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Theory and Methodology

Diagnosis and treatment of congestion in central urban areas

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Abstract

The development and dispersal of area-wide traffic jams is a matter of considerable social concern. Work at Middlesex University, supported by EPSRC, has enabled the construction of a simulation model with greater geographical scope than most conventional congestion simulation models. Our simulation concentrates on a holistic view of traffic jam formation in a setting of isotropic flow.

In the model, traffic incidents can effectively be introduced anywhere in the network. The growth of traffic jams can be observed using a graphical display and options are included to disperse and control the formation of traffic queues.

Simulation results have confirmed that the uncontrolled growth of the traffic jam is both rapid and potentially irreversible. Experiments with dispersing the traffic jam have given greater insight to the 'gridlock' phenomena. We suggest a number of possible, practical counter-measures, which would both inhibit the growth process and contribute to the controlled dispersion of queues in congested networks. The effectiveness of the proposed strategies is evaluated via the simulation model and as a result, we provide a coherent set of remedies which would assist in the diagnosis and treatment of central urban congestion problems.

Keywords: Traffic congestion; Queueing; Simulation; Control policies

1. Introduction

The form of a traffic jam in a simple, idealised, one-way road network is characterised by irreversible nodes or knots which develop at specific locations within the jam area. These knots persist even when traffic demand falls away at the end of the peak period. External measures are required to break the interlocking queues apart in order to restart vehicular movement. In real life, these measures take the form of a set of rules, which channel vehicles away from the sensitive locations of the network. However, if demand is heavy, control measures such as these may only lead to a temporary halt in jam growth, which is later resumed.

The term 'gridlock' is associated with traffic jams featuring these irreversible knots of vehicles. There are several ways to deter the spread of such jams. Here we deal only with the vehicle movement ban, either restricting movement to *ahead* or *turn* only. A *gating* mechanism has also been investigated. It is thought that such measures, while affecting freedom of movement for the motorist, could be fairly easily implemented via signalling facilities already present on urban road networks.

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2. Background

Traffic congestion is a growing problem in cities throughout the world. Effective mechanisms are needed for reducing the frequency of jam formation, and for dispersing jams once they have formed.

The process of traffic jam development and dispersal can be studied either by observation or by direct computer-simulation modelling. The latter method is usually preferred and [1] cites a number of reasons for this:

(1) Data-collection exercises for full observations are expensive particularly when considered over large areas.
(2) The generalisation of the results of one particular congestion study to similar or different ones might be difficult.
(3) A data-collection approach is not conducive to sensitivity analyses of the resulting congestion.
(4) It is not possible to investigate the effects of remedial strategies in real-life observation studies.

It is generally accepted that surveys of the process of traffic jam formation are prohibitively expensive and difficult to conduct. In addition, some consideration should also be given to the generality of the results of such surveys. However, the validity and credibility of the simulation approach also needs to be considered, but in this context, the advantages outweigh the disadvantages.

This research investigates traffic jam growth and dispersal using computer simulation applied to idealised rectangular grid networks. This has enabled us to identify fundamental aspects of jam behaviour independently of network configuration. Unlike real-life observation studies, the model can be used for the analysis and evaluation of remedial control strategies as well as for detailed sensitivity analyses. While the model results are not immediately applicable, nevertheless they highlight some important features regarding traffic jam growth and dispersal. This paper describes control strategies for idealised traffic jams and discusses their application to less theoretical situations.

3. A traffic simulation model

The simulation model provides a framework for the congestion study. The model is both interactive and graphical. It enables the 'horizontal' modelling of queues, a feature which takes the effect of queue interaction into account. An area-wide view of the developing traffic jam is provided along with real-time simulation of events on the network which include removing the obstruction and implementing control strategies.

The computer-model has been developed for a one-way grid network. It consists of equally spaced streets intersecting at right angles. A sequence of alternating sources and sinks is constructed at the edges of the square grid. Vehicles travel from any source towards any sink.

A Poisson model is used to generate vehicles from each of the sources. The expected mean of the demand at each access point is described by a constant (μ), which represents the number of vehicle arrivals per cycle. It has the same value for all the sources to create a steady flow of vehicles throughout the system.

The mechanism of vehicle movement mimics simple traffic control. Vehicles are partially segregated into traffic lanes and progress subject to space being available downstream, capacity constraints at junctions, and interactions between queueing vehicles.

The model does not track vehicles through the system. Instead, when vehicles discharge from a link during a given time-slice, they are split into two groups: ahead and turning. The groups are progressed respectively to the downstream ahead and turning queues, regardless of origin. Implicitly therefore, the O-D matrix is predetermined with even flows between each origin and destination pair, although it is not possible to refer the matrix directly. The pattern of queue development is thus determined by the overall turning movements as opposed to the specific routes followed by individual vehicles.

In the simulation model, a road link is divided into two distinct zones: a downstream queue storage area where vehicles were organised into separate turning movements, and an upstream 'reservoir' where the turning movements are mixed. The interactions occur at the transition between these two zones, [2].

3.1. Simulation dynamics

The traffic simulation model has been developed on a *Digital Alpha AXP 3000* workstation. In the model, time is divided into a number of equal time-slices. At the end of each time-slice, all the queues are updated according to the inputs and outputs of the particular link. A typical model cycle involved all of the east-west roads being processed in turn, starting with the link at the downstream end, and moving progressively upstream from link to link. Then, all the north-south roads are processed in similar fashion. Initially, this cycle is carried out a number of times to allow the system to stabilise. An obstruction was then introduced on a link near the centre of the grid. This activated the growth of the traffic jam. The cycle is then repeated as required. The growth of the traffic jam with time is presented in an animated visual form.

The program is intended to deal with large networks at high speed, to enable a screen display of the salient features of traffic jam growth in less than real time. A range of network parameter variations can be explored at a reasonable cost in terms of computer resources. The program can handle a jam extending over a grid of 19×19 blocks (i.e., 760 links and 400 junctions) in about two minutes.

The existing software includes facilities for manipulating the time interval between successive updates of the vehicle queues, the traffic demands, and the queue storage arrangements. In addition, the software can be used to investigate the way in which jams disperse by removing the blockage and introducing external counter-measures.

3.2. Graphical output

Fig. 1 shows a 4×4 rectangular grid network which has already stabilised. The right-hand drive convention is adopted in the network. The segregated turning queues are shaded in grey whereas the ahead segregated queues are shaded in black. The wider areas (also shaded in black) represent the reservoir portion of the link where vehicles are mixed.

Fig. 2 shows a traffic jam which has formed as a result of an obstruction. The pattern of queue propagation is fundamental to the development of control strategies. The spatial form is roughly diamond shaped. The growth pattern emanates from the the centre of the jam where a core of locked vehicles has formed.

4. Experiment design

The aim of this research is to investigate the effect of certain parameters on the total delay (described below) incurred by the system for the duration of the dispersion process of a traffic jam.

An experiment has been designed which considers the pattern of traffic jam decay when subjected to a number of forms of intervention which have been implemented under a variety of conditions.

The chief explanatory variables which have been considered are the level of demand, the proportion of turning vehicles and the allocation of stopline space devoted to the segregated queues. The response variable measured in vehicle minutes is the total delay Δ_i^*, (see the Appendix), incurred by the presence of the traffic jam.

We have developed a number of measures which can be applied to control the spread of congestion in the network. The effectiveness of the treatment applied depends on the nature of the congestion problem. The severity of congestion has been linked with three parameters, the level of demand (μ), the propensity of vehicles to turn (p), and the stopline width allocated between the segregated queues (α) (In the context of this research $\alpha = 0.66$ denotes the situation of two lanes for ahead traffic and one for turning vehicles. The values of α have been limited to the parameter set $\alpha \in \{0.50, 0.66, 0.75, 0.80\}$, as these form a representative set of road network configurations.

Each simulated traffic jam has been treated by employing a selection of different control measures. The efficiency of one strategy in relation to another has been compared in terms of the total delay incurred.

4.1. Steady state conditions

The simulation is run in two phases. During the first phase, known as the RUNUP period, the simulation program is activated with no obstruction present on the network. Time series tests are made on the statistical data obtained at the end of each time slice to ascertain whether the system has reached a stable state. Once this condition has been established, amongst others, an

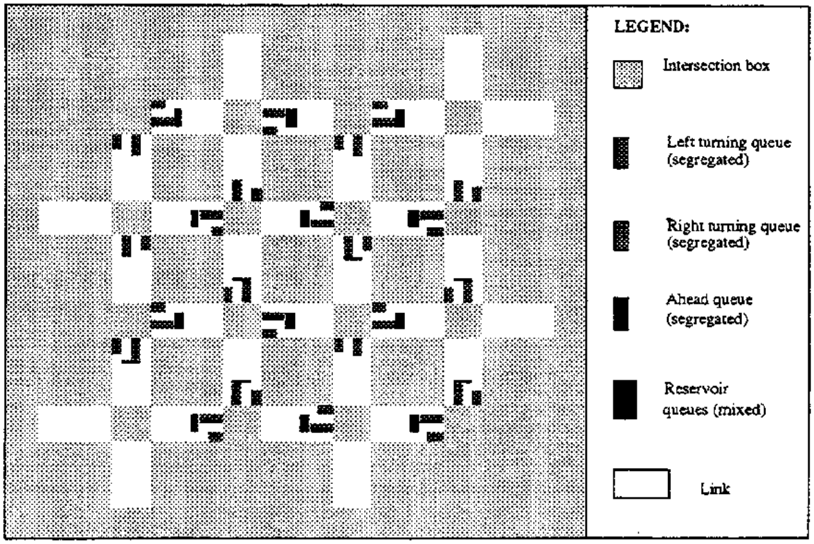

Fig. 1. 4 × 4 steady state road network.

estimate is made of the mean and standard deviation of the number of vehicles in the steady state road network.

In the RUNUP period, we have chosen to record the total input to the road network at the beginning of each time slice and likewise to calculate the total output at the end of each time slice. The difference between these two variables forms a sequence which can be tested for stationarity using time-series methods. The technique we have used to locate the steady state is described in [3].

Once the road network has achieved its steady state, the second phase of the simulation may begin. During the simulation period, the experiment described in the previous section is carried out. Summary statistics, such as the record of blocked links, are gathered for the duration of the experiment.

4.2. Definition of delay

The simulation model was not originally built to compute delays in networks. Since vehicles are not individually tracked, it is not possible to calculate the individual delays experienced by drivers in the network. However it is possible to compute the total delay caused by the congestion as a function of the difference between the total number of vehicles in the system in the steady state with the expected number of vehicles in the congested state.

The estimated delay denoted by Δ_i^*, represents the total delay in the system incurred as a result of the traffic jam, assuming that the original obstruction has been removed. The method is described in the Appendix. The method is not a sophisticated one and is only intended as an indicator of performance.

5. Intervention strategies

In their discussion of the treatment of 'catastrophic' or severe urban congestion, Huddart and Wright [4], and Quinn [5] propose a number of approaches for tackling the problem. They suggest that

(1) the control system be altered to disperse or free critical queues;

(2) reserve capacity be provided to relieve congested links; or

(3) the level of demand be reduced albeit temporarily.

Rathi [6] categorises the treatment of congestion in terms of internal and external metering. Internal metering is implemented to cope with queues along critical intersections whereas external metering is applied along the periphery of a control area to reduce flow into the congested region. The paper deals extensively

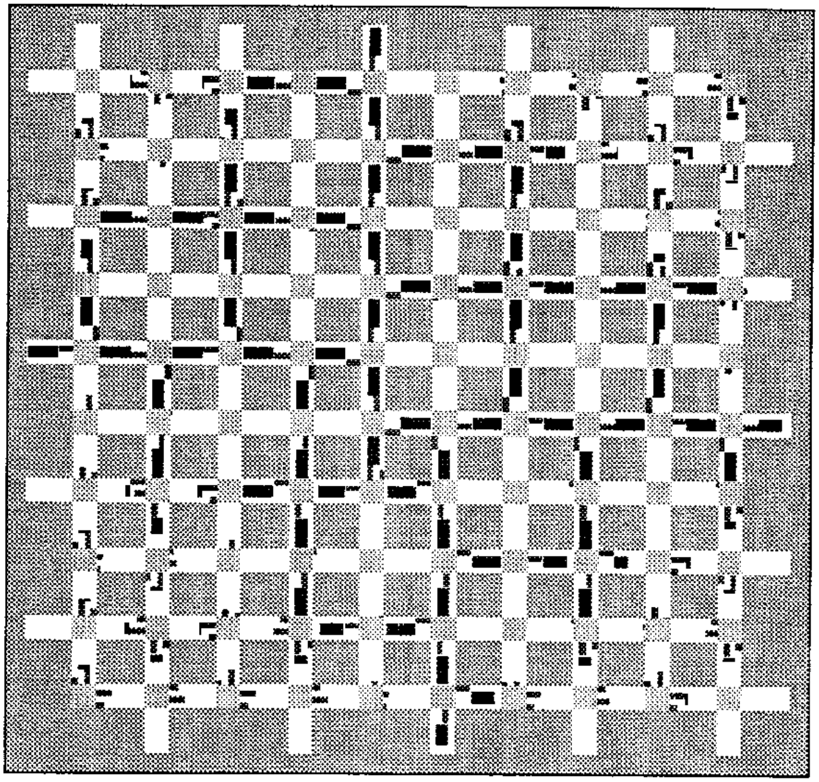

Fig. 2. Queues emanate from *gridlock* core located towards centre of grid.

with various external metering control-test scenarios.

The implementation of vehicle-bans follows a methodology which is similar to the ones proposed above. The bans can be applied in two forms: turn or ahead. Turn bans can be imposed on selected links to break gridlock cores at the heart of the jam, thus dislodging critical queues. Ahead bans around the envelope of the jam reduce input into critical sections of the road. These ahead bans can be used in two ways. Vehicles using the banned junctions can either be queued outside the congested region or else be re-routed away from the jam.

Experiments with bans have yielded the following strategies which do not always appear to be very promising when applied in isolation but can be extremely powerful when applied in combination. The strategies can be classified in three groups:

- Nucleus intervention aimed at the centre of the traffic jam;
- boundary intervention directed at the envelope of the traffic jam;
- combination of both.

5.1. Nucleus intervention

This type of intervention is directed at, or near, the point of the original obstruction. When four sides of a city block in the network have become jammed with turning vehicles an irreversible knot or core is formed. The traffic can be released from this core using a set of turn bans which are superimposed on the four locking turns in the network. Because nucleus intervention focusses on the irreversible cores located towards the centre of the traffic jam, this control measure is referred to as the *The Core Strategy*, [7] and will be used in further discussion.

If the demand is fairly light or if the jam has not been active for more than a few time slices, it may

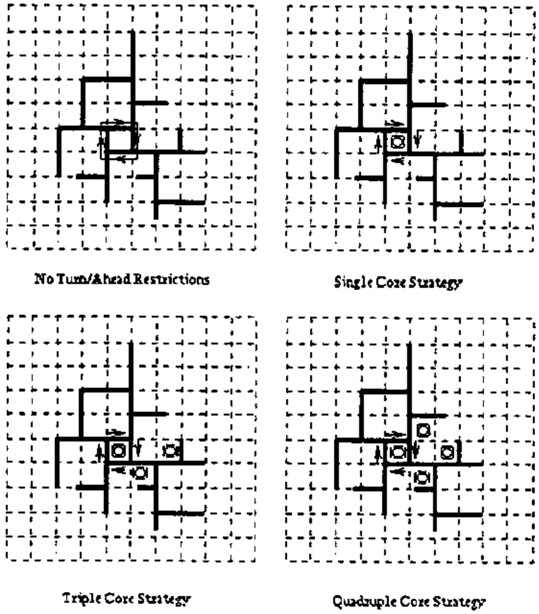

Fig. 3. Core intervention strategies.

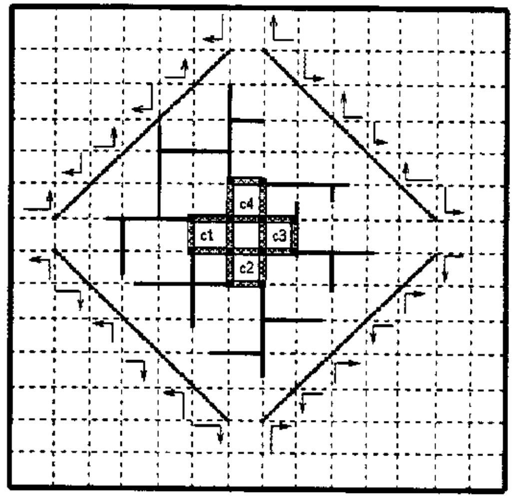

Fig. 4. Diamond re-routing strategy.

be sufficient to ban a small number of critical turning movements to clear the whole jam. However, experiments have demonstrated that this simple expedient often forces the locking core to migrate to a new location, close by in the network. This problem has been dealt with by using compound *Core Strategies* which have treated core migration phenomenon with increasing success. However multiple core strategies become less effective when demand increases and when the jam has already assumed area-wide proportions.

To distinguish between the single and compound versions of the *Core Strategy* the compound core strategy has been referred to as the *Triple Core Strategy* for three *cores* and the *Quadruple Core Strategy* for four such *cores*. Fig. 3 graphically displays the location of both versions of the *Core Strategy* within the jam structure. The top left part of the figure shows the system when no restrictions are active. The closed loop of direction arrows highlights the state of locked queues which needs to be released. The remaining part of the figure graphically demonstrates the operation of the *Core Strategies*. The arrow system has been disjointed to point out that vehicles are forced ahead, and are banned from turning. (The principal axis of the jam is the axis along which the traffic jam develops once the obstruction is set.)

5.2. *Boundary intervention*

An alternative strategy aimed at redirecting traffic away from the traffic jam complex sets a cordon of ahead bans, which channels approaching vehicles away from the jam. Because of the predictable shape of the emerging jam on the idealised network it is possible to set up a cordon which neatly encompasses the jam at whatever node the obstruction originates. This cordon can be altered in size and is context sensitive. It is conjectured that the cordon will work best when its size parameter is just sufficient to include all of the currently developed jam. This strategy has been given the appellation *Diamond Re-routing Strategy* owing to the shape and nature of the cordon placed around the growing traffic jam. