communication links and complex resource allocation is required particularly if the system is spread over a geographically large area.

The use of a single resource shared by many users is governed by queuing type phenomena. Delays rise non-linearly with demand, near saturation delays increase rapidly and are highly variable, and performance is limited by the reaction speed of the processor. This sharing causes strong interactions between users. These are manifest by a requirement for cooperation or control to ensure an optimal sharing.

Centralised systems are vunerable to faults, particularly as informal links are easily created as the result of any type of failure. They are costly to make redundant, difficult to diagnose and expensive to maintain. (4)

Distributed Systems

An array of locally sited processors performing particular tasks are interconnected by 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 reconfigurations 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 vunerable 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 obsolescence. Duplicated standby 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. (5)

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 decouples the system but at the expense of reducing potential system performance.

The structure of hierarchies provides substantial inbuilt 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. (6)

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
$F(m) = F(m-1) = F(1)$
and the reliability with m components.
$R(m)$ is greater than $R(1)$
In the second approach failures cause a change in the transfer function of the unit but the redundancy is such that the function 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. transistor 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 a substantial body of theory exists. The onset of a failure can be considered as changing the transfer function of a systems 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 occurrance the output state of a device shifts outside permissable limits. The output state of a device depends on
1) Its design
2) Its environment
3) Its initialisation — settings
4) Its inputs — software
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 as 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. There are three classes of information associated with a function.
The states which correspond to the function specification and are therefore the correct states
The actual states generates by the function
The states accpeted 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 deplcyed 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 a 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 timedependency of disruption is governed by the timescale of the failed function. If repair times are short with respect to the failed time scale then there need only be minimal control of system disruption. If repair times are slow 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 are means of identifying and forstalling faults for minimum system disruption since by for example maintaining the system at weekends or during the night the necessary loss of service has minimum cost.

Interim Control of System Disruption
Switching Systems

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 requirements and so 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 standardised information is input. The information is chosen specifically to minimise 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 vunerable. 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 occurrance. 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 pratice. 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.

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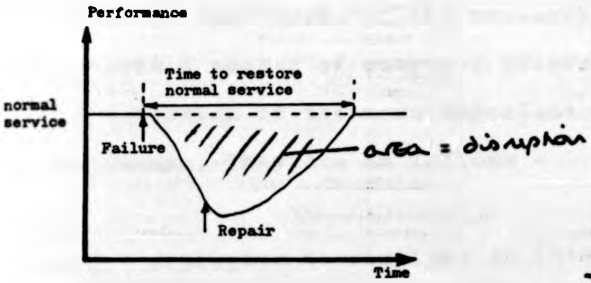
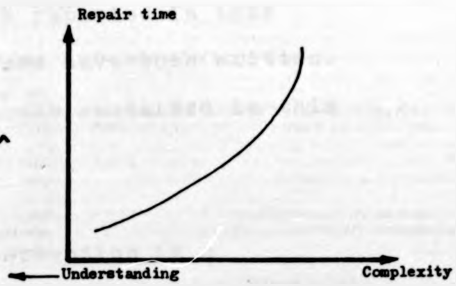
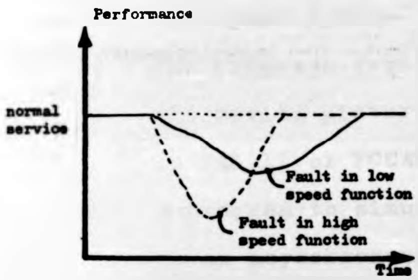


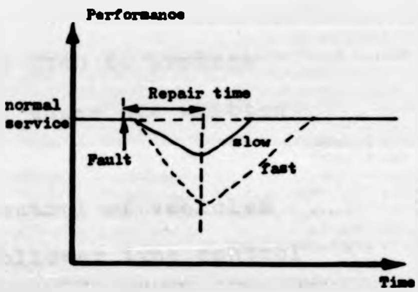
Dia. 1 – Time dependency of system performance following a fault



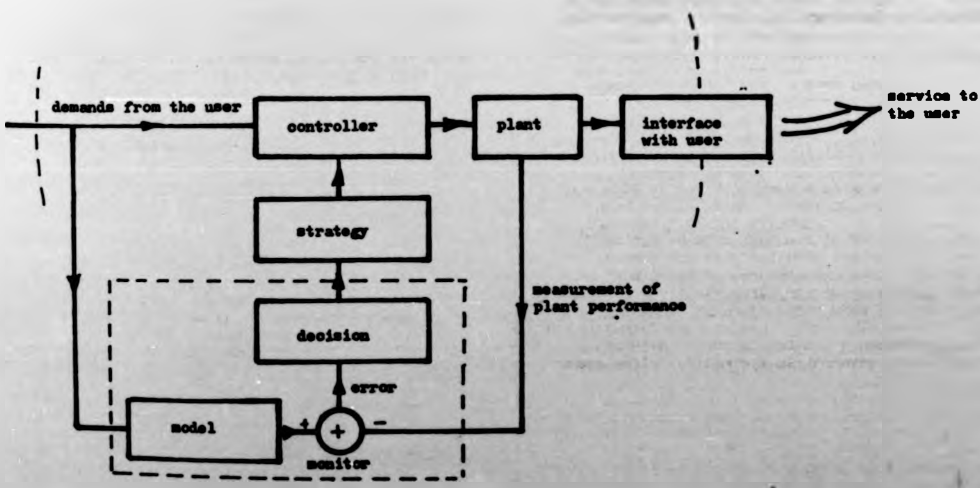
Dia. 3 – Effect of complexity on repair time



Dia. 2 – Fault performance of low speed function compared with that of a high speed function



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 11 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)

```
C
C THIS PROGRAM SIMULATES AN INTERSECTION WITH CONTINUOUS
C VEHICLE-FOLLOWER TYPE CONTROL.
C
C! STD (LO,LP),(DO,LO),(LL,LO)
C! PAUSE T3 TO TO
C!EXTRABGD
C!ALLOBT (FIL,G0),(RSI,30),(FOR,8),(FSI,950)
C!FORTRANH GO.S
      COMMON TARGET(100,4),VEHA(2,8,50),ITARG(2,50),IPOINT(2,2),
     CNAR(10),JPOINT(2),IFLOW(2),ITYPE,ITIME,DELT,LSPMAX,
     CLSPNML,ACCNML,ACCEMG,INTPOS,CRLPOS,SPEED,CONCON,FFHDWY,FCHDWY,
     CVELJNC,JFLOW,FTIME,AFLOW(3,3),LFLOW(3,2),IPARAM,PCOCC,OCCJNC,
     CTOSLIP,NVEH,DELAY(2,2,20),AVDEL(2,3),FACDEL(6),VL,
     CNOAH,TOTAL,TIMLAG,ISTA(2,2,50),AHDWY(100,2),MA(2,2),
     CP(2),PCOCCP(2),PEROCC(2),SLIPTO(2),TARRY,ITARRY
     C,NXVH(2)
     C,NBACK(100)
     C,KOUNT(2,2)
      INTEGER TBLOCK
      DIMENSION HSTA(50)
      REAL LSPMAX,LSPNML,INTPOS
      DIMENSION ASPACE(2),NNN(2)
C READ IN RUN DATA.
      READ(105,1)DELT,LSPMAX,LSPNML,ACCNML,ACCEMG,INTPOS,CRLPOS,SPEED,
     CCONCON,FFHDWY,FCHDWY,VL
      READ(105,2) JFLOW,IPRINT,ASPACE(1),ASPACE(2),NNN(1),NNN(2)
      READ(105,222)IPARAM,NVEH
      READ(105,110) TIMLAG,TOTAL,TSTOP
      READ(105,111)TBLOCK,NO,LANE,IPLOT
      READ(105,62)MAR
      READ(105,300) P(1),P(2)
      GOTO 5
    6 STOP
C WRITE HEADER.
    5 CONTINUE
      WRITE(108,79)
```

```
      WRITE(108,90)
      WRITE(108,3)DELT,LSPMAX,LSPNML,ACCNML,ACCEMG,INTPOS
      WRITE(108,82)
      WRITE(108,81)CRLPOS,SPEED,CONCON,FFHDWY,FCHDWY,VL
      WRITE(108,83)
      WRITE(108,4)JFLOW,IPRINT,ASPACE(1),ASPACE(2),NNN(1),NNN(2)
      WRITE(108,220)
      WRITE(108,221)IPARAM,NVEH,TIMLAG,TOTAL
      WRITE(108,223)
      WRITE(108,225)IPLOT,TBLOCK,NO,LANE
      WRITE(108,900)
      WRITE(108,901) P(1),P(2)
      WRITE(108,224)
C INITIALISE LOCAL COUNTERS.
      KFLOW=0
      FTIME =0
      NPRINT=0
      ITIME =0
      NPARAM=0
      NNO=0
      NPLOT=0
      IFLOW (1)=0
      IFLOW(2)=0
      DO 7 I=1,2
      DO 7 J=1,50
      STIME=0.
    7 ITARG(I,J)=0
C INITIALISE ALL SUBROUTINES.
      CALL SPACES(NNN,ASPACE)
      CALL VMOVE1
      CALL TAG1
      CALL DIS
      CALL WINIT
      CALL DIS1
      JFLAG=0
      IF (TBLOCK.EQ.1) GOTO 8
      CALL ILDWD
```

```
      PAUSE
C INITIALISE MOVING PICTURE DRAWING BY SENDING NETWORK TABLE TO GT40.
       CALL GRAPH1(.FALSE.,IPLOT)
    8 CONTINUE
      IF (ITIME*DELT.LT.TSTOP) GOTO 20
      ENDFILE 1
C END FILE ON MAGNETIC TAPE RECORD.
      CALL WRIFIN
      STOP
   20 CONTINUE
      IF (KFLOW.NE.JFLOW) GOTO 101
C CALCULATE HISTOGRAM.
      CALL DISTR1
      KFLOW=0
  101 CONTINUE
      IF (NPARAM.NE.IPARAM) GOTO 226
C CALCULATE MEANS AND STANDARD DEVIATION.
      CALL CRITE
      NPARAM=0
  226 IF (NPRINT.NE.IPRINT) GOTO 102
C OUTPUT DATA TO LINE PRINTER.
      CALL PRINT
      NPRINT=0
  102 IF (NPLOT.NE.IPLOT) GOTO 103
C OUTPUT DATA TO MAGNETIC TAPE FOR SUBSEQUENT PLOTTING.
      CALL WRITER(LANE)
      NPLOT=0
  103 CONTINUE
      IF (NNO.NE.NO) GOTO 19
      IF (TBLOCK.EQ.1) GOTO 19
C OUTPUT NEXT FRAME OF MOVING PICTURE.
      CALL GRAPH(JFLAG)
      IF (JFLAG.EQ.1) GOTO 6
      NNO=0
   19 CONTINUE
C INCREMENT COUNTERS.
      KFLOW=KFLOW+1
```

```
      NNO=NNO+1
      NPLOT=NPLOT+1
      NPARAM=NPARAM+1
      NPRINT=NPRINT+1
      ITIME =ITIME+1
C MANOEUVRE VEHICLES.
      CALL VMANOV
      CALL VMOVE2
C     MPLOT=(ITIME*DELT-STIME)/TIMLAG
C     IF (MPLOT.EQ.0) GOTO 8
      STIME=ITIME*DELT
C       IF (MAR(8).NE.0) GOTO 16
C     IF (MAR(7).NE.0) GOTO 13
      DO 10 I=1,2
      DO 10 J=1,2
      DO 11 K=1,50
   11 HSTA(K)=FLOAT(ISTA(I,J,K))/FLOAT(KOUNT(I,J))
C OUTPUT HISTOGRAMS OF HEADWAYS. (LANE BY LANE)
   10 CALL PLOTER(HSTA,50,.TRUE.,ITIME*DELT,J,I)
      GOTO 16
   13 CONTINUE
      DO 14 I=1,2
      DO 15 K=1,50
   15 HSTA(K)=(FLOAT(ISTA(1,I,K)+ISTA(2,I,K)))/FLOAT(KOUNT(1,I)+KOUNT(
     C2,I))
C (ALL LANES AVERAGE TOGETHER).
   14 CALL PLOTER(HSTA,50,.TRUE.,ITIME*DELT,I,3)
   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 TIME2')
  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,F20.3,2I20)
  224 FORMAT(//)
```

```
   1  FORMAT(6F10.3,/,6F10.3)
   2  FORMAT(2I10,2F10.7,2I10)
   4  FORMAT(T2,I9,I20,2F20.7,2I20)
  79  FORMAT(1H1,'RUN CONSTANTS ARE')
  90  FORMAT(1H0,'TIME INTERVAL',T20,'MAX LINE SPEED',T40,'NORMAL LINE S
     CPEED',T60,'NORMAL ACCN',T80,'EMERGENCY ACCN',T100,'POSN OF INTERSE
     CCTION')
 222  FORMAT(2I10)
  82  FORMAT(1H0,'POSN OF CONTROL',T20,'INITIAL JUNC SPEED',T40,'SERVO C
     CONSTANT',T60,'FOLLOWING FACTOR',T80,'CROSSING FACTOR',T100,'VEHICL
     CE LENGTH')
  83  FORMAT(1H0,'FLOW VEHICLES',T20,'PRINT TIME STEPS',T40,
     C'HEADWAY TYPE 1',T60,'HEADWAY TYPE 2',T80,'NO OF VEH/HDWY FRACTIIO
     C 1,2')
  62  FORMAT(10I1)
  81  FORMAT(T2,F 9.3,5F20.3)
   3  FORMAT(T2,F 9.3,5F20.3)
 110  FORMAT(3F10.3)
 111  FORMAT(4I)
 900  FORMAT(1H0,'LANE 1 PERIOD',T20,'LANE 2 PERIOD')
 901  FORMAT(F10.3,T20,F10.3)
 300  FORMAT(2F10.2)
      END
```

```
C
C THIS ROUTINE MOVES VEHICLES, ADDS VEHICLES AT ENTRANCE
C AND DELETES THEM AT EXIT.
C
      SUBROUTINE VMOVE1
      REAL LEEWAY
      REAL LSPMAX,LSPNML,INTPOS
      DIMENSION DSTACK(100,2)
      DIMENSION SPACEN(2)
      DIMENSION N4(2)
      LOGICAL EMERG(2,50)
      COMMON TARGET(100,4),VEHA(2,8,50),ITARG(2,50),IPOINT(2,2),
     CNAR(10),JPOINT(2),IFLOW(2),ITYPE,ITIME,DELT,LSPMAX,
     CLSPNML,ACCNML,ACCEMG,INTPOS,CRLPOS,SPEED,CONCON,FFHDWY,FCHDWY,
     CVELJNC,JFLOW,FTIME,AFLOW(3,3),LFLOW(3,2),IPARAM,PCOCC,OCCJNC,
     CTOSLIP,NVEH,DELAY(2,2,20),AVDEL(2,3),FACDEL(6),VL,
     CNOAH,TOTAL,TIMLAG,ISTA(2,2,50),AHDWY(100,2),MA(2,2),
     CP(2),PCOCCP(2),PEROCC(2),SLIPTO(2),TARRY,ITARRY
     C,NXVH(2)
     C,NBACK(100)
     C,KOUNT(2,2)
      DIMENSION DTIME(2)
      DIMENSION ISECT(2)
      IF (NVEH.EQ.0) NOAH=20
      IF (NVEH.NE.0) NOAH=NVEH
C INITIALISATION.
      ICOUNT =0
      ISECT(1)=1
      ISECT(2)=1
      MA(1,1)=1
      MA(1,2)=1
      MA(2,1) =1
      MA(2,2)=1
      DTIME(1)=0.
      DTIME(2)=0.
      DO 9 I=1,2
      DO 20 J=1,50
```

```
      VEHA(I,3,J)=0.0
   20 EMERG(I,J)=.FALSE.
      IPOINT(I,1)=50
      IPOINT(I,2)=2
      VEHA(I,1,1)=0
      VEHA(I,2,1) =LSPNML
      VEHA(I,3,1) =0
      EMHDWY =(LSPNML*LSPNML/(2*ACCEMG)+VL)
      VEHA(I,4,1) =EMHDWY*FFHDWY
      VEHA(I,5,1) =0
      VEHA(I,6,1) =99999
      VEHA(I,7,1) =EMHDWY
      N4(I)=1
      LFLOW(1,I)=1
      LFLOW(2,I)=0
      LFLOW(3,I)=0
      DO 209 J=1,2
      DO 209 K=1,NCAH
  209 DELAY(I,J,K)=0
    9 CONTINUE
      CALL SPACE(SPACEN(1),1)
      CALL SPACE(SPACEN(2),2)
      RETURN
C
      ENTRY VMOVE2
      DO 10 I=1,2
C FRONT VEHICLE.
      N2 =IPOINT(I,2)-1
      IF (N2.EQ.0) N2=50
      POSN=99999.+EMHDWY*FFHDWY
C NO VEHICLES IN LANE.
      IF (N2.EQ.IPOINT(I,1)) GOTO 1
      POSN = VEHA(I,3,N2)
C IS VEHICLE DUE TO ENTER JUNCTION?
    1 IF(ABS(ITIME*DELT-SPACEN(I)).GT.DELT/1.5) GOTO 11
   12 N2 =IPOINT(I,2)
      CALL PRINT1('VEHICLE ENTERING JUNCTION AT',ITIME*DELT,28,I,N2)
```

```
C INITIALISE VARIABLES.
      VEHA(I,1,N2) =0
      VEHA(I,2,N2) =LSPNML
      VEHA(I,3,N2) =0
      VEHA(I,4,N2) =EMHDWY*FFHCWY
      VEHA(I,5,N2) =0
      VEHA(I,6,N2) =POSN=VEHA(I,4,N2)
      VEHA(I,7,N2) =EMHDWY
C INCREMENT QUEUE POINTER.
      IPOINT(I,2) =IPOINT(I,2)+1
      IF (IPOINT(I,2).EQ.51) IPOINT(I,2)=1
C FIND HEADWAY TO NEXT INCIMONG VEHICLE.
      CALL SPACE(SPACEN(I),I)
      CALL DISRIB(SPACEN(I),I,1)
      SPACEN(I) =SPACEN(I)+ITIME*DELT
      LFLOW(1,I)=LFLOW(1,I)+1
   11 IF (N2.EQ.IPOINT(I,1)) GOTO 10
      N1 = IPOINT(I,1) +1
      IF (N1.EQ.51) N1=1
      POSN =VEHA(I,3,N1)
      BOUNDJ =2*INTPOS
C HAS VEHICLE LEFT JUNCTION?
      IF (POSN-BOUNDJ)14,14,13
   13 LFLOW(3,I)=LFLOW(3,I)+1
      CALL PRINT1('VEHICLE LEAVING JUNCTION AT',ITIME*DELT,28,I,N1)
C SAVE DELAY VARIABLES.
      DELAY(1,I,N4(I))=VEHA(I,8,N1)
      DELAY(2,I,N4(I))=VEHA(I,5,N1)
      DSAVE=VEHA(I,5,N1)
      CALL DISTR2(VEHA(I,5,N1),I)
      CALL CRITE1(DSAVE,I)
      VEHA(I,3, N1)=0.0
      N4(I)=N4(I)+1
      IF (N4(I).EQ.NOAH+1) N4(I)=1
      IPOINT(I,1) =N1
      N1=N1+1
      IF (N1.EG.51) N1=1
```

```
      VEHA(I,6,N1) =99999
      ICOUNT=ICOUNT+1
      IF (ICOUNT-NOAH.LT.0) GOTO 14
      IF (DTIME(I).NE.0.) GOTO 116
      DTIME(I)=ITIME*DELT
      GOTO 14
C FIND TIME HEADWAY AT EXIT.
 116  THDWY =ITIME*DELT-DTIME(I)
      CALL DISRIB (THDWY,I,2)
      DTIME(I)=ITIME*DELT
      AHDWY(MA(I,1),I)=THDWY
      DSTACK(MA(I,1),I)=DSAVE
      MA(I,1)=MA(I,1)+1
      IF (MA(I,1).LE.90) GOTO 30
      MA(I,1)=1
C WRITE BLOCK OF HEADWAYS TO DISK FOR RECYCLING OF OUTPUTS TO INPUTS.
      CALL DISKWT(ISECT(I),AHDWY(1,I),I)
      ISECT(I)=ISECT(I)+1
      IF (ISECT(I).EQ.13) ISECT(I)=1
      AHDWY(91,I)=I
      AHDWY(92,I)=ITIME*DELT
      DSTACK(91,I)=I
      DSTACK(92,I)=ITIME+DELT
C SAVE ON MAG TAPE, HEADWAY INFORMATION FOR DISTRUBUTION CALCULATION.
      CALL BUFFEROUT(22,1,DSTACK(1,I),92,IST)
      CALL BUFFEROUT(22,1,AHDWY(1,I),92,IST)
  30  CONTINUE
 14   N2 =IPOINT(I,2)-1
      IF (N2.EQ.0) N2=50
      IF (N2.EQ.IPOINT(I,1)) GOTO 10
      N1 =IPOINT(I,1)+2
      IF (N1.EQ.51) N1=1
      IF (N1.EQ.52) N1=2
      IF (N1.EQ.IPOINT(I,2)) GOTO 58
      J=N1
  15  CONTINUE
      N3=J-1
```

```
      N2=IPOINT(I,2)+1
      IF (N3.EQ.0) N3=50
      POSN1=VEHA(I,3,N3)
      POSN2=VEHA(I,3,J)
      DIST=POSN1-POSN2
C CHECK THAT VEHICLES ARE SEPARATED BY MORE THAN MINIMUM HEADWAY.
      IF (VEHA(I,6,J))16,16,17
   16 EMHDWY=VEHA(I,7,J)
      IF (DIST-EMHDWY)18,18,19
   18 IF (EMERG(I,J))GOTO 21
      CALL PRINT1('EMERGENCY HEADWAY INFRINGED AT',ITIME*DELT,31,I,J)
      EMERG(I,J) =.TRUE.
      STOP 1
   21 ACCN =-ACCEMG
      GOTO 22
   19 IF (.NOT.EMERG(I,J))GOTO 23
      CALL PRINT1('EMERGENCY DECN END AT',ITIME *DELT,22,I,J)
      EMERG(I,J) =.FALSE.
   23 GOTO 24
   17 IF (ITARG(I,J).NE.0)GOTO25
C CALCULATE ACCELERATION TO APPLY TO VEHICLE.
   24 ACCN =VEHA(I,6,J)*CONCON/VEHA(I,4,J)
      IF (ABS(ACCN).LT.ACCNML)GOTO 26
      ACCN =SIGN(ACCNML,ACCN)
   26 VEL =VEHA(I,2,J)
      IF ((VEL.LE.0).AND.(ACCN.LT.0)) ACCN=0
      IF ((VEL.GE.LSPMAX).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.51) J=1
      GOTO 15
   58 N1=IPOINT(I,1)+1
      IF (N1.EQ.51) N1=1
```

```
      N2=IPOINT(I,2)-1
      IF (N2.EQ.0) N2=50
      J=N1
   27 CONTINUE
      U=VEHA(I,2,J)
      IF (U.GT.0) GOTO 208
      U=0
C MOVE VEHICLES FORWARD ONE TIME INCREMENT.
  208 A=VEHA(I,1,J)
      V=U+A*DELT
      VEHA(I,2,J)=V
      S=U*DELT+A*DELT*DELT/2
      POSN=VEHA(I,3,J)+S
      VEHA(I,3,J)=POSN
      DELAYV=DELT-S/LSPNML
      VEHA(I,5,J)=VEHA(I,5,J)+CELAYV
      EMHDWY=V*V/(2*ACCEMG)+VL
      HDWY=EMHDWY*FFHDWY
      IF(J.EQ.N1) GOTO 28
      N3=J-1
      IF (N3.EQ.0) N3=50
      LEEWAY=VEHA(I,3,N3)-POSN-HDWY
      VEHA(I,6,J)=LEEWAY
   28 VEHA(I,7,J)=EMHDWY
      VEHA(I,4,J)=HDWY
      IF (J.EQ.N2)GOTO 10
      J=J+1
      IF (J.EQ.51) J=1
      GOTO 27
   10 CONTINUE
      RETURN
      END
```

```
C
C
      SUBROUTINE VMANOV
      LOGICAL FLAG
      REAL LSPMAX,LSPNML,INTPOS
      COMMON TARGET(100,4),VEHA(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,CONCON,FFHDWY,FCHDWY,
     CVELJNC,JFLOW,FTIME,AFLOW(3,3),LFLOW(3,2),IPARAM,PCOCC,OCCJNC,
     CTOSLIP,NVEH,DELAY(2,2,20),AVDEL(2,3),FACDEL(6),VL,
     CNOAM,TOTAL,TIMLAG,ISTA(2,2,50),AHDWY(100,2),MA(2,2),
     CP(2),PCOCCP(2),PEROCC(2),SLIPTO(2),TARRY,ITARRY
     C,NXVH(2)
     C,NBACK(100)
     C,KOUNT(2,2)
      THDWYE=SPEED/(2.*ACCEMG)+VL/SPEED
      THDWYCO=THDWYE*(FCHDWY+FFHDWY)/2.
        SA=LSPNML*LSPNML/ACCNML
      DO 37 I=1,2
      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 37
      J=N1
    6 POSN=VEHA(I,3,J)
      FLAG=.FALSE.
      ACCN=0
      IF  (POSN-CRLPOS)39,40,4C
C HAS VEHICLE ENTERED JUNCTION CONTROL ZONE?
   40 IF (POSN-INTPOS+0.5)41,42,42
   41 M=ITARG(I,J)
      IF (M.NE.0)GOTO 44
        CALL PRINT1('VEH CROSSING CONTROL BOUNDARY AT',ITIME *DELT,33,
     CI,J)
C GIVE IT A TARGET NUMBER.
      CALL TAG3(I,J)
```

```
      IFLOW(I)=IFLOW(I)+1
      M=ITARG(I,J)
   44 CONTINUE
      UV=VEHA(I,2,J)
      UJ=TARGET(M,2)
      S=ABS((UV*UV-UJ*UJ)/(2*ACCNML))
      DTTJ=(INTPOS-POSN)
      IF (DTTJ.GT.S) GOTO 52
C CALCULATE INTERMEDIATE SPEEDS FOR ALL VEHICLES IN CONTROL ZONE
C PRIOR TO INTERSECTION.
      ACCN=-ACCNML
      IF (UV.LT.UJ)ACCN=ACCNML
      GOTO 39
   52 TTTJ =TARGET(M,1)-ITIME*DELT
      IF (TTTJ.GT.0.) GOTO 700
      FLAG=.TRUE.
      UI=LSPMAX
      GOTO 57
  700 IF (UV.GT.UJ) GOTO 53
      D1=(UJ*UJ-UV*UV)/(2*ACCNML)
      D2=(UJ-UV)/ACCNML
      T3=(DTTJ-D1)/UJ+D2
      T4=(DTTJ-D1)/UV+D2
      IF ((TTTJ-.1).GT.T4) GOTO 54
      IF (TTTJ.GT.T3) GOTO 55
      A=-2
      B=2*TTTJ*ACCNML+2*(UV+UJ)
      C=-UV*UV-UJ*UJ-2*ACCNML*DTTJ
      D4=B*B-4*A*C
      IF (D4.GE.0) GOTO 205
      D5=(2*ACCNML*DTTJ+UV*UV+UJ*UJ)/2
      UI=SQRT(D5)
      FLAG=.TRUE.
      GOTO 57
  205 D3=SQRT(D4)
      UI=(-B+D3)/(2*A)
      GOTO 57
```

```
55    UI=(DTTJ-D1)/(TTTJ-D2)
      GOTO 57
54    A=2
      B=2*TTTJ*ACCNML-2*(UV+UJ)
      C=UV*UV+UJ*UJ-2*ACCNML*DTTJ
      D4=B*B-4*A*C
      IF (D4.GE.0) GOTO 206
      ACCN=-ACCEMG
      CALL PRINT1('EMERGENCY DECN TO REACH INT VEL AT',ITIME*DELT,
     C35,I,J)
      STOP 2
      GOTO 39
206   D3=SQRT(D4)
      UI=(-B+D3)/(2*A)
      GOTO 57
53    D1=(UJ*UJ-UV*UV)/(-2*ACCNML)
      D2=(UJ-UV)/(-ACCNML)
      T1=(DTTJ-D1)/UJ+D2
      T2=(DTTJ-D1)/UV+D2
      IF ((TTTJ-.1).GT.T1) GOTO 154
      IF (TTTJ.GT.T2) GOTO 155
      A=-2
      B=2*TTTJ*ACCNML+2*(UV+UJ)
      C=-UJ*UJ-UV*UV-2*DTTJ*ACCNML
      D4=B*B-4*A*C
      IF (D4.GE.0) GOTO 204
      D5=(2*ACCNML*DTTJ+UV*UV+UJ*UJ)/2
      UI=SQRT(D5)
      FLAG=.TRUE.
      GOTO 57
204   D3=SQRT(D4)
      UI=(-B+D3)/(2*A)
      GOTO 57
155   UI=(DTTJ-D1)/(TTTJ-D2)
      GOTO 57
154   A=2
      B=2*TTTJ*ACCNML-2*(UV+UJ)
```

```
      C=UV*UV+UJ*UJ-2*DTTJ*ACCNML
      D4=B*B-4*A*C
      IF (D4.GE.0) GOTO 207
      ACCN=-ACCEMG
      CALL PRINT1('EMERGENCY DECN TO REACH INT VEL AT',ITIME*DELT,
     C35,I,J)
      STOP 2
      GOTO 39
  207 D3=SQRT(D4)
      UI=(-B+D3)/(2*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 ACCN=-ACCNML
      GOTO 203
  201 ACCN=0
      GOTO 203
  202 ACCN=0
      IF((UI-UV).GT.0.1)ACCN=ACCNML
  203 GOTO 39
   42 M=ITARG(I,J)
C VEHICLE HAS PASSEED INTERSECTION.
      IF (M.LE.0) GOTO 46
      IF (ITIME*DELT-TARGET(M,1).GT.0) GOTO 45
      CALL PRINT1('VEH IS TOO EARLT AT JUNCTION AT',ITIME*DELT,
     C32,I,J)
   45 IF (ABS(TARGET(M,2)-VEHA(I,2,J)).LE..1) GOTO 38
      CALL PRINT1('ERROR IN VEH SPEED OF ',VEHA(I,2,J)-TARGET(M,2),
     C22,I,J)
   38 CALL TAG4(I,J)
      GOTO 47
   46 IF (M.EQ.0) GOTO39
   47 IF (VEHA(I,2,J).GE.LSPNML)GOTO 48
      ACCN =ACCNML
```

```
      GOTO 39
 48   ACCN=0
      VEHA(I,2,J)=LSPNML
      ITARG(I,J)=0
 39   VEHA(I,1,J)=ACCN
      IF (FLAG) CALL TAG5(I,J,LI)
      IF(J.EQ.N2) GOTO37
      J=J+1
      IF (J.EQ.51) J=1
       GOTO 6
 37   CONTINUE
      RETURN
      END
```

```
C
C WRITE MESSAGE TO LINE PRINTER.
C
      SUBROUTINE PRINT1(M,A,K,I,J)
      COMMON TARGET(100,4),VEHA(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,CONCON,FFHDWY,FCHDWY,
     CVELJNC,JFLOW,FTIME,AFLOW(3,3),LFLOW(3,2),IPARAM,PCOCC,OCCJNC,
     CTOSLIP,NVEH,DELAY(2,2,20),AVDEL(2,3),FACDEL(6),VL,
     CNOAM,TOTAL,TIMLAG,ISTA(2,2,50),AHDWY(100,2),MA(2,2),
     CP(2),PCOCCP(2),PEROCC(2),SLIPTO(2),TARRY,ITARRY
     C,NXVH(2)
     C,NBACK(100)
     C,KOUNT(2,2)
      DIMENSION M(20)
      IF (MAR(6).NE.0) RETURN
      K1=K/4
      K2=K1*4
      IF (K2.LT.K)K1=K1+1
      WRITE(108,78)K1,(M(JJ),JJ=1,K1),A,I,J
   78 FORMAT(I2,NA4,F10.3,2X,'LANE NO ',I2,2X,'VEHICLE NO',I3)
      RETURN
      END
```

```
C
C CALCULATES VARIABLES OF INTEREST.
C
      SUBROUTINE CRITE
      DIMENSION TDLY(2),TDLYSQ(2),MCOUNT(2)
      DIMENSION TOTDEL (2,2),VARIS(2,2)
      COMMON TARGET(100,4),VEHA(2,8,50),ITARG(2,50),IPOINT(2,2),
     CMAR(10),JPOINT(2),IFLOW(2),ITYPE,ITIME,DELT,LSPMAX,
     CLOPNML,ACCNML,ACCEMG,INTFOS,CRLPOS,SPEED,CONCON,FFHDWY,FCHDWY,
     CVELJNC,JFLOW,FTIME,AFLOW(3,3),LFLOW(3,2),IPARAM,PCOCC,OCCJNC,
     CTOSLIP,NVEH,DELAY(2,2,20),AVDEL(2,3),FACDEL(6),VL,
     CNOAH,TOTAL,TIMLAG,ISTA(2,2,50),AHDWY(100,2),MA(2,2),
     CP(2),PCOCCP(2),PEROCC(2),SLIPTO(2),TARRY,ITARRY
     C,NXVH(2)
     C,NBACK(1C0)
     C,KOUNT(2,2)
      DIMENSION NO(2)
      DO 7 I=1,2
      DO 7 J=1,2
      VARIS(I,J)=0.
    7 TOTDEL(I,J)=0
      DO 1 I=1,3
      DO 2 J=1,2
C CALCULATE AVERAGE FLOWS.
    2 AFLOW(I,J) =LFLOW(I,J)/(IPARAM*DELT)
    1 AFLOW(I,3)=(LFLOW(I,1)+LFLOW(I,2))/(IPARAM*DELT)
       DO 3 I=1,3
      DO 3 J=1,2
    3 LFLOW(I ,J)=0
C PERCENTAGE JUNCTION OCCUPANCY.
      PCOCC =100*OCCJNC/(OCCJNC+TOSLIP)
      PCOCCP(1)=100.*PEROCC(1)/(PEROCC(1)+SLIPTO(1))
      PCOCCP(2)=100.*PEROCC(2)/(PEROCC(2)+SLIPTO(2))
      DO 4 I=1,2
      NO(I)=NOAH
      DO 5 J=1,NOAH
      TOTDEL(1,I)=DELAY(1,I,J)+TOTDEL(1,I)
```

```
      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)/NC(I)
      AVDEL(1,I)=TDLY(I)/MCOUNT(I)
    4 AVDEL(2,I)=TOTDEL(2,I)/NC(I)
      AVDEL(1,3)=(TOTDEL(1,1)+TOTDEL(1,2))/(NO(1)+NO(2))
      AVDEL(1,3)=((TDLY(1)+TDLY(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)=SQRT(TDLYSQ(I)/MCOUNT(I)-AVDEL(1,I)**2)
    6 FACDEL(I)=SQRT(VARIS(2,I)/NOAH-AVDEL(2,I)**2)
      FACDEL(6)=SQRT((TDLYSQ(1)+TDLYSQ(2))/(MCOUNT(1)+MCOUNT(2))-
     *AVDEL(1,3)**2)
      FACDEL(3)=SQRT((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 CRITE1(DL1,LANE)
      TDLY(LANE)=TDLY(LANE)+DL1
      TDLYSQ(LANE)=TDLYSQ(LANE)+DL1**2
      MCOUNT(LANE)=MCOUNT(LANE)+1
      RETURN
      END
```

```
C
C GENERATES RANDOM NUMBERS WITH UNIFORM DISTRIBUTION BETWEEN 0 AND 1.
C
      SUBROUTINE RANDOM(IX,IY,YFL)
      IY=IX*65539
      IF (IY)5,6,6
    5 IY=IY+2147483647+1
    6 YFL=IY
      YFL=YFL*.4656613E-9
      RETURN
      END
```

```
C
C FINDS THE TIME HEADWAY TO THE NEXT INCOMING VEHICLE.
C
      SUBROUTINE SPACES(NNN,ASPACE)
      REAL LSPMAX,LSPNML,INTPOS
      COMMON TARGET(100,4),VEHA(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,CONCON,FFHDWY,FCHDWY,
     CVELJNC,JFLOW,FTIME,AFLOW(3,3),LFLOW(3,2),IPARAM,PCOCC,OCCJNC,
     CTOSLIP,NVEH,DELAY(2,2,20),AVDEL(2,3),FACDEL(6),VL,
     CNOAH,TOTAL,TIMLAG,ISTA(2,2,50),AHDWY(100,2),MA(2,2),
     CP(2),PCOCCP(2),PEROCC(2),SLIPTO(2),TARRY,ITARRY
     C,NXVH(2)
     C,NBACK(100)
     C,KOUNT(2,2)
      DIMENSION TL(2)
      DIMENSION SPACEA(100,2),N(2)
      DIMENSION ASPACE(2),NNN(2)
      DIMENSION II(2),JJ(2)
      N(1)=1
      N(2)=1
      TL(1)=TIMLAG
      TL(2)=TOTAL
      II(1)=1
      II(2)=7
      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(I).GE.1.0) GOTO 84
      IF (ASPACE(I).LT.0) GOTO 60
```

```
C
C FINDS THE TIME HEADWAY TO THE NEXT INCOMING VEHICLE.
C
      SUBROUTINE SPACES(NNN,ASPACE)
      REAL LSPMAX,LSPNML,INTPOS
      COMMON TARGET(100,4),VEHA(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,CONCON,FFHDWY,FCHDWY,
     CVELJNC,JFLOW,FTIME,AFLOW(3,3),LFLOW(3,2),IPARAM,PCOCC,OCCJNC,
     CTOSLIP,NVEH,DELAY(2,2,20),AVDEL(2,3),FACDEL(6),VL,
     CNOAH,TOTAL,TIMLAG,ISTA(2,2,50),AHDWY(100,2),MA(2,2),
     CP(2),PCOCCP(2),PEROCC(2),SLIPTO(2),TARRY,ITARRY
     C,NXVH(2)
     C,NBACK(100)
     C,KOUNT(2,2)
      DIMENSION TL(2)
      DIMENSION SPACEA(100,2),N(2)
      DIMENSION ASPACE(2),NNN(2)
      DIMENSION II(2),JJ(2)
      N(1)=1
      N(2)=1
      TL(1)=TIMLAG
      TL(2)=TOTAL
      II(1)=1
      II(2)=7
      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(I).GE.1.0) GOTO 84
      IF (ASPACE(I).LT.0) GOTO 60
```

```
      IF (ITIME+DELT.LT.TL(I)) GOTO 1
      ASPACE(I)=-1.
      CALL DISKRD(N(I),SPACEA(1,I),I)
      SPACEN=SPACEA(MA(I,2),I)
      MA(I,2)=MA(I,2)+1
      N(I)=N(I)+1
      RETURN
    1 EMHDWY = LSPNML/(2*ACCEMG)+VL/LSPNML
      HDWY=EMHDWY*FFHDWY
      I1=0
  212 II(I)=JJ(I)
      CALL RANDOM(II(I),JJ(I),RN)
      I1=I1+1
      IF (RN.GE.ASPACE(I)) GOTO 217
      GOTO 212
C CALCULATE HEADWAY ACCORDING TO DISTRIBUTION.
  217 GAP=FLOAT(I1)*HDWY/NNN(I)
      IF (GAP.LT.HDWY) GAP=HDWY
      SPACEN=GAP
      RETURN
   60 CONTINUE
      SPACEN=SPACEA(MA(I,2),I)
      MA(I,2)=MA(I,2)+1
      IF (MA(I,2).LE.90) GOTO 61
      MA(I,2)=1
      CALL DISKRD(N(I),SPACEA(1,I),I)
      N(I)=N(I)+1
      IF (N(I).EQ.13)  N(I)=1
   61 CONTINUE
      RETURN
   84 SPACEN=99999
   50 FORMAT (2F10.3)
      RETURN
      END
```

```
C
C ROUTINE TO OUTPUT VEHICLE DATA TO LINE PRINTER.
C
      SUBROUTINE PRINT
      REAL LSPMAX,LSPNML,INTPOS
      COMMON TARGET(100,4),VEHA(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,CONCON,FFHDWY,FCHDWY,
     CVELJNC,JFLOW,FTIME,AFLOW(3,3),LFLOW(3,2),IPARAM,PCOCC,OCCJNC,
     CTOSLIP,NVEH,DELAY(2,2,20),AVDEL(2,3),FACDEL(6),VL,
     CNOAH,TOTAL,TIMLAG,ISTA(2,2,50),AHDWY(100,2),MA(2,2),
     CP(2),PCOCCP(2),PEROCC(2),SLIPTO(2),TARRY,ITARRY
     C,NXVH(2)
     C,NBACK(100)
     C,KOUNT(2,2)
      IF (MAR(1).NE.0)RETURN
      TIME =ITIME*DELT
      WRITE(108,103)
      WRITE(108,65)TIME
      IF (MAR(2).NE.0)GOTO 63
      WRITE(108,66)
      DO 64 I=1,2
      N1=IPOINT(I,1)+1
      N2=IPOINT(I,2)-1
      IF (N1.EQ.51) N1=1
      IF (N2.EQ.0) N2=50
      WRITE(108,67)I
      WRITE(108,68)
      IF (N1.EQ.IPOINT(I,2)) GOTO 64
      J=N1
  100 CONTINUE
C VEHICLE DATA.
      WRITE(108,69)J,(VEHA(I,K,J),K=1,7),ITARG(I,J)
      IF (J.EQ.N2)GOTO 64
      J=J+1
      IF (J.EQ.51) J=1
      GOTO 100
```

```
 64   CONTINUE
 63   IF (MAR(3).NE.0) GOTO 73
      WRITE(108,104)
      WRITE(108,71)
      WRITE(108,74)
      M1=JPOINT(1)+1
      M2=JPOINT(2)-1
      IF (M1.EQ.101) M1=1
      IF (M1.EQ.JPOINT(2)) GOTO 73
      IF (M2.EQ.0) M2=100
      J=M1
 80   CONTINUE
      IF (TARGET(J,1) .EQ.0.) GOTO 1
C TARGET DATA.
      WRITE(108,72)J,TARGET(J,1),TARGET(J,2),TARGET(J,3),
     CTARGET(J,4),NBACK(J)
  1   IF (J.EQ.M2) GOTO 73
      J=J+1
      IF (J.EQ.101) J=1
      GOTO 80
 73   IF (MAR(4).NE.0) GOTO 75
      WRITE(108,76)
      WRITE(108,240) AFLOW(1,1),AFLOW(1,2),AFLOW(1,3)
      WRITE(108,241)AFLOW(2,1),AFLOW(2,2),AFLOW(2,3)
      WRITE(108,242)AFLOW(3,1),AFLOW(3,2),AFLOW(3,3)
      WRITE(108,77) AVDEL(2,1),AVDEL(2,2),AVDEL(2,3)
      WRITE(108,77)AVDEL(1,1),AVDEL(1,2),AVDEL(1,3)
      WRITE(108,243) FACDEL(1),FACDEL(2),FACDEL(3)
      WRITE(108,243)FACDEL(4),FACDEL(5),FACDEL(6)
       WRITE(108,244) PCOCC
      IF (P(1).LE.0..AND.P(2).LE.0.) GOTO 75
      WRITE(108,2) PCOCCP(1)
      WRITE(108,3) PCOCCP(2)
      WRITE(108,104)
 65   FORMAT(X,'TIME = ',F10.3)
 66   FORMAT(1H0,'VEHICLE DATA')
 67   FORMAT(X,'LANE NO = ',I1)
```

```
 68  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(I14,7F15.3,I8)
 71  FORMAT(1H0,'TARGET DATA')
 72  FORMAT(I5,T20,F10.3,T40,F10.3,T60,F10.3,T80,F10.3,T100,I10)
 74  FORMAT(1H0,'TARGET NO',T20,'TARGET TIME',T40,'TARGET VELOCITY',T60
    C,'TARGET HDWY',T80,'TAR B/END / A TIME',T100,'BACK POINT')
 76  FORMAT(1H0,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
     END
```

```
C
C INTERSECTIONS TARGET CALCULATING ROUTINE.
C
      SUBROUTINE TAG1
      DIMENSION ENDP(2),LASTV(2)
      DIMENSION NFV(2),ART(2),PART(2)
      DIMENSION TDART(2)
      DIMENSION  IPQ(2),IPANE(2)
      EQUIVALENCE(ENDP,IPQ),(LASTV,IPANE)
      LOGICAL FLAG
      REAL LSPMAX,LSPNML,INTPOS
      COMMON TARGET(100,4),VEHA(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,CONCON,FFHDWY,FCHDWY,
     CVELJNC,JFLOW,FTIME,AFLOW(3,3),LFLOW(3,2),IPARAM,PCOCC,OCCJNC,
     CTOSLIP,NVEH,DELAY(2,2,20),AVDEL(2,3),FACDEL(6),VL,
     CNOAH,TOTAL,TIMLAG,ISTA(2,2,50),AHDWY(100,2),MA(2,2),
     CP(2),PCOCCP(2),PEROCC(2),SLTPTO(2),TARRY,ITARRY
     C,NXVH(2)
     C,NBACK(100)
     C,KOUNT(2,2)
      NXVH(1)=2
      NXVH(2)=1
      KPOINT=1
      VELJNC=SPEED
      S=ABS((SPEED*SPEED-LSPNML*LSPNML)/(2*ACCNML))
      POSN=VEHA(1,3,1)
      TA=((INTPOS-POSN-S)/LSPNML)+ABS(SPEED-LSPNML)/ACCNML
      OFFSET=(INTPOS-CRLPOS-S)/LSPNML+(LSPNML-SPEED)/ACCNML
C INITIALISATION.
      STAR1=TA
      JTYPE=1
      JPOINT(1)=100
      JPOINT(2)=2
      TARGET(1,1)=TA
      TARGET(1,2)=VELJNC
      TARGET(1,3)=0
```

```
      VEHA(1,8,1)=((TA-(INTPOS-POSN)/LSPNML)*2.)
      ITARG(1,1)=1
      IFLOW(1)=1
      ITYPE=1
      TARRY=0.
      ITARRY=0
      OCCJNC=0.
      PEROCC(1)=0.
      PEROCC(2)=0.
      TOSLIP=0
      THDWYE=SPEED/(2*ACCEMG)+VL/SPEED
      THDWYC=THDWYE*FCHDWY
      THDWYF=THDWYE*FFHDWY
      IF ((P(1).LE.0.).AND.(P(2).LE.0.)) RETURN
 301  ENDP(1)=TA + P(1)
      ENDP(2)=TA + P(1)+P(2)
      TARGET(1,3)=0.
      TARGET(2,1)=ENDP(1)+THDWYC
      TARGET(2,2)=VELJNC
      TARGET(2,3)=THDWYC
      TARGET(1,4)=TA+P(1)
      TARGET(2,4)=TA+P(1)+P(2)
      VEHA(2,8,1)=VEHA(1,8,1)
      ITARG(2,1)=2
      LASTV(1)=1
      LASTV(2)=2
      JPOINT(2)=3
      IFLOW(2)=1
      RETURN
C
      ENTRY TAG2
      FLOW=FLOAT(JFLOW)/(ITIME*DELT-FTIME)
      IF (IFLOW(1)-IFLOW(2))29,30,30
  29  RATIO = FLOAT(IFLOW(2))/FLOAT(IFLOW(1))
      GOTO 31
  30  RATIO = FLOAT(IFLOW(1))/FLOAT(IFLOW(2))
  31  A=1/(2*ACCEMG)
```

```
      B=-(RATIO+1)/(FLOW*(2*FCHDWY+(RATIO-1)*FFHDWY))
      C=VL
      D=B*B-4*A*C
      IF (D.GT.0)GOTO105
      VELJNC=SQRT(VL*2*ACCEMG)
      GOTO 106
 105  CONTINUE
      VELJNC=(-B+SQRT(B*B-4*A*C))/(2*A)
 106  CONTINUE
      IF (VELJNC.GE.LSPMAX)VELJNC=LSPMAX
      THDWYE =VELJNC/(2*ACCEMG)+VL/VELJNC
      THDWYC=THDWYE*FCHDWY
      THDWYF =THDWYE*FFHDWY
      IFLOW(1) =0
      IFLOW(2) =0
      RETURN
C
      ENTRY TAG3(I1,I2)
      IF (P(1))305,306,307
  305 TARGET(JPOINT(2),4)=ITIME*DELT
      GOTO 306
 307  CONTINUE
      TAGTIM=TARGET(M1,1)+THDWYF
C CALCULATE NEW TARGET FOR A FIXED TIME CYCLE STRATEGY.
      THDWYN=THDWYF
      IF (TAGTIM.LT.ENDP(I1)) GOTO 303
      I3=1
      IF (I1.EQ.1)I3=2
      TAGTIM=ENDP(I1)+P(I3)+THDWYC
      THDWYN=THDWYC
      ENDP(I1)=ENDP(I1)+P(1)+P(2)
 303  TARGET(JPOINT(2),1)=TAGTIM
      TARGET(JPOINT(2),4)=ENDP(I1)
      LASTV(I1)=JPOINT(2)
      GOTO 304
 306  CONTINUE
      IF (ITYPE.EQ.I1)GOTO 32
```

```
C CALCULATE FIRST COME FIRST SERVED TARGET.
      THDWYN=THDWYC
      GOTO 33
  32  THDWYN=THDWYF
  33  ITYPE =I1
      M2=JPOINT(2)-1
      IF (M2.EQ.0) M2=100
      TARGET(JPOINT(2),1)=TARGET(M2,1)+THDWYN
 304  CONTINUE
      TARGET(JPOINT(2),2)=VELJNC
      TARGET(JPOINT(2),3)=THDWYN
      ITARG(I1,I2)=JPOINT(2)
      NBACK(JPOINT(2))=(I1-1)*50+I2
      JPOINT(2)=JPOINT(2)+1
      IF (JPOINT(2).EQ.101) JPOINT(2)=1
C CALCULATE MINIMUM DELAY.
      UV=LSPNML
      S=(UV*UV-VELJNC*VELJNC)/(2*ACCNML)
      TTH=S/UV
      TAC=(UV-VELJNC)/ACCNML
      THDELY=(TAC-TTH)*2
      VEHA(I1,8,I2)=THDELY
      IF (P(1).GE.0.) RETURN
      DO 2000 I=1,2
C CALCULATE NEXT ALTERNATE PRIORITY TARGET.
      NFV(I)=ITARG(I,NXVH(I))
      IF (NFV(I).EQ.0) RETURN
 2000 ART(I)=TARGET(NFV(I),4)+OFFSET
      STAR=TARGET(KPOINT,1)
      DO 2001 I=1,2
      THDWYN=THDWYC
      IF (I.EQ.JTYPE) THDWYN=THDWYF
      PART(1)=STAR1+THDWYN
      IF (ART(I).GT.PART(1)) PART(1)=ART(I)
      PART(2)=PART(1)+THDWYC
      IF (ART(3-I).GT.PART(2)) PART(2)=ART(3-I)
 2001 TDART(I)=PART(1)-ART(I)+PART(2)-ART(3-I)
```

```
C FIND A VEHICLE TO BE GIVEN AF TARGET.
      LNEXT=1
      IF (TDART(2).LT.TDART(1)) LNEXT=2
      KPOINT=KPOINT+1
      IF (KPOINT.EQ.101) KPOINT=1
      LPNEXT=NXVH(LNEXT)
      NPOST=ITARG(LNEXT,LPNEXT)
      DO 2003 I=1,4
      TARBUF=TARGET(KPOINT,I)
      TARGET(KPOINT,I)=TARGET(NPOST,I)
 2003 TARGET(NPOST,I)=TARBUF
      THDWYN=THDWYC
      IF (LNEXT.EQ.JTYPE) THDWYN=THDWYF
      STAR1=STAR1+THDWYN
      IF (ART(LNEXT).GT.STAR1) STAR1=ART(LNEXT)
      TARGET(KPOINT,1)=STAR+THDWYN
      TARGET(KPOINT,3)=THDWYN
C EXCHANGE PLACES IN TARGET QUEUE (IF REQUIRED).
      NXVH(LNEXT)=NXVH(LNEXT)+1
      IF (NXVH(LNEXT).EQ.51) NXVH(LNEXT)=1
      ITARG(LNEXT,LPNEXT)=KPOINT
      NQ=NBACK(KPOINT)
      LANE=1
      IF (NQ.LE.50) GOTO 2004
      NQ=NQ-50
      LANE=2
 2004 ITARG(LANE,NQ)=NPOST
      JTYPE=LNEXT
         NBACK(KPOINT)=(LNEXT-1)*50+LPNEXT
         NBACK(NPOST)=(LANE-1)*50+NQ
      N1=KPOINT+1
      IF (N1.EQ.101) N1=1
      IF (N1.EQ.JPOINT(2)) RETURN
      N2=JPOINT(2)-1
      IF (N2.EQ.0) N2=100
   12 J=N1
      IF (N1.EQ.N2) GOTO 13
```

```
11    JJ=J+1
      IF (JJ.EQ.101) JJ=1
      IF (TARGET(JJ,4).GE.TARGET(J,4)) GOTO 10
      DO 4 I=1,4
      TARBUF=TARGET(J,I)
      TARGET(J,I)=TARGET(JJ,I)
 4    TARGET(JJ,I)=TARBUF
      NQ=NBACK(J)
      NBACK(J)=NBACK(JJ)
      NBACK(JJ)=NQ
      DO 700 I=1,2
      NQ=J
      IF (I.EQ.2) NQ=JJ
      IPQ(I)=NBACK(NQ)
      IPANE(I)=1
      IF (IPQ(I).LE.50) GOTO 700
      IPQ(I)=IPQ(I)-50
      IPANE(I)=2
700   CONTINUE
      NQ=ITARG(IPANE(1),IPQ(1))
      ITARG(IPANE(1),IPQ(1))=ITARG(IPANE(2),IPQ(2))
      ITARG(IPANE(2),IPQ(2))=NQ
      MARK=1
10    J=JJ
      IF (J.NE.N2) GOTO11
      IF (MARK.EQ.0) GOTO 13
      N2=N2-1
      IF (N2.EQ.0) N2=100
      MARK=0
      GOTO 12
13    CONTINUE
      N2=JPOINT(2)-1
      IF(N2.EQ.0) N2=100
      ITYPE=JTYPE
      J=KPOINT
50    JJ=J+1
      IF (JJ.EQ.101) JJ=1
```

```
      LANE=1
      IF (NBACK(JJ).GT.50) LANE=2
      THDWYN=THDWYC
      IF (LANE.EQ.ITYPE) THDWYN=THDWYF
      TARGET(JJ,1)=TARGET(J,1)+THDWYN
      TARGET(JJ,3)=THDWYN
      J=JJ
      ITYPE=LANE
      IF (J.EQ.N2) GOTO 40
      GOTO 50
   40 CONTINUE
      RETURN
C
      ENTRY TAG 4(I1,I2)
      M=ITARG(I1,I2)
      TTARG=TARGET(M,1)
      OCCJNC=TARGET(M,3)+OCCJNC
C CALCULATE SLIPPAGE WHEN A VEHICLE PASSES THROUGH INTERSECTION.
      TOSLIP =ITIME*DELT -OCCJNC-TA
      IF (P(1))2,1,3
    3 CONTINUE
      PEROCC(I1)=TARGET(M,3)+PEROCC(I1)
      SLIPTO(I1)=(ITIME*DELT-TA)*P(I1)/(P(1)+P(2))-PEROCC(I1)
      GOTO 1
    2 CONTINUE
         NV=ITARG(I1,I2)+1
         IF (NV.EQ.0) GOTO 60
         NA=0
         NB=0
         IF (KPOINT.LT.JPOINT(2).AND.JPOINT(2).LT.JPOINT(1)) NA=100
         IF (NV.LT.JPOINT(2).AND.JPOINT(2).LT.JPOINT(1)) NB=100
         IF (NV+NB.LE.KPOINT+NA) GOTO 60
      KPOINT=KPOINT+1
      IF (KPOINT.EQ.101) KPOINT=1
      LANE=1
      IF (NBACK(KPOINT).GT.50) LANE=2
      NXVH(LANE)=NXVH(LANE)+1
```

```
      IF (NXVH(LANE).EQ.51) NXVH(LANE)=1
   60 CONTINUE
    1 CONTINUE
      LFLOW(2,I1)=LFLOW(2,I1)+1
      SLIP =ITIME*DELT-TTARG
      IF (SLIP) 35,35,36
   36 M2=M+1
      IF (M2.EQ.101) M2=1
      IF (P(1).LE.0..AND.P(2).LE.0.) GOTO 415
      IF (SLIP.LE..2) GOTO 35
      M=ITARG(I1,I2)
      N=0
      I=I2
      FLAG=.TRUE.
      GOTO 409
  413 FLAG=.FALSE.
      GOTO 35
  415 I=M
      M2=JPOINT(2)-1
      IF (M2.EQ.0) M2=100
      NSLANE=I1
C ADJUST ALL LATER TARGETS.
    5 TARGET(I,1)=TARGET(I,1)+SLIP
      IF (I.EQ.M2) GOTO 35
      MM=I
      I=I+1
      IF (I.EQ.101) I=1
      NFLANE=NSLANE
      NSLANE=1
      IF (NBACK(I).GT.50) NSLANE=2
      THDWYN=THDWYC
      IF (NSLANE.EQ.NFLANE) THDWYN=THDWYF
      SLIP=TARGET(MM,1)+THDWYN-TARGET(I,1)
      IF (SLIP)35,35,5
   35 ITARG(I1,I2)=-ITARG(I1,I2)
C CALCULATE SLIP ENROUTE BECAUSE VEHICLE CANNOT ACHIEVE SET TARGET.
      M=-ITARG(I1,I2)
```

```
      M1=JPOINT(1)+1
      IF (M1.EQ.101) M1=1
      IF (M1.NE.M) GOTO 460
      JPOINT(1)=M1
  800 M1=M1+1
      IF (M1.EQ.101) M1=1
      IF (M1.EQ.JPOINT(2)) GOTO 59
      IF (TARGET(M1,1).GT.0.) GOTO 59
      JPOINT(1)=M1
      GOTO 800
   59 CONTINUE
      CALL PRINT1('VEH HAS PASSED JUNCTION LATENESS=',SLIP,35,I1,I2)
      TARRY=ITIME*DELT
      ITARRY=I1
      RETURN
  460 TARGET(M,1)=0.
      GOTO 59
C
      ENTRY TAG5(I1,I2,UI)
      M=ITARG(I1,I2)
      TTARG=TARGET(M,1)
      UJ=TARGET(M,2)
      UV=VEHA(I1,2,I2)
      POSN=VEHA(I1,3,I2)
      DTTJ=INTPOS-POSN
      T=(DTTJ+(UJ*UJ+UV*UV-2*UI*UI)/(2*ACCNML))/UI
     C+(2*UI-UV-UJ)/ACCNML
      TTARGN=ITIME*DELT+T
      SLIP=TTARGN-TTARG
      IF (SLIP.LE.0.05) GOTO 210
      IF ((P(1).LE.0.).AND.(P(2).LE.0.)) GOTO 350
      N=0
      I=I2
  409 BLOEND=TARGET(M,4)
      GOTO 410
  401 BENDN=BLOEND+P(1)+P(2)
      I3=1
```

```
      IF (I1.EQ.1) I3=2
      TAGN=BLGEND+P(I3)+THDWYC
      GOTO 408
407   IF (TARGET(M,4).GT.BLGEND) GOTO 400
      SLIP=TARGET(MM,1)+THDWYF-TARGET(M,1)
      IF (SLIP)401,401,410
410   TARGET(M,1)=TARGET(M,1)+SLIP
414   IF (TARGET(M,1).GT.BLGEND) N=N+1
      I=I+1
      IF (I.EQ.51) I=1
      MM=M
      M=ITARG(I1,I)
      IF (M.NE.0) GOTO 407
      GOTO 401
400   BENDN=BLGEND+P(1)+P(2)
      I3=1
      IF (I1.EQ.1) I3=2
      TAGN=BLGEND+P(I3)+THDWYC
408   N1=N
      IF (N1.EQ.0) GOTO 411
403   IF (N.EQ.0) GOTO 402
      I=I-1
      IF (I.EQ.0) I=50
      M2=ITARG(I1,I)
      TARGET(M2,4)=BENDN
      N=N-1
      GOTO 403
402   M3=ITARG(I1,I)
      TAGG =TARGET(M3,1)
      SLIP=TAGN-TAGG
950   CONTINUE
      BLGEND=BENDN
      N2=0
412   TARGET(M3,1)=TARGET(M3,1)+SLIP
      IF (TARGET(M3,1).GT.BLGEND) N2=N2+1
      N=N+1
      IF (N.EQ.N1) GOTO 404
```

```
      I=I+1
      IF (I.EQ.51) I=1
      M3=ITARG(I1,I)
      GOTO 412
404   TAGN=TARGET(M3,1)+THDWYF
      N=N2
      I=I+1
      IF (I.EQ.51) I=1
      M=ITARG(I1,I)
      IF (M.EQ.0) GOTO 401
      TAGO=TARGET(M,1)
      SLIP=(TAGN-TAGO)
      IF (SLIP)401,401,410
350   CONTINUE
      M2=JPOINT(2)-1
      IF (M2.EQ.0) M2=100
      I=M
      NFLANE=I1
211   TARGET(I,1)=TARGET(I,1)+SLIP
      IF (I.EQ.M2) GOTO 210
      K=I+1
      IF (K.EQ.101) K=1
      NSLANE=1
      IF (NBACK(K).GT.50) NSLANE=2
      THDWYN=THDWYC
      IF  (NSLANE.EQ.NFLANE) THDWYN=THDWYF
      SLIP=TARGET(I,1)+THDWYN-TARGET(K,1)
      IF (SLIP)210,210,212
212   NFLANE=NSLANE
      I=K
      GOTO 211
411   CONTINUE
      IF (FLAG) GOTO 413
210   RETURN
      END
```

```
C
C CALCULATES DISTRIBUTIONS AND PLOTS LINE PRINTER HISTOGRAMS.
C
      SUBROUTINE DIS
      COMMON TARGET(100,4),VEHA(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,CONCON,FFHDWY,FCHDWY,
     CVELJNC,JFLOW,FTIME,AFLOW(3,3),LFLOW(3,2),IPARAM,PCOCC,OCCJNC,
     CTOSLIP,NVEH,DELAY(2,2,20),AVDEL(2,3),FACDEL(6),VL,
     CNOAH,TOTAL,TIMLAG,ISTA(2,2,50),AHDWY(100,2),MA(2,2),
     CP(2),PCOCCP(2),PEROCC(2),SLIPTO(2),TARRY,ITARRY
     C,NXVH(2)
     C,NBACK(100)
     C,KOUNT(2,2)
      REAL LSPMAX,LSPNML,INTPOS
      DIMENSION KPLAT(2),NCOUNT(2),PAVER(2)
      DIMENSION DSTA(30,2),MCOUNT(2),QSTA(30)
      EQUIVALENCE (DSTA,QSTA)
      IF (MAR(9).NE.0) GOTO 17
      WRITE(108,227)(PAVER(I),I=1,2)
  227 FORMAT(1H0,'AVERAGE PLATOON SIZE LANE 1',F6.1,5X,'LANE 2',F6.1)
   17 CONTINUE
      DO 1 I=1,2
      KPLAT(I)=1
      NCOUNT(I)=0
      PAVER(I)=0.
      DO 1 J=1,2
      KOUNT(I,J)=0
      DO 1 K=1,50
    1 ISTA(I,J,K)=0
      HDWYM =(LSPNML/(2*ACCEMG) + VL/LSPNML)*FFHDWY
      RETURN
C
      ENTRY DIS1
      DO 5 I=1,2
      MCOUNT(I)=0
      DO 5 J=1,30
```

```
    5 DSTA(J,I)=0.
      RETURN
C
      ENTRY DISTR1
      IF (MAR(10).EQ.1) GOTO 7
      IF (MAR(10).EQ.0) GOTO 8
      DO 6 I=1,30
    6 QSTA(I)=QSTA(I)/MCOUNT(1)
      CALL PLOTER(QSTA,30,.TRUE.,ITIME*DELT,2,-1)
      DO 9 I=1,30
    9 QSTA(I)=DSTA(I,2)/MCOUNT(2)
      CALL PLOTER(QSTA,30,.TRUE.,ITIME*DELT,2,-2)
      GOTO 10
    8 DO 11 I=1,30
   11 QSTA(I)=(QSTA(I)+DSTA(I,2))/(MCOUNT(1)+MCOUNT(2))
      CALL PLOTER(QSTA,30,.TRUE.,ITIME*DELT,2,-3)
   10 DO 12 I=1,2
      MCOUNT(I)=0
      DO 12 J=1,30
   12 DSTA(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
      DSTA(INT,I)=DSTA(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
      ISTA(II,KK,INT)=ISTA(II,KK,INT)+1
```

```
 5    DSTA(J,I)=0.
      RETURN
C
      ENTRY DISTR1
      IF (MAR(10).EQ.1) GOTO 7
      IF (MAR(10).EQ.0) GOTO 8
      DO 6 I=1,30
 6    QSTA(I)=QSTA(I)/MCOUNT(1)
      CALL PLOTER(QSTA,30,.TRUE.,ITIME*DELT,2,-1)
      DO 9 I=1,30
 9    QSTA(I)=DSTA(I,2)/MCOUNT(2)
      CALL PLOTER(QSTA,30,.TRUE.,ITIME*DELT,2,-2)
      GOTO 10
 8    DO 11 I=1,30
11    QSTA(I)=(QSTA(I)+DSTA(I,2))/(MCOUNT(1)+MCOUNT(2))
      CALL PLOTER(QSTA,30,.TRUE.,ITIME*DELT,2,-3)
10    DO 12 I=1,2
      MCOUNT(I)=0
      DO 12 J=1,30
12    DSTA(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
      DSTA(INT,I)=DSTA(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
      ISTA(II,KK,INT)=ISTA(II,KK,INT)+1
```

```
      KOUNT(II,KK)=KOUNT(II,KK)+1
      IF (KK.EQ.1) GOTO 3
      I=II
      IF (HDWY.GT.1.1*HDWYM) 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
```

```
C
C WRITES BLOCKS OF DATA TO MAGNETIC TAPE TO ALLOW SUBSEQUENT
C PLOTTING OF POSITION TIME CURVES.
C
      SUBROUTINE WRITER(K)
      COMMON TARGET(100,4),VEHA(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,CONCON,FFHDWY,FCHDWY,
     CVELJNC,JFLOW,FTIME,AFLOW(3,3),LFLOW(3,2),IPARAM,PCOCC,OCCJNC,
     CTOSLIP,NVEH,DELAY(2,2,20),AVDEL(2,3),FACDEL(6),VL,
     CNOAH,TOTAL,TIMLAG,ISTA(2,2,50),AHDWY(100,2),MA(2,2),
     CP(2),PCOCCP(2),PEROCC(2),SLIPTO(2),TARRY,ITARRY
     C,NXVH(2)
     C,NBACK(1CO)
     C,KOUNT(2,2)
      REAL LSPMAX,LSPNML,INTPOS
      DIMENSION SAVE(10,51)
      IF (MAR(5).NE.0) RETURN
      DO 1 I=1,50
      SAVE(J,I)=0.
      IQ=0
      IF (VEHA(K,3,I).EQ.0.) GOTO 1
      IQ=VEHA(K,3,I)*10.+.5
      IQ=IQ*100
      SAVE(J,I)=VEHA(K,4,I)+IQ
    1 CONTINUE
      IF ((3-ITARRY).NE.K) ITARRY=C
      SAVE(J,51)=ITARRY
      ITARRY=0
      J=J+1
      IF (J.NE.11) RETURN
      J=1
  100 FORMAT(10(5(/,X,10F7.1),/,X,F7.1))
      CALL BUFFEROUT(1,1,SAVE,510,IST)
      RETURN
C
      ENTRY WINIT
```

```
      IF (MAR(5).NE.0) RETURN
      J=1
      RETURN
C
      ENTRY WRIFIN
      IF (MAR(5).NE.0) RETURN
      END FILE 1
      RETURN
      END
```

```
C
C
      SUBROUTINE GRAPH1(FLAG,IFLOT)
      COMMON TARGET(100,4),VEHA(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,CONCON,FFHDWY,FCHDWY,
     CVELJNC,JFLOW,FTIME,AFLOW(3,3),LFLOW(3,2),IPARAM,PCOCC,OCCJNC,
     CTOSLIP,NVEH,DELAY(2,2,20),AVDEL(2,3),FACDEL(6),VL,
     CNOAH,TOTAL,TIMLAG,ISTA(2,2,50),AHDWY(100,2),MA(2,2),
     CP(2),PCOCCP(2),PEROCC(2),SLIPTO(2),TARRY,ITARRY
     C,NXVH(2)
     C,NBACK(100)
      REAL LOPMAX,LSPNML,INTPOS
      LOGICAL FLAG
      IPICTX(X)=(X-CRLPOS)*SFACT+100.5
      IPICTY(Y)=(Y-CRLPOS)*SFACT+10.5
      DIST=2.*(INTPOS-CRLPOS)
      SFACT=760./DIST
      DO 100 I=1,3
      CALL LDWD2(0)
      IF (I.NE.3) GOTO 101
      CALL LDWD1(0)
      CALL WDSEND
       PAUSE
       ITIMEU=IPLOT*DELT*10
       ITIMES=ITIME*DELT*10
       ITIMES=ITIMES-ITIMEU
       IF (ITIMES.LT.0) ITIMES=100000+ITIMES
C SEND CO-ORDINATES OF PICTURE OF INTERSECTION.
       DO 2 I=1,5
       ITIMET=ITIMES/10
       ITIMEV=ITIMEU/10
       IA=ITIMES-ITIMET*10+16
       II=ITIMEU-ITIMEV*10+32
       ITIMES=ITIMET
       ITIMEU=ITIMEV
       CALL LDWD2(IA)
```

```
      CALL LDWD2(II)
2     CONTINUE
      CALL LDWD2(0)
      CALL WDSEND
      PAUSE
      RETURN
101   CALL LDWD1(I)
      IDATA=2.*(INTPOS-CRLPOS)*SFACT
      CALL LDWD1(IDATA)
      IF (I.EQ.2) GOTO 102
      CALL LDWD1(IPICTX(CRLPOS))
      CALL LDWD1(IPICTY(INTPOS))
      CALL LDWD1(IPICTX(2.*INTPOS-CRLPOS))
      CALL LDWD1(IPICTY(INTPOS))
      GOTO 100
102   CALL LDWD1(IPICTX(INTPOS))
      CALL LDWD1(IPICTY(CRLPOS))
      CALL LDWD1(IPICTX(INTPOS))
      CALL LDWD1(IPICTY(2.*INTPOS-CRLPOS))
100   CONTINUE
C
      ENTRY GRAPH(JFLAG)
      DO 200 I=1,2
      PLAST=CRLPOS
      CALL LDWD2(0)
      CALL LDWD1(I)
      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)*SFACT+2.5
      IF (IPOS.EQ.0) IPOS=1024+1
```

```
      CALL LDWD2(IPOS)
      PLAST=VEHA(I,3,J)
C SEND MOVING PICTURE FRAME.
      IHDWY=VEHA(I,4,J)*SFACT-1.5
      CALL LDWD2(IHDWY)
      PLAST=PLAST+VEHA(I,4,J)
  700 IF (J.EQ.N1) GOTO 200
      J=J-1
      IF (J.EQ.0) J=50
      GOTO 300
  200 CONTINUE
      CALL LDWD1(0)
      CALL LDWD2(0)
      CALL WDSEND
      RETURN
      END
```

```
C
C
      SUBROUTINE ILDWD
      DIMENSION IBUF(25),IARR(3)
      DIMENSION IHOLD(100)
      EQUIVALENCE(IARR(1),INTEG),(IARR(2),IHIORD),(IARR(3),ILOORD)
      LOGICAL FLAG
      NAMELIST L,IC
      DATA BOUT /'HERE'/
      L=4
       IST=0
      INPUT
C INITIALISE CCC COMMUNICATIONS.
      CALL BCSET(L,132,0)
      ICHAR=4
      CALL BCWRITE(L,BOUT,0,ICHAR,IST)
      IPT=0
      IST=0
      CALL BCSET(L,19,0)
      RETURN
C
      ENTRY LDWD1(MNO)
      INTEG=MNO
      IHIORD=INTEG/128
      ILOORD=INTEG-IHIORD*128
      DO 1 I=2,3
      INTEG=IARR(I)
C SEND BYTES OF INFORMATION.
S         LW,4       IPT
S         LW,9       INTEG
S         STB,9      IBUF,4
      IPT=IPT+1
      IF (IPT.NE.100) GOTO 1
      INDEX=3
      GOTO 9
    1 CONTINUE
      RETURN
```

```
C
      ENTRY LDWD2(MNO)
      INTEG=MNO
      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 IHIORD=INTEG/128
      ILOORD=INTEG-IHIORD*128
      IF (ILOORD.NE.0) GOTO 10
      ILOORD=1
      IHIORD=IHIORD+8
   10 CONTINUE
      INTEG=0
      IARR(1)=0
      IHIORD=IHIORD+ISIGN
      N=3
    4 DO 7 I=1,N
      INTEG=IARR(I)
S        LW,4        IPT
S        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,0,IPT,IST)
```

```
      IPT=0
      GOTO (7,8,1) INDEX
      END
      SUBROUTINE PLOTER(X,N,BAR,TIME,NPOS,LANE)
      REAL X(N),HEAD(10)
      INTEGER LINE(100),BLANK,STAR
      LOGICAL BAR
      DATA BLANK,STAR/' ','*'/
      IF(N.LT.1)GO TO 25
      WRITE( 108,902)
      DO 1 I=1,100
    1 LINE(I)=BLANK
      XMAX=-1.E70
      XMIN= 1.E70
      DO 2 I=1,N
      IF(X(I).LT.XMIN) XMIN=X(I)
      IF(X(I).GT.XMAX) XMAX=X(I)
    2 CONTINUE
      IF(XMAX-XMIN)25,3,4
    3 XMAX=XMIN+1.
      XMIN=XMIN-1.
    4 CONTINUE
      DO 5 I =1,10
      Z=I
    5 HEAD(I)=(XMAX-XMIN)*Z/10.+XMIN
      IF (IABS(LANE).EQ.3) WRITE(108,3003)
      IF (IABS(LANE).LT.3) WRITE(108,3004)LANE
      IF (LANE.GT.0) WRITE(108,3001)TIME,NPOS
      IF (LANE.LT.0) WRITE(108,3005)TIME,NPOS
      WRITE( 108,907) XMIN,HEAD
      IF (LANE.GT.0)WRITE(108,3002)
      IF (LANE.LT.0)WRITE(108,3006)
      DO 6 I=1,N
      KPLOTX=((X(I)-XMIN)/(XMAX-XMIN))*100.+.5
      IF (KPLOTX.GT.100) KPLOTX=100
      IF (KPLOTX.EQ.0) GOTO 11
      IF(.NOT.BAR) GO TO 6
```

```
C
C PLOTS HISTOGRAMS ON LINE PRINTER.
C
      SUBROUTINE PLOTER(X,N,BAR,TIME,NPOS,LANE)
      REAL X(N),HEAD(10)
      INTEGER LINE(100),BLANK,STAR
      LOGICAL BAR
      DATA BLANK,STAR/' ','*'/
      IF(N.LT.1)GO TO 25
      WRITE( 108,502)
      DO 1 I=1,100
    1 LINE(I)=BLANK
      XMAX=-1.E70
      XMIN= 1.E70
      DO 2 I=1,N
      IF(X(I).LT.XMIN) XMIN=X(I)
      IF(X(I).GT.XMAX) XMAX=X(I)
    2 CONTINUE
      IF(XMAX-XMIN)25,3,4
    3 XMAX=XMIN+1.
      XMIN=XMIN-1.
    4 CONTINUE
      DO 5 I =1,10
      Z=I
    5 HEAD(I)=(XMAX-XMIN)*Z/10.+XMIN
      IF (IABS(LANE).EQ.3) WRITE(108,3003)
      IF (IABS(LANE).LT.3) WRITE(108,3004)LANE
      IF (LANE.GT.0) WRITE(108,3001)TIME,NPOS
      IF (LANE.LT.0) WRITE(108,3005)TIME ,NPOS
      WRITE( 108,507) XMIN,HEAD
      IF (LANE.GT.0)WRITE(108,3002)
      IF (LANE.LT.0)WRITE(108,3006)
      DO 6 I=1,N
      KPLOTX=((X(I)-XMIN)/(XMAX-XMIN))*100.+.5
      IF (KPLOTX.GT.100) KPLOTX=100
      IF (KPLOTX.EQ.0) GOTO 11
      IF(.NOT.BAR) GO TO 8
```

```
C
C PLOTS HISTOGRAMS ON LINE PRINTER.
C
      SUBROUTINE PLOTER(X,N,BAR,TIME,NPOS,LANE)
      REAL X(N),HEAD(10)                                              00300080
      INTEGER  LINE(100),BLANK,STAR                                   00300090
      LOGICAL BAR                                                     00300100
      DATA BLANK,STAR/' ','*'/                                        00300110
      IF(N.LT.1)GO TO 25                                              00300120
      WRITE( 108,502)                                                 00300130
      DO 1 I=1,100                                                    00300140
    1 LINE(I)=BLANK                                                   00300150
      XMAX=-1.E70                                                     00300160
      XMIN= 1.E70                                                     00300170
      DO 2 I=1,N                                                      00300180
      IF(X(I).LT.XMIN) XMIN=X(I)                                      00300190
      IF(X(I).GT.XMAX) XMAX=X(I)                                      00300200
    2 CONTINUE                                                        00300210
      IF(XMAX-XMIN)25,3,4                                             00300220
    3 XMAX=XMIN+1.                                                    00300230
      XMIN=XMIN-1.                                                    00300240
    4 CONTINUE                                                        00300250
      DO 5 I =1,10                                                    00300260
      Z=I                                                             00300270
    5 HEAD(I)=(XMAX-XMIN)*Z/10.+XMIN                                  00300280
      IF (IABS(LANE).EQ.3) WRITE(108,3003)
      IF (IABS(LANE).LT.3) WRITE(108,3004)LANE
      IF (LANE.GT.0) WRITE(108,3001)TIME,NPOS
     CIF (LANE.LT.0) WRITE(108,3005)TIME ,NPOS
      WRITE( 108,507) XMIN,HEAD                                       00300300
      IF (LANE.GT.0)WRITE(108,3002)
      IF (LANE.LT.0)WRITE(108,3006)
      DO 6 I=1,N                                                      00300330
      KPLOTX=((X(I)-XMIN)/(XMAX-XMIN))*100.+.5
      IF (KPLOTX.GT.100) KPLOTX=100
      IF (KPLOTX.EQ.0) GOTO 11
      IF(.NOT.BAR) GO TO 8                                            00300350
```

```
      DO 7 K=1,KPLOTX
    7 LINE(K)=STAR
   11 CONTINUE                                                            00300380
    8 LINE(KPLOTX)=STAR
         SPACE=.9+(I*.1)
      IF (LANE.LT.0) SPACE=I*2.-1.
      WRITE(108,508) SPACE,X(I),LINE
      IF(.NOT.BAR) GO TO 10                                               00300400
      DO 9 K =2,KPLOTX                                                    00300410
    9 LINE(K-1)=BLANK                                                     00300420
   10 LINE(KPLOTX)=BLANK                                                  00300430
    6 CONTINUE                                                            00300440
      RETURN                                                              00300460
   25 WRITE( 108,506)                                                     00300470
      RETURN                                                              00300480
  502 FORMAT (1H1 )                                                       00300490
 3003 FORMAT(1X,'LANES 1& 2 AVERAGED TOGETHER',/)
 3004 FORMAT(1X,'LANE',I5,3X,'AVERAGED',/)
 3005 FORMAT(20X,'TIME',F10.3,2X,'POSITION',I5,10X,'PROBABILITY OF DELAY
     & X')
 3006 FORMAT(1X,9HDELAY    ,15(1H-),1HI,10(9X,1HI)/
     &1X,6H(SECS),15X,1HX,2X,1HI,10(9X,1HI))
 504  FORMAT(1X,24(1H-),1H.,20(5H----.),1H-)
  507 FORMAT(16X,11(F9.3,1HX))
 508  FORMAT(1X,F6.2,7X,F11.4,1HI,99A1,A1)
  506 FORMAT ( 1X, 12HPLOTER ERROR )                                      00300530
 3001 FORMAT(20X,'TIME ',F10.3,'  POSITION ',I5,10X,'PROBABILITY OF   SPA
     CCING X')
 3002 FORMAT(1X,9HSPACING  ,15(1H-),1HI,10(9X,1HI)/
     C1X,16H(* MIN HEADWAY ),5X,1HX,2X,1HI,10(9X,1HI))
      END                                                                 00300560
```

```
C
C WRITES AND READS FROM A PARTICULAR DISK SECTOR.
C
      SUBROUTINE DISKRD(ISA,BUFFER,IU)
      I=2Z10
      GOTO 1
C
      ENTRY DISKWT(ISA,BUFFER,IU)
      I=2Z11
    1 J=IU
S           LI,1        F:2
S           LW,9        J
S           CI,9        2
S           BNE         $+2
S           LI,1        F:3
S           LW,9        I
S           STB,9       1
S           LW,2        =X'F1000010'
S           LI,3        2S
S           LI,4        2S
S           LW,5        BUFFER
S           BGEZ        $+2
S           LW,5        *5
S           LI,6        360
S           LW,7        *ISA
S           BGEZ        $+2
S           LW,7        *7
S           CAL1,1      1
      RETURN
    2 PAUSE  'PROG DISK ERROR'
      END
```

```
C!MACRSYM SI,GO
         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
C!ALLOBT (FIL,X2),(FSI,80)
C!OLOAD GO,(UDCB,5),(PUBLIB,COCLIB)
C:ASS (F:22,0)
C:ASS (F:2,D1,LB1)
C:ASS (F:3,D1,LB2)
C:ASS (F:1,TO)
C:ASS (F:20,OC)
C!EXTRABGD
```

```
C
C THIS PROGRAM SIMULATES NETWORKS.
C
C!FORTRANH
      COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPFEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
     &,MAR(10),ICODE(20),ICRL(20),JPRINT,JPLOT,JPICT,JFLOW,JPARAM,JMAG
      COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SDUM
     &,IVEHA(100,4),LINKP(20,2),LI,NCRL(20)
     &,ITIME,NPRINT,NPLOT,NPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
     &,BAL1(21)
     &,BAL2(14)
     &,BAL3(21)
     &,BAL6(5)
     &,BAL17(3)
      COMMON /VREAD/ IBC,IST,L,IM,IBUF1(10)
      COMMON /CONST3/ LINKST(20),IPST(20),SFACT
      COMMON /WRIT/ SETTIM,ISTEP,IKNOW,IFLG,TSAVE,IPRT
     &,ITRACE,ILINK,IVNO
     &,ITMO
     &,NONSTOP
      COMMON /CARRY/ NODE,HSTORE,WSTORE
     &,SCSTX,SCSTY
      FLAG=1
      CALL SEGLOD(1)
C INPUT DATA AND UNITS HEADER.
      CALL DATARD
      NDUM=NLINKS-1
      DO 6 I=0,NDUM
      IF (I.EQ.0) GOTO 10
C SET UP LINK VEHICLE QUEUE POINTERS.
      LINKP(I+1,1)=LEND(I,1)+1
      GOTO 6
   10 LINKP(I+1,1)=1
    6 LINKP(I+1,2)=LEND(I+1,1)
```

```
C INITIALISE LØCAL CØUNTERS.
      ISTEP=0
      ITIME=0
      NPRINT=0
      NPLØT=0
      NPICT=0
      NFLØW=0
      NPARAM=0
      NMAG=0
      DØ 950 I=1,5
  950 LINKST(I)=0
C ITRANS TRANSLATES ARRAY PØSITIØN INTØ VEHICLE NUMBER FØR LINK.
      DØ 960 I=1,100
  960 ITRANS(I)=0
      TSAVE=-1.
      IPRT=0
      NØNSTØP=0
      ITRP=1
      FLAG=3
      CALL SEGLØD(3)
      CALL ILDWD
      ITEST2=1
      ITMØ=0
      IKNØW=0
      IFLG=0
      HSTØRE=HIEGHT
      WSTØRE=WIDTH
      FLAG=2
      CALL SEGLØD(2)
C INITIALISE SUBRØUTINES.
      CALL PRINT2(1)
      CALL SPACES(0)
      CALL INØD
      LI=7
      CALL RANDØM(LI,LI,RAND)
      CALL ICØNTRØL
C INITIALISE A VEHICLE AT EACH ENTRANCE.
```

```
      DO 7 I=1,NIN
      J=LINKP(I,1)
      CALL ENTRY(I,J)
    7 TIMEN(I)=SPACE(I)
      FLAG=4
      CALL SEGLOD(4)
      CALL WRIFIN
      CALL WRITER
      GOTO 93
C INCREMENT TIME.
   20 TIME=ITIME*DELT
      IF (IPRT.EQ.1) GOTO 500
C SKIP READ CHECK.
      IF (ISTEP)320,322,500
C CHECK READ.
  322 CALL CHECK(L,IM,IST,IBC)
      IF (IAND(IST,1).EQ.1) GOTO 500
C HERE IF READ FINISHED.
      IBYTE=0
      IST=0
      CALL BCMOVE(L,IBUF1,IBYTE,IBC,IST)
  320 CALL SEGLOD(3)
C STOP PICTURE DISPLAY.
      CALL PSTOP
      I=2
C CHECK IF MAIN DIALOGUE TO BE SKIPPED.
      IF (ICH(IBUF1,I).EQ.2Z47) NONSTOP=1
      IST=0
      IBC=1
C SET UP READ FOR TIMING CHARACTER.
      CALL BCREAD(L,IBC,IST)
      CALL SEGLOD(4)
   93 CONTINUE
      FLAG=4
C BRANCH TO DIALOGUE.
      CALL DECIDE
  500 CONTINUE
```

```
C IFLG = 1 FOR MAGNIFIED PICTURE.
      IF (IFLG.NE.1) GOTO 334
      FLAG=3
      CALL SEGLOD(3)
C DRAW MAGNIFIED PICTURE OF NETWORK.
      CALL NEWPIC
      ITMO=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
      ITMO=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
      ITEST1=1
      IF (IKNOW.NE.-1) GOTO 324
      FLAG=4
      CALL SEGLOD(4)
C MOVE BACK ONE STEP ON MAG TAPE.
      CALL BACK
```

```
      ITEST1=-1
 324  CONTINUE
      IF (ITEST1.EQ.ITEST2) GOTO 31
      ITMO=ITEST1
  31  ITEST2=ITEST1
      FLAG =3
      CALL SEGLOD(3)
      IF (ITMO.EQ.50) GOTO 30
C CHANGE CLOCK IF DIRECTION OF STEEPING CHANGES.
      CALL CLOCK(ITMO)
      ITMO=50
  30  CONTINUE
C SEND VEHICLE PICTURE.
      CALL VEHPIC
      NPICT=0
      IF (ITRACE.NE.1.OR.NPRINT.EQ.0) GOTO 41
      FLAG=1
      CALL SEGLOD(1)
C PRINT IF TRACE OPTION SELECTED.
      CALL PRINT
  41  CONTINUE
C IF STEPPING BACKWARDS IGNORE WRITE TO MAGNETIC TAPE.
      IF (IKNOW.EQ.-1) GOTO 44
      IF (NMAG.LT.JMAG) GOTO 44
      IF (FLAG.EQ.4) GOTO 45
      CALL SEGLOD(4)
      FLAG=4
C OUTPUT TO MAG TAPE
  45  CALL WRITER
      NMAG=0
  44  CONTINUE
C LOAD CORRECT SEGMENT.
      IF (FLAG.EQ.2) GOTO 43
      FLAG=2
      CALL SEGLOD(2)
   43 CONTINUE
C STOP CONDITION.
```

```
      IF (TIME.LE.TSTOP) GOTO 46
      ENDFILE 1
      STOP
   46 CONTINUE
C MOVE VEHICLES ONE TIME STEP.
      CALL CRLCHK
      CALL ECHECK(1)
      CALL ECHECK(0)
      CALL VMOVE
      CALL ASVEH
C INCREMENT LOCAL COUNTERS.
      ITIME=ITIME+1
      NPRINT=NPRINT+1
      NPLOT=NPLOT+1
      NPICT=NPICT+1
      NFLOW=NFLOW+1
      NPARAM=NPARAM+1
      NMAG=NMAG+1
      GOTO 20
      END
```

```
C
C VEHICLE CONTRØL SUBRØUTINE.
C
      SUBRØUTINE ICØNTRØL
      CØMMØN /CØNST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PRØB(4,4)
     &,CRL(20),CØNST1,CØNST2,ACCJK,DELT,HIEGHT,WIDTH
      CØMMØN /CØNST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NØUT
     &,MAR(10),ICØDE(20),ICRL(20),JPRINT,JPLØT,JPICT,JFLØW,JPARAM,JMAG
      CØMMØN /VAR/ TIME,TSTØP,VEHA(100,8),TIMEN(4),HDWYS(100),SFACT
     &,IVEHA(100,4),LINKP(20,2),LI,NCRL(20)
     &,ITIME,NPRINT,NPLØT,NPICT,NFLØW,NPARAM,NMAG,ITRANS(100),ITRP
     &,BAL1(21)
     &,BAL2(14)
     &,S,ØFFSET,KPØINT,JPØINT,KLANE,LLVEH,THDWYE,THDWYC
     &,THDWYF,DTIME,KLINK,NFV(2),LANE(2),PART(2),ART(2),TØTDEL(2)
     &,BAL6(5)
     &,BAL17(3)
      LØGICAL FLAG
      FLAG=.FALSE.
C INITIALISATIØN.
      DØ 21 I=1,5
      GØTØ (23,24,25,26,27) I
   23 N=1
      M=1
      NØ=0
      DØ 33 J=1,NLINKS
      IF (NCRL(J).EQ.0) GØTØ 33
      NØ=NØ+NCRL(J)
      DØ 34 K=M,NØ
      IF (ICRL(K).NE.1) GØTØ 34
      LANE(N)=J
      N=2
      PØSN=PEND(J)
   34 CONTINUE
      M=M+NCRL(J)
   33 CONTINUE
```

```
      SPNML=SPEEDL(LANE(1))
      S=ABS(SPNML*SPNML-CSPEED*CSPEED)/(2.*ACCNML)
      OFFSET=(POSN-S)/SPNML+ABS(SPNML-CSPEED)/ACCNML
      KPOINT=LINKP(LANE(1),1)
      JPOINT=LINKP(LANE(2),1)
      NFV(1)=-KPOINT
      NFV(2)=-JPOINT
      KLANE=1
      LLVEH=KPOINT
      THDWYE=CSPEED/(2*ACCEMG)+VL/CSPEED
      THDWYC=THDWYE*FCHDWY
      THDWYF=THDWYE*FFHDWY
      GOTO 21
   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)
      DO 36 K=M,NO
      IF (ICRL(K).NE.3) GOTO 36
      DTIME=PEND(J)/CSPEED
      KLINK=J
      GOTO 37
   36 CONTINUE
      M=M+NCRL(J)
   35 CONTINUE
   37 CONTINUE
   26 GOTO 21
   27 GOTO 21
   21 CONTINUE
      RETURN
C
      ENTRY CONTROL(JJ,PPOSM,NSTRAT)
      J=JJ
      POSN=PPOSM
```

```
      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),IABS(NFV(2)),1)
      KLANE=2
      GOTO 28
   20 NFV(1)=-MARK(LANE(1),IABS(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 (-NFV(I).EQ.J) NFV(I)=-NFV(I)
      DO 1 I=1,2
      IF (NFV(I).GT.0) GOTO 1
      NFLANE=IVEHA(LLVEH,2)
      NSLANE=IVEHA(J,2)
      THDWYN=THDWYC
      IF (NFLANE.EQ.NSLANE) THDWYN=THDWYF
      VEHA(J,4)=VEHA(LLVEH,4)+THDWYN
      IVEHA(LLVEH,4)=-J
   82 CONTINUE
      LLVEH=J
      MPOINT=1
      I=NSLANE
      GOTO 11
    1 ART(I)=VEHA(NFV(I),5)+OFFSET
      STAR=VEHA(KPOINT,4)
      DO 2 I=1,2
      THDWYN=THDWYC
      IF (I.EQ.KLANE) THDWYN=THDWYF
```

```
      PART(1)=STAR+THDWYN
      IF (ART(I).GT.PART(1)) PART(1)=ART(I)
      PART(2)=PART(1)+THDWYC
      IF (ART(3-I).GT.PART(2)) PART(2)=ART(3-I)
    2 TOTDEL(I)=PART(1)-ART(I)+PART(2)-ART(3-I)
      LNEXT=1
      IF (TOTDEL(2).LT.TOTDEL(1)) LNEXT=2
      THDWYN=THDWYC
      IF (LNEXT.EQ.KLANE) THDWYN=THDWYF
      K=NFV(LNEXT)
      VEHA(K,4)=STAR+THDWYN
      IF (K.NE.J) GOTO 50
      KSTORE=IVEHA(KPOINT,4)
      IVEHA(KPOINT,4)=K
      IVEHA(K,4)=KSTORE
      NXVEH=K
      NFLANE=IVEHA(K,2)
   51 KSTORE=IVEHA(NXVEH,4)
      IF (KSTORE.EQ.0) GOTO 61
      K1=-KSTORE
      NSLANE=IVEHA(K1,2)
      THDWYN=THDWYC
      IF (NSLANE.EQ.NFLANE) THDWYN=THDWYF
      SLIP=VEHA(NXVEH,4)+THDWYN-VEHA(K1,4)
      IF (SLIP.LE.0.) GOTO 61
      VEHA(K1,4)=VEHA(K1,4)+SLIP
      NXVEH=K1
      NFLANE=NSLANE
      GOTO 51
   50 NXVEH=IVEHA(KPOINT,4)
      IF (-NXVEH.EQ.K) GOTO 52
      OUTPUT(108)'TARGET TABLE FAILURE',TIME
   52 IVEHA(KPOINT,4)=K
   61 KPOINT=NFV(LNEXT)
      KLANE=LNEXT
      NFV(LNEXT)=-MARK(LANE(LNEXT),KPOINT,1)
      NFVEH=KPOINT
```

```
  101 KSTORE=IVEHA(NFVEH,4)
      IF (KSTORE.NE.NFV(LNEXT)) GOTO 102
      NFV(LNEXT)=-NFV(LNEXT)
  102 CONTINUE
      IF (J.NE.K.AND.NFV(LNEXT).GT.0) GOTO 40
      IF (J.EQ.K) GOTO 851
   60 K1=K
  901 KSTORE=IVEHA(K1,4)
      IF (KSTORE.EQ.0) GOTO 900
      K1=-KSTORE
      GOTO 901
  900 LLVEH=K1
C CALCULATE INTERMEDIATE SPEEDS.
      NFLANE=IVEHA(LLVEH,2)
      NSLANE=IVEHA(J,2)
      THDWYN=THDWYC
      IF (NSLANE.EQ.NFLANE) THDWYN=THDWYF
      VEHA(J,4)=VEHA(LLVEH,4)+THDWYN
      IVEHA(LLVEH,4)=-J
      LLVEH=J
  851 CONTINUE
      SPNML=SPEEDL(IVEHA(J,2))
      VEHA(J,7)=SPNML
      MPOINT=1
      I=IVEHA(J,2)
   11 CONTINUE
      IF (NSTRAT.EQ.1) RETURN
      UJ=VEHA(J,6)
      UV =VEHA(J,2)
      DTTJ=PEND(I)-POSN
      TTTJ=VEHA(J,4)-TIME
      IF (TTTJ.GT.0.) GOTO 3
      SPNML=SPEEDL(I)
      VEHA(J,7)=SPNML
      FLAG=.TRUE.
      GOTO 8
    3 D1=ABS(UJ*UJ-UV*UV)/(2*ACCNML)
```

```
      D2=ABS(UJ-UV)/ACCNML
      T1=(DTTJ-D1)/UJ+D2
      T2=(DTTJ-D1)/UV+D2
      IF (UV.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.0.) GOTO 6
      VEHA(J,7)=SPNML
      FLAG=.TRUE.
      GOTO 8
6     D3=SQRT(D3)
      VEHA(J,7)=(-B+D3)/(2*A)
      GOTO 8
5     VEHA(J,7)=(DTTJ-D1)/(TTTJ-D2)
      GOTO 8
4     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.0.) GOTO 7
      CALL PRINT1('INTERSECTION SPEED REQUD TOO LOW',TIME,I,J)
      VEHA(J,7)=1.
      GOTO 8
7     D3=SQRT(D3)
      VEHA(J,7)=(-B+D3)/(2*A)
8     IF (VEHA(J,7).LT.SPNML) GOTO 9
      VEHA(J,7)=SPNML
      FLAG=.TRUE.
9     IF (.NOT.FLAG) GOTO 90
```

```
      FLAG=.FALSE.
      UI=VEHA(J,7)
      T=(DTTJ+(UJ*UJ+UV*UV-2*UI*UI)/(2*ACCNML))/UI+(2*UI-UV-UJ)/ACCNML
      TTARGN=TIME+T
      SLIP=TTARGN-VEHA(J,4)
        NXVEH=J
 15   VEHA(NXVEH,4)=VEHA(NXVEH,4)+SLIP
        NFLANE=IVEHA(NXVFH,2)
        KSTORE=IVEHA(NXVFH,4)
        IF (KSTORE.EQ.0) GOTO 90
      K1=IABS(KSTORE)
        NSLANE=IVEHA(K1,2)
        THDWYN=THDWYC
        IF (NSLANE.EQ.NFLANE) THDWYN=THDWYF
        SLIP=VEHA(NXVEH,4)-VEHA(K1,4)+THDWYN
        NXVEH=K1
        IF (SLIP)90,90,15
 90   GOTO (91,61) MPOINT
 91   CONTINUE
      IF (VEHA(J,7).GE.1.) RETURN
      VEHA(J,7)=1.
      CALL PRINT1('INTERMEDIATE SPEED REQUD TOO LOW',TIME,I,J)
      RETURN
 12   VEHA(J,4)=VEHA(J,4)+DTIME
      I=KLINK
      GOTO 11
 13   VEHA(J,4)=0.
      SPNML=SPEEDL(IVEHA(J,2))
      VEHA(J,7)=SPNML
      RETURN
 14   VEHA(J,7)=VEHA(J,6)
      RETURN
 110  CONTINUE
      DO 92 I=1,2
      IF (J.NE.NFV(I)) GOTO 92
      NFVEH=J
      GOTO 93
```

```
      FLAG=.FALSE.
      UI=VEHA(J,7)
      T=(DTTJ+(UJ*UJ+UV*UV-2*UI*UI)/(2*ACCNML))/UI+(2*UI-UV-UJ)/ACCNML
      TTARGN=TIME+T
      SLIP=TTARGN-VEHA(J,4)
        NXVEH=J
 15   VEHA(NXVEH,4)=VEHA(NXVEH,4)+SLIP
        NFLANE=IVEHA(NXVEH,2)
        KSTORE=IVEHA(NXVEH,4)
        IF (KSTORE.EQ.0) GOTO 90
      K1=IABS(KSTORE)
        NSLANE=IVEHA(K1,2)
        THDWYN=THDWYC
        IF (NSLANE.EQ.NFLANE) THDWYN=THDWYF
        SLIP=VEHA(NXVEH,4)-VEHA(K1,4)+THDWYN
        NXVEH=K1
        IF (SLIP)90,90,15
 90   GOTO (91,61) MPOINT
 91   CONTINUE
      IF (VEHA(J,7).GE.1.) RETURN
      VEHA(J,7)=1.
      CALL PRINT1('INTERMEDIATE SPEED REQUD TOO LOW',TIME,I,J)
      RETURN
 12   VEHA(J,4)=VEHA(J,4)+DTIME
      I=KLINK
      GOTO 11
 13   VEHA(J,4)=0.
      SPNML=SPEEDL(IVEHA(J,2))
      VEHA(J,7)=SPNML
      RETURN
 14   VEHA(J,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.KPOINT) GOTO 97
     NFVEH=-IVEHA(KPOINT,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
     LANET=IVEHA(KPOINT,2)
     DO 95 I=1,2
95   IF (LANE(I).EQ.LANET) 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
```

```
C
C FOR ENCODING AND TRANSMITTING PICTURE ROUTINE CHARACTERS.
C
      SUBROUTINE ILDWD
      COMMON /CILDWD/ IPT,IBUF(25),IARR(3)
      COMMON /VREAD/ IBC,IST,L,IM,IBUF1(10)
      COMMON /WRIT/ SETTIM,ISTEP,IKNOW,IFLG,TSAVE,IPRT
     &,ITRACE,ILINK,IVNO
     &,ITMO
     &,NONSTOP
      COMMON /VAR/ TIME
      COMMON /CONST2/ IBUF2(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
      DIMENSION IHOLD2(100)
      EQUIVALENCE (IARR(1),INTEG),(IARR(2),IHIORD),(IARR(3),ILOORD)
      NAMELIST L,TSAVE
C INITIALISATION.
      IPT=0
      IPT2=0
      INPUT(20)
      IST=0
      IKNOW=0
      RETURN
C
      ENTRY LDWD1(MNO)
      INTEG=MNO
C IHOLD SAVES DATA FOR DEBUGGING.
      IHOLD2(IPT2+1)=INTEG
      IPT2=IPT2+1
C DIVIDE NUMBER INTO A HIGH ORDER AND LOW ORDER COMPONENT BREAKPT 2**8
      IHIORD=INTEG/128
      ILOORD=INTEG-IHIORD*128
C SAVE BYTES IN OUTPUT BUFFER.
      DO 1 I=2,3
      INTEG=IARR(I)
S     LW,4      IPT
S     LW,9      INTEG
S     STB,9     IBUF,4
```

```
      IPT=IPT+1
      IF (IPT.NE.100) GOTO 1
      INDEX=3
      GOTO 9
    1 CONTINUE
      RETURN
C
      ENTRY LDWD2(MNO)
      INTEG=MNO
      IHOLD2(IPT2+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)5,6,6
    5 ISIGN=64
      INTEG=-INTEG
C CONVERT TO TWO BYTE TYPE.
    6 IHIORD=INTEG/128
      ILOORD=INTEG-IHIORD*128
C ENSURE LOW ORDER NOT ZERO.
      IF (ILOORD.NE.0) GOTO 10
      ILOORD=1
C ADD ZERO FLAG BIT.
      IHIORD=IHIORD+8
   10 CONTINUE
      INTEG=0
      IARR(1)=0
C ADD SIGN BIT.
      IHIORD=IHIORD+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=IARR(I)
S        LW,4    IPT
S        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 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 BCWRITE(L,IBUF,0,IPT,IST)
  300 CONTINUE
  100 FORMAT(1H0,10(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
  310 CALL CHECK(L,IM,IST,IBC)
C HAS READ ENDED
      IF (IAND(IST,1).EQ.1) GOTO 310
      IBYTE=0
      IST=0
      CALL BCMOVE(L,IBUF1,IBYTE,IBC,IST)
      DO 210 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.2Z42) IKNOW=-1
      IF (ICH(IBUF1,I).EQ.2Z50) IPRT=1
      GOTO 210
 222  OUTPUT(108) TIME
C OUTPUT DATA SAVED TO LINE PRINTER.
      WRITE(108,100) (IHOLD2(II),II=1,IPT2)
      IPT2=0
 210  IST=0
      IBC=2
      IF (ISTEP.EQ.-1) GOTO 200
      CALL BCREAD(L,IBC,IST)
 200  CONTINUE
      GOTO (7,8,1) INDEX
      END
```

```
C
C
      SUBROUTINE WRITER
      COMMON /VAR/ISAVE(1540)
      COMMON /WRIT/ SETTIM,ISTEP,IKNOW,IFLG,TSAVE,IPRT
     &,ITRACE,ILINK,IVNO
     &,ITMO
     &,NONSTOP
      EQUIVALENCE (ISAVE(1),TIME)
      IF (TIME.LE.TSAVE) GOTO 1
C TSAVE IS LAST RECORDED TIME ON TAPE.
      TSAVE=TIME
C SAVE ALL VARIABLES DEFINING PROGRAM.
      CALL BUFFEROUT(1,1,ISAVE,1540,IST,N)
      RETURN
C READ IN FROM SAVED DATA.
    1 CALL BUFFERIN(1,1,STO,1,IST,N)
      RETURN
C
      ENTRY WRIFIN
C END FILE UNLESS ALREADY ENDED ELSEWHERE.
      IF (TIME.LE.TSAVE) GOTO 30
      ENDFILE 1
      RETURN
C
      ENTRY READER
      INDEX=1
      IF (SETTIM.EQ.TIME) GOTO 32
      IF (SETTIM.LT.TIME) GOTO 20
C MOVE POSITION ON DATA TAPE FROM TIME TO SET TIME.
   21 IF (TIME.GE.TSAVE) GOTO 32
      CALL BUFFERIN(1,1,ISAVE,1540,IST,N)
      IF (IST.NE.3) GOTO 22
      INDEX=3
      GOTO 20
C BUFFERIN MORE.
   22 IF (TIME.LT.SETTIM) GOTO 21
```

```
      GOTO 32
C BUFFERIN BY READING TAPE BACKWARDS.
 20   CONTINUE
S        LI,9        F:1
S        AW,9        =8Z10000000
S        LW,10       =8Z60000030
S        LI,11       30S
S        LI,12       ISAVE
S        CAL1,1      9
      GOTO (31,32,32)INDEX
 31   IF (TIME.GT.SETTIM) GOTO 20
      GOTO 32
 30   CALL SKIPFILE(1,1)
 32   RETURN
C READ BACKWARDS ONE BLOCK.
C
      ENTRY BACK
      INDEX=2
      GOTO 20
      END
```

```
C
C
      SUBROUTINE SENDER
      DIMENSION IBUF(20)
      COMMON /VREAD/ IBC,IST,L,IM,IBUF1(10)
C READ IN FOCAL PROGRAM LINE FROM DATA FILE.
    3 CALL BUFFERIN(10,1,IBUF,20,IST)
      IF (IST.NE.2) GOTO 4
C REMOVE TRAILING BLANKS.
      DO 1 J=80,1,-1
    1 IF (ICH(IBUF,J).NE.Z240) GOTO 2
      IF (J.LE.0)J=1
C ADD CARRIAGE RETURN TO LINE ENDS.
S2       LW,1       J
S        LI,9       X'OD'
S        STB,9      IBUF,1
         J=J+1
   20 CONTINUE
C CHECK READ FINISHED.
      CALL CHECK(L,IM,IST,IBC)
      IF (IAND(IST,2).EQ.2) GOTO 20
C WAITING TO ENSURE GT40 CAN KEEP UP.
      DO30 I=1,20000
   30 CONTINUE
C TRANSMIT LINE.
      IST=0
      CALL BCWRITE(L,IBUF,0,J,IST)
      GOTO 3
    4 RETURN
      END
```

```
C
C OPERATOR DIALOGUE.
C
      SUBROUTINE DECIDE
      COMMON /WRIT/ SETTIM,ISTEP,IKNOW,IFLG,TSAVE,IPRT
     &,ITRACE,ILINK,IVNO
     &,ITMO
     &,NONSTOP
      COMMON /CARRY/ NODE,HSTORE,WSTORE
     &,SCSTX,SCSTY
      COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      DIMENSION IMESS1(5),IMESS2(8),IMESS3(9),IMESS4(9),IMESS5(11)
     &,IMESS6(5),IMESS7(11),IMESS8(4)
      DIMENSION IMESS9(4)
      DIMENSION IMESS10(5)
      COMMON /VREAD/ IBC,IST,L,IM,IBUF(10)
      DIMENSION IMESS11(10)
      DIMENSION IMESS4A(9),IMO(20),IMESS12(5)
      DIMENSION IMESS13(6)
      DIMENSION IMESS9A(12)
      COMMON /CONST2/ FILL1(219)
      EQUIVALENCE (FILL1(216),JPICT)
      COMMON /VAR/ FILL(1540)
      EQUIVALENCE (FILL(1),TIME)
      DIMENSION LINKP(20,2)
      DIMENSION ITRANS(100)
      EQUIVALENCE (FILL(1308),LINKP(1,1))
      EQUIVALENCE (FILL(1376),ITRANS(1))
      DIMENSION MAR(10)
      DIMENSION IMESS14(7)
      EQUIVALENCE (FILL1(164),MAR(1))
      DATA ICR/8Z0D000000/
      DATA IMESS1/'C TYPE CONTROL T',8Z0D000000/
      DATA IMESS2 /'WHICH OPTION IS ','REQUIRED ?',8Z0D000000/
      DATA IMESS3 /'RESET TIME #R ST','EP PICTURES #S',8Z0D000000/
```

```
      DATA IMESS4 /'WRONG CHARACTER ','INPUT TRY AGAIN',8Z0D000000/
      DATA IMESS5 /'INPUT IN SECS CH','ANGE IN TIME REQ','UIRED',8Z0D000
     &000/
      DATA IMESS6 /'STEP OPERATION ',8Z0D000000/
      DATA IMESS7/'C TYPE CONTROL T',' & INDICATE TO C','ONTINUE',8Z0D00
     &0000/
      DATA IMESS8 /'D 1.1;G 1.3',8Z0D000000/
      DATA IMESS9 /'WHICH NODE ?',8Z0D000000/
      DATA IMESS10/'HIEGHT & WIDTH ?',8Z0D000000/
      DATA IMESS11 /'NO OF TIME STEPS',' BETWEEN PICTURE','S ?',8Z0D0000
     &00/
      DATA IMESS4A /'MAGNIFY PICTURES',' #Q MESSAGE #M',8Z0D000000/
      DATA IMESS12/'INPUT MESSAGE',8Z0D000000/
      DATA IMESS13/'INPUT LINE & VEH','ICLE',8Z0D000000/
      DATA IMESS9A /'SCREEN X & Y COO','RDS ( 0<X<1000 ;',' 0<Y<760)',8Z
     &0D000000/
      DATA IBL/8Z40404040/
      DATA IMESS14/'DIAGNOSTIC SUPRE','SSION ?',8Z0D000000/
C CHECK READ FINISHED FOR TIMING CHARACTER FROM GT40.
    9 CALL CHECK(L,IM,IST,IBC)
      IF (IAND(IST,1).EQ.1) GOTO 9
      IST=0
      IBYTE=0
      CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
      IFLG=0
      ISTEP=0
      ITRACE=0
      ITMO=50
      LOAD=0
      MAR(3)=0
C CHANGE CDC STATUS TO ECHO.
      CALL BCSET(L,132,0)
C SKIP CHANGES IF NONSTOP SET.
      IF (NONSTOP.EQ.1) GOTO 54
C CHANGE GT40 STATUS SCREEN/PROGRAM.
   52 CALL BCWRITE(L,IMESS7,0,41,IST)
      IBC=1
```

```
      IST=0
C READ ONE CHARACTER TO CONTINUE.
      CALL BCREAD(L,IBC,IST)
 800  CALL CHECK(L,IM,IST,IBC)
C CHECK IT HAS ARRIVED.
      IF (IAND(IST,8).NE.8) GOTO 800
      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 SENDER
      LOAD=0
      IST=0
      GOTO 52
  20  CONTINUE
      IST=0
C WRITE TO GT40 'WHICH OPTION REQUIRED'.
      CALL BCWRITE(L,IMESS2,0,29,IST)
      GOTO 6
   7  IST=0
C WRITE OUT OPTION AVAILABLE.
      CALL BCWRITE(L,IMESS3,0,33,IST)
   6  IBC=10
      IST=0
C READ IN MAXIMUM 10 CHARACTER.
      CALL BCREAD(L,IBC,IST)
   1  CALL CHECK(L,IM,IST,IBC)
      IF (IAND(IST,8).NE.8) 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 SENSE CHARACTER FOR OPTION REQUIRED.
      DO 3 K=1,2
      IF (ICH(IBUF,K).EQ.27D9) GOTO 4
      IF (ICH(IBUF,K).EQ.27E2) GOTO 5
```

```
      IF (ICH(IBUF,K).EQ.27D4) GOTO 22
      IF (ICH(IBUF,K).EQ.270D) GOTO 10
      IF (ICH(IBUF,K).EQ.27D8) GOTO 21
      IF (ICH(IBUF,K).EQ.27C6) GOTO 40
      IF (ICH(IBUF,K).EQ.27E3) GOTO 41
      IF (ICH(IBUF,K).EQ.27D3) GOTO 51
    3 CONTINUE
C WRONG CHARACTER INPUT.
      IST=0
      CALL BCWRITE(L,IMESS4,0,33,IST)
      IST=0
C OPTION AVAILABLE.
      CALL BCWRITE(L,IMESS4A,0,33,IST)
      GOTO 7
   22 IST=0
C MESSAGE OPTION.
      CALL BCWRITE(L,IMESS12,0,17,IST)
   25 IST=0
      IBC=80
C READ IN MESSAGE.
      CALL BCREAD(L,IBC,IST)
   23 CALL CHECK(L,IM,IST,IBC)
      IF (IAND(IST,8).NE.8) GOTO 23
      IST=0
      IBYTE=0
C FILL BUFFER WITH BLANKS.
      DO 26 I=1,20
   26 IMO(I)=IBL
C LOAD WITH MESSAGE.
      CALL BCMOVE(L,IMO,IBYTE,IBC,IST)
C END WITH 2* CR
      IF (IBC.EQ.1) GOTO 20
C WRITE TO LINE PRINTER.
      WRITE(108,24) IMO
   24 FORMAT(X,20A4)
      GOTO 25
C ENDFILE ON TAPE AND STOP.
```

```
   40  ENDFILE 1
       STOP
C LOAD FOCAL PROGRAM.
   51  LOAD=1
       GOTO 52
C SET TRACE OPTION.
   41  ITRACE=1
       IST=0
       CALL BCWRITE(L,IMESS13,0,21,IST)
       IST=0
C READ IN LINK NUMBER AND VEHICLE FOR TRACING, COUNTED FROM END OF LINK.
       IBC=20
       CALL BCREAD(L,IBC,IST)
   42  CALL CHECK(L,IM,IST,IBC)
       IF (IAND(IST,8).NE.8) GOTO 42
       IST=0
       IBYTE=0
       CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
       DECODE(10,103,IBUF,N) ILINK,IVNO
  103  FORMAT(2I5)
       IVNO=IVNC-1
       J=MARK(ILINK,LINKP(ILINK,2),-IVNO)
       IVNO=ITRANS(J)
       IST=0
C EVENT DIAGNOSTIC OUTPUT CANCELLED.
       CALL BCWRITE(L,IMESS14,0,25,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.27E8) MAR(3)=1
C RETURN TO OPTION SELECT.
       GOTO 20
```

```
   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,IM,IST,IBC)
       IF (IAND(IST,8).NE.8) GOTO 80
       IST=0
       IBYTE=0
       CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
       IF (ICH(IBUF,1).NE.27D9) GOTO 120
       IFLG=-1
C RESTORE NORMAL SIZED PICTURE. IF D9 (R) TYPED.
       HIEGHT=HSTORE
       WIDTH=WSTORE
       GOTO 20
  120  CONTINUE
       DECODE(5,101,IBUF,N) NODE
  101  FORMAT(I5)
       IST=0
C READ IN NEW CO-ORDINATES FOR CHOSEN NODE.
       CALL BCWRITE(L,IMESS9A,0,45,IST)
       IST=0
       IBC=16
       CALL BCREAD(L,IBC,IST)
   83  CALL CHECK(L,IM,IST,IBC)
       IF (IAND(IST,8).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,IM,IST,IBC)
      IF (IAND(IST,8).NE.8) GOTO 82
      IST=0
      IBYTE=0
      CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
      DECODE(16,102,IBUF,N) HIEGHT,WIDTH
  102 FORMAT(2F8.2)
C RETURN FOR NEW OPTION.
      GOTO 20
    4 IST=0
C ASK CHANGE IN TIME REQUIRED.
      CALL BCWRITE(L,IMESS5,0,41,IST)
      IST=0
      IBC=10
      CALL BCREAD(L,IBC,IST)
    2 CALL CHECK(L,IM,IST,IBC)
      IF (IAND(IST,8).NE.8) GOTO2
      IST=0
      IBYTE=0
      CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
      DECODE(10,100,IBUF,N) DISP
  100 FORMAT(F.3)
C NEW TIME FOUND.
      SETTIM=TIME+DISP
C CHANGE TAPE POSITION ACCORDINGLY.
      CALL READER
   12 CONTINUE
C WRITE TO GT40 TIME NOW FOR SCREEN DISPLAY.
      ENCODE(24,110,IBUF,N)TIME,ICR
  110 FORMAT('PRESENT TIME',F10.3,A1)
      IST=0
      CALL BCWRITE(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 BCWRITE(L,IMESS6,0,17,IST)
 10   IST=0
      IF (IABS(IFLG).EQ.1) GOTO 905
      CALL BCWRITE(L,IMESS7,0,41,IST)
 54   NONSTOP=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 BCWRITE(L,IMESS8,0,13,IST)
      ITMO=0
C CHANGE CDC STATUS TO NO ECHO.
      CALL BCSET(L,19,0)
      IST=0
      IBYTE=0
      CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
      IST=0
      IBC=1
C READ TIMING CHARACTER FROM FOCAL 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
```

```
      IBC=2
C SET UP TWO WAY CHARACTER READ FOR STOPPING READ.
      CALL BCREAD(L,IBC,IST)
      RETURN
 905  IST=0
C ASK FOR NUMBER OF TIME STEPS BETWEEN PICTURES, ONLY COME HERE IF
C PICTURE SIZE IS CHANGED.
      CALL BCWRITE(L,IMESS11,0,37,IST)
      IBC=10
      IST=0
      CALL BCREAD(L,IBC,IST)
 906  CALL CHECK(L,IM,IST,IBC)
      IF (IAND(IST,8).NE.8) GOTO 906
      IST=0
      IBYTE=0
      CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
      IF (IBC.EQ.1) GOTO 907
      DECODE(10,101,IBUF,N) JPICT
 907  RETURN
      END
```

```
C!MACRSYM SI,GO
        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          SAVE RETURN ADDRESS
        CAL3,0  0           ENTER FGD PROG
    B   *5,4
        END
C!ALLOBT (FIL,X1),(FSI,300)
C!ALLOBT (FIL,X2),(FSI,120)
C!ALLOBT (FIL,X3),(FSI,10)
C!ALLOBT (FIL,X4),(FSI,10)
C!ALLOBT (FIL,X5),(FSI,10)
C!OLOAD (UDCB,3),(PUBLIB,COCLIB),(TEMP,400)
C:ROOT (FIL,BT,GO,2),(OPLB,MT,3)
C:SEG (LINK,1),(OPLB,MT,2)
C:SEG (LINK,2),(OPLB,MT,1),(FIL,BT,GO,1),(OPLB,MT,8)
C:SEG (LINK,3),(OPLB,MT,1),(FIL,BT,GO,1),(OPLB,MT,4)
C:SEG (LINK,4),(FIL,BT,GO,3)
C:ASS (F:20,CR)
C:ASS (F:1,MT),(RECL,6160)
C:ASS (F:10,D3,EDITOUT)
C!ROV
C
C THE FOLLOWING ROUTINES ARE COMPILED SEPARATELY WHEN RUNNING
C THIS PROGRAM.
C
C!FORTRANH GO,S
C
C GET NEXT LINK IN VEHICLE ROUTE.
C
```

```
      FUNCTION NLINK(J)
      COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
     &,MAR(10),ICODE(20),ICRL(20),JPRINT,JPLOT,JPICT,JFLOW,JPARAM,JMAG
      COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SFACT
     &,IVEHA(100,4),LINKP(20,2),LI,NCRL(20)
     &,ITIME,NPRINT,NPLOT,NPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
     &,BAL1(21)
     &,BAL2(14)
     &,BAL3(21)
     &,BAL6(5)
     &,BAL17(3)
      L=IVEHA(J,1)
      M=IVEHA(J,3)
      N=IVEHA(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.N) GOTO 3
      NLINK=JNEY(L,M,1)
      IF (NLINK.EQ.0) NLINK=IVEHA(J,3)
      RETURN
    3 DO 1 I=1,5
    1 IF (JNEY(L,M,I).EQ.N.OR.JNEY(L,M,I).EQ.0) GOTO 2
C FIND PRESENT LINK IN TABLE.
      CALL PRINT1('UNABLE TO ACCESS NEXT LINK      ',TIME,N,J)
      STOP
    2 I=I+1
C FIND NEXT LINK
      NLINK=JNEY(L,M,I)
C IF ZERO THEN LAST LINK, NEGATIVE NOT AVAILABLE THEREFOR FAULT AND
C EXIT WITH NLINK = NEXT LINK.
      IF (NLINK)5,6,4
    6 NLINK=IVEHA(J,3)
      GOTO 4
```

```
    5  CONTINUE
       CALL PRINT1('ROUTE DEMANDED IS NONEXISTANT    ',TIME,N,J)
       STOP
    4  RETURN
       END
```

```
C
C
      FUNCTION MARK(N,I,J)
      COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
     &,MAR(10),ICODE(20),ICRL(20),JPRINT,JPLOT,JPICT,JFLOW,JPARAM,JMAG
      COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SFACT
     &,IVEHA(100,4),LINKP(20,2),LT,NCRL(20)
     &,ITIME,NPRINT,NPLOT,NPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
     &,BAL1(21)
     &,BAL2(14)
     &,BAL3(21)
     &,BAL6(5)
     &,BAL17(3)
      MARK=I+J
      M=N-1
      NN=0
C CONVERT QUEUE POSITION INTO ARRAY LOCATION.
C N = LINK NUMBER  I = PRESENT POSITION  J = DISPLACEMENT.
      IF (M.NE.0) NN=LEND(M,1)
      IF (J.GT.0) GOTO 2
      IF (MARK.GT.NN) GOTO 1
      MARK=LEND(N,1)-NN+MARK
    2 IF (MARK.LE.LEND(N,1)) GOTO 1
      MARK=NN+MARK-LEND(N,1)
    1 RETURN
      END
```

```
C
C OUTPUTS ERROR MESSAGES TWO TO A LINE.
C
      SUBROUTINE PRINT1(M,AA,II,JJ)
      COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
     &,MAR(10),ICODE(20),ICRL(20),JPRINT,JPLOT,JPICT,JFLOW,JPARAM,JMAG
      COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SFACT
     &,IVEHA(100,4),LINKP(20,2),LI,NCRL(20)
     &,ITIME,NPRINT,NPLOT,NPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
     &,BAL1(21)
     &,I(2),J(2),A(2),K(8)
     &,BAL3(21)
     &,BAL6(5)
     &,L,NUMBER(2)
      DIMENSION M(8)
      IF (MAR(3).NE.0) RETURN
      A(L)=AA
      I(L)=II
      J(L)=ITRANS(JJ)
      IF (L.NE.1) GOTO 2
      DO 1 N=1,8
    1 K(N)=M(N)
C SAVE MESSAGE
      L=2
      RETURN
C OUTPUT TWO MESSAGES TOGETHER
    2 WRITE(108,3)(K(N),N=1,8),A(1),I(1),J(1),(M(N),N=1,8),A(2),I(2),J(2
     &)
      IF (NUMBER(2).EQ.0) GOTO 10
      WRITE(108,20) NUMBER(2)
      NUMBER(2)=0
C ADD IN BY BACK SPACING EXTRA INFORMATION.
   10 IF (NUMBER(1).EQ.0) GOTO 11
      WRITE(108,21) NUMBER(1)
```

```
      NUMBER(1)=0
   11 CONTINUE
      WRITE(108,22)
   22 FORMAT(X)
   21 FORMAT(1H=,28X,I4)
   20 FORMAT(1H=,92X,I4)
      L=1
      RETURN
C INITIALISE PRINT1 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(1),I(1),J(1)
      GOTO 10
    3 FORMAT(1H=,2(X,8A4,' AT',F7.1,2X,'LINK',I3,2X,'VEH',I4,'      '))
      END
```

```
C
C INPUTS DATA AND WRITES HEADER.
C
      SUBROUTINE DATARD
      COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
     &,MAR(10),ICODE(20),ICRL(20),JPRINT,JPLOT,JPICT,JFLOW,JPARAM,JMAG
      COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SFACT
     &,IVEHA(100,4),LINKP(20,2),LI,NCRL(20)
     &,ITIME,NPRINT,NPLOT,NPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
     &,BAL1(21)
     &,BAL2(14)
     &,BAL3(21)
     &,BAL6(5)
     &,BAL17(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,JPLOT,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(108,200) IBUF
      WRITE(108,201)
      WRITE(108,202) SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA,DELT,
```

```
     &CSPEED,TSTOP
      WRITE(108,220)
      WRITE(108,221)CONST1,CONST2,ACCJK
      WRITE(108,203)
      WRITE(108,204) JPRINT,JPLOT,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
      DO 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)=SQRT(A*A+B*B)
      SPEEDL(I)=AMIN1(SPNML,SPEEDL(I))
      GOTO 1
    3 RADIUS=ABS(RADIUS)
      IF (RADIUS.GT.4.) GOTO 4
C CALCULATE RADIUS FROM SUBTENDED ANGLE.
      RADIUS=SQRT(A*A+B*B)/(2*SIN(RADIUS/2))
C CLACULATE LENGTH OF ARC LINK.
    4 PEND(I)=2*RADIUS*ASIN(SQRT(A*A+B*B)/(2*RADIUS))
      SPEEDL(I)=AMIN1(SPEEDL(I),SQRT(SIDEA*RADIUS))
      XYTAB(I,7)=SIGN(RADIUS,XYTAB(I,7))
    1 CONTINUE
      DO 2 I=1,NIN
      DO 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),PROB(I,J)
      WRITE(108,209)
      WRITE(108,210)(I,I=1,4)
      WRITE(108,212)
```

```
C WRITE TO HEADER.
      DO 5 I=1,NIN
    5 WRITE(108,211)I,(((JNEY(I,J,K),K=1,5),PROB(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,NO)
      WRITE(108,214)I,((CRL(J),ICRL(J)),J=M,NO)
      M=M+NCRL(I)
      GOTO 9
C WRITE REST OF HEADER.
    8 WRITE(108,215) I
    9 CONTINUE
      WRITE(108,231)
      DO 900 I=1,NLINKS
  900 WRITE(108,230)I,LEND(I,3),LEND(I,2),SPEEDL(I)
      WRITE(108,130)
  130 FORMAT(/)
      RETURN
  120 FORMAT(F10.3)
  230 FORMAT(3I10,10X,F10.3)
  231 FORMAT(1H0,'LINK NO',2X,'START NODE',2X,'END NODE',10X,
     &'SPEED LIMIT'/30('-')/)
  106 FORMAT(5I10,F10.3)
  209 FORMAT(1H0,'JOURNEY MATRIX   INPUT TO EXIT &  INTERMEDIATE LINKS')
  210 FORMAT(X,52('-')/3X,'EXIT',3X,4(12X,I2,12X))
  212 FORMAT(X,'INPUT')
  211 FORMAT(6X,I2,4(X,5I3,'(',F4.2,')',4X))
  103 FORMAT(3I10,2F10.3)
  105 FORMAT(7F10.3)
  100 FORMAT(20A4)
  111 FORMAT(10I1)
```

```
101 FORMAT(10F8.2/10F8.2)
102  FORMAT(6I10)
110  FORMAT(20I4)
104  FORMAT(4F10.8)
200  FORMAT(1H1,20A4,/,X,120('-'),/,X,'CONSTANTS',/,X,10('-'))
201  FORMAT(1H0,2X,'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(1H0,'NO OF TIME STEPS FOR O/P',7X,'PRINT',8X,'PLOT',5X,'PIC
    &TURE',3X,'FLOW CALC',2X,'PARAM CALC',5X,'MAG O/P')
204  FORMAT(X,24('-'),6I12)
207  FORMAT(1H0,'VEH GENERATORS',15X,'LEVEL 1',5X,'LEVEL 2',5X,
    &'LEVEL 3',5X,'LEVEL 4')
208  FORMAT(X,13('-'),11X,4F12.6)
220  FORMAT(1H0,2X,'POSN CONST',3X,'VEL CONST'4X,'MAX JERK')
221  FORMAT(X,3F12.3)
213  FORMAT(1H0,'LINK NO / CONTROL POINTS AND ASSOCIATED STRATEGIES',/,
    &50('-'),/)
112  FORMAT(I5)
113  FORMAT((5(F10.3,I5),/))
214  FORMAT(X,I5,5X,(5(F10.3,I10),/))
215  FORMAT(X,I5,4X,'NO CONTROL')
     END
```

```
C
C OUTPUT SIMULATION DATA.
C
      SUBROUTINE PRINT
      COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
     &,MAR(10),ICODE(20),ICRL(20),JPRINT,JPLOT,JPICT,JFLOW,JPARAM,JMAG
      COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SFACT
     &,IVEHA(100,4),LINKP(20,2),LT,NCRL(20)
     &,ITIME,NPRINT,NPLOT,NPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
     &,BAL1(21)
     &,BAL2(14)
     &,BAL3(21)
     &,BAL6(5)
     &,BAL17(3)
      COMMON /WRIT/FILL(6),ITRACE,ILINK,IVNO
      DIMENSION ISAVE(25,2)
      IF (MAR(1).NE.0) RETURN
      CALL PRINT2(2)
      IF (ITRACE.EQ.1.AND.NPRINT.NE.0) GOTO 10
      WRITE(108,105)
      WRITE(108,100) TIME
      WRITE(108,101)
C FOR EACH LINK.
      DO 2 I=1,NLINKS
      J=LINKP(I,1)
C REACHED END OF QUEUE FOR LINK.
      IF (MARK(I,J,-1).EQ.LINKP(I,2)) GOTO 2
      WRITE(108,102)
    1 LV=0
      IF (IVEHA(J,4).EQ.0) GOTO 5
      LV=ISIGN(ITRANS(IABS(IVEHA(J,4))),IVEHA(J,4))
    5 CONTINUE
C WRITE VEHICLE DATA.
      WRITE(108,103)ITRANS(J),(VEHA(J,K),K=1,7),HDWYS(J),(IVEHA(J,K),K=1
```

```
     &,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.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'=')
      RETURN
   10 CONTINUE
C TRANSLATE TRACE NUMBER (IUNO) INTO ARRAY LOCATION.
      DO 20 J=1,100
   20 IF (ITRANS(J).EQ.IVNO) GOTO 30
   30 CONTINUE
      LV=0
      IF (IVEHA(J,4).EQ.0) GOTO 50
      LV=ISIGN(ITRANS(IABS(IVEHA(J,4))),IVEHA(J,4))
   50 CONTINUE
```

```
     &,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.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'-')
      RETURN
   10 CONTINUE
C TRANSLATE TRACE NUMBER (IUNO) INTO ARRAY LOCATION.
      DO 20 J=1,100
   20 IF (ITRANS(J).EQ.IVNO) GOTO 30
   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) ITRANS(J),(VEHA(J,K),K=1,7),HDWYS(J),(IVEHA(J,K),K=
     &1,3),LV
      RETURN
  100 FORMAT(//,X,'TIME',F10.3,30X,'DATA',60X,'LINKS')
  101 FORMAT(1H0,' NO',5X,'ACCN',9X,'VEL',8X,'POSN',6X,'T/TIME',6X,'A/TI
     &ME',4X,'NODE VEL',3X,'INT SPEED',5X,'HEADWAY',10X,'IN',3X,'NOW',3X
     &,'OUT',X,'TABLE')
  102 FORMAT(1H0)
  103 FORMAT(X,I3,F9.3,7F12.3,6X,4I6)
      END
```

```
C
C CHECKS IF ANY VEHICLE IS AT A CONTROL POINT.
C
      SUBROUTINE CRLCHK
      COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
     &,MAR(10),ICODE(20),ICRL(20),JPRINT,JPLOT,JPICT,JFLOW,JPARAM,JMAG
      COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SFACT
     &,IVEHA(100,4),LINKP(20,2),LI,NCRL(20)
     &,ITIME,NPRINT,NPLOT,NPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
     &,BAL1(21)
     &,BAL2(14)
     &,BAL3(21)
     &,BAL6(5)
     &,BAL17(3)
      K=0
C DO FOR EACH LINK FRONT AND BACK QUEUE POINTERS.
      DO 1 I=1,NLINKS
      NO=NCRL(I)
      J=LINKP(I,1)
      JJ=LINKP(I,2)
      IF (MARK(I,J,-1).EQ.JJ) GOTO 5
    4 POSN=VEHA(J,3)
      IF (VEHA(J,8).GT.0.) GOTO 3
      NDUN=K+1
      NDUM=K+NO
      DO 2 JJ=NDUN,NDUM
      NSTRAT=ICRL(JJ)
C LOOK AT EACH VEHICLE ON LINK.
C IF AT CONTROL POINT CALL CONTROL.
      IF (POSN.LT.CRL(JJ).OR.POSN.GT.CRL(JJ)+VL) GOTO 2
      CALL CONTROL (J,POSN,NSTRAT)
    2 CONTINUE
      IF (IVEHA(J,3).EQ.I) GOTO 3
      S=PEND(I)-ABS(VEHA(J,2)*VEHA(J,2)-VEHA(J,6)*VEHA(J,6))/(2*ACCNML)
```

```
      TT=ABS(VEHA(J,2)-VEHA(J,6))/ACCNML
C IF VEHICLE WITHIN SLOWING DOWN DISTANCE OF NODE CALL CONTROL ROUTINE.
      IF (POSN.LT.S.OR.POSN.GT.S+VL.OR.TIME.LT.VEHA(J,4)-TT) GOTO 3
      CALL CONTROL(J,POSN,5)
    3 IF (J.EQ.LINKP(I,2)) GOTO 5
      J=MARK(I,J,1)
      GOTO 4
    5 K=NO+K
    1 CONTINUE
      RETURN
      END
```

```
C
C CHECKS THE TIME SPACINGS OF VEHICLES THROUGH A NODE.
C VEHICLES ON DIFFERENT ROUTES MUST BE SEPARATED BY CROSSING HEADWAY
C ELSE FOLLOWING.
C
      SUBROUTINE NODCHK(I,J)
      COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
     &,MAR(10),ICODE(20),ICRL(20),JPRINT,JPLOT,JPICT,JFLOW,JPARAM,JMAG
      COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SFACT
     &,IVEHA(100,4),LINKP(20,2),LI,NCRL(20)
     &,ITIME,NPRINT,NPLOT,NPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
     &,TNODE(10),NODE(10),LASTRT
     &,BAL2(14)
     &,BAL3(21)
     &,BAL6(5)
     &,L,NUMBER(2)
      GOTO 2
C
      ENTRY INOD
      LASTRT=0
      RETURN
    2 NODEP=LEND(I,2)
      NUMBER(L)=NODEP
      CALL PRINT1('VEHICLE PASSING NODE            ',TIME,I,J)
      IF (LASTRT.EQ.0) GOTO 1
      PASTIM=TNODE(NODEP)
      LASTRT=NODE(NODEP)
      NEXTRT=NLINK(J)*100+I
      THDWYE=VEHA(J,6)/(2*ACCEMG)+VL/VEHA(J,6)
      THDWY=THDWYE*FCHDWY
      IF (NEXTRT.EQ.LASTRT) THDWY=THDWYE*FFHDWY
      IF (PASTIM+THDWY.GT.TIME+.5) CALL PRINT1('VEHICLE TIME INFRINGED A
     &T NODE  ',TIME,I,J)
    1 TNODE(NODEP)=TIME
```

```
      NODE(NODEP)=NEXTRT
      LASTRT=1
      RETURN
      END
```

```
C
C ENTER A NEW VEHICLE INTO A VEHICLE QUEUE AT ENTRANCE.
C
      SUBROUTINE ENTRY(I,J)
      COMMON /CONST1/SPNML,ACCNML,ACCEM[illegible],L,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
     &,MAR(10),ICODE(20),ICRL(20),JPRINT,JPLOT,JPICT,JFLOW,JPARAM,JMAG
      COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SFACT
     &,IVEHA(100,4),LINKP(20,2),LI,NCRL(20)
     &,ITIME,NPRINT,NPLOT,NPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
     &,BAL1(21)
     &,BAL2(14)
     &,BAL3(21)
     &,BAL6(5)
     &,BAL17(3)
C INITIALISE ARRAY CONSTANTS.
      SPNML=SPEEDL(I)
      VEHA(J,1)=0.
      VEHA(J,2)=SPNML
      VEHA(J,5)=TIME
      VEHA(J,3)=0.
      VEHA(J,4)=0.
      VEHA(J,6)=CSPEED
      VEHA(J,7)=SPNML
      VEHA(J,8)=0.
      IVEHA(J,1)=I
      IVEHA(J,2)=I
      CALL RANDOM(LI,LI,RAND)
      SET=0.
C SELECT ROUTE ACCORDING TO PROBABLITIES.
      DO 1 K=1,4
      SET=PROB(I,K)+SET
      IF (RAND.LT.SET) GOTO 2
    1 CONTINUE
    2 IVEHA(J,4)=0
```

```
C RESET POINTER.
      IVEHA(J,3)=K+NIN
      LINKP(I,2)=MARK(I,LINKP(I,2),1)
      ITRANS(J)=ITRP
      ITRP=ITRP+1
      IF (ITRP.EQ.101) ITRP=1
      RETURN
      END
```

```
C
C FOR EACH LINK AND VEHICLE CHECK THAT NO EMERGENCY HEADWAYS ARE
C INFRINGED.
C
      SUBROUTINE ECHECK(NUM)
      COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
     &,MAR(10),ICODE(20),ICRL(20),JPRINT,JPLOT,JPICT,JFLOW,JPARAM,JMAG
      COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SFACT
     &,IVEHA(100,4),LINKP(20,2),LI,NCRL(20)
     &,ITIME,NPRINT,NPLOT,NPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
     &,BAL1(21)
     &,BAL2(14)
     &,BAL3(21)
     &,BAL6(5)
     &,BAL17(3)
      DO 1 I=1,NLINKS
      J=LINKP(I,1)
      JCHECK=MARK(I,J,-1)
      IF (JCHECK.EQ. LINKP(I,2)) GOTO 1
      EMHDWY=VEHA(J,2)*VEHA(J,2)/(2*ACCEMG)+VL
      HDWY=EMHDWY*FFHDWY
      HDWYS(J)=HDWY
      IF (I.NE.IVEHA(J,3)) GOTO 8
      IF (NUM.EQ.1) GOTO 7
      GOTO 3
    8 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
    9 CONTINUE
      POSN2=VEHA(J,3)
      POSN1=VEHA(K,3)+PEND(I)
```

```
      GOTO 4
    5 POSN1=VEHA(K,3)
      POSN2=VEHA(J,3)
    4 EMHDWY=VEHA(J,2)*VEHA(J,2)/(2*ACCEMG)+VL
      IF (NUM.EQ.1) GOTO 6
      IF (POSN1-POSN2.GE.EMHDWY) GOTO 3
      CALL PRINT1('EMERGENCY HEADWAY INFRINGED AT  ',TIME,I,J)
      HDWYS(J)=-HDWYS(J)
      VEHA(J,1)=-ACCEMG
    3 IF (J.EQ.LINKP(I,2)) GOTO 1
      K=J
      J=MARK(I,J,1)
      GOTO 5
    1 CONTINUE
      RETURN
C CALCULATE ACCELERATION ACCORDING TO HEADWAY LAWS.
    6 HDWY=EMHDWY*FFHDWY
      HDWYS(J)=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 ACCN1=ACCN
      IF (ABS(ACCN).GT.ACCNML)ACCN1=SIGN(ACCNML,ACCN)
      IF (VEHA(J,7)-VEHA(J,2)) 13,14,15
   13 ACCN=-ACCNML
      GOTO 16
   14 ACCN=0
      GOTO 16
   15 ACCN=ACCNML
   16 ACCN=AMIN1(ACCN1,ACCN)
      VEHA(J,1)=AJERK(VEHA(J,1),ACCN)
      GOTO 3
      END
```

```
C
C GENERATE TIME HEADWAYS ACCORDING TO DISTRIBUTION.
C
      FUNCTION  SPACE(I)
C
      ENTRY SPACES(I)
      COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
     &,MAR(10),ICODE(20),ICRL(20),JPRINT,JPLOT,JPICT,JFLOW,JPARAM,JMAG
      COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SFACT
     &,IVEHA(100,4),LINKP(20,2),LI,NCRL(20)
     &,ITIME,NPRINT,NPLOT,NPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
     &,BAL1(21)
     &,BAL2(14)
     &,BAL3(21)
     &,HDWY,II(4)
     &,BAL17(3)
      IF (I.EQ.0) GOTO 4
      I1=0
    2 CALL RANDOM(II(I),II(I),RN)
      I1=I1+1
      IF (RN.GT.ASPACE(I)) GOTO 3
      GOTO 2
    3 GAP=I1*HDWY/10.
      IF (GAP.LT.HDWY) GAP=HDWY
      SPACE=GAP
      RETURN
    4 CONTINUE
      DO 1 III=1,4
      II(III)=III*100-1
    1 CALL RANDOM(II(III),II(III),RN)
      HDWY=(SPNML/(2*ACCEMG)+VL/SPNML)*FFHDWY
      RETURN
      END
```

```
C
C TRANSFER VEHICLES FOR ONE LINK QUEUE TO THE NEXT WHEN A NODE
C IS PASSED.
C
      SUBROUTINE ASVEH
      COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
     &,MAR(10),ICODE(20),ICRL(20),JPRINT,JPLOT,JPICT,JFLOW,JPARAM,JMAG
      COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SFACT
     &,IVEHA(100,4),LINKP(20,2),LI,NCRL(20)
     &,ITIME,NPRINT,NPLOT,NPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
     &,BAL1(21)
     &,BAL2(14)
     &,BAL3(21)
     &,BAL6(5)
     &,BAL17(3)
C FOR EACH LINK.
      DO 1 I=1,NLINKS
      J=LINKP(I,1)
C NO VEHICLES?
      IF (MARK(I,J,-1).EQ.LINKF(I,2)) GOTO 1
C ANY VEHICLES PASSED?
      IF (VEHA(J,3).LT.PEND(I)) GOTO 1
C FIND THE NEXT LINK.
      NEXTL=NLINK(J)
      IF (I.EQ.IVEHA(J,3)) GOTC 2
      CALL NODCHK(I,J)
      IVEHA(J,2)=NEXTL
      IPL=LINKP(NEXTL,2)
      IPL=MARK(NEXTL,IPL, 1)
      DO 3 K=1,8
      IF (K.LE.6) GOTO 9
      VEHA(J,K)=0.
    9 CONTINUE
C ADD VEHICLE TO NEXT LINK QUELE AND REMOVE FROM OLD LINK QUEUE.
```

```
      VEHA(IPL,K)=VEHA(J,K)
    3 VEHA(J,K)=0.
      HDWYS(IPL)=HDWYS(J)
      HDWYS(J)=0.
      VEHA(IPL,3)=VEHA(IPL,3)-PEND(I)
      DO 4 K=1,4
      IVEHA(IPL,K)=IVEHA(J,K)
    4 IVEHA(J,K)=0
      IVEHA(IPL,4)=0
      LINKP(NEXTL,2)=IPL
      ITRANS(IPL)=ITRANS(J)
      GOTO 5
    2 CONTINUE
      DO 6 K=1,8
      HDWYS(J)=0.
    6 VEHA(J,K)=0.
C DELETE ANY VEHICLES MOVING OUT OF NETWORK.
      DO 7 K=1,4
    7 IVEHA(J,K)=0
    5 LINKP(I,1)=MARK(I,J,1)
      ITRANS(J)=0
    1 CONTINUE
C INSERT ANY VEHICLES ENTERING NETWORK.
      DO 8 I=1,NIN
      IF (TIME.LT.TIMEN(I)) GOTO 8
      J=LINKP(I,2)
      J=MARK(I,J,1)
      CALL ENTRY(I,J)
      TIMEN(I)=SPACE(I)+TIME
    8 CONTINUE
      RETURN
      END
```

```
C
C INTEGRATE VEHICLES FORWARD ONE INCREMENT.
C
      SUBROUTINE VMOVE
      COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CBPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
     &,MAR(10),ICODE(20),ICRL(20),JPRINT,JPLOT,JPICT,JFLOW,JPARAM,JMAG
      COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SFACT
     &,IVEHA(100,4),LINKP(20,2),LI,NCRL(20)
     &,ITIME,NPRINT,NPLOT,NPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
     &,BAL1(21)
     &,BAL2(14)
     &,BAL3(21)
     &,BAL6(5)
     &,BAL17(3)
      DO 1 I=1,NLINKS
      J=LINKP(I,1)
      IF (MARK(I,J,-1).EQ.LINKF(I,2)) GOTO 1
    2 DP=VEHA(J,2)*DELT+VEHA(J,1)*DELT*DELT/2.
      VEHA(J,3)=VEHA(J,3)+DP
      VEHA(J,8)=VEHA(J,8)-DP
      VEHA(J,2)=VEHA(J,2)+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(IX,IY,YFL)
      IY=IX*65539
      IF (IY)5,6,6
    5 IY=IY+2147483647+1
    6 YFL=IY
      YFL=YFL*.4656613E-9
      RETURN
      END
```

```
C
C GENERATES RANDOM NUMBERS WITH EQUAL PROBABILITY BETWEEN 0 AND 1
C
      SUBROUTINE RANDOM(IX,IY,YFL)
      IY=IX*65539
      IF (IY)5,6,6
    5 IY=IY+2147483647+1
    6 YFL=IY
      YFL=YFL*.4656613E-9
      RETURN
      END
```

```
C
C JERK LIMITS ANY CHANGE IN ACCELERATION.
C
      FUNCTION AJERK(ACCN1,ACCN2)
      COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
     &,MAR(10),ICODE(20),ICRL(20),JPRINT,JPLOT,JPICT,JFLOW,JPARAM,JMAG
      COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SFACT
     &,IVEHA(100,4),LINKP(20,2),LI,NCRL(20)
     &,ITIME,NPRINT,NPLOT,NPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
     &,BAL1(21)
     &,BAL2(14)
     &,BAL3(21)
     &,BAL6(5)
     &,BAL17(3)
      ADIFFM=ACCJK*DELT
      DELACC=ACCN2-ACCN1
      AJERK=ACCN2
      IF (ABS(DELACC).GT.ADIFFM) AJERK=SIGN(ADIFFM,DELACC)+ACCN1
      RETURN
      END
```

```
C
C SEND DATA TO BRANCH TO CLOCK SUBROUTINE IN FOCAL.
C
      SUBROUTINE CLOCK(ISUB)
         COMMON /VREAD/ IBC,IST,L,IM,IBUF(10)
      COMMON /CONST1/ FILL(234)
      COMMON /CONST2/ FILL1(219)
      COMMON /VAR/ TIME
      EQUIVALENCE (FILL(232),DELT)
      EQUIVALENCE (FILL1(216),JPICT)
      DIMENSION IA(5),II(5)
      ISIGN=0
      IF (ISUB) 3,1,4
   3  ISIGN=64
   4  CALL LDWD2(0)
      CALL LDWD2(80)
      CALL LDWD2(1)
         CALL WDSEND
   1  ITIMEU=JPICT*DELT*10
      ITIMES=TIME*10
      ITIMES=ITIMES-ITIMEU
      IF (ITIMES.LT.0) ITIMES=100000+ITIMES
C SEND CLOCK DATA TO RESET PICTURE CLOCK.
      DO 2 I=1,5
      ITIMET=ITIMES/10
      ITIMEV=ITIMEU/10
      IA(I)=ITIMES-ITIMET*10+16
      II(I)=ITIMEU-ITIMEV*10+32+ISIGN
      ITIMES=ITIMET
      ITIMEU=ITIMEV
      CALL LDWD2(IA(I))
   2  CALL LDWD2(II(I))
      CALL LDWD2(0)
      CALL WDSEND
      IF (ISUB.NE.0) RETURN
C CHECK FOR TIMING CHARACTER FROM GT40.
   5  CALL CHECK(L,IM,IST,IBC)
```

```
      IF (IAND(IST,1).EQ.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.
0
      CALL BCREAD(L,IBC,IST)
      RETURN
      END
```

```
C
C DRAWS MOVING VEHICLE PICTURE ON GT40.
C
      SUBROUTINE VEHPIC
      COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
     &,MAR(10),ICODE(20),ICRL(20),JPRINT,JPLOT,JPICT,JFLOW,JPARAM,JMAG
      COMMON /CONST3/ LINKST(20),IPST(20),SFACT
      COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SDUM
     &,IVEHA(100,4),LINKP(20,2),LI,NCRL(20)
     &,ITIME,NPRINT,NPLOT,NPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
     &,BAL1(21)
     &,BAL2(14)
     &,BAL3(21)
     &,BAL6(5)
     &,BAL17(3)
      LOGICAL SEND
      IF (MAR(4).NE.0) RETURN
      FLAG=0
C BRANCH IF MAGNIFIED PICTURE.
      IF (LINKST(1).NE.0) GOTO 1
C DO FOR EACH LINK.
      DO 2 I=1,NLINKS
      J=LINKP(I,2)
    8 IF (MARK(I,J,1).EQ.LINKP(I,1)) GOTO 2
C SEND LINK NUMBER.
      CALL LDWD2(0)
      CALL LDWD1(I)
      PLAST=0
   10 CONTINUE
      IPOS=(VEHA(J,3)-PLAST)*SFACT+.5
C SET ZERO FLAG.
      IF (IPOS.EQ.0) IPOS=1024+1
      IF (HDWYS(J).GE.0.) GOTO 100
      IPOS=IPOS+ISIGN(4096,IPOS)
```

```
C HDWYS NEGATIVE WHEN EMERGENCY HEADWAYS INFRINGED.
      HDWYS(J)=-HDWYS(J)
  100 CALL LDWD2(IPOS)
      PLAST=VEHA(J,3)
      IF (VEHA(J,3)+HDWYS(J).LT.PEND(I)) GOTO 4
      NEXTL=NLINK(J)
      IF (I.EQ.IVEHA(J,3)) GOTO 5
C SPECIAL CASES WHEN VEHICLE HEADWAY OVERLAPS INTO ANOTHER LINK,
CWHEN VEHICLE ON LAST LINK.
      IHDWY=(VEHA(J,3)+HDWYS(J)-PEND(I))*SFACT-1.5
      CALL LDWD2(0)
      CALL LDWD1(NEXTL)
      GOTO 40
    5 IHDWY=(PEND(I)-VEHA(J,3))*SFACT-1.5
      PLAST=PEND(I)
      GOTO 40
    4 IHDWY=HDWYS(J)*SFACT-1.5
      PLAST=PLAST+HDWYS(J)
   40 IF (IHDWY.EQ.0) IHDWY=1024+1
C SEND HEADWAY.
      CALL LDWD2(IHDWY)
      IF (J.EQ.LINKP(I,1)) GOTO 2
      J=MARK(I,J,-1)
      GOTO 10
    2 CONTINUE
      CALL LDWD1(0)
      CALL LDWD2(0)
C SEND PICTURE.
      CALL WDSEND
      RETURN
      ENTRY PSTOP
C STOP PICTURE DISPLAY AND BRANCH TO DIALOGUE IN GT40
      CALL LDWD2(0)
      CALL LDWD2(16)
      CALL LDWD2(1)
      CALL WDSEND
      RETURN
```

```
C DO FOR EACH LINK.
    1  DO 20 I=1,NLINKS
       DO 20 K=1,20
   21  IF (IABS(LINKST(K)).EQ.I) GOTO 22
       GOTO 20
   22  IPLAST=0
       IF (LINKST(K).LT.0) IPLAST=IPST(K)
       SEND=.FALSE.
       J=LINKP(I,2)
C NO VEHICLES.
   38  IF (MARK(I,J,1).EQ.LINKP(I,1)) GOTO 20
       IHDWY=ABS(HDWYS(J))*SFACT-1.5
       IPOS=VEHA(J,3)*SFACT+.5
C BRANCH IF PART OF LINK SEEN IS FIRST PART OF VEHICLE SEEN?
       IF (LINKST(K).LT.0) GOTO 23
       IF (IPOS.GT.IPST(K)) GOTO 24
       IF (IPOS+IHDWY.LT.IPST(K)) GOTO 25
       IF (IPOS+IHDWY.GT.PEND(I)*SFACT) GOTO 30
       IHDWY=IPST(K)-IPOS
   25  IPOS1=IPOS-IPLAST
       IPLAST=IPOS+IHDWY
   11  IF (SEND) GOTO 26
C TRANSMIT LINK NUMBER.
       CALL LDWD2(0)
       CALL LDWD1(K)
       SEND=.TRUE.
   26  IF (IPOS1.EQ.0) IPOS1=1024+1
       IF (IHDWY.EQ.0) IHDWY=1024+1
       IF (HDWYS(J).GE.0) GOTO 200
C ADD FLAGS FOR ZERO AND EMERGENCY BRAKING.
       IPOS1=IPOS1+ISIGN(4096,IPOS1)
       HDWYS(J)=-HDWYS(J)
  200  CONTINUE
       CALL LDWD2(IPOS1)
       IF (FLAG.EQ.0) GOTO 14
C SEND NEW LINK NUMBER IF VEHICLE OVERLAPS INTO NEXT LINK.
       CALL LDWD2(0)
```

```
      CALL LDWD1(L)
      FLAG=0
   14 CONTINUE
      CALL LDWD2(IHDWY)
      GOTO 24
C COME HERE IF PART OF LINK SEEN IS LAST PART.
   23 IF (IPOS+IHDWY.LT.IPST(K)) GOTO 24
      IF (IPOS.GT.IPST(K)) GOTO 27
      IHDWY=IPOS+IHDWY-IPST(K)
      IPLAST=IPLAST+IHDWY
      IPOS1=0
      GOTO 11
   27 IF (IPOS+IHDWY.GT.PEND(I)*SFACT) GOTO 30
      IPOS1=IPOS-IPLAST
      IPLAST=IPOS+IHDWY
      GOTO 11
   30 NEXTL=NLINK(J)
C VEHICLE SYMBOL OVERLAPS NEXT LINK.
      IPOS1=IPOS-IPLAST
      IPLAST=IPOS1+IHDWY
      IHDWY=IPOS+IHDWY-PEND(I)*SFACT
C FIND IF NEXT LINK IS DISPLAYED.
      DO 12 L=1,20
   12 IF (IABS(LINKST(L)).EQ.NEXTL) GOTO 13
   13 FLAG=1
      GOTO 11
   24 IF (J.EQ.LINKP(I,1)) GOTO 20
      J=MARK(I,J,-1)
      GOTO 38
   20 CONTINUE
C TERMINATE PICTURE.
      CALL LDWD1(0)
      CALL LDWD2(0)
      CALL WDSEND
      RETURN
      END
```

```
C
C SEND STANDARD PICTURE TABLE TO GT40.
C
      SUBROUTINE PICT2
      COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
     &,MAR(10),ICODE(20),ICRL(20),JPRINT,JPLOT,JPICT,JFLOW,JPARAM,JMAG
      COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SDUM
     &,IVEHA(100,4),LINKP(20,2),LI,NCRL(20)
     &,ITIME,NPRINT,NPLOT,NPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
     &,BAL1(21)
     &,BAL2(14)
     &,BAL3(21)
     &,BAL6(5)
     &,BAL17(3)
      COMMON /VREAD/ IBC,IST,L1,IM,IBUF1(10)
      COMMON /WRIT/ SETTIM,ISTEP,IKNOW,IFLG,TSAVE,IPRT
     &,ITRACE,ILINK,IVNO
     &,ITMO
     &,NONSTOP
      COMMON /CONST3/ LINKST(20),IPST(20),SFACT
      IF (MAR(4).NE.0) RETURN
C RESET LINKSTORE.
      DO 31 I=1,5
   31 LINKST(I)=0
C CALCULATE SCALE FACTOR.
      SFACT=AMIN1(760./HIEGHT,1000./WIDTH)
C SET UP GT40 READY FOR TABLE.
      CALL TABLO(NLINKS)
      DO 1 I=1,NLINKS
C SEND LINK  NUMBER.
      CALL LDWD2(0)
      CALL LDWD1(I)
      IX=SFACT*XYTAB(I,1)+.5
      IY=SFACT*XYTAB(I,2)+.5
```

```
      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/3.142+.5
      IDATA=SFACT*PEND(I)/NINTP+.5
C SEND SEGMENT LENGTH AND X AND Y CO-ORDINATES.
   12 CALL LDWD1(IDATA)
      CALL LDWD1(IX)
      CALL LDWD1(IY)
      IF (RADIUS)10,3,10
   11 IDATA=SFACT*PEND(I)
      GOTO 12
   10 KK=NINTP-1
      DO 7 J=1,KK
      THETA=L*THETAM*J/NINTP
      IX =(XYTAB(I,5)+RADIUS*COS(THETA+THI))*SFACT+.5
      IY =(XYTAB(I,6)+RADIUS*SIN(THETA+THI))*SFACT+.5
C SEND INTERMEDIATE X,Y CO-ORDINATES.
      CALL LDWD1(IX)
      CALL LDWD1(IY)
    7 CONTINUE
    3  IX=XYTAB(I,3)*SFACT+.5
      IY=XYTAB(I,4)*SFACT+.5
C SEND END X,Y CO- ORDINATES.
      CALL LDWD1(IX)
      CALL LDWD1(IY)
    1 CONTINUE
C END OF DATA.
      CALL LDWD2(0)
      CALL LDWD1(0)
      CALL WDSEND
      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/3.142+.5
      IDATA=SFACT*PEND(I)/NINTP+.5
C SEND SEGMENT LENGTH AND X AND Y CO-ORDINATES.
   12 CALL LDWD1(IDATA)
      CALL LDWD1(IX)
      CALL LDWD1(IY)
      IF (RADIUS)10,3,10
   11 IDATA=SFACT*PEND(I)
      GOTO 12
   10 KK=NINTP-1
      DO 7 J=1,KK
      THETA=L*THETAM*J/NINTP
      IX =(XYTAB(I,5)+RADIUS*COS(THETA+THI))*SFACT+.5
      IY =(XYTAB(I,6)+RADIUS*SIN(THETA+THI))*SFACT+.5
C SEND INTERMEDIATE X,Y CO-ORDINATES.
      CALL LDWD1(IX)
      CALL LDWD1(IY)
    7 CONTINUE
    3  IX=XYTAB(I,3)*SFACT+.5
      IY=XYTAB(I,4)*SFACT+.5
C SEND END X,Y CO- ORDINATES.
      CALL LDWD1(IX)
      CALL LDWD1(IY)
    1 CONTINUE
C END OF DATA.
      CALL LDWD2(0)
      CALL LDWD1(0)
      CALL WDSEND
      IF (IBTEP.NE.0) GOTO 21
```

```
C CHECK IF TIMING CHARACTER FROM GT40 RECIEVED.
 20   CALL CHECK(L1,IM,IST,IBC)
      IF (IBC.LT.1) GOTO 20
 21   CONTINUE
      RETURN
      END
```

```
C
C
      SUBROUTINE NEWPIC
      COMMON /VREAD/IBC,IST,L2,IM,IBUF1(10)
      COMMON /WRIT/ SETTIM,ISTEP,IKNOW,IFLG,TSAVE,IPRT
     &,ITRACE,ILINK,IVNO
     &,ITMO
      COMMON /CONST3/ LINKST(20),IPST(20),SFACT
      COMMON /CARRY/ NODE,HSTORE,WSTORE
     &,SCSTX,SCSTY
      COMMON /CONST1/SPNML,ACCNML,ACCEMG,VL,FFHDWY,FCHDWY,SIDEA
     &,CSPEED,PEND(20),SPEEDL(20),XYTAB(20,7),ASPACE(4),PROB(4,4)
     &,CRL(20),CONST1,CONST2,ACCJK,DELT,HIEGHT,WIDTH
      COMMON /CONST2/ IBUF(20),LEND(20,3),JNEY(4,4,5),NLINKS,NIN,NOUT
     &,MAR(10),ICODE(20),ICRL(20),JPRINT,JPLOT,JPICT,JFLOW,JPARAM,JMAG
      COMMON /VAR/ TIME,TSTOP,VEHA(100,8),TIMEN(4),HDWYS(100),SDUM
     &,IVEHA(100,4),LINKP(20,2),LT,NCRL(20)
     &,ITIME,NPRINT,NPLOT,NPICT,NFLOW,NPARAM,NMAG,ITRANS(100),ITRP
     &,BAL1(21)
     &,BAL2(14)
     &,BAL3(21)
     &,BAL6(5)
     &,BAL17(3)
      DIMENSION SOLN(5,2,2)
      DIMENSION ASOLN(20)
      EQUIVALENCE(SOLN,ASOLN)
      DIMENSION  INODES(10),XNODES(10),YNODES(10)
      IF (MAR(4).NE.0) RETURN
C RECALCULATE SCALE FACTOR.
      SFACT=AMIN1(760./HIEGHT,1000./WIDTH)
      J=0
      DO 565 I=1,20
  565 LINKST(I)=0
      DO 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)=SCSTX
      YNODES(INDPT)=SCSTY
  540 CONTINUE
      XPC=XNODES(INDPT)
      YPC=YNODES(INDPT)
      DO 1 I=1,NLINKS
      DO 500 I90=1,J
  500 IF (I.EQ.IABS(LINKST(I90))) GOTO 1
C ONLY LINKS ATTACHED TO REFERENCE NODE SELECTED .
      IF (LEND(I,3).EQ.NODE) GOTO 2
      IF (LEND(I,2) .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
    3 CALL LDWD2(0)
C TRANSMIT NEW LINK NUMBER.
      CALL LDWD1(J)
      DO 11 II=1,20
   11 ASOLN(II)=0.
      K=1
      IF (LINKST(J).LT.0) K=3
      CXNODE=XYTAB(I,K)*SFACT
      CYNODE=XYTAB(I,K+1)*SFACT
      XM=XPC-CXNODE
      YM=YPC-CYNODE
      SOLN(5,1,1)=XYTAB(I,4-K)*SFACT+XM
      SOLN(5,1,2)=XYTAB(I,5-K)*SFACT+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.
     60..AND.SOLN(5,1,2).LE.760.) GOTO 100
      IF (RADIUS) 4,5,6
```

```
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)7,8,7
  7   IF (DY)9,10,9
C SORT OUT VERTICAL AND HORIZONTAL LINKS.
  8   SOLN(3,1,1)=XPC
      SOLN(4,1,1)=XPC
      SOLN(4,1,2)=760.
      GOTO 12
 10   SOLN(1,1,2)=YPC
      SOLN(2,1,1)=1000.
      SOLN(2,1,2)=YPC
      GOTO 12
  9   GRAD=DY/DX
      C=XYTAB(I,2)*SFACT+YM-GRAD*(XYTAB(I,1)*SFACT+XM)
C CALCULATE X,Y INTERSECTS FOR SLOPING STRAIGHT LINKS.
      DO 15 II=1,4
      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=0.
      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(II,1,1)=X
      SOLN(II,1,2)=Y
```

```
   15 CONTINUE
   12 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))*SFACT
      DELX2=XPC-SOLN(II,1,1)
      IF (LINKST(J).LT.0) DELX2=-DELX2
      IF (ISIGN(1,DELX1)-ISIGN(1,DELX2))18,19,18
   18 SOLN(II,1,1)=0.
      SOLN(II,1,2)=0.
      GOTO 17
   19 IIMIN=II
      JJMIN=1
   17 CONTINUE
  180 IX=SOLN(IIMIN,JJMIN,1)+.5
      IY=SOLN(IIMIN,JJMIN,2)+.5
      XFLT=FLOAT(IX)
      YFLT=FLOAT(IY)
      IDATA=IFIX(SQRT((XFLT-XPC)*(XFLT-XPC)+(YFLT-YPC)*(YFLT-YPC)))
      IF (LINKST(J).GT.0) GOTO 50
      IPST(J)=PEND(I)*SFACT-IDATA+.5
      GOTO 21
   50 IPST(J)=IDATA
      IX=XPC
      IY=YPC
      GOTO 21
    4 L=-1
      RADIUS=-RADIUS
    6 RADIUS=RADIUS*SFACT
      F=XYTAB(I,5)*SFACT+XM
      G=XYTAB(I,6)*SFACT+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.GE.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,1,1)=A
      SOLN(II,1,2)=G+SQRT(ARG)
      SOLN(II,2,1)=A
      SOLN(II,2,2)=G-SQRT(ARG)
      DO 28 JJ=1,2
      IF (SOLN(II,JJ,2).GE.0..AND.SOLN(II,JJ,2).LE.760.) GOTO 28
      SOLN(II,JJ,1)=0.
      SOLN(II,JJ,2)=0.
28    CONTINUE
      GOTO 25
27    SOLN(II,1,1)=F+SQRT(ARG)
      SOLN(II,1,2)=A
      SOLN(II,2,1)=F-SQRT(ARG)
      SOLN(II,2,2)=A
      DO 25 JJ=1,2
      IF (SOLN(II,JJ,1).GE.0..AND.SOLN(II,JJ,1).LE.1000.) GOTO 25
      SOLN(II,JJ,1)=0.
      SOLN(II,JJ,2)=0.
25     CONTINUE
      THI=ATAN2(YPC-G,XPC-F)
      THEMIN=6.284
      DO 31 II=1,4
      DO 31 JJ=1,2
      IF (SOLN(II,JJ,1).EQ.0..AND.SOLN(II,JJ,2).EQ.0.) GOTO 31
      THETHI=ATAN2(SOLN(II,JJ,2)-G,SOLN(II,JJ,1)-F)
      THE=THETHI-THI
      L1=1
      IF (LINKST(J).LT.0) L1=-1
      IF (L.LT.0) L1=-L1
      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(THE).GT.THEMIN) GOTO 31
      THESTO=THE
      THEMIN=ABS(THE)
```

```
      IIMIN=II
      JJMIN=JJ
31    CONTINUE
      DO 32 II=1,4
      DO 32 JJ=1,2
      IF (II.EQ.IIMIN.AND.JJ.EQ.JJMIN) GOTO 32
      SOLN(II,JJ,1)=0.
      SOLN(II,JJ,2)=0.
32    CONTINUE
      LONG=THEMIN*RADIUS
104   IF (LINKST(J).GT.0) GOTO 40
      IPST(J)=PEND(I)*SFACT-THEMIN*RADIUS+.5
      IX=SOLN(IIMIN,JJMIN,1)+.5
      IY=SOLN(IIMIN,JJMIN,2)+.5
      GOTO 41
40    IPST(J)=THEMIN*RADIUS+.5
      THESTO=0.
      IX=XPC
      IY=YPC
41    NINTP=6.*THEMIN/3.142+.5
      IDATA=LONG/NINTP+.5
21    CALL LDWD1(IDATA)
      IF (IX.EQ.0) IX=1
      IF (IY.EQ.0) IY=1
      CALL LDWD1(IX)
      CALL LDWD1(IY)
      IF (RADIUS) 70,71,70
70    KK=NINTP-1
      IF (KK.EQ.0) GOTO 71
      DO 80 JJ=1,KK
      THETA=L*THEMIN*JJ/NINTP
      IX=F+RADIUS*COS(THETA+THI+THESTO)+.5
      IY=G+RADIUS*SIN(THETA+THI+THESTO)+.5
      IF (IX.EQ.0) IX=1
      IF (IY.EQ.0) IY=1
      CALL LDWD1(IX)
      CALL LDWD1(IY)
```

```
      IIMIN=II
      JJMIN=JJ
   31 CONTINUE
      DO 32 II=1,4
      DO 32 JJ=1,2
      IF (II.EQ.IIMIN.AND.JJ.EQ.JJMIN) GOTO 32
      SOLN(II,JJ,1)=0.
      SOLN(II,JJ,2)=0.
   32 CONTINUE
      LONG=THEMIN*RADIUS
  104 IF (LINKST(J).GT.0) GOTO 40
      IPST(J)=PEND(I)*SFACT-THEMIN*RADIUS+.5
      IX=SOLN(IIMIN,JJMIN,1)+.5
      IY=SOLN(IIMIN,JJMIN,2)+.5
      GOTO 41
   40 IPST(J)=THEMIN*RADIUS+.5
      THESTO=0.
      IX=XPC
      IY=YPC
   41 NINTP=6.*THEMIN/3.142+.5
      IDATA=LONG/NINTP+.5
   21 CALL LDWD1(IDATA)
      IF (IX.EQ.0) IX=1
      IF (IY.EQ.0) IY=1
      CALL LDWD1(IX)
      CALL LDWD1(IY)
      IF (RADIUS) 70,71,70
   70 KK=NINTP-1
      IF (KK.EQ.0) GOTO 71
      DO 80 JJ=1,KK
      THETA=L*THEMIN*JJ/NINTP
      IX=F+RADIUS*COS(THETA+THI+THESTO)+.5
      IY=G+RADIUS*SIN(THETA+THI+THESTO)+.5
      IF (IX.EQ.0) IX=1
      IF (IY.EQ.0) IY=1
      CALL LDWD1(IX)
      CALL LDWD1(IY)
```

```
 80   CONTINUE
 71   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 LDWC1(IY)
  1   CONTINUE
      INDPT=INDPT+1
      NODE=INODES(INDPT)
      IF (NODE.NE.0) GOTO 540
      CALL LDWD1(0)
      CALL LDWD2(0)
      CALL TABLO(J)
      CALL WDSEND
      IF (ISTEP.NE.0) GOTO 210
200   CALL CHECK(L2,IM,IST,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
      DO 520 I91=1,10
      IF (INODES(I91).EQ.0) GOTO 530
520   IF (LEND(I,KP).EQ.INODES(I91)) GOTO 510
530   INODES(I91)=LEND(I,KP)
      XNODES(I91)=SOLN(IIMIN,JJMIN,1)
      YNODES(I91)=SOLN(IIMIN,JJMIN,2)
510   CONTINUE
```

```
      IF (RADIUS)101,180,103
101   L=-1
      RADIUS=-RADIUS
103   RADIUS=RADIUS*SFACT
      F=XYTAB(I,5)*SFACT+XM
      G=XYTAB(I,6)*SFACT+YM
      THI=ATAN2(YPC-G,XPC-F)
      THETHI=ATAN2(SOLN(IIMIN,JJMIN,2)-G,SOLN(IIMIN,JJMIN,1)-F)
      THE=THETHI-THI
      L1=1
      IF (LINKST(J).LT.0) L1=-1
      IF (L.LT.0) L1=-L1
      IF (THE.LT.0..AND.L1.GT.C) THE=6.284-THE
      IF (THE.GT.0..AND.L1.LT.C) THE=THE-6.284
      THEMIN=ABS(THE)
      THESTO=THE
      LONG=THEMIN*RADIUS
      GOTO 104
      END
```

```
      SUBROUTINE TABLO(NL)
      COMMON /VREAD/IBC,IST,L,IM,IBUF1(10)
      COMMON /CONST3/LINKST(20),IPST(20),SFACT
      DIMENSION IMESS1(8),IMESS2(8),IMESS3(3)
      DIMENSION IMESS4(6)
      DATA ICR/8Z0D000000/
      DATA IMESS1/'PICTURE TABLE RE','ADY TO SEND',8Z0D000000/
      DATA IMESS2 /'TYPE CONTROL T A','ND INDICATE',8Z0D000000/
      DATA IMESS3 /'G 1.1',8Z0D000000/
      IST=0
      IBC=2
C PICTURE TABLE READY TO SEND TO GT40.
C SET GT40 TO RECEIVE, READ TIMING CHARACTER FROM GT40.
      CALL BCSET(L,132,0)
      CALL BCWRITE(L,IMESS1,0,29,IST)
      IST=0
      CALL BCWRITE(L,IMESS2,0,29,IST)
      IST=0
      IBC=1
      CALL BCREAD(L,IBC,IST)
  500 CALL CHECK(L,IM,IST,IBC)
      IF (IAND(IST,8).NE.8) GOTO 500
      IBYTE=0
      IST=0
      CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
      ENCODE(22,110,IMESS4,N)NL,SFACT,ICR
  110 FORMAT('S N=',I2,';S SF=',F7.3,';G',A1)
      IST=0
C SEND COMMANDS TO GT40.
      CALL BCWRITE(L,IMESS4,0,N,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 (IAND(IST,1).EQ.1) GOTO 1
      IST=0
      IBYTE=0
      CALL BCMOVE(L,IBUF1,IBYTE,IBC,IST)
      IST=0
      IBC=2
C SET UP 2 CHARACTER ASYNCHRONOUS READ.
      CALL BCREAD(L,IBC,IST)
C PAUSE LIMITED TIME.
      DO 455 I=1,20000
  455 CONTINUE
      RETURN
      END
```

```
; SAVES PICTURE
;CLOCK DATA AS A BASE AND INCREMENT . TIME CALCULATED BY ADDING
; INCREMENT TO BASE EACH PICTURE CYCLE.
; ARITHMETIC DONE IN BCD FOR SIMPLICITY (SINCE NO DECODING REQUIRED FOR
; PRINTING ON SCREEN).
; DATA IS MAX 5 BCD CHARACTERS. FOR EACH OF INCREMENT AND BASE TIME
; END WITH A ZERO CHARACTER.
; BIT 4 = SET INDICATES BASE NUMBER.
; BIT 5 = SET INDICATES NEGATIVE NUMBER.
;FUNCTION CALL FU()
        SP=%6
        R2=%2
        R1=%1
        R0=%0
        PC=%7
        RDONE=200
        RBUF=175612
        RCSR=175610
        RDECO=20
        RNEG=100
        RALL=160
        R5=%5
        HIORD=177600
        .=21524
DECO:   .=.+10.
TIME:   .=.+10.
BEGIN:  MOV     #TIME,R0        ;SET UP INITIAL VALUES.
        MOV     #DECO,R1
        MOV     R5,-(SP)        ;SAVE REG ON STACK.
CON:    BIT     #RDONE,RCSR     ;CHARACTER RECIEVED?
        BEQ     CON
        MOVB    RBUF,R2         ;SAVE BYTE IN REGISTER.
        BICB    #HIORD,R2       ;CLEAR BIT 7 AND HIORDER BITS.
        BEQ     STOP            ;IF ZERO RETURN FROM.
        CLR     R5
        BIT     #RDECO,R2       ;IS IT AN INCREMENT VALUE?
        BEQ     LOOP1
```

```
        INC     R5
LOOP1:  BIT     #RNEG,R2        ;IS NEGATIVE VALUE.
        BEQ     POS
        BIC     #RALL,R2        ;CLEAR FLAG BITS.
        NEG     R2              ;INVERT R2
        BR      LOOP2
POS:    BIC     #RALL,R2
LOOP2:  TST     R5              ;R5 IS 1 IF CHARACTER IS INCREMENT ELSE 0.
        BEQ     LTIME
        MOV     R2,(R1)+        ;SAVE CHARACTER IN INCREMENT STORE.
        BR      CON
LTIME:  MOV     R2,(R0)+
        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()
        R0=%0
        R1=%1
        R2=%2
        R3=%3
        R4=%4
        R5=%5
        SP=%6
        PC=%7
        BOTTOM=1652
        STACKC=1706
        RDONE=000200
        ERRORC=201
        INTB=100000
        SIGN=020000
        .=22202
RCSR:   175610
RBUF:   175612
BUFFER: 0
TABLE:  .=.+100.                ;TABLE HOLDS DATA.
ADTAB:  .WORD     TABLE         ;ADTAB, ADDRESS OF EACH LINK START POINT.
        .=.+20.
ENTRY:  MOV       ADTAB,R5      ;TABLE BASE TO R5.
        MOVB      @RBUF,R1
        CLR       R2            ;INITIALISE.
        MOV       R4,-(SP)      ;SAVE R4 ON STACK.
        BIS       #2,@RCSR
LOOP0:  MOV       #2,R0
```

```
        MOV     #2,R1
LOOP1:  BIT     #RDONE,@RCSR
        BEQ     LOOP1           ;LOOK FOR CHARACTER.
        NOP
        DEC R1                  ;COUNT
        MOVB    @RBUF,BUFFER(R1)
; SAVE CHARACTER IN LOCATION CLEAR 7TH BIT.
        BICB    #200,BUFFER(R1)
        NOP
        BNE     LOOP2           ;BRANCH IF CHARACTER NOT ZERO.
        DEC     R0
LOOP2:  TST     R1
        BNE     LOOP1           ;BRANCH IF NOT RECEIVED A PAIR OF CHARACTERS.
LOOP3:  TST     R2
        NOP
        BNE     LOOP4           ;BRANCH IF DATA NOT A PAIR XY'S.
        TST     R0
        BEQ     LOOP5           ;BRANCH IF 2 ZERO'S RECEIVED.
        BR      LOOP4
LOOP5:  BIT     #RDONE,@RCSR    ;RECEIVE ANOTHER CHARACTER.
        BEQ     LOOP5
        NOP
        MOVB    @RBUF,BUFFER
        BICB    #200,BUFFER     ;BRANCH IF NOT ZERO.
        BNE     LOOP6
        BIS     #INTB,BUFFER    ;SET BIT 15 IN TABLE AS FLAG.
        MOV     BUFFER,(R5)+
        MOV     (SP)+,R4        ;SHOWING END OF LINK DATA.
        RTS     PC              ;RETURN.
LOOP6:  DEC     BUFFER          ;MULTIPLY BUFFER BY 2 TO TURN INTO
        ASL     BUFFER          ;DISPLACEMENT FOR NEW LINK ADDRESS.
        MOV     BUFFER,R4
        MOV     R5,ADTAB(R4)
        MOV     #-1,R2
        NOP                     ;NOW READY FOR NEW LINK DATA.
        BR      LOOP0
LOOP4:  TST     R2
```

```
        BNE     L00P7
        MOV     #2,R2
L00P7:  ROLB    BUFFER          ;CONDITION THE TWO CHARACTERS IN BUFFER
        ROR     BUFFER          ;SO THAT THEY FORM A 14 BIT NUMBER.
        TST     R2
        NOP
        BLT     L00P9           ;IF 1ST DATA SET AFTER NEW LINK START.
        BIT     #SIGN,BUFFER
        BEQ     L00P10
        BIC     #SIGN,BUFFER
        NEG     BUFFER          ;NEGATE CONTENTS OF BUFFER IF SIGN BIT SET.
L00P10: MOV     BUFFER,(R5)+    ;SAVE DATA IN TABLE.
        DEC     R2
        NOP
        BR      L00P0           ;RETURN FOR NEW VALUES.
L00P9:  BIS     #INTB,BUFFER
        MOV     BUFFER,(R5)+    ;SET FLAG BIT (INDICATING END OF PREVIOUS
        MOV     #0,R2           ;LINK DATA.
        NOP
        BR      L00P0
        .END    11330
```

```
;
; DISPLAY LINK NUMBER STARTING AT FØCAL DISPLAY LØC.
;
;FUNCTIØN CALL FR(LØC,LINK)
        BE=001616
        HØRD=001620
        MBIT=040000
        ADTAB=22354
     TABLE=22210
        EVAL=104660
        STACK=3
        FPUT=60
        FINT=007071
        FPP=007000
        PBASE=25202
        IMMED=5
        FADD=007010
        FMUL=007040
        PØINT=114000
        LFIN=100000
        SIGN=020000
        LØNGV=110000
        R0=%0
        R1=%1
        R2=%2
        R3=%3
        R4=%4
        R5=%5
        SP=%6
        PC=%7
        BØTTØM=1652
        STACKE=1706
        .=21662
SAVE:   0
SAVE1:  0
X:      0
Y:      0
```

```
XX:     0
YY:     0
INST:   0
START:  CLR     X
        CLR     Y
        MOV     R0,-(SP)        ;SAVE REGISTERS.
        MOV     R1,-(SP)
        MOV     R2,-(SP)
        MOV     R5,-(SP)
        MOV     R3,-(SP)
        MOV     R4,-(SP)
        NOP
        CMP     -(SP),-(SP)
        FPP+FPUT+STACK          ; SAVE 1ST ARGUEMENT.
        EVAL
        MOV     SP,R1
        CMP     (R1)+,(R1)+     ; EVALUATE 2ND ARGUEMENT.
        MOV     R4,(R1)+        ; R4 & R3 CHANGED THEREFORE SAVE
        MOV     R3,(R1)         ; AGAIN ON STACK IN CORRECT POSITION.
        NOP
        FINT
        DEC     R1
        ASL     R1
        MOV     R1,SAVE         ; CALCULATE LINK NUMBER.
        NOP
        FPP+STACK
        FMUL+IMMED              ; CONVERT LOC NUMBER INTO CORE LOCATION OFFSET
        000003                  ; FROM PICTURE BASE.
        060000
        FINT
        FPP+STACK
        MOV     SAVE,R5
        NOP
        CMP     (SP)+,(SP)+
        ADD     #PBASE,R1
        MOV     #POINT,INST     ; MOVE ABSOLUTE POINT INTO PICTURE INSTRUCTION
        MOV     ADTAB(R5),R3    ; REGISTER.
```

```
XX:     0
YY:     0
INST:   0
START:  CLR     X
        CLR     Y
        MOV     R0,-(SP)        ;SAVE REGISTERS.
        MOV     R1,-(SP)
        MOV     R2,-(SP)
        MOV     R5,-(SP)
        MOV     R3,-(SP)
        MOV     R4,-(SP)
        NOP
        CMP     -(SP),-(SP)
        FPP+FPUT+STACK          ; SAVE 1ST ARGUEMENT.
        EVAL
        MOV     SP,R1
        CMP     (R1)+,(R1)+     ; EVALUATE 2ND ARGUEMENT.
        MOV     R4,(R1)+        ; R4 & R3 CHANGED THEREFORE SAVE
        MOV     R3,(R1)         ; AGAIN ON STACK IN CORRECT POSITION.
        NOP
        FINT
        DEC     R1
        ASL     R1
        MOV     R1,SAVE         ; CALCULATE LINK NUMBER.
        NOP
        FPP+STACK
        FMUL+IMMED              ; CONVERT LOC NUMBER INTO CORE LOCATION OFFSET
        000003                  ; FROM PICTURE BASE.
        060000
        FINT
        FPP+STACK
        MOV     SAVE,R5
        NOP
        CMP     (SP)+,(SP)+
        ADD     #PBASE,R1
        MOV     #POINT,INST     ; MOVE ABSOLUTE POINT INTO PICTURE INSTRUCTION
        MOV     ADTAB(R5),R3    ; REGISTER.
```

```
        TST(R3)+
LOOP3:  MOV     (R3)+,XX        ; FIND X CO-ORDINATE FROM TABLE.
        BIT     #LFIN,XX        ; TEST BIT FOR END OF LINK DATA.
        NOP
        BEQ     LOOP0
        MOV     (SP)+,R4        ; RESTORE REGISTERS AND RETURN FROM SUBROUTINE.
        MOV     (SP)+,R3
        MOV     (SP)+,R5
        MOV     (SP)+,R2
        MOV     (SP)+,R1
        MOV     (SP)+,R0
        NOP
        RTS     PC
LOOP0:  MOV     INST,(R1)+      ;MOVE DISPLAY GRAPHICS INST INTO PICTURE FILE.
        MOV     (R3)+,YY        ; FIND Y CO-ORDINATE FROM TABLE.
        FADD+IMMED
        000001
        040000
        MOV     XX,R0
        SUB     X,R0
        BGE     LOOP1           ; FIND DATA INCREMENT.
        NEG     R0
        BIS     #SIGN,R0
        NOP
LOOP1:  BIS     #MBIT,R0        ; CONDITION BITS FOR DISPLAY DATA.
        MOV     R0,(R1)+        ; SAVE X DATA IN PICTURE FILE.
        MOV     XX,X
        MOV     YY,R0
        SUB     Y,R0
        BGE     LOOP2           ; DO SIMILARLY FOR Y CO-ORDINATES.
        NEG     R0
        BIS     #SIGN,R0
LOOP2:  MOV     R0,(R1)+
        MOV     YY,Y
        MOV     #LONGV,INST     ; CHANGE PICTURE INSTRUCTION TO
        NOP                     ; VECTOR INSTRUCTION.
        BR      LOOP3
```

```
;FUNCTION .END  FVL  11330
        R0=%0
        R1=%1
        R2=%2
        R3=%3
        R4=%4
        R5=%5
        SP=%6
        PC=%7
        ZERO=002000
        ZBYTE=000177
        BOTIOF=1652
        STACKC=1706
        EVAL=104460
        FINT=007571
        PSIGN=020000
        FMUL=07040
        IMMED=5
        DPT=56
        PBASE=25202
        RCOME=000200
        HBIT=200
        JINST1=100000
        JINST2=140000
        MSS=040006
        ADTAB=22356
        COLLIDE=010000
        FETEEN=100000
        RSIGN=020000
        INT=040000
        LONGY=110000
        STOP=004000
        TIME=21536
        DECO=21526
        CLOCK=21550
        .=17350
TEXT:   .ASCII   / TIME /
```

```
;FUNCTION CALL FV(LOC1,LOC2,END)
        R0=%0
        R1=%1
        R2=%2
        R3=%3
        R4=%4
        R5=%5
        SP=%6
        PC=%7
        ZERO=002000
        ZBYTE=002177
        BOTTOM=1652
        STACKO=1706
        EVAL=104660
        FINT=007071
        PSIGN=020000
        FMUL=07040
        IMMED=5
        DPT=56
        PBASE=25202
        RDONE=000200
        HBIT=200
        JINST1=100000
        JINST2=160000
        MSB=040000
        ADTAB=22354
        COLLIDE=010000
        FFTEEN=100000
        RSIGN=020000
        INT=040000
        LONGV=110000
        STOP=004000
        TIME=21536
        DECO=21524
        CLOCK=21550
        .=17350
TEXT:   .ASCII    / TIME /
```

```
FLAG:     0
END:      0
LØC2:     0
LØC1:     0
RCSR:     175610
RBUF:     175612
BUFFER:   0
SUM:      0
TBASE:    0
DATAE:    0
DATAM:    0
INTEG:    0
FRACT:    0
YYES:     0
STØRE:    0
SIGN:     0
LASTX:    0
LASTY:    0
ENFLAG:   0
VEHB:     0
CTEST:    0
PØINT:    114000
BEGIN:    MØV       #1,FLAG        ;BUILD P1
          MØV       #BUFFER,R1
LØØP18:   MØV       #0,(R1)+       ;INITIALISE
          CMP       R1,#CTEST+2
          BNE       LØØP18
          MØV       #1,VEHB        ;FIRST DATA VEH BACK
          MØV       #4,R0
          MØV       #0,CTEST       ;INITIALISE CLLISIØN TEST FLAG
          MØV       R0,-(SP)
          MØV       R1,-(SP)
LØØP99:   FMUL+IMMED
          000003
          060000
          MØV       (SP)+,R1
          MØV       (SP)+,R0
```

```
        FINT                    ;CALCULATE ADDRESS OF
        ADD     #PBASE,R1       ;FIXED POINTS &
        MOV     R1,END(R0)      ;STORE
        TST     R0              ;LAST ARG?
        BEQ     START
        TST     -(R0)           ;DEDUCT TWO
        MOV     R0,-(SP)
        MOV     R1,-(SP)
        EVAL                    ;EVALUATE ARGS
        BR      LOOP99
START:  MOV     R3,-(SP)        ;SAVE IMPORTANT REGISTERS
        MOV     R4,-(SP)        ;FOR RETURN
        MOV     LOC2,R5         ;INITIALISE PICTURE INSERT REGISTER
        BIS     #2,@RCSR
        MOV     END,R0
        ADD     #12,R0
        MOV     R0,TBASE
        ADD     #4,R0
        MOV     #4,R1
TEXT0:  MOV     TEXT(R1),(R0)
        TST     -(R1)
        TST     -(R0)
        TST R1
        BGE     TEXT0
        ADD     #6,TBASE
        BR      COUNT1
        NOP
G01:    CLR     R0
        CLR     R1                       ; INCREMENT CLOCK BY SPECIFIED AMOUNT.
G02:    ADD     TIME(R0),R1
        ADD     R1,DEC0(R0)
        CLR     R1
        MOV     #10.,-(SP)
        TST     DEC0(R0)
        BLT     G03
        CMP     (SP),DEC0(R0)
        BGT     COUNT3
```

```
        INC     R1
COUNT4: SUB     (SP),DECO(RO)
COUNT3: CMP     (RO)+,(SP)+
        CMP     #8.,RO
        BEQ     COUNT1
        BR      GO2
GO3:    DEC     R1
        NEG     (SP)
        BR      COUNT4
COUNT1: MOV     #8.,RO
         CLR     R2
        ADD     TBASE,R2
COUNT2: MOV     DECO(RO),R1
        ADD     #000060,R1
        MOVB    R1,(R2)
         TSTB    (R2)+
        SUB     #2,RO
        BGT     COUNT2
        BLT     GO
        MOVB    #DPT,(R2)
        TSTB    (R2)+
        BR      COUNT2
GO:     BIT     #RDONE,@RCSR      ;RECEIVE FIRST CHAR
        BEQ     GO
        MOVB    @RBUF,BUFFER
        BICB    #HBIT,BUFFER
;ENSURE THAT THE EIGHTH BIT IS CLRAR
        MOVB    BUFFER,RO
        NOP
        BEQ     LOOP6
        JMP     LOOP20
LOOP6:  MOV     #1,RO         ;ZERO COUNT
        MOV     #2,R1         ;CHAR COUNT
LOOP2:  BIT     #RDONE,@RCSR    ;RECEIVE TWO CHARS
        BEQ     LOOP2         ;CHECK FOR ZEROS
        NOP
        DEC     R1
```

```
        MOVB    @RBUF,BUFFER(R1)    ;FIRST CHAR INTO HIORDER BIT
        BICB    #HBIT,BUFFER(R1)
                                    ;SECOND CHAR IN THE LOW ORDER BIT
        BNE     LOOP3
        DEC     RO
LOOP3:  TST     R1                  ;TEST FOR CONDITIONS
        BNE     LOOP2               ;ONE ZERO BUFFER=LINK NO
        TST     RO
        NOP
        BNE     LOOP8               ;NO ZEROS  BUFFER=INC DATA
        JMP     LOOP4
LOOP8:  BGT     LOOP5               ;ALL ZEROS  PICTURE FINISH
        CLR     SUM
        MOV     #JINST1,(R5)+
                                    ;R5 POINTS TO PICTURE END
        MOV     #JINST2,(R5)+
                                    ;INSERT JUMP INSTRUCTION
        MOV     END,(R5)            ;INSERT JUMP ADDRESS
        MOV     LOC1,R5             ;RESET R5
        TST     -(R5)               ;FIRST JMP ADDR LOCN
        TST     FLAG                ;WHICH PICT TO BUILD
        BNE     LOOP98              ;NO 1
        MOV     LOC1,@R5            ;NO 2 MOVE PICT INSTR ST ADD
        INC     FLAG                ;INTO JMP
        MOV     LOC2,R5             ;RESET
        NOP
        BR      GO1
LOOP98: MOV     LOC2,@R5            ;MOV PICT 2 ST ADD TO
        DEC     FLAG                ;JMP 1
        MOV     LOC1,R5             ;RESET R5
        NOP
        BR      GO1
LOOP5:  MOV     BUFFER,RO           ;CONDITION INCREMENT DATA
        ROLB    RO
        ROR     RO
        BIT     #ZERO,RO
        BEQ     LOOP1
```

```
        BIC     #ZBYTE,RO
LOOP1:  NOP
        BIT     #STOP,RO        ;TEST STOP CONDITION
        BEQ     LOOP7
        BIT     #RSIGN,RO
        BEQ     FINAL
        JSR     PC,CLOCK
        BR      GO
FINAL:  MOV     (SP)+,R4
        MOV     (SP)+,R3
        RTS     PC
LOOP7:  BIT     #COLLIDE,RO ;CHECK COLLISION BIT
        BEQ     LOOP29
        MOV     #1,CTEST        ;YES SET FLAG
        BIC     #COLLIDE,RO ;CLEAR BIT
        BIS     #003600,POINT   ;INTENSIFY VECTORS
LOOP29: BIT     #RSIGN,RO       ;TEST SIGN
        BEQ     LOOP0
        BIC     #RSIGN,RO       ;CLEAR SIGN BIT
        NEG     RO              ;NEGATE
        NOP
        BR      LOOP0
LOOP20: NOP
LOOP0:  ADD     RO,SUM          ;PULL 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     DATAE,R3        ;SUM EXPONENTS
        INC     R3              ;EXPONENT OF DIVISION
        NOP
```

```
        MOV     DATAM,RO      ;SET UP REGISTERS FOR DIVIDE
        MOV     R3,-(SP)      ;R1/RO=R2  SAVE R3
        MOV     #040000,R3    ;+VE NORMALISED NOS USED
DIVIDE: CLR     R2
LOOP62: SUB     RO,R1
LOOP63: BLT     LOOP61
        BIS     R3,R2
        ASR     R3
        BEQ     LOOP64
        ASR     RO
        BR      LOOP62
LOOP61: ASR     R3
        BEQ     LOOP64
        ASR     RO
        ADD     RO,R1
        BR      LOOP63
LOOP64: MOV     (SP)+,R3      ;R2 HOLDS MANTISSA
        NOP                   ;R3 HOLDS EXP
        CLR     RO
        TST     R3
        BLT     LOOP12
        BEQ     LOOP14
        ASL     R2
        ASL     R2
LOOP11: ROL     RO
        ASL     R2
        DEC     R3
        BNE     LOOP11        ;CREATE INTEGER AND FRACTION IN RO & R2 RESPECT
        ROR     R2
        ROR     R2
        BR      LOOP14
LOOP12: NEG     R3
LOOP13: ASR     R2
        DEC     R3
        BNE     LOOP13
LOOP14: NOP
        MOV     RO,INTEG      ;RO CONTAINS INTERER
```

```
        MOV     R2,FRACT     ;R2 CONTAINS FRACTION
        BR      LOOP31       ;STORE IF X CORD CALC
LOOP30: MOV     INTEG,RO     ;UNSTORE IF Y COORD CALC
        MOV     FRACT,R2
LOOP31: MOV     ADTAB(R4),R3
        TST     (R3)+        ;R4 HOLDS LINK DISPL R3 TABLE LINK ST ADD
        TST     YYES         ;YCOORD ?
        NOP
        BEQ     LOOP32       ;NO
        TST     (R3)+        ;MOV PAST X COORD IN TABLE
LOOP32: ASL     RO
        ASL RO  ;MULTIPLY INTEGER PART BY 4 FOR DATA DISPL
        ADD     RO,R3
        MOV     (R3)+,STORE  ;SAVE LOWER COORD
        TST     (R3)+        ;MOVE PAST OTHER COORD
        MOV     (R3),R1      ;EXTRACT OTHER COORD
        TST     ENFLAG
        BNE     LOOP72
        BIT     #FFTEEN,R1   ;FOUND NEXT LINK
        NOP
        BNE     LOOP73
        SUB     STORE,R1     ;R1 HOLDS THE DIFFERENCE
        CLR     SIGN
        TST     R1
        BNE     LOOP37
        CLR     RO
        BR      LOOP46
LOOP37: BGT     LOOP35
;PREPARE FOR THE NORMALISATION OF THE DIFFERENCE
        INC     SIGN
        NEG     R1           ;STORE SIGN
LOOP35: MOV     #15.,RO
LOOP44: BIT     #MSB,R1      ;NORMALISE R1 GIVING
        BNE     LOOP46       ;EXPONENT IN RO &
        ASL R1  ;MANTISSA IN R1
        DEC RO
        BR      LOOP44
```

```
LOOP46:  CLR     R3
         ASL     R2
LOOP71:  ASR     R1              ;R1*R2=R3 +VE NORMALISED NOS
         ASL     R2
         BCC     LOOP74
         ADD     R1,R3
         BR      LOOP71          ;R3 CONTAINS MANTISSA RO THE EXPONENT
LOOP74:  BNE     LOOP71
         SUB     #15.,RO
         NEG     RO
UNNORM:  BEQ     LOOP50
         ASR     R3
         DEC     RO
         BR      UNNORM
LOOP50:  TST     SIGN
         BEQ     LOOP51
         NEG     R3              ;CORRECR SIGN CONDITION
LOOP51:  ADD     STORE,R3        ;R3 NOW CONTAINS ABS COORD
         NOP
         BR      LOOP52
LOOP73:  INC     ENFLAG
         BR      LOOP34
LOOP72:  DEC     ENFLAG
LOOP34:  MOV     STORE,R3
LOOP52:  TST     VEHB            ;VEHICLE END
         BEQ     LOOP80          ;NO
         TST     YYES            ;YES    Y COORD ?
         BEQ     LOOP81          ;NO
         MOV     R3,(R5)+
         MOV     R3,LASTY        ;SAVE ABS COORD
         MOV     POINT,(R5)+     ;INSERT POINT INSTRUCTION
         MOV     LASTX,R2        ;CALC COOORD FOR
         ADD     #040000,R2
         ADD     #2,R3
         MOV     R2,(R5)+        ;FIRST POINT
         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)+ ;X  COORD
        MOV     R3,LASTX    ;SAVE ABS POINT
        SUB     #2,R3
        BIS     #INT,R3
        MOV     R3,(R5)+        ;INSERT
        TST     CTEST           ;COLLISION
        BEQ     LOOP87          ;NO
        BIC     #003600,POINT   ;YES CHANGE INTENSITY
LOOP87: INC     YYES
        JMP     LOOP30
LOOP80: MOV     R3,-(SP)        ;SAVE ABS POINT ON STACK
        TST     YYES            ;Y COORD ?
        BEQ     LOOP82          ;NO
        SUB     LASTY,R3        ;YES CALC INCR
        BGE     LOOP53
        NEG     R3              ;SORT OUT SIGN BIT
        BIS     #RSIGN,R3
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     GO
LOOP55: BIS     #002600,POINT
        CLR     CTEST
        NOP
        JMP     GO
LOOP82: SUB     LASTX,R3        ;CALC X INC
        BGE     LOOP54
        NEG     R3              ;SORT OUT SIGN
        BIS     #PSIGN,R3
LOOP54: BIS     #INT,R3         ;SET INTENSITY BIT
        MOV     #LONGV,(R5)+
        MOV     R3,(R5)+        ;X COORD
        INC     YYES
        MOV     (SP)+,LASTX ;SAVE ABS POINT
        NOP
        JMP     LOOP30
LOOP4:  MOV     BUFFER,R4
        MOV     BUFFER,R4       ;START NEW LINK
        DEC     R4
        ASL     R4              ;CALC LINK OFFSET
        MOV     ADTAB(R4),R3
        MOV     (R3)+,R1        ;R1 HOLDS DATA DIST BTWN INTERP PTS
        MOV     #15.,R0
LOOP67: BIT     #MSB,R1         ;NORMALISE DATA
        BNE     LOOP68
        ASL     R1
        DEC     R0
        BR      LOOP67
LOOP68: NOP
        MOV     R1,DATAM
        MOV     R0,DATAE
        TST     VEHB
        BNE     LOOP56
        MOV     #LONGV,(R5)+
        MOV     (R3),R1
        SUB     LASTX,R1
```

```
        BGE     LOOP57
        NEG     R1
        BIS     #PSIGN,R1
LOOP57: BIS     #INT,R1
        MOV     R1,(R5)+
        MOV     (R3)+,LASTX
        MOV     (R3),R1
        SUB     LASTY,R1
        BGE     LOOP58
        NEG     R1
        BIS     #PSIGN,R1
LOOP58: MOV     R1,(R5)+
        MOV     (R3),LASTY
        BR      LOOP42
LOOP56: MOV     POINT,(R5)+
        MOV     (R3),LASTX
        MOV     (R3)+,(R5)+
        MOV     (R3),LASTY
        MOV     (R3),(R5)+
LOOP42: NOP
        CLR     SUM
        JMP     GO
        .END 11330
```

```
C
C FOCAL PROGRAM TO DISPLAY MOVING PICTURES.
C
C:FOCAL-11,LFOCA-A

  1.10 X FX(-1,175610,2) ; DISABLE FOCAL INTERRUPT.
C SEND TIMING CHARACTER AND RECEIVE DATA TABLE.
  1.15 O H;T "*";X FT();O S
  1.20 X FDIS(0,1,0,0);S L=FSET(1,0,0);D 3;G 1.4
  1.30 O H;T "*";X FU();T "*";O S;D 1.7;G 1.85
O S;G 1.7
  1.40 F I=1,N;S L=FR(L,I)
C DISPLAY LINKS.
  1.50 X FDIS (0,4,0,0);S L=FSET(L,0,0);S L=FSKP(L,850)
C SET UP SKIPS, ONE PICTURE S BUILT, ONE DISPLAYED, THESE ARE SWITCHED
C WHEN BUILD COMPLETED AND THEN NEXT PICTURE IS BUILT.
  1.70 X FSKP(850);T "                    SECS"
C DRAW MOVING PICTURE,
  1.80 O H;T "*";X FU();
C EXIT FOR COMMUNICATION.
  1.85 O H;T "*";X FV(L,500,850)
  1.90 X FSKP(850);X FX(-1,175610,66);T "*";O S;Q

  2.10 T "TYPE CONTROL F";F I=1,1000;
  2.20 X FX(-1,175610,66);X FSKP(500);Q

  3.10 S Q=51;S P=48;S L=FTXT(L,OM,OE,OT,OR,OE,OS)
C WRITE SCALING LABEL ON SCREEN.
  3.20 S L=FPT(L,100,10);S L=FVEC(L,0,-10)
  3.30 F I=1,3;D 4
  3.40 F I=0,3;S L=FPT(L,100+(3-I)*SF*10,0);S L=FTXT(L,Q,P); S Q=50-I
  3.50 R

  4.10 S L=FVEC(L,10*SF,0);S L=FVEC(L,0,10)
  4.20 S L=FMOV(L,0,-10);R
```

```
C
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
C!FORTRANH GO,S
       INTEGER BUF(3)
      DIMENSION IA(50)
      DIMENSION IMESS(20)
      DIMENSION IBUF(2),NIV(8)
      INTEGER V1
      LOGICAL NOTFORE
      LOGICAL STOPNOW
      DIMENSION PDEL(2)
      DIMENSION FTIME1(2)
      DIMENSION CONPT(5),V(10,4),ACCN(10,4),TJ(10,4),AJERK(10,4)
     &,SINC(10,4),H(10,4),COEFF(5,10,4),S(10,4),T(10,4)
      DIMENSION IFCOUNT(2),SAFRING(2)
      DIMENSION ACOEFF(200),FRINGE(10,4),ISTACK(20)
      REAL KON
      COMMON /PLAT/ TBLOCK,BOUNDH,BOUNDL,START,QTIME,ENDTIM
     *,DDELT
      COMMON TSTART,TFIN,FLEVEL1,FLEVEL2
      COMMON TFINC,TTOT,HOLD
      COMMON /SWAP/NUM,IF,IB,IN,SPEEDI,STARTM1,STARTM2,STIME,FTIME
      COMMON /CHAN/ ISTORE(4,2),RSTORE(4,2)
      EQUIVALENCE (ACOEFF(1),COEFF(1,1,1))
      LOGICAL NOOUT
      LOGICAL ISBEGIN
      LOGICAL FRONTOK,BACKOK,SPEEDOK
      NAMELIST
      ISFG=5
      HOLD=2.5
      NOOUT=.FALSE.
      TTOT=0.
      NIV(1)=0
```

```
      NIV(2)=0
      NIV(3)=0
C PICK UP LINE NUMBER OF RUNNING FROM TERMINAL.
S      LH,1        X'1E9'
S      BEZ         4444S
S      AND,1       =X'7'
S      STW,1        L
      GOTO 445
 4444 L=4
 445  CONTINUE
      MUM=0
      NUM=0
      VELSTRT =12.
      VELEND =4.5
      VELMAX=12.
      ACCNML =1.2
      FACTOR=0.
      KON =1.2
      CKON=2.
      ACCEMG =2.5
      VL =4.
      FLEVEL1 =.95
      FLEVEL2 =.95
      FLEVEL3=0.
      ABJERK =1.2
C SET LOCATIONS OF CONTROL POINTS.
      CONPT(1) =0.
         CONPT(2)=200.
         CONPT(3)=250.
         CONPT(4)=450.
         CONPT(5)=500.
      EPS1 =1.
      EPS2 =.1
         CONSTIT=-.5
      SPEEDI=VELMAX
C INITIALISATION AND DEFAULT VALUES.
      DEGREE=.5
```

```
      IV1=0
      IV2=0
      MUM=700
      INOIT=0
      STOPNOW=.FALSE.
      BOUNDH=CONPT(5)
      BOUNDL=CONPT(1)
      OTIME=0.
      ENDTIM=300.
      DDELT=.5
      TBLOCK=1C.
C INPUT ANY DATA.
      INPUT(105)
      CALL AC
C WRITE HEADER.
      WRITE(108,903)
      WRITE(108,904) VELSTRT,VELEND,VELMAX,ACCNML,ACCEMG,VL
      WRITE(108,905)
      WRITE(108,906) CONPT,FLEVEL1,FLEVEL2,FLEVEL3,DEGREE
      WRITE(108,902)
      ISUM=0
      DESQ=0.
      DELAYS=0.
      TTH=(CONPT(5)-CONPT(1))/VELSTRT
      PDEL(1)=0.
      PDEL(2)=C.
      THI=ATAN(VELEND)
      API=3.14159
      AKINT=KON/(2*ACCEMG)
C CALCULATE HEADWAYS.
      HSTART=(VELSTRT*VELSTRT)*AKINT + VL*KON
      HFIN=(VELEND*VELEND)*AKINT + VL*KON
      TSTART=HSTART/VELSTRT
      TFIN=HFIN/VELEND
      TFINC=TFIN*CKON/KON
      DO 491 I=1,50
 491  IA(I)=0
```

```
      Z=GAP(3)
      ISBEGIN=.TRUE.
C INITIALISE POINTERS.
      STARTM1=CONPT(2)
      STARTM2=CONPT(4)
      STIME=0.
      FTIME=CONPT(4)/VELSTRT
      LANE=1
      IF=1
      IB=2
      IN=1
      SPEEDOK=.FALSE.
      IF (NOOUT) GOTO 355
      CALL COCLINE(L)
      CALL WTNL
C SET UP FOR COMMUNICATION TO FOCAL PROGRAM, ROLLING GRAPH DISPLAY
C RUNNUNG ON GT40.
      CALL BCSET(L,3,0)
      IST=1
      IBC=8
      CALL BCREAD(L,IBC,IST)
      GOTO 355
  350 CONTINUE
      IFCOUNT(1)=0
      IFCOUNT(2)=0
      SAFRING(1)=-100.
      SAFRING(2)=-100.
      IF (FTIME-STIME.GT.TIMEJ) GOTO 355
      FTIME=STIME+TIMEJ
      FSTIME=FTIME
      SPEEDI=VELMAX
  355 CONTINUE
C SET UP TRAJECTORY VELOCITIES.
      V(1,IN)=VELSTRT
      V(2,IN)=VELSTRT
      V(5,IN)=SPEEDI
      V(6,IN)=SPEEDI
```

```
      V(9,IN)=VELEND
      V(10,IN)=VELEND
C SET UP ACCELERATION AND JERK VALUES.
      DO 2 I=1,10
      ACCN(I,IN)=0.
      TJ(I,IN)=0.
      AJERK(I,IN)=0.
      SINC(I,IN)=0.
    2 CONTINUE
      DO 1 II=1,2
      I=(II-1)*4
      DV=V(5+I,IN)-V(2+I,IN)
      AJERK(2+I,IN)=SIGN(ABJERK,DV)
      AJERK(4+I,IN)=-AJERK(2+I,IN)
      DELT=SQRT(ABS(DV)/ABJERK)
      ACCN(3+I,IN)=SIGN(AMIN(ABJERK*DELT,ACCNML),DV)
      ACCN(4+I,IN)=ACCN(3+I,IN)
C TIME DURATION OF TRAJECTORY SEGMENTS.
      TJ(2+I,IN)=ACCN(3+I,IN)/AJERK(2+I,IN)
      TJ(4+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.-
     &ACCN(3+I,IN)*TJ(4+I,IN)-AJERK(4+I,IN)*TJ(4+I,IN)**2/2.)/ACCN(3+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,
     &IN)**2/2.
C LENGTH OF TRAJECTORY SEGMENTS.
      SINC(2+I,IN)=V(2+I,IN)*TJ(2+I,IN)+AJERK(2+I,IN)*TJ(2+I,IN)**3/6.
      SINC(3+I,IN)=V(3+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
      NOTFORE=.FALSE.
      FRONTOK=.FALSE.
      BACKOK=.FALSE.
C POSITION OF TRAJECTORY SEGMENTS.
```

```
      S(1,IN)=CONPT(1)
      S(2,IN)=STARTM1
      S(3,IN)=S(2,IN)+SINC(2,IN)
      S(4,IN)=S(3,IN)+SINC(3,IN)
      S(5,IN)=S(4,IN)+SINC(4,IN)
 559  CONTINUE
      S(6,IN)=STARTM2
      S(7,IN)=S(6,IN)+SINC(6,IN)
      S(8,IN)=S(7,IN)+SINC(7,IN)
      S(9,IN)=S(8,IN)+SINC(8,IN)
      IF (S(9,IN).LE.CONPT(5)) GOTO 558
      STARTM2=STARTM2-S(9,IN)+CONPT(5)
      NOTFORE=.TRUE.
      GOTO 559
 558  CONTINUE
      S(10,IN)=CONPT(5)
      FTIME=FSTIME+DEGREE*FACTOR
C SET UP TIMES OF TRAJECTORY SEGMENTS.
      T(1,IN)=STIME
      T(2,IN)=(S(2,IN)-S(1,IN))/VELSTRT+T(1,IN)
      T(3,IN)=T(2,IN)+TJ(2,IN)
      T(4,IN)=T(3,IN)+TJ(3,IN)
      T(5,IN)=T(4,IN)+TJ(4,IN)
      IF (.NOT.ISBEGIN.OR.LANE.EQ.2) GOTO 555
C ONLY HERE ON INITIALISATION.
      T(6,IN)=(S(6,IN)-S(1,IN))/VELSTRT
      T(7,IN)=T(6,IN)+TJ(6,IN)
      T(8,IN)=T(7,IN)+TJ(7,IN)
      T(9,IN)=T(8,IN)+TJ(8,IN)
      T(10,IN)=(S(10,IN)-S(9,IN))/VELEND+T(9,IN)
      FTIME=T(10,IN)
      TIMEJ=FTIME
      GOTO 556
 555  CONTINUE
      T(10,IN)=FTIME
      T(9,IN)=T(10,IN)-(S(10,IN)-S(9,IN))/VELEND
      T(8,IN)=T(9,IN)-TJ(8,IN)
```

```
      T(7,IN)=T(8,IN)-TJ(7,IN)
      T(6,IN)=T(7,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*KON
    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.EQ.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
      ACOEFF(I)=0.
    4 CONTINUE
C CALCULATE COEFFICIENTS OF POLYNOMIALS DESCRIBING EACH SEGMENT
```

```
C OF TRAJECTORIES.
      DO 14 I=1,9,4
      COEFF(1,I,IF)=S(I,IF)
      COEFF(2,I,IF)=V(I,IF)
      COEFF(1,I,IB)=H(I,IB)
      COEFF(2,I,IB)=V(I,IB)
   14 CONTINUE
      COEFF(1,10,IF)=S(10,IF)
      COEFF(2,10,IF)=V(10,IF)
      COEFF(1,10,IB)=H(10,IB)
      COEFF(2,10,IB)=V(10,IB)
      DO 15 I=1,2
      DO 15 J=1,3
      K=4*I-3+J
      COEFF(1,K,IF)=S(K,IF)
      COEFF(2,K,IF)=V(K,IF)
      COEFF(3,K,IF)=ACCN(K,IF)/2.
      COEFF(4,K,IF)=AJERK(K,IF)/6.
      COEFF(1,K,IB)=H(K,IB)
      COEFF(2,K,IB)=V(K,IB)+2.*ACCN(K,IB)*V(K,IB)*AKINT
      COEFF(3,K,IB)=ACCN(K,IB)/2.+ACCN(K,IB)**2*AKINT+AJERK(K,IB)*V(K,IB
     1)*AKINT
      COEFF(4,K,IB)=AJERK(K,IB)/6.+AJERK(K,IB)*ACCN(K,IB)*AKINT
      COEFF(5,K,IB)=AJERK(K,IB)**2*AKINT/4.
   15 CONTINUE
      DO 10 K=1,2
      IP1=IF
      IP2=IB
      IF (K.EQ.1) GOTO 16
      IP1=IB
      IP2=IF
   16 CONTINUE
      DO 10 J=1,10
      I=2
   12 CONTINUE
      IF (T(J,IP1).LT.T(I,IP2))GOTO 11
      I=I+1
```

```
      IF (I.NE.11)GOTO 12
      I=10
   11 I=I-1
      DT=T(J,IP1)-T(I,IP2)
      FRIS=COEFF(1,I,IP2)+COEFF(2,I,IP2)*DT+COEFF(3,I,IP2)*DT**2
     &+COEFF(4,I,IP2)*DT**3+COEFF(5,I,IP2)*DT**4
C FIND THE INFRINGEMENTS WITH PREVIOUS TRAJECTORY.
      IF (K.EQ.1)FRINGE(J,IP1)=S(J,IP1)-FRIS
      IF (K.EQ.2)FRINGE(J,IP1)=FRIS-H(J,IP1)
   10 CONTINUE
      I=1
      J=1
      K=0
      FNEXT=T(I,IF)
      BNEXT=T(J,IB)
  120 K=K+1
      IF (FNEXT.GT.BNEXT)GOTO 100
      ISTACK(K)=IF
      I=I+1
      IF (I.EQ.11)GOTO 110
      FNEXT=T(I,IF)
      GOTO 120
  100 ISTACK(K)=IB
      J=J+1
      IF (J.EQ.11) GOTO 130
      BNEXT=T(J,IB)
      GOTO 120
C SORT INTO TIME ORDER THE TRAJECTORY BREAK POINTS.
  110 K=K+1
      ISTACK(K)=IB
      J=J+1
      IF (J.EQ.11)GOTO 140
      GOTO 110
  130 K=K+1
      ISTACK(K)=IF
      I=I+1
      IF (I.EQ.11)GOTO 140
```

```
      GOTO 130
  140 CONTINUE
      VAR=1
      GOTO 1000
 1001 CONTINUE
      DO 145 M=1,2
      FRINGEM=1000.
      IF (M.EQ.2) GOTO 147
      IF (FRONTOK) GOTO 145
      I=0
      J=0
      K=0
  155 K=K+1
      IF (J.EQ.5.AND.M.EQ.1) GOTO 170
      IF (J.EQ.10.AND.M.EQ.2) GOTO 170
      IF (K.EQ.21) GOTO 170
      IF (ISTACK(K).EQ.IF) GOTO 150
      J=J+1
      IF (FRINGE(J,IB).GE.FRINGEM) GOTO 155
      FRINGEM=FRINGE(J,IB)
      GOTO 155
  150 I=I+1
      IF (FRINGE(I,IF).GE.FRINGEM) GOTO 155
      IF (M.EQ.2.AND.J.LT.6) GOTO 155
      FRINGEM = FRINGE(I,IF)
      GOTO 155
  170 IF (ABS(FRINGEM).GT.EPS1) GOTO 180
      IF (M.EQ.1) FRONTOK=.TRUE.
      IF (M.EQ.2) BACKOK=.TRUE.
C FIND WORST INFRINGMENTS DURING FRONY AND BACK SPEED
C CHANGE MANOEUVRES.
  180 IF (M.EQ.1) STARTM1 =STARTM1+FRINGEM
      IF (M.EQ.2.AND.NOTFORE.AND.FRINGEM.GT.0) GOTO 473
      IF (M.EQ.2) STARTM2=STARTM2+FRINGEM
      IF (FRINGEM.GT.SAFRING(M)) GOTO 232
      IFCOUNT(M)=IFCOUNT(M)+1
      GOTO 233
```

```
  232 IFCOUNT(M)=0
  233  SAFRING(M)=FRINGEM
      GOTO 145
  147 IF (BACKOK) GOTO 145
      K=K-1
      GOTO 155
  473 BACKOK=.TRUE.
  145 CONTINUE
C START POINT FIRST MANOEUVRE.
      IF (STARTM1.GT.CONPT(1))GOTO 220
      ITT1=1
C BACKED UP TOO FAR.
      WRITE(108,1810) ITT1,LANE,NUM
 1810 FORMAT(X,'B',I1,' VIOLATED L',I1,2X,'V ',I4)
      STOP
  220 IF (STARTM1.LT.CONPT(2))GOTO 225
      STARTM1=CONPT(2)
      FRONTOK=.TRUE.
  225 CONTINUE
      IF (IFCOUNT(2).GE.3) GOTO 234
C START POINT FOR SECOND MANOELVRE.
      IF (STARTM2.GT.CONPT(3)) GOTO 270
      ITT1=3
C BACKED UP TOO FAR.
      WRITE(108,1810)ITT1,LANE,NUM
      STOP
  234 CONTINUE
C ITERATION FAILS TO FIND A START POINT FOR SECOND MANOEUVRE,
C THEREFORE CHANGE TARGET TIME AND START AGAIN.
      IFCOUNT(2)=0
      STARTM2=CONPT(4)
      FACTOR=FACTOR+1.
      GOTO 330
      GOTO 280
  270 IF (STARTM2.LT.CONPT(4)) GOTO 280
      STARTM2=CONPT(4)
      BACKOK=.TRUE.
```

```
  280  CONTINUE
C HAVE SATISFACTORY FRONT AND BACK START POINTS BEEN FOUND? IF NOT
C RE-ITERATE SOLUTION.
       IF (.NOT.(FRONTOK.AND.BACKOK)) GOTO 330
       DISTI=S(6,IB)-S(5,IB)
       IF (DISTI.GT.0.) GOTO 300
C DISTANCE AVAILABLE FOR MANOEUVRE IS INADEQUATE. THIS IS A FAULT.
       WRITE(108,1820) LANE,NUM
 1820  FORMAT(' -VE DIST L',I1,'   V ',I4)
       STOP
       DISTI=0.
  300   TIMEI=T(6,IB)-T(5,IB)
       IF (TIMEI.GE.0.) GOTO 310
C TIME AVAILABLE FOR MANOEUVRE IS INADEQUATE. MAKE TARGET TIME LATER
C AND RE-ITERATE.
       WRITE(108,1840) LANE,NUM
 1840  FORMAT(' -VE TIME L',I1,'   V ',I4)
       FTIME=FTIME-TIMEI
       FSTIME=FTIME
       GOTO 330
  310  IF (SPEEDOK) GOTO 320
       SPEED=DISTI/TIMEI
       IF (ABS(SPEEDI-SPEED).LT.EPS2) SPEEDOK=.TRUE.
C CALCULATE NEW INTERMEDIATE SPEED.
       SPEEDI=SPEED+(SPEED-SPEEDI)*CONSTIT
       INOIT=INOIT+1
       IF (INOIT.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., ETC.
       DELAY=FTIME-STIME+PDEL(LANE)-TTH
       FTIME1(LANE)=FTIME
       FLOW=NUM/STIME
```

```
      ISUM=ISUM+1
      DESQ=DESQ+DELAY*DELAY
      DELAYS=DELAYS+DELAY
      DELAYA=DELAYS/ISUM
      FLOWA=ISUM/STIME
      VARI=DESQ/ISUM-DELAYA*DELAYA
      VARI=SQRT(VARI)
      FRINMIN=1000.
      DO 492 I=1,10
      DO 492 J=1,2
      IQ=IB
      IF (J.EQ.2) IQ=IB
      IF (FRINGE(I,IQ).GT.FRINMIN) GOTO 492
      FRINMIN=FRINGE(I,IQ)
  492 CONTINUE
      IF (SPEEDI.LE.VELMAX) GOTO 390
      DISPT=DISTI/VELMAX-TIMEI
C CHECK THAT INTERMEDIATE SPEED IS WITHIN ALLOWED TRACK LIMITS.
      FTIME=FTIME+DISPT
      FSTIME=FTIME
      SPEEDI=VELMAX
      GOTO 350
  390 CONTINUE
      IF (ISUM.NE.MUM) GOTO 391
      STOPNOW=.TRUE.
      WRITE(108,907) FLOWA,DELAYA,VARI,OCCP
      WRITE(108,928) IA
  928 FORMAT(2(X,25I4,/))
      WRITE(108,902)
      STOP
  391 CONTINUE
      IPPT=STARTM1/25.
      IF (IPPT.LT.1) IPPT=1
      IF (IPPT.GT.50) IPPT=50
C HISTOGRAM ARRAY SAVING THE START POINTS OF FRONT SPEED CHANGE MANOEUVRE.
      IA(IPPT)=IA(IPPT)+1
      OCCP=TTOT/FTIME
```

```
      CALL PLOTP(COEFF,T,IB,IF,LANE)
      VAR=2
      GOTO 1000
 1002 CONTINUE
      INOIT=0
C CHANGE OVER POINTERS.
      IB=3-IB+(LANE-1)*4
      IF=3-IF+(LANE-1)*4
      IN=IB
      SPEEDOK=.FALSE.
      NUM=NUM+1
      THETA=0.
      FACTOR=0.
  356  CONTINUE
      SAVET=STIME
      CALL SAVE(LANE)
C FIND NEW LANE.
      CALL NEWLANE(LANE,SAVET)
      CALL UNSAVE(LANE)
      FSTIME=FTIME
      GOTO 350
 1000 CONTINUE
      IF (NOOUT) GOTO 1114
C HAS TIMING CHARACTERS FROM FOCAL PLOTTING ROUTINE BEEN RECEIVED?
  801 CALL CHECK(L,IM,IST,IBC)
      IF (IAND(IST,1).EQ.1) GOTO 801
      IST=0
      IBYTE=0
      CALL BCMOVE(L,IBUF,IBYTE,IBC,IST)
C IV1 IS DECODED INTO FLAGS INDICATING WHICH OPTION HAS
C BEEN SELECTED FROM GT40.   (NIV(1-7))
        DECODE(IBC,1802,IBUF,N) IV1
 1802 FORMAT(I)
  803 CONTINUE
        CALL BCSET(L,132,0)
        IEX=7
        IV2=IV1
```

```
802 IF (IV2-2**IEX.LT.0) GOTO 806
     IV2=IV2-2**IEX
     NIV(IEX+1)=1
     GOTO  804
806  NIV(IEX+1)=0
804  IEX=IEX-1
     IF (IEX.NE.-1) GOTO 802
    IF (NIV(7).EQ.1) STOP
    IF (NIV(6).EQ.1) GOTO 1015
    IF (NIV(3).EQ.0) GOTO 1014
    CALL BCSET(L,132,0)
    ICC=-1
C READ THING CHARACTER IF GRAPH TO BE PLOTTED.
    CALL RD(ICC,V1)
    IBOY=(VAR-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 BINDEC(ISFG,BUF,IBOY)
    CALL WTNL(ISFG,BUF)
    DO 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.2Z40) GOTO 1004
    ISFG=5
C SEND DATA TO DRAW GRAPH ON GT40.
    V1=T(I,IN)*12+.5
       CALL BINDEC(ISFG,BUF,V1)
    CALL WTNL(ISFG,BUF)
    ICC=-1
    CALL RD(ICC,V1)
    ISFG=5
    V1=S(I,IN)*1.4+.5
       CALL BINDEC(ISFG,BUF,V1)
    CALL WTNL(ISFG,BUF)
    ICC=-1
    CALL RD(ICC,V1)
```

```
      ISFG=5
      V1=H(I,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)H
      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,FLOW,DELAYA,VARI,FRINMIN,OCCP
      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 BCSET(L,3,0)
     IST=0
     IBC=8
     CALL BCREAD(L,IBC,IST)
     GOTO 801
 900 FORMAT(X,10F10.3,3(/,X,10F10.3))
 901 FORMAT(X,'L',I1,X,'V ',I4,X,'C1 ',F6.1,X,'C2 ',F6.1,X,
    &'ST ',F6.1,X,'FT ',F6.1,X,'(',F6.1,')',X,'I SP ',F5.1,X,'D ',
    &F5.1,X,'F ',F3.2,X,'AD ',F6.2,X,'VAR ',F6.2,X,'IM ',F6.2
    &,' OC ',F4.3)
 902  FORMAT(/,X,'L ',I1,2X,'V ',I4)
 903  FORMAT(X,'START SPEED   END SPEED   MAX SPEED   NML ACCN    EMG A
    &CCN    VEH LENGTH')
 904  FORMAT(X,6F12.2,/)
 905 FORMAT(3X,'CONTROL PTS 1-5',44X,' LEVELS 1-3   ',25X,'DEGREES')
 906  FORMAT(X,9F12.3)
 907  FORMAT(X,'FLOW',F8.3,2X,'DELAY',F8.3,' S D ',F8.3,' OCC ',F8.3)
      END
```

```
C
C RANDOM NUMBER GENERATOR.
C
      SUBROUTINE RANDOM(IX,IY,YFL)
      IY=IX*65539
      IF(IY)5,6,6
    5 IY=IY+2147483647+1
    6 YFL=IY
      YFL=YFL*.4656613E-9
      RETURN
      END
```

```
C
C GENERATE HEADWAY TO NEXT VEHICLE.
C
      FUNCTION GAP(I)
      COMMON TSTART,TFIN,FLEVEL1,FLEVEL2
      DIMENSION II(2)
      GOTO(1,2,3)I
    3 II(1)=1
      II(2)=117
      CALL RANDOM(II(1),II(1),RN)
      CALL RANDOM(II(2),II(2),RN)
      GAP=0.
      RETURN
    2 CONTINUE
    1 IC=0
    4 CALL RANDOM(II(I),II(I),RN)
      IC=IC+1
      IF (RN.LT.FLEVEL1)GO TO 4
      GAP=FLOAT(IC)*TSTART/10.
      IF (GAP.LT.TSTART)GAP=TSTART
      RETURN
      END
```

```
C
C CHOOSE NEXT LANE THROUGH INTERSECTION ACCORDING TO ORDERING POLICY.
C (HERE FCFS AND HOLD)
C
      SUBROUTINE NEWLANE(LANE,SAVET)
      COMMON TSTART,TFIN,FLEVEL1,FLEVEL2
      COMMON TFINC,TTOT,HOLD
      COMMON /SWAP/NUM,IF,IB,IN,SPEEDI,STARTM1,STARTM2,STIME,FTIME
      COMMON /CHAN/ ISTORE(4,2),RSTORE(4,2)
      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
```

```
C
C SET UP NEW VARIABLES FOR NEW LANE SELECTED.
C
      SUBROUTINE UNSAVE(LANE)
      COMMON /SWAP/NUM,IF,IB,IN,SPEEDI,STARTM1,STARTM2,STIME,FTIME
      COMMON /CHAN/ ISTORE(4,2),RSTORE(4,2)
      NUM=ISTORE(1,LANE)
      IF=ISTORE(2,LANE)
      IB=ISTORE(3,LANE)
      IN=ISTORE(4,LANE)
      SPEEDI=RSTORE(1,LANE)
      STARTM1=RSTORE(2,LANE)
      STARTM2=RSTORE(3,LANE)
      STIME=RSTORE(4,LANE)
      RETURN
      END
```

```
C
C SAVE OLD VARIABLES FROM LAST LANE.
C
      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
C SEND AXES TO PLOTTER FOR HARD COPY GRAPH PLOT.
C
      SUBROUTINE AC
      COMMON /PLAT/ TBLOCK,BOUNDH,BOUNDL,START,QTIME,ENDTIM
     *,DDELT
      DIMENSION MESS(3)
      SCALET=TBLOCK/10.
      SCALEP=(BOUNDH-BOUNDL)/8
      CALL OFFSET(QTIME,SCALET,BOUNDL,SCALEP)
      CALL PLOT(0.,.5,-3)
      CALL PLOT(QTIME,BOUNDH,12)
      START=QTIME
      ENTRY AXIS
      CALL PLOT(START,BOUNDL,13)
      DO 6 K=1,10
      X=K*10.+START
      CALL PLOT(X,BOUNDL,12)
      ENCODE(12,7,MESS,IBC) X
    7 FORMAT(F4.0)
      CALL WHERE(X1,Y1,FCTR)
      CALL PLOT(X1,-0.15,2)
      CALL SYMBOL(X1,-.15,.1,MESS,0.,IBC)
    6 CALL PLOT(X1,Y1,3)
      START1=X
      CALL PLOT(START1,BOUNDH,13)
      CALL PLOT(START,BOUNDH,12)
      START=START1
      RETURN
      END
```

```
C
C DRAW TRAJECTORY OF LAST VEHICLE AND HEADWAY PROFILE OF PRESENT VEHICLE.
C
      SUBROUTINE PLOTP(COEFF,T,IB,IF,LANE)
      COMMON /PLAT/TBLOCK,BOUNDH,BOUNDL,START,QTIME,ENDTIM
     *,DDELT
      DIMENSION COEFF(5,10,4),T(10,4)
      IF (LANE.EQ.1) RETURN
      ISEG=1
      TS=T(1,IF)
      IMOD=13
      P=COEFF(1,ISEG,IF)
    3 CONTINUE
      IF (TS.LT.QTIME.OR.TS.GT.ENDTIM) GOTO 1
      IF (P.LT.BOUNDL.OR.P.GT.BOUNDH) GOTO 1
      CALL PLOT(TS,P,IMOD)
    7 TS=TS+DDELT
      IF(ISEG.EQ.10) GOTO 2
      IF (TS.LT.T(ISEG+1,IF)) GOTO 2
      ISEG=ISEG+1
      IF (ISEG.GT.10) ISEG=10
    2 CONTINUE
      DT=TS-T(ISEG,IF)
      P=COEFF(1,ISEG,IF)+COEFF(2,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
    1 CONTINUE
      IF (TS.GT.ENDTIM) GOTO 5
      IF (P.GT.BOUNDH) GOTO 6
      GOTO 7
    6 CONTINUE
      IF (TS.GT.START) CALL AXIS
      ISEG=1
      IMOD=13
      TS=T(1,IB)
      P=COEFF(1,ISEG,IB)
```

```
8     CONTINUE
      IF (TS.LT.OTIME.OR.TS.GT.ENDTIM) GOTO 9
      IF (P.LT.BOUNDL.OR.P.GT.BOUNDH) GOTO 9
      CALL PLOT(TS,P,IMOD)
10    CONTINUE
      TS=TS+DDELT
      IF (ISEG.EQ.10)  GOTO 11
      IF (TS.LT.T(ISEG+1,IB)) GOTO 11
      ISEG=ISEG+1
      IF (ISEG.GT.10) ISEG=10
11    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
9     CONTINUE
      IF (TS.GT.ENDTIM) GOTO 5
      IF (P.GT.BOUNDH) RETURN
      GOTO 10
5     CALL CLRPLT
      RETURN
      END
```

```
C!MACRSYM SI,GO,BA
          DEF       NOECHO
          REF       VDUDCB
NOECHO    LI,1      X'20000'
          STS,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
```

```
C:CLOAD GO,(UDCB,2),(PUBLIB,CBCLIB)
C:SY
C:RADEDIT
C:COP (FIL,BT,OV),(FIL,FP,FGP2)
```

```
CCC:FOCAL-11,LFOCA-A

C NECESSARY MODIFICATIONS TO FOCAL BINARY FOR SATISFACTORY
C COMMUNICATIONS TO SIGMA 5.
  1.01 C PATCH 104440 INTO 5252 (104472) NO :
  1.02 C PATCH 104440 INTO 5232 (104475) NO =
  1.03 C PATCH 5306 INTO 2766 (3566) NO ECHO
C SENSE KEYS ON GT40 SELECT FUNCTIONS
  1.04 C F0-SUMMARY ALL;F1-FULL DATA ALL;F0 & F1-SUMMARY FINAL
  1.05 C F2-GRAPHS;F3-FINAL ONLY;F4-LANE 1;F5-MESSAGE;F6-STOP
  1.06 D 40;I (1-(PO(7)+PO(6)))1.07;E;O S;D 2;G 42.1
C RETURN TO TELETYPE MODE (FW).
  1.07 O H;X FW(1);Q

C INITIALISE POINTERS FOR ROLLING DISPLAY.
  2.10 S L(1)=1;S L(2)=1;S L(3)=85;S L(4)=85;S L(5)=850;S A=0;S 7=1
  2.20 O S;S CO=0;S AT=0;S SP=1.0;S ST=1;S EF=3;S EE=3;S PE=1
  2.30 X FSKP(350,850);S LQ=85;T "DONT FORGET BGDCOC!"!,%3.00;O 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(EE)-21,L(EE))
  3.15 I (PE-CO)3.3;D 2;S ST=ST/2;D 12;G 42.1
  3.30 I (L(EE)-L(EE+1))3.4;S L(EE)=1;S L(EE+1)=1;S EE=4-EE;S PE=PF
  3.40 I (EE-EF)3.45,3.5,3.45
  3.45 S I=0;F LQ=L(EF),21,L(EF+1)-21;D 10
  3.50 S I=0;F LQ=L(EE),21,L(EE+1)-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 SCREEN UNITS.
  5.10 I (I-1)5.76,5.76;I (I-11)5.3,5.8;I (I-21)5.6,5.9,5.9
  5.30 S IT=FITR(DT(I)+FSGN(DT(I))*.5);S IP=FITR(DP(I)+FSGN(DP(I))*.5)
  5.35 S LQ=FVEC(LQ,IT,IP);R
  5.60 S IT=FITR(-DT(22-I)-FSGN(DT(22-I))*.5)
```

```
 5.61 S IP=FITR(-DH(22-I)-FSGN(DH(22-I))*.5);S LQ=FVEC(LQ,IT,IP);R
 5.76 S LQ=FSET(LQ,AT,0);R
 5.80 S IP=FITR(H1+FSGN(H1)*.5);X FDIS(1,3,0,0);S LQ=FMOV(LQ,C,IP);R
 5.90 S IP=FITR(-H2-FSGN(H2)*.5);X FDIS(0,3,0,0);S LQ=FMOV(LQ,0,IP);R

10.10 X FDIS(0,3,0,0);X FSET(LQ,TS(PF+I)-TS(PE),0);S I=I+1

11.10 X FDIS(C,3,0,0);X FSET(LQ,TS(PF+I)-TS(PE),0);S I=I+1

12.10 S C0=C0+1;S L(EF+1)=LG
12.25 I (1-C0)12.3;S TL=T(1)*ST
12.30 F I=1,10;S TT(I)=T(I)*ST;S PP(I)=P(I)*SP;S HH(I)=H(I)*SP
12.35 S H1=HH(10)-PP(10);S H2=HH(1)-PP(1);F I=1,10;D 4
12.40 S TS(C0)=TT(1);I (1000-TT(10)+TS(PE))3.1;
12.45 I (L(EF+1)+21-L(5))12.5,12.5;S EF=4-EF;S PF=C0
12.50 S LQ=L(EF+1);S AT=TS(C0)-TS(PE);F I=1,21;D 5
12.60 S TL=TS(C0);S PL=0;S HL=0;G 13.4
12.70 A V1

C ASK FOR CODE CHARACTER FROM SIGMA 5.
 13.10 S VN=FITR(V1/4);S LA=FITR((V1-VN*4)/2);S IR=FITR(V1-VN*4-LA*2)
 13.14 S LA=LA+1;0 S
C DECODE INTO PLOT ROUTINE IF REQUIRED, OTHERWISE SEND
C '1' TO SIGMA 5 TO CONTINUE SIMULATING.
 13.15 T "L",%1.00,LA," V N",%3.00,VN," IT",%1.00,IR,%3.00,!;0 H
 13.16 I (P0(3)-IR)13.17,13.17,13.5
 13.17 I (P0(4)-LA+1)13.5,13.2,13.5
 13.20 D 14;I (Z)13.3,13.3,12.1
 13.30 D 12.3;D 12.35;S TS(C0)=TT(1);D 12.5;G 12.6
 13.40 S Z=IR;G 42.1
 13.50 T "1";G 42.1

 14.10 F I=1,10;A T(I),P(I),H(I)

C READ SENSE KEYS, DECODE IF CHANGED.
 40.10 S A=FX(C,177570,-1);I (IV-A)40.15,40.3,40.15
 40.15 S IV=A;S E=7
```

```
 40.20 I (FITR(A)-FITR(2^E))40.22;S A=FITR(A-FITR(2^E));
C DECØDE LØWEST 8 KEYS INTØ PØ(N).
 40.21 S PØ(E)=1;G 40.25
 40.22 S PØ(E)=0
 40.25 S E=E-1;I (-E)40.2,40.2;
 40.30 R

 42.05 T !;Ø H
C IF 7 SET WAIT.
 42.10 D 40;I (-PØ(7))42.1;I (-PØ(5))42.2;S PP=0
 42.20 I (PP)42.3,42.3,42.1
C SEND CØDED FLAGS TØ SIGMA 5.
C IF ØNLY LINE PRINTER ØUTPUT NØ FURTHER PARTICIPATIØN REQUIRED
C FRØM GT40 EXCEPT TØ SEND CØDED FLAGS.
 42.30 T IV,!
 42.35 I (PØ(5))42.36,42.36;S PP=1;Ø S;G 42.9
 42.36 I (PØ(2))42.1,42.1;D 12.7;G 13.1
C MESSAGE TYPED ØN KEY BØARD IS TRANSMITTED TØ SIGMA 5.
 42.80 R
 42.90 S ZZ=FCHR(FCHR(-1));I (ZZ-13)42.9,42.05,42.9
```