CONTRAM: STRUCTURE OF THE MODEL

by D R Leonard, P Gower and N B Taylor

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CONTRAM: STRUCTURE OF THE MODEL

ABSTRACT

CONTRAM is a traffic assignment model developed by the Transport and Road Research Laboratory for use in the design of traffic management schemes in urban areas. Given the traffic demands between origins and destinations for a network it predicts routes of vehicles and flows and queues on links. It is a capacity restrained model which takes account of the interactive effects of traffic between junctions over a network and the variation through time of traffic conditions—in particular it models the build up and decay of congestion such as occurs during peak periods. The outputs from CONTRAM can be used for economic assessment and traffic engineering purposes and for comparing O-D speeds between schemes.

This report describes the basic structure and mechanism of CONTRAM. The description is relevant for all versions of CONTRAM: recent developments in the modelling in CONTRAM version 5 are listed briefly.

An iterative procedure is used to assign vehicles to their minimum journey time routes through a network taking into account the delay at each junction along a route at the time that a vehicle reaches each junction. The assignment procedure, which uses a packet structure to represent elements of flow of vehicles for movements between Origins and Destinations, allows multi-routeing for vehicles with freedom of choice of route; fixed route vehicles, such as buses, are sent along their predefined routes, but still encounter the same delays at junctions experienced by other vehicles. The modelling in CONTRAM is consistent with the queue calculations in ARCADY, PICADY and OSCADY.

Facilities allow for: a full range of junction types (signal controlled, priority and roundabouts); three classes of vehicle (cars, buses and lorries); blocking-back between junctions; three options for inputting signal data (fixed cycle/fixed splits, fixed cycle/optimised splits, optimised cycle/optimised splits); fixed route vehicles (e.g. buses); fuel consumption; banned vehicle movements (without recoding) and 'point-to-point' speeds for comparisons of speeds for selected O-D movements. Recent developments in CONTRAM 5 include speed/flow relationships for links, minimum behavioural (or perceived) cost assignment, a more detailed modelling of the effect of linked signals, an improved fuel consumption model, estimation of geometric delay at junctions, a condensed output file for post analysis work, variable and automatic packet sizing, variable saturation flows and capacities for individual time intervals.

1 INTRODUCTION

The growth of traffic in urban areas has led to periods of congestion in networks of roads many of which were not designed to cope with modern volumes of traffic. The interactive effects of traffic in such networks have become too complex to predict using simple manual techniques and hence there is a need for a model of traffic behaviour to help in the design of traffic management schemes, to enable more efficient use to be made of road networks. Such schemes can range from local improvements to junctions, costing tens of thousands of pounds, up to the installation of complete UTC systems and new roads costing several millions of pounds. It is therefore essential to predict whether a proposed scheme will work, how well it will work and the extent to which the scheme will benefit some road users at the expense of others. The CONTRAM model has been developed to predict the interactive effects of traffic over a network in order to provide quantitative answers to questions of this type.

There are a number of factors which are important for designing schemes to manage traffic in urban areas. Congestion, in the form of widespread queues and long delays, is essentially a transitory condition and hence there is a need to model the variation of flows through time and the build up and decay of queues for periods such as the morning and evening peak periods. A further need for modelling time variation in traffic conditions is to enable the examination of the benefits of control strategies such as staggering the start times of large traffic demands from factories and businesses.

Drivers will often change their routes to avoid congestion and hence a model should incorporate an assignment procedure which reflects the effect of time variation in traffic conditions on route choice. It will also need to represent the interactive effects of traffic between junctions, such as blocking-back and signal linking, to cater for different classes of vehicle, and to model fixed route vehicles such as buses.

The information provided by such a model should be sufficiently detailed to predict: the time variation in flows and queues on links for local traffic engineering purposes; and journey times, distance travelled and fuel consumption, for different classes of vehicle, to provide a basis for economic assessments.

CONTRAM is such a model. This report describes the basic structure and mechanism for all versions of the model and supersedes the earlier report—LR 841 (Leonard, Tough and Baguley (1978)), since which significant changes have been introduced into the modelling.
2 GENERAL DESCRIPTION OF CONTRAM

CONTRAM (CONtinuous TRaffic Assignment Model) is a computer based assignment model which predicts flows, queues and routes of vehicles as they travel through a network of roads. It models the growth and decay of congestion through time under temporary oversaturated conditions such as occur during peak periods. Vehicles are normally assigned to their minimum journey time route through the network with the exception of fixed route vehicles, such as buses and delivery vehicles, which are sent along predefined routes.

The minimum journey time routes take into account the junction delays encountered at the times that the vehicles arrive at each junction along their routes. Three class of vehicle can be represented—usually cars, buses and lorries. A full range of junction types can be modelled including signal controlled, major/minor junctions and roundabouts. Allowance is made for ‘blocking-back’ effects which occur when the queue on a link fills the link and restricts traffic entering it from the upstream junction.

Time variation is modelled by subdividing the period being analysed into a series of consecutive time intervals. The flows and queues on each link, calculated for each time interval, are carried over in a consistent manner from one time interval to the next. The traffic demand on the network is defined in terms of a time-varying set of flows, one for each time interval, for each origin-destination (O-D) movement. The vehicle for each O-D movement are treated in groups called ‘packets’. Each packet is assigned independently to its route through the network—this corresponds to a progressive ‘incremental’ form of loading. The number of vehicles in a packet, for a given class of vehicle, is converted to equivalent pcu (passenger car unit) values where they are needed for flow and queue calculations.

To take account of the congestion delay generated by other vehicles the model uses an iterative procedure for assigning packets which is repeated until the procedure has converged satisfactorily.

Traffic signal operation in CONTRAM is essentially modelled by fixed time plans and allowance is made for the effect of coordinated signals along a route. The effect of Pelican and Zebra crossings can be taken into account by treating the crossings as signal controlled junctions.

A simple ‘banned entry’ facility exists for modelling banned turning movements or changes to a network, such as pedestrianising a street. These can be made without the need to re-code the rest of the network.

Fuel consumption estimates are made for each class of vehicle and ‘point-to-point’ speeds calculated for selected O-D movements to provide a measure for comparing the effects of alternative traffic management schemes on particular traffic movements.

The output from CONTRAM consists of the following information for use in traffic engineering and economic assessments of traffic management schemes:

- overall summaries of journey times, distance travelled, average speed and fuel consumption
- link by link values, for each time interval, of flows, queues, delays, percentage saturation, total time spent, distance travelled and average speed; the identification of blocking when it occurs
- summary tables, for each time interval, of flows, queues, mean queue times and average speeds on links
- turning movements at junctions for each time interval
- vehicle route information
- average ‘point-to-point’ O-D speeds
- convergence parameters

The inputs and outputs for CONTRAM (Section 4) are described in detail in the Userguide for CONTRAM (Leonard and Gower (1982)). The input data can also be prepared using the interactive User-Friendly Data-Entry System for CONTRAM—UFDESC (Section 4.1) and a User-Friendly Post-Analysis System for CONTRAM—UPPASC used to help with the analysis of outputs and the comparison of different schemes (Section 4.1).

Recent changes to the modelling in CONTRAM include improvements to queue calculations and a choice between fixed and variable packet sizing. Modifications to the program have been made in such a way that it will accept previous input data sets.

3 PRINCIPLES OF CONTRAM

3.1 OVERALL STRUCTURE

The overall structure of CONTRAM is outlined in Figure 1. The inputs are the Traffic Demand and Network data files together with a Control file (Section 4). The bases of the program are the assignment process, which calculates and stores vehicle route information, and the calculation of the variation through time of the delays on links derived from the flows and queues of vehicles. The detailed summary and link by link information in the output is derived from an analysis of these parameters in subroutine RMODEL of the program (Section 5); vehicle route information is available to examine
journey patterns in the network and an optional data file is produced for use with a user-friendly post-analysis system—UFPASC (Section 4.1).

3.2 NETWORK DESCRIPTION

A network is described in terms of origins, destinations, links and junctions. A link is a unidirectional section of road between two junctions or the connection to an origin or destination. More than one link can be used between adjacent junctions to model different streams of traffic. Three types of link can be modelled:—give-way, signal controlled and uncontrolled—the latter occur where roads merge with no right of way, or as the major road at give-way junctions. A full range of junction types can be modelled using combinations of these three types of link. Figure 2(a) illustrates a conventional give-way junction and Figures 2(b) and 2(c) show two alternative ways of modelling roundabouts as series of give-way junctions around a central island. The representation in Figure 2(c) is more appropriate for mini-roundabouts. Figure 2(d) demonstrates the use of a dummy junction and an additional link to model right turning traffic at a signal controlled junction.

Vehicles enter a network at Origins and leave at Destinations, both of which can be located within or at the boundary of the network to enable internal to internal as well as internal to external journeys, etc, to be modelled. Origins are connected to the upstream ends of one or more links, and more than one origin can be connected to a given link—thus it is possible to represent entries from zones as well as individual origins. Destinations are connected to the downstream ends of one or more links and can therefore also represent zones.

The detailed coding of data for a network is specified in the CONTRAM Userguide (Leonard and Gower (1982)). The method of coding describes the inter-connections between origins, destinations and links. In addition, throughput capacities, link lengths, cruise times (Section 3.5.1) and junction control information are required for each link. The throughput capacity values (Section 3.7.1) are used in the queue calculations. A banned movement code used with the link data is described in Section 3.13.

3.3 TIME VARIATION—TIME INTERVALS

CONTRAM differs from other models in its ability to model explicitly time variation in traffic conditions throughout, for example, a peak period. This is achieved by subdividing the period to be modelled into a sequence of time intervals. For example, in modelling a morning peak from 07.15 am to 10.30 am the time might be subdivided as shown below:—

<table>
<thead>
<tr>
<th>Time interval</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>07.00</td>
<td>07.30</td>
<td>08.00</td>
<td>08.15</td>
</tr>
<tr>
<td>hrs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Uncontrolled links

Give way link

Links entering a junction

Links leaving a junction

Fig. 2(a) Give way junction

Fig. 2(b) and (c) Alternative schemes for modelling roundabouts

Right turning link

Dummy uncontrolled junction

Uncontrolled link

Fig. 2(d) Modelling right turning traffic at signals
The sub intervals, which are the same for all traffic movements (Section 3.4.2), do not have to be the same length. A maximum of 13 intervals is normally allowed by the program.

The flows and queues of vehicles on links are calculated for each time interval in the assignment procedure (Section 3.6) and are carried over in a consistent manner from one time interval to the next.

The selection of suitable time interval lengths is influenced by a number of factors:

(a) Time intervals should be sufficiently short to represent the underlying time variations in traffic patterns adequately but not so short, say less than 10 minutes, that they reflect 'noise' in a particular set of flow measurements.

(b) The intervals should not be so long that average values for flows mask any changes in the underlying variation of flow with time.

(c) In particular there should be an adequate number of time intervals to reflect changes in flow patterns covering the times when demand in the network nears or exceeds capacity on some links.

3.3.1 Time resolution for calculations

All times used in calculations are converted to integer seconds relative to the start of the simulation period in order to minimise program storage requirements.

3.4 REPRESENTATION OF TRAFFIC

The traffic, for each Origin—Destination movement, is handled in groups called 'packets', each packet consisting of an integral number of vehicles. Such packets are increments in the cumulative flows on links. The progression of packets through a network is calculated according to statistical and queueing theory relations between the flow increments, the capacities at junctions, and the journey times from one point to another in the network according to the route taken. CONTRAM is thus a high resolution time-dependent model based on traffic flow interactions, rather than a detailed simulation of individual vehicle trajectories and interactions in real time.

For the purpose of assignment, all of the vehicles in a given packet are assigned to the same minimum journey time route, taking into account the delays encountered at each junction on that route. Multirouting is therefore possible as the routes for different packets travelling from the same origin to the same destination may be different. By calculating the delay at the time when each packet arrives at a junction CONTRAM ensures consistency between the delay calculations and the assignment process through time, and provides a more closely defined representation of traffic behaviour than do models based on traditional transportation modelling.

The grouping of vehicles into packets can be regarded, for assignment purposes, as a process in which the behaviour of one vehicle in a packet is taken as typical of the behaviour of the other vehicles in that packet. This reflects the tendency of drivers travelling between a particular origin and destination, and starting their journeys about the same time, to take the same route, since they will be influenced in their choice of route by similar traffic conditions.

3.4.1 Packet structure

The statistical nature of packets should always be borne in mind. Because a packet represents an increment of average flow for flow and queue calculations (Section 3.7), it should not be regarded as a 'chain' of vehicles moving together through a network, especially when interpreting the effects of queue build up and blocking-back (Section 3.11). Essentially, packets are used, rather than individual vehicles, in order to reduce computation time.

3.4.2 Time varying traffic demand and packet size

The traffic demand on a network consists of a set of fixed Origin—Destination (O—D) movements. The pattern of demand for a particular O—D movement normally varies with time throughout a simulation period—as in Figure 3(a). This variation is approximated by a histogram—Figure 3(b). The data entry therefore takes the form of a time varying flow matrix for each O—D movement—Figure 3(c).

The patterns of demand for each O—D movement are independent of one another and hence may peak at different times during a simulation period. As more than one origin can be coupled to a link it is possible to model multiple movements between the same origin and destination locations by using more than one origin number for the same origin—and similarly for destinations. This flexibility can be used, for example, to differentiate between drivers travelling to work and drivers travelling for pleasure. The modelling allows for independent demands for different classes of vehicles (Section 3.8) and for fixed route vehicles (Section 3.9).

There are two methods for subdividing the vehicles entering the network into packets:

The first (and original form in CONTRAM) assumes fixed packet size for each given O—D movement; the packet size can be different for different O—D movements. The choice of packet size is dependent on the level of demand for the O—D movement and on the size of the time intervals. Ideally the demand during each time interval should be represented by at
Fig. 3(a) Time varying traffic demand from origin A to destination B

Fig. 3(b) Representation of traffic demand as a histogram of flows

<table>
<thead>
<tr>
<th>Time interval</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand flow</td>
<td>30</td>
<td>100</td>
<td>180</td>
<td>200</td>
<td>140</td>
<td>60</td>
<td>20</td>
<td>0</td>
</tr>
</tbody>
</table>

(veh/hr)

Fig. 3(c) Time varying matrix element of traffic demand, from A to B

Packet size for O-D demand A → B = 5 vehs

Fig. 4 Packet entry times corresponding to Fig. 3(b)
least 5 packets, but low demands may dictate fewer packets. For the demand in Figure 3(b), a packet size of 5 vehicles would result in 3 packets for time interval 1 and 10 packets for time interval 4 (Figure 4). For some heavy O–D movements a packet size as large as 20 vehicles may be appropriate, but for very small demands, such as bus movements, a packet size of 1 would be needed. If possible, the packet size for each O–D movement should be chosen so that it is an exact submultiple of the expected demand during each time interval, to avoid discrepancies between the number of vehicles corresponding to the expected demand and the number actually entered by the program.

The second option overcomes this problem by using a variable packet size for each O–D movement; it may vary both within a time interval and from time interval to time interval. The variable packet size algorithm uses the packet size for an O–D movement, specified in the usual way in the O–D demand data (Leonard and Gower (1982), Section 3.2.2), as an upper limit for packet size for that movement. The algorithm calculates the minimum number of packets required to ensure that the packet size is within the upper limit, deducing an ‘average’ packet size which is used to determine the time spacing between packets. Individual (integral) packet sizes are then calculated for each packet entry during a time interval, such that the cumulative number of vehicles from each packet up to and including that packet, approximates the average demand rate for the time interval. This ensures that the totals of expected and actual vehicles are in agreement at the end of each time interval within 1 vehicle ie minimising rounding errors.

The choice of method is optional—the variable packet size option gives the more accurate representation but the fixed packet size option can be used with existing data sets to allow comparisons with previous results.

The assignment process (Section 3.6) requires that all vehicles reach their destinations before the end of the simulation period. A final (clearance) interval with zero demand must therefore be included, of sufficient length to ensure that all queues are dissipated and all traffic movements completed within the simulation period.

3.4.3 Packet entry time onto a network

The packets for a given O–D movement enter the network at equally spaced intervals of time through each time interval—the number of packets in a time interval being determined by the level of demand flow and the packet size. The inter-packet time is given by

$$t_i = \frac{(3600 \times p_i)}{q_i} \text{ seconds}$$

where $p_i$ is the packet size (vehicles) and $q_i$ is the flow (veh/hr) in the $i$th time interval. The entry time of the first packet for the O–D movement in the first time interval is given by

$$t_{entry} = \frac{1}{2} t_1 \text{ seconds}$$

after the start of the interval. Entry times are rounded and stored by the program as integer values.

3.5 JOURNEY TIME ALONG A LINK

The journey time for a vehicle (packet) travelling along a link is modelled as the sum of two components: a cruise time along the link and the time delayed at the downstream stopline. The breakdown into the two components is illustrated in Figure 5 which shows the trajectory (time/distance diagram) for vehicles travelling along a signal controlled link. CONTRAM, in common with other traffic models, calculates queueing delays for a ‘vertical’ queue at the downstream stopline. The time spent delayed on the link is derived from the vertical queue which, in earlier versions, was assumed to vary linearly through a time interval between the initial queue at the start of the time interval and the final queue at the end (Section 3.7), but in CONTRAM5 is calculated separately for each arriving packet. Allowance is made for the physical length that the (vertical) queue would occupy along a link when considering blocking-back effects between junctions (section 3.11).

3.5.1 Cruise time

The cruise time along a link is the unimpeded or free run time taken by a vehicle travelling at the average speed of traffic along the full length of the link excluding any delay time due to queueing at the downstream stopline. It includes boundary or interference effects due to vehicles parking at the side of the road, regular obstructions due to vehicle movements at bus stops and vehicles delivering goods, road gradient and bendiness, and geometric delays due to the need to slow down or stop at junctions in the absence of other traffic. Cruise times are best obtained by direct measurement using a vehicle travelling at the same average speed as other vehicles through a network at a time which is as close as possible to the conditions being modelled but excluding queueing effects. Such measurements may be difficult for links on which there is persistent queueing. In these cases cruise times may have to be estimated by extrapolation from measurements along part of the link or based on assumed ‘reasonable’ speeds and the length of the link. The latter method is used when estimating cruise times for links which have still to be built. Separate calculations can be performed to estimate geometric delays, using the methods in Burrow (1987), Semmens (1985 (a) and (b)).

The cruise time along a link is the same for all vehicles of the same class. Allowance can be made for slower moving vehicles, such as buses and heavy goods vehicles, by the use of multiplying factors with
3.5.2 Delay at a stopline

The delay component of the journey time, for a packet travelling along a link, is the time taken to discharge the (vertical) queue of vehicles encountered by the packet at the time that the packet reaches the downstream stopline after travelling the full length of the link at its cruise speed—see Figure 6.

A packet enters the upstream end of a link at time $t_u$ and arrives at the stopline at time $t = t_u + \text{cruise time}$. The queue $L(x)$ encountered by the packet is calculated using the methods described in Section 3.7 and Appendix A, assuming that total arrivals and capacity are uniformly distributed during the time interval in which the packet arrives.

The delay time for the packet on the link (i.e., the time to move through the queue of vehicles $(L(x))$ and emerge from the junction) is

$$t_{\text{delay}} = \frac{(L + 1)}{M} \times 3600 \text{ seconds}$$

where $M \text{ (pcu/hr)}$ is the throughout capacity rate for the time interval taking into account the type of junction control for the link.

If the journey time for a packet spans more than one time interval then cruise time and delay for the packet are divided between time intervals in the same proportion as the division of journey time. Figure 7 illustrates the method.

The most recent version of CONTRAM—version 5—allows speed/flow relationships to be used instead of a fixed cruise time.
Time interval (t)

Fig. 6 Queue and delay calculation — linear variation in queue length during a time interval

Since the class of a vehicle and packet size are identified in the route information, stored for each packet journey (section 3.6), the cruise time and delay time can be accumulated separately for each class of vehicle for each time interval.

3.6 ASSIGNMENT AND ITERATION

Packets, which are the unit of traffic movement in CONTRAM, are assigned to their minimum journey time routes through a network by an iterative procedure—Figure 8. After the initial loading iteration the sequence of operations for assigning each packet is:

(i) Remove the increment of flow, due to the packet, from the flows stored for each link (in the appropriate time intervals) for the route taken by the packet in the previous iteration.

(ii) Recalculate the queues on links affected by the previous route of the packet.

(iii) Assign the packet to its new minimum journey time route—the new route may be the same as the one during the previous iteration.

(iv) Add the flow due to the packet to the links on the new route and recalculate the queues affected by the new route.

(v) Take next packet and repeat steps (i) to (iv).

In the first iteration a packet route file (a 'scratch' file—Appendix E) is set up in which the traffic demand and route information is stored on a packet by packet basis in the time order of entry for the packets onto the network. For each packet the route file contains the packet entry time, its origin and destination, class of vehicle and packet size, and the packet route information. The packet route information consists of the entry time interval and link number for each link along the packet's route. Each packet is assigned to its quickest journey time route (or fixed route if appropriate)—the sequence of calculations being the same as for the second and subsequent iterations although, of course, in the first
The updating of flows and queues on links and the recalculation of delays for the reassignment of each packet is made for the appropriate time intervals during which a packet travels along each link of its journey. In this respect CONTRAM is believed to be unique in its ability to assess current traffic conditions along routes as each packet moves through the network.

The iterative procedure is continued until a satisfactory state of convergence has been reached. Ideally this exists when all packets are re-assigned to the same routes in consecutive iterations. However, exact convergence is not necessary for practical applications of the program. 'Practical' convergence...
Read Network data
Read Traffic demand data
and set up Packet Route file
Load Traffic on to network (1st iteration)

Take 1st packet

Take next packet

Subtract flow on links, due to packet, from previous route

Recalculate queues on links affected by previous route

Assign packet to new minimum journey time route (taking into account delays encountered by packet)

Add flow due to packet to links on new route and recalculate queues affected by new route

Any more packets?

More iterations?

Yes

No

Yes

No

END

Fig. 8 Packet assignment procedure in CONTRAM
is assessed from changes, between iterations, of network totals of journey times and distance travelled and changes in link flows for each time interval. These parameters are listed at output for inspection. Criteria for convergence for a given network are found by experience—usually between 5 and 10 iterations are adequate for practical purposes.

The iterative process is in some ways analogous to the ‘learning’ process by which drivers become familiar with traffic conditions in a network with repeated use over a period of time and choose their routes accordingly.

3.6.2 Quickest route algorithm

The quickest route algorithm is of the ‘once through’ tree building type (Steenbrink (1974)). The process can be regarded as advancing an exploration envelope, defined by extending (in time order) the ends of chains outwards from the origin to nodes in the network, until the destination is reached by one of the chains, such that no other chain can reach it in a shorter time (Figure 9(a) and 9(b)). The mechanism is described in Appendix B.

Note:—fixed route vehicles are identified before the assignment procedure is entered and such vehicles are sent along the predefined links of their routes.

3.7 LINK QUEUE CALCULATIONS

The queue on a link at a given time of day will, in real life, fluctuate from one day to the next, even if the average flow and capacity for the link follow the same patterns each day. If the detailed vehicle—vehicle interaction rules were known such stochastic effects could, in principle, be modelled by a vehicle by vehicle simulation. However, such modelling would require many repeated runs and a statistical analysis to establish statistically reliable average queueing lengths and delays. The flow rates on links predicted by CONTRAM represent statistical average values for each time interval; the flow rates are assumed to be constant during each time interval although the level will normally vary from one to the next. The statistically average nature of the demand matrix, and of the flows and delays predicted by CONTRAM, should be borne in mind when interpreting the flow and delay values on a day by day basis for design purposes—the degree of variation which occurs in practice is discussed by Kimber and Daly (1986). When calculating the queue length it is assumed that the initial queue on a link at the start of a time interval is the same as the final queue from the previous interval.

Time dependent queueing formulae developed by Kimber and Hollis (1979) and Kimber, Summersgill and Burrow (1986) are used to estimate the queue at any point in a time interval. The formulae take into account:

- the type of link, ie, link control characteristics;
- the initial queue on a link at the start of the time interval;
- the vehicle arrival and departure (throughput capacity) rates;
- randomness in the arrival and departure patterns;
- the length of the time available for the queue to develop which may be part or all of the time interval.

The formulae for each type of link are described in Appendix A.

3.7.1 Throughput capacity

A principal input parameter for queue calculations is the throughput capacity. It is defined as the average flow rate at which vehicles discharge from a queue on a link. Throughput capacity values can either be estimated, using road layout information, or measured on site. Where practicable, measurements give the more precise estimate and are preferable; they should be made during the period to be modelled so as to allow for site specific conditions and for daylight or darkness as appropriate (Burrow (1986)). Throughput capacity is expressed in pcu’s (passenger car units) per hour which take account of the mix of different classes of vehicle. The formulae and methods of measurement depend on the type of link:

Signal controlled links. The throughput capacity is the product of the ‘saturation flow’ and the fraction of the cycle time for which the signal is green, where the saturation flow is as defined by Kimber, McDonald and Hounsell (1985): throughput capacity is calculated within the program from the saturation flow. Site measurements of saturation flow are made by measuring the flow rate at which a queue discharges across a stopline after the signal changes to green. The measurements require a sufficiently large queue to form for vehicles to discharge at a steady rate over a reasonable length of time. The basic method for measurement is described in Road Note 34 (Road Research Laboratory (1963)). The method has been automated, using a hand held micro computer (Wood (1986)), so that estimates of saturation flow can be obtained immediately at the time of measurement. Measurements should be repeated for at least 10 cycles, each with a minimum of three 6 second periods with queueing vehicles, to ensure that reliable averages are obtained.

Formulae for calculating saturation flow values from the geometric details at a stopline have recently been developed and are described in Kimber, McDonald and Hounsell (1986).
Current quickest route to Destination D (time $t_D$) is $O \rightarrow B \rightarrow G \rightarrow D$

Time at $J$, $t_J > t_D$ — no further extensions to be considered from this node

Time at $A$, $t_A < t_D$ — consider further extensions — see Figure below

Time at $F$, $t_F < t_D$ — consider further extensions — see Figure below

Fig. 9(a) Example of tree building algorithm — current exploration envelope

Extensions from $A$:

- to $F$: $t_F$ (via $AF$) $> t_D$ (via $BF$) — reject $AF$
- to $K$: $t_K < t_D$ — $K$ is valid extension of envelope

Repeat process from $F$ and $K$

Fig. 9(b) Example of tree building algorithm — extension of exploration envelope
Give-way links. Unlike the conditions for signal controlled links, where vehicles have clearly defined periods for crossing stoplines, all vehicles must slow down or stop on a give-way link to yield to traffic on the major road. The level of flow on the major road controls the rate of discharge from the give-way link. The throughput capacity for such links—the discharge rate from a stable queue—can be measured along with the flows on the major road. Measurements need to cover the full range of flow on the major road and require sufficient traffic to form queues on the give-way link. The process, which is described in Semmens (1985(a) and (b)) is more complicated than for a traffic signal junction, but again provides a valuable improvement in accuracy when it is practically possible.

In CONTRAM it is assumed that the throughput capacity varies linearly with the flow on the controlling links on the major road:

\[ Q_s = \max \{ q_s - f \times q, 60 \} \text{ pcu/hr} \]

where \( Q_s \) is the throughput capacity for the give-way link (pcu/hr), \( q_s \) is the maximum capacity for the give-way link (pcu/hr), \( f \) is the throughput capacity slope (non dim) and \( q \) is the sum of the controlling flows on the major road (pcu/hr).

The cut-off at 60 pcu/hr reflects the fact that many drivers force their way into a stream of traffic if the delay on reaching the give-way line is longer than about one minute. The formula is based on extensive research by TRRL (Kimber and Coombe (1980) and Kimber (1980)) and is more reliable for representing traffic conditions in Great Britain at give-way junctions than the use of formulae based on gap acceptance theories.

Uncontrolled links. Site measurements of throughput capacity are not practicable as queues rarely form at the end of uncontrolled links unless there is blocking-back from a downstream junction. Throughput capacity values are therefore normally calculated using the saturation flow formulae for signal controlled links (Kimber, McDonald and Hounsell (1986)), using the measured width available to the stream as an equivalent stop line width.

3.8 CLASSES OF VEHICLE AND PCU EQUIVALENTS

Three classes of vehicle can be modelled—these are usually cars, buses and lorries (heavy goods vehicles) denoted by C, B and L respectively. Allowance is made for the effect of each class of vehicle by use of ‘passenger car unit’ (pcu) equivalence factors (Kimber, McDonald and Hounsell (1985)) to represent the effect on the stop line capacity of the presence of vehicles of the various classes. It is possible to use the B and L classes to represent other types of vehicle if a particular class is not required for its normal use. For example a pcu equivalent factor of 1.0 for class L vehicles could be used to identify the movements of taxis in a network, without otherwise influencing the calculations.

Arrival flows, time spent and distance travelled on each link for each time interval are identified separately for each class of vehicle in the output as well as the total time spent travelling and delayed, total distance travelled and total fuel consumption for each time interval.

Allowance can be made for the slower speeds along links of the larger vehicles, such as buses, by applying multiplying factors to cruise times for class B or class L vehicles. These effectively increase the cruise times for the vehicle classes along all links of the network but do not affect the delays calculated at the stopline.

The storage capacity on a link (used in the blocking-back procedure—section 3.11) is expressed in pcu’s. On links where there are long stationary queues the storage can be obtained by observation but if no figure is entered in the input data for CONTRAM then the program estimates a storage capacity from the saturation flow value for the link (which allows the numbers of lanes to be inferred), and the length of the link, assuming that 1 pcu occupies a 5.75 m length of road space. A correct estimate of storage capacity is only important where blocking back is likely to occur. For critical links the storage capacity should be measured.

3.9 FIXED ROUTE VEHICLES (BUSES)

Certain vehicles, such as buses, are constrained to travel along fixed routes through a network. The fixed routes are defined in the input data as series of prescribed links. The assignment procedure for a fixed route packet is the same as for other packets (section 3.6) with the exception that the tree building algorithm (step iii) is bypassed as the ‘new’ route is already defined. The flows and queues affected by the packet on the fixed route are updated as before. This procedure ensures that fixed route vehicles are subjected to the correct delays at junctions as would be experienced by other vehicles. Thus, CONTRAM does not ‘pre-load’ fixed route vehicles onto a network before assigning other vehicles, ie it does not give them an (unrealistic) pre-emptive priority.

It is possible to use selected fixed route vehicle movements in conjunction with the ‘point-to-point O-D speeds’ (section 3.14) to examine the effects of traffic management schemes on journey speeds along preselected routes.

3.10 SIGNAL CONTROL PLANS

Signal control is essentially modelled in CONTRAM by fixed time plans, each junction being treated as if it were an isolated junction. Allowance is also made
for representing the effects of linking between signals (section 3.10.1) at adjacent junctions, and there are facilities to produce 'optimal' signal timings for individual junctions between iterations, based on the flows in the preceding iteration.

Three types of plan are available for specifying signal settings:

Fixed cycle and Fixed split FC/FS—Cycle and green times are specified for all iterations
Fixed cycle and Optimised split FC/OS—Green times are recalculated for 2nd and subsequent iterations
Optimised cycle and Optimised split OC/OS—Cycle and green times are recalculated for 2nd and subsequent iterations.

The optimised signal timings are based on methods developed by Webster and Cobbe (1966) to equalise saturation on the busiest arms at a junction. The flows used for the calculations are the flows, for the appropriate time intervals, stored by the program at the end of the previous iteration (As there are no 'preceeding' flows for a first iteration an option is available for pre-setting timings for the first iteration if optimisation is to be used). Although CONTRAM does not model vehicle actuation of signals as such, the OC/OS method of optimisation gives results similar to vehicle actuation during periods when the arms of a junction are saturated, which are likely to be the most important for traffic management purposes.

The cycle and split times are used in the queue calculations (section 3.7) and apply to the average conditions on a link over the relevant time interval.

Some issues concerning the interaction between optimised signal settings and the assignment are discussed in Appendix C.

3.10.1 Allowance for linked signals

The principal purpose of coordinating signal settings in a network is to produce optimised settings which minimise the total delay to vehicles over the network as a whole; settings for use in CONTRAM, may be calculated using programs such as TRANSYT9 (Vincent, Mitchell and Robertson (1980)). The net effect of coordination, for drivers, is that delay tends to be reduced at signals along routes which carry similar to vehicle actuation during periods when the OC/OS method of optimisation gives results

CONTRAM normally models each junction as if it were isolated; recent improvements in the modelling allow for the effects of signal co-ordination between junctions—the new modelling does not simulate cyclic flow profiles as such but allows for their overall average effect.

It should be noted that, in the context of optimising signal timings over a network, an assumption of minimum journey time in the assignment process for individual packets does not imply that the total journey time for all vehicles in the network will be a minimum. CONTRAM can be used to establish system 'optimum' conditions by re-running the program with different signal settings on a trial and error basis.

3.11 BLOCKING-BACK

Blocking-back occurs when the queue of vehicles on a link extends back to the previous junction thereby ‘blocking’ free access to the link from the upstream links. The net effect is to reduce the throughput capacity of the upstream links for as long as the blocking-back condition persists. In practice blocking-back can either be spasmodic, arising from isolated incidents along a link, such as a vehicle breaking down or parking, which only temporarily interrupt the flow of traffic, or due to persistent oversaturated demand on the link. CONTRAM models the latter which is more likely to occur on a regular day to day basis. Spasmodic blocking-back incidents tend only to last for relatively short periods and, as they only occur irregularly from day to day, are less likely to have a significant effect on a driver’s choice of route.

Before describing the operation of the blocking-back mechanism in CONTRAM it is necessary to define two terms—the ‘current’ and ‘usual’ traffic patterns. CONTRAM updates and stores flows and queues for each link at the time of assignment of each packet. Immediately after the assignment of the P'th packet entering the network the traffic pattern over the network consists of two parts: flows and queues on links due to packets 1 to P, which have been assigned during the current iteration, ie the 'current' values, and flows and queues due to the combined effect of packets 1 to P (already assigned in the current iteration) together with packets (P+1) onwards from the previous iteration. The combined patterns are called the 'usual' pattern for the time interval. The two sets of patterns are stored separately. Clearly the 'current' and 'usual' patterns for each link become identical at the end of an iteration and the 'current' patterns during each time interval have the property that they are (monotonically) increasing during each time interval.

The basis of the blocking-back mechanism is as follows: because the CONTRAM model is based on vertical queueing at a stopline, the onset of blocking-back on a link is detected by comparing the equivalent length of the queue, expressed in passenger car units (pcu's), with the number of pcu's which can be stored on the link. The comparison is made immediately after each packet has been assigned to its new route, for each of the links in turn along the packet's route working backwards from the destination to the origin. If the queue on a link calculated, using the 'current' arrivals, is found to
exceed its storage capacity then the throughput of the upstream link is reduced to match the sum of the initial queue on the link and the 'current' arrivals at the stopline, for the rest of the time interval for the remainder of the iteration.

The reduction in throughput capacity is not carried forward to the next iteration, when the whole reassignment process is repeated, as this could erroneously label a link as being full, whereas it might not carry so much traffic in the next iteration because of redistribution of traffic to other links.

The blocking-back mechanism just described is slightly modified in the model in order to avoid sudden effects on the upstream throughput capacity which is first reduced when eighty percent of the downstream link storage capacity is reached, and linearly decreased until the link is full.

The method for reducing throughput capacity on an upstream link when blocking-back occurs, does not act to prevent vehicles from continuing to be assigned along the blocked link. This is a reflection of real life conditions in which drivers may not have viable alternative routes and are therefore prepared to accept any inconvenience due to blocking-back; such conditions are only likely to arise in overloaded networks with limited route choice. A consequence, for CONTRAM 5, of vehicles being assigned to use a link after blocking-back has been identified is that the theoretical queue on the link can exceed the storage capacity for the link. Delays for vehicles using the link take this into account, ie there is no double counting of delay between queues on adjacent links. The net result is that the overall delays along the route of a vehicle are correct (within the assumption of minimum journey time), but some of the delay attributed by CONTRAM to vehicles on the blocking link is actually incurred physically on the upstream feeding link.

3.12 FUEL CONSUMPTION

The fuel model in CONTRAM takes into account fuel consumed at steady cruise speed, additional fuel consumed while accelerating (and any fuel saved when decelerating), together with fuel consumed while stationary or moving up in a queue. The parameters of the fuel model can be input separately for each of the three vehicle classes.

3.13 BANNED TRAFFIC MOVEMENTS

A feature common to many traffic management schemes is the restriction of specific vehicle movements, eg bus only movements through pedestrian areas or bans to heavy goods vehicles. It is desirable that the effects of banning movements can be examined without the need to re-code a network. This is achieved in CONTRAM by the use of a single character code, entered with the link data, to identify selected class or classes of vehicle. The banned vehicle code for a link is examined in conjunction with the vehicle type code during the assignation procedure for each packet—a link cannot form part of a route if the code prohibits entry for that vehicle type onto the link. The banned code applying to a link can be set selectively for one or more classes of vehicle and for particular turning movements.

3.14 POINT-TO-POINT O—D SPEEDS

A parameter which allows for the geographic distance between an origin and destination, is the speed based on 'crow-flight' distances. A 'point-to-point' speed, for a given O—D movement, is defined as the 'crow-flight' distance (or straight line distance) divided by the average journey time for all the vehicles travelling between the origin and destination.

The point-to-point speeds enable changes in journey times to be compared more easily both for the same O—D movement and with other O—D movements, particularly for cases where the crow-flight distances are considerably different in size.

The point-to-point speeds are calculated for each time interval for selected O—D movements. The 'crow-flight' distance specified in the input data, can be the geographic straight line distance or, more practically, the length of the most realistic minimum distance route.

The point-to-point speed calculation can be used with real distances for vehicles travelling along fixed routes (section 3.9) to obtain speeds related to 'real' journeys, bearing in mind the statistical problems involved when making comparisons.

3.15 NEW FACILITIES IN CONTRAM 5

New facilities in CONTRAM which have been introduced in CONTRAM 5 (October 1988) are:

- Speed/flow relationships for high-speed roads and buffer networks. (Speed/flow relationships are used in place of cruise time values for links)
- Modelling the effect of signal co-ordination
- Automatic method of setting up packet sizes, and variable packet sizes
- Choice of minimum journey-time or behavioural cost assignment
- New model of fuel consumption
- Ability to vary saturation flow or capacity between time intervals
- Improved facilities for changing network parameters between runs
More efficient assignment algorithm

Compatibility with existing data sets.

A description of the new facilities will be given in a subsequent report.

4 INPUT AND OUTPUT

The data inputs and outputs for CONTRAM are described in detail in the Userguide to CONTRAM and its amendment (Leonard and Gower (1982)). For completeness of the present report they are briefly summarised in Appendix D together with comments on new facilities in CONTRAM 5 which have been introduced since the issue of the Userguide.

4.1 USER-FRIENDLY DATA-ENTRY AND POST-ANALYSIS SYSTEMS

Two interactive programs have been produced to assist with the data entry and the analysis of the output for CONTRAM. The programs are primarily designed to run on IBM-compatible micro-computers using a system of menu driven screens.

The User-Friendly Data-Entry System for CONTRAM (UFDESC) allows free format entry of data, in response to line by line prompts, the program entering the data in the correct format and field position. It carries out a number of checks on the entries to identify logical errors and values which are outside predefined ranges. The program incorporates a system for calculating saturation flow values using geometric data, and a simple procedure for setting up the time varying flow profiles for the O-D demand matrix. Use of UFDESC has shown that the logical checks on the data, together with error detection procedures in CONTRAM, have minimised the number of errors in setting up the data input files needed for a correct run of CONTRAM. UFDESC can be used to modify existing data sets as well as for the creation of new sets.

The normal CONTRAM 'Results' file contains a considerable amount of detailed link by link and network summary information, for each time interval, which often needs to be examined selectively when assessing a scheme and to provide the traffic inputs for environmental pollution models. The User-Friendly Post-Analysis System for CONTRAM (UFPASC) has been developed to reduce the effort required to extract specific data from the results file and to carry out selected comparisons between results for up to 5 different runs of CONTRAM. The outputs from UFPASC can be stored on file for printing at a later stage and the set of instructions used for extracting information from one set of results can be stored for use in a similar analysis on other sets.

UFPASC also incorporates systems for analysing the vehicle route information stored in the 'Routes' file and provides graphical outputs for selected parameters in the form of histograms or annotated network diagrams.

5 PROGRAM STRUCTURE AND OPERATION

The CONTRAM program is written in FORTRAN IV and consists of a main program CONTRM and six subroutines CONTRL, INNET, INFLOW, RMODEL, ROUTPT and TURMOV. The main program CONTRM serves to transfer control from one subroutine to another. The operation of the program, outlined in Figure 11, is described in Appendix E.

5.1 MAINFRAME AND MICRO VERSIONS, NETWORK SIZE AND RUN TIME

The original version of CONTRAM was written for an ICL 470 mainframe computer. In general only small modifications are needed to the FORTRAN source to run the program on other computers—changes are normally due to the use of different compilers or system library calls and routines. The mainframe version has been successfully run on ICL, IBM, VAX and other computers. Versions exist to run on IBM compatible personal computers with 512K or more bytes of memory and with or without an 8087, 80287 or 80387 maths co-processor.

The CONTRAM 5 source code is identical for both mainframe and PC versions, with the exception of certain machine-dependent subroutines. The maximum size of network that can be accommodated depends on the memory available. On a PC with 640K bytes of memory networks of around 300 links can typically be handled, though in individual cases the maximum size depends also on the number of time intervals and O-D movements. Use of CONTRAM on a network of 490 links is reported by Coombe, Annesley and Goodwin (1983) and networks of over 500 links have been run successfully.

Run time for CONTRAM depends on the size of network (number of links), traffic demand (number of packets) and number of iterations. The run time increases approximately linearly with both the number of packets entering a network and with the number of iterations. The increase in run time for increase in the number of links is non-linear. This is due to the greater number of combinations of links which need to be examined in the tree building process for determining the shortest journey time route (section 3.6.2). However the amount of increase in run time is very dependent on the local network configuration (connections between links) and on practical limitations of route choice. Examples of run time for different sizes and types of network...
### CONTRAM 5 Run Time

<table>
<thead>
<tr>
<th>Number of links</th>
<th>CONTRAM 5 Run Time (CYBER 720/815 cpu seconds per iteration for 1000 packets)</th>
<th>Type of network</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>14</td>
<td>Small, no signals, limited route choice.</td>
</tr>
<tr>
<td>32</td>
<td>45</td>
<td>Small, multiple route choice (hypothetical network—Userguide example).</td>
</tr>
<tr>
<td>120</td>
<td>37</td>
<td>Medium.</td>
</tr>
<tr>
<td>150</td>
<td>58</td>
<td>Medium/large, close to saturation.</td>
</tr>
<tr>
<td>190</td>
<td>94</td>
<td>Medium, busy, multiple route choice.</td>
</tr>
<tr>
<td>232</td>
<td>75</td>
<td>Large, undersaturated.</td>
</tr>
</tbody>
</table>

are shown above for runs on a CDC Cyber 720 computer; for comparative purposes times have been normalised for 1 iterative cycle and 1000 packet movements.

Run times for personal-computers using twin floppy discs are considerably longer than for personal computers using hard discs due to the need to transfer data from disc to disc. The use of the maths co-processor also reduces run time. For example run time for the CONTRAM Userguide example, containing 32 links, is reduced by about a factor of 4 from 32 minutes (for 10 iterations) to 8 minutes.

### 6 SUMMARY AND CONCLUSIONS

CONTRAM is a computer based traffic assignment model which has been developed for use in the design of traffic management schemes in urban areas. Given the traffic demand between origins and destinations for a network it predicts routes of vehicles, and flows and queues on links. It is a capacity restrained model which takes into account the interactive effects between junctions over a network. The outputs from CONTRAM can be used for economic assessment and traffic engineering purposes, and for comparing the effects of traffic management schemes on point-to-point O—D speeds.

This report describes the basic structure and mechanism of CONTRAM. Vehicles are normally assigned to their minimum journey time routes through a network. The model caters for a full range of junction types, 3 classes of vehicle (usually cars, buses and lorries), fixed route vehicles, banned vehicle movements, different types of signal plan; and it models the effect of linking between signals; it predicts turning movements, estimates fuel consumption; and takes into account the effects of blocking-back between junctions.

Three types of output are produced: a ‘Results’ file which contains detailed network summaries and link by link data for economic assessment and traffic engineering purposes, as well as as ‘point-to-point’ O—D speeds for assessing whether a traffic management scheme benefits the journey times for particular O—D movements at the expense of others; a ‘Routes’ file which provides vehicle route data for further analysis to enable more detailed information to be obtained on journey patterns over a network; and a third ‘UFPASC’ data file for input to the User-Friendly Post-Analysis System for analysing the CONTRAM output.

Well-established time dependent queuing theory, which is also used in ARCADY, PICADY and OSCADY, is employed. The assignment process, using a ‘packet’ structure to handle vehicle movements, allows vehicles travelling between the same Origin and Destination to handle vehicle movements, allows vehicles travelling between the same Origin and Destination to handle vehicle movements, allows vehicles travelling between the same Origin and Destination to handle vehicle movements.

In conclusion CONTRAM is a high resolution, time dependent, assignment model which predicts vehicle routes and the time variation in flows, queues and delays on links for traffic engineering purposes. It models interactive effects between junctions and the build up and decay of congestion as it varies through time throughout a peak period. An important feature is that the delays calculated along the routes of vehicles, in the assignment process, are consistent with the junction delays over the network; this is considered to be necessary for the proper economic assessment of traffic management schemes.

### 7 ACKNOWLEDGEMENTS

The work described in this report was carried out in the Traffic Management Division (Division Head: Mr M Grimmer) and Traffic Safety Division (Division Head: Dr R M Kimber) of the Traffic Group of TRRL. The authors are grateful for valuable feedback from users of the program.
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APPENDIX A

FORMULAE FOR LINK QUEUE CALCULATIONS

Queueing at road junctions is a time-dependent phenomenon. During peak periods, when congested reassignment is important, traffic flows are frequently very close to the capacities of junctions. In such circumstances neither steady-state queueing theory, which predicts delays tending to infinity, nor deterministic queueing theory, which predicts zero delay, provide a realistic basis for estimating queue length.

A time dependent queueing theory has therefore been developed and tested (Kimber and Hollis (1979), Kimber, Summersgill and Burrow (1986), Burrow (1987)), to reflect the stochastic time-dependent nature of the queueing process. It takes as asymptotic limits, the general steady-state Pollaczek-Khintchine queueing formula at very low traffic loadings, for well under-saturated conditions, and the
deterministic formula when capacity for a link is substantially exceeded. The formulae implemented in CONTRAM are the same as those in the programs ARCADY 2, PICADY 2 and OSCADY (see Semmens (1985(a) and (b)), Burrow (1987), Kimber and Daly (1986), Kimber and Hollis (1979)) and are implemented for the three types of link as follows.

The average queue, $L(t)$, after time $t$ into the current time interval is:

1. Uncontrolled link
   
   $L(t) = L_d$

2. Give way link
   
   $L(t) = L_r (0, 1, 1)$

3. Signalised link
   
   $L(t) = L_r (0, 0.6) + L_p$

where

$L_d$ is the deterministic queue function

$L_r (l, K)$ is the random queue function with vehicle-in-service parameter $l$ and randomness parameter $K$

$L_p$ is the mean phase queue at a signal

$L_m$ is the maximum (end-of-red) queue at a signal

Also $L_m$ is the maximum (end-of-red) queue at a signal

These functions are defined in the following way:

Let, $L_0$ be the random-and-oversaturation queue at the end of the previous time interval, $\lambda$ be the capacity for the current time interval, $\rho$ be the demand flow/capacity ratio for the current time interval, $t$ be the time after the start of the current time interval at which the queue is to be evaluated

Then, the deterministic queue is given by:

$L_d = \max \left\{ L_0 + (\rho - 1) \mu t, 0 \right\}$

The steady state equilibrium queue is given by:

$\ell = \frac{L_0 + K_0^2}{1 - \rho}$

Now define $F$ as a queueing function given by:

$F(x) = F(x, l, K) = \frac{-B + (B^2 - 4AC)^{1/2}}{2A}$

where

$A = \mu - \lambda - \mu l + 1$

$B = (1 - \rho)(\mu l )^2 + (2\rho(K - l) - l)\mu x$

$C = -\rho (l(K - l) + l)(\mu x)^2$

and $x$ is a time variable

There are a number of cases depending on the values of $\rho$ and $L_0$:

(a) If $L_0 = \ell$ then $L_r = \ell$

(b)(i) If $\rho > 1$, or $\rho < 1$ and $\alpha < L_0 < \rho$ then let $L^* = L_0$

(b)(ii) If $\rho < 1$ and $\rho < L_0 < 2\ell$ then let $L^* = 2\ell - L_0$

in either case (b)(i) or (b)(ii)

Let $t_c = \frac{L^* + l + 2\rho(K - l) + (l^* + l)^2 + 4\rho^2(K - l)^2)}{2\rho} [\rho(l^* + l + \rho(K - l) - l^*)]$

then, in case (b)(i) $L_r = F(t + t_c)$

in case (b)(ii) $L_r = 2\ell - F(t + t_c)$

(c) If $L_0 > 2\ell$ then, if $K \neq 1$

Let $w = \frac{\mu}{2} [(L_0 + l^2 + 4\rho_0(K - l)^2)(1 - L_0 + l - 2\rho_0(K - l))]}{2(K - l)}$

or, if $K = 1$

Let $w = \mu \left( \frac{L_0}{L_0 + 1} - \rho \right)$

and let $t_c = \frac{L_0 - 2\ell}{w}$

then, if $t < t_c$ $L_r = L_0 - wt$

if $t > t_c$ $L_r = 2\ell - F(t - t_c)$

Similarly $L_0$ and $L_m$ depend on the value of $\rho$.

Define, $c$ as the cycle time

$\lambda$ as the proportion of the cycle which is effectively green.

There are again a number of cases depending on the value of $\rho$:

(i) If $\rho > 1$, then $L_o = \mu(1 - \lambda)c/2$

$L_m = \mu(1 - \lambda)c$

(ii) If $\rho < 1$ and $\rho$ was not at or above 1 for the previous segment,

then $L_p = \frac{\rho \mu(1 - \lambda)^2 c}{2(1 - \lambda)}$

$L_m = \frac{\rho \mu(1 - \lambda)c}{2}$

(iii) if $\rho < 1$, but $\rho$ was at or above 1 for the previous segment,

then let $t_0 = \frac{(L' - \rho c)}{\mu(1 - \rho)}$

if $t_0 > t$ then,

$L_0 = \mu(1 - \rho)c/2$

$L_m = \mu(1 - \rho)c$

and the following segment is treated as if $\rho$ had been at or above 1 for this segment.

If $t_0 < t$ then,

$L_0 = \mu(1 - \rho)c/2$

$L_m = \mu(1 - \rho)c$

and $t_0 + \rho(t - t_0)$

In CONTRAM individual vehicles may be present in the queue during more than one time interval and may be subject to different discharge rates in these time intervals because the capacities are different. The total queueing delay is therefore calculated in a piecewise manner. The results are summarised as follows:

If $\bar{p}$ is the average capacity in the period during which the vehicle remains in the queue:
For an uncontrolled link
\[ D = \frac{L}{\mu} \]

For a give-way link
\[ D = \frac{L + 1}{\mu} \]

For a signalised link
\[ D = D_r + D_p \]
where
\[ D_r = \frac{L_r + 0.5}{\mu} \]
\[ D_p = \frac{L_p(1-\lambda)c}{L_m} \]

**APPENDIX B**

**QUICKEST ROUTE ALGORITHM**

The route between an origin and a destination is constructed by assembling 'chains' of sequentially connected links outwards from the origin. The algorithm considers, in time order sequence, the extension to the end link of a chain. This extension is checked to see whether it has been reached before, at an earlier time, on a previously established chain. If the time is earlier than the entry time recorded previously for the link under examination, then a flag is set to identify its connection to its feeding link, on the chain, and the connecting flag on the previous chain is cancelled. A check is also made to see whether the entry time to the link is greater than or equal to the time already established to reach the destination—if the destination has already been reached in a shorter time then no further chains are constructed from that link thereby reducing unnecessary extensions to chains which would otherwise be considered. The process is repeated examining in turn the extension to the next chain taken in time order sequence. Eventually the process establishes the shortest journey time to the destination, and the route is identified by working backwards between connected links, which have been flagged, to the origin. It can be shown (Steenbrink (1974)) that this algorithm leads to a unique solution for the construction of the shortest journey time route. In pseudo code the algorithm has the following form:

- **PERM (I)** holds a permanent list of links to which the quickest time has already been found.
- **TEMP (J)** holds all of PERM plus the links immediately downstream of the links in PERM.
- **TIME (J)** holds the earliest times to reach the upstream end of the link J.
- **FLAG (J)** holds, for each link J, the number of the upstream link feeding J by the current quickest route to J

MARK (J) indicates, for each link J, that it is not to be considered again.

All these stores are initially empty, except **TIME (D)** for the destination which is set to a very large number.

**START**

For each link K which the packet can enter from the origin add K to TEMP, set **TIME (K)** to the packet entry time onto the network, and set **FLAG (K)** to indicate its connection to the origin.

**REPEAT**

Find a Link L in TEMP which has not been MARKed and has the minimum value of **TIME (L)** where **TIME (L) < TIME (D)**.

Add L to **PERM**

Set **MARK (L)** as having been dealt with

FOR each link M which the packet can reach from L

DO: BEGIN

Calculate the time t when the packet would reach the upstream end of M from L

If M is already in TEMP, and **TIME (M) < t**

THEN: no action

ELSE: BEGIN

IF M not in TEMP

THEN: add M to TEMP

ELSE: no action

Set **TIME (M)** to t

Set **FLAG (M)** to L

END

END

UNTIL L is the packet destination and all unMARKed values in **TIME > TIME (D)**

**STOP**

The quickest route is held in **FLAG**, and is found by identifying the chain of links in reverse order, starting at the link feeding the destination.

**APPENDIX C**

**OPTIMISED SIGNAL SETTINGS AND ASSIGNMENT**

Care needs to be taken with the use of optimised signal setting options in conjunction with an interactive assignment process as it is known that, with such processes, signal settings in an early iteration can influence flows in subsequent iterations resulting in 'biased' assignments. The process may
also affect the convergence of the program to stable conditions. The interaction between signal settings and assignment, resulting in biased assignment, is usually only of concern where junctions are seriously overloaded. This condition, which is thought to occur in real traffic situations, is the subject of current academic research in network optimisation. It is suggested that, if there is a possibility of biased assignment, then the consequences of such settings is examined by using long cycle times, to maximise capacity, and trying 3 or 4 fixed split settings at the critical junction(s).

APPENDIX D

DATA INPUT AND OUTPUT

The data inputs required by CONTRAM are the Network, Demand and Control files:

The Network file specifies Time interval lengths, Origins and connections to links, link properties (link interconnections, cruise time, length, maximum throughput capacity rates and capacity slopes, storage capacity), parts of the signal control data, pcu equivalence values for different classes of vehicle, and Fuel coefficients. The first entry in the Network data, card type 1, used in previous versions of CONTRAM to indicate the time resolution in the modelling, is now used to identify a call for selecting a third output file for input to the User-Friendly Post-Analysis System for CONTRAM—UFPASC, which is described in the next section.

The Demand file consists of Vehicle Information: vehicle type, packet size, 'crow-flight' distance for point-to-point speeds and the matrix of time varying flows for each O—D movement. (The facility for specifying individual start codes is no longer available, as it is of no practical value, and the default value of 5000 is used.)

The Control file contains instructions for selecting the Number of iterations required, Output options (point-to-point speeds, turning movements), Signal control plans and Fixed route information. A new Control card (type 59) is used, in conjunction with the packet sizes entered in the Demand file, to select fixed or variable packet sizes (Section 3.4.2).

CONTRAM produces three Output files:—the normal 'Results' file (RESULTS), a Vehicle Route file (ROUTES) and an optional Summary Data file (UFPASC) for input to UFPASC. Normally only the RESULTS file would be printed; the ROUTES file can be stored for subsequent analysis and the UFPASC file is only used in conjunction with the UFPASC program.

The RESULTS file contains data for economic assessments and traffic engineering purposes. It also provides point-to-point speeds for comparing the effect of alternative traffic management schemes on O—D movements. The listing starts with the 3 Data Input files which, together with any error or warning messages, enables the input data to be checked for corrections. These are followed by a single page of Network Summary Information for economic assessment purposes: total journey time spent travelling and delayed (veh-hrs); total journey time (veh-hrs); total distance travelled (veh-kms); totals of final queues (pcu's), and fuel consumption (litres). Values are given for each time interval and for the whole simulation period.

The next three sets of tables contain interval by interval information for assessing convergence: Summary totals of journey times, distance travelled and final queues, for the last 5 iterations; Two tables of RMS changes in demand and total numerical (arithmetic) changes in demand on links between consecutive iterations. (Note—demand on a link, in a given time interval, is defined, for the purpose of output in CONTRAM, as the initial queue on the link plus the down stream stop line arrivals for the time interval); and Numerical changes in demand on each link between the final two iterations.

For traffic engineering (and more detailed economic assessment) purposes link by link data are listed for each time interval: Initial queue (pcu), Vehicle arrivals (vehs)—by class of vehicle, Number of departures (pcu), Final queue (pcu), Spare throughput capacity (pcu), Link store left (pcu)—indicating occurrence of blocking-back, Degree of saturation (percentage), Average queue time (sec), Time spent on link (veh-hrs) and Distance travelled (veh-kms)—by class of vehicle, Average journey speed (km-hr), and Junction number and Signal plan data (if appropriate).

Summaries of the link by link data are then listed in matrix form for: Arrival flows (pcu/hr), Final queues (pcu), Average queue times (secs), Queueing delays (veh-hrs), and Average speeds of cars (km/hr).

The 'point-to-point' O—D speeds (km/hr) are listed at this stage for selected O—D movements.

Additional (optional) information is listed for Turning movements for selected junctions or for all links.

The output from CONTRAM Version 5 is similar in layout and content but there are detailed differences. In particular: Flows and queues and capacities are expressed in vehicles instead of pcus. An option in the input data allows delay outputs to be expressed in vehicle-minutes, and vehicles/minute for compatibility with ARCADY 2, PICADY 2 and OSCADY (Semmens (1985(a) and (b), Burrow (1987)).

Total delay on each link in each time interval is disaggregated into Freemoving (including cruise time and geometric delay), Flow-delay (obtained from speed/flow relationships) and Queueing delay, for all vehicle classes.
Degree of saturation, $\rho$, is defined as the ratio of arrivals (at the downstream stopline) to throughput capacity. Link store left is replaced by percentage link occupancy in terms of vehicles.

Also output are the estimated percentage of vehicles forced to stop on a link and, in the case of a signal, a measure of the degree of co-ordination between the arriving traffic and the green stages.

Matrix-form tables of perceived and resource cost are output if these quantities are calculated.

The ROUTES file contains detailed information for each packet journey: Origin, Destination, Start time (secs), Vehicle type, Number of vehicles in the packet, Link numbers and link exit times for the links along the packet's route. The data can be used to examine route patterns over a network—an example of route plots is shown in Figure 10.

The 'UFPASC' output file is only produced if input is required for the User-Friendly Post-Analysis System for CONTRAM—UFPASC (Section 4.1). The file contains, in summary form, all of the data contained in the RESULTS file but without the explanatory text.

APPENDIX E
STRUCTURE AND OPERATION OF PROGRAM

The basic operation of the program is outlined in Figure 11.

At the input stage INNET reads the network description and stores the link data, checking for errors. INFLOW reads the traffic demand data, checks for errors and creates a scratch file of packets using the network in time order of entry on to the network. CONTRL reads the program control parameters, stores route information for fixed route vehicles, calculates signal timings and checks for errors—CONTRL also sets parameter values used by the program for selecting the next appropriate subroutine.

During the calculation stage RMODEL reads route information for each packet in turn from the packet route file (scratch file), assigns each packet to its quickest route (or fixed route) recalculating queues and delays as necessary, and then updates the packet route file after each packet assignment. RMODEL also calculates certain parameters for the output stage. One complete operation of RMODEL constitutes an iteration. CONTRL runs alternately with RMODEL, re-calculating signal timings between iterations if required.

The output of CONTRAM is mainly calculated in ROUTPT and TURMOV. ROUTPT processes the link by link data (flows, queues, delays, etc) stored by RMODEL and TURMOV deduces turning movements from the packet route file.

A recent modification to the output produces a summary file of selected parts of the CONTRAM output in a form suitable for input to the post analysis program UFPASC (Section 4.1).

Error checking procedures in INNET, INFLOW and CONTRL have been designed so that the program
always completes the data input stage, even if one or more fatal errors have been detected, to provide information for checking input data. The program also provides warning messages (Leonard and Gower (1982), Section 6.2) if certain parameters are outside prescribed ranges—such messages are informative and do not prevent the program running through to completion.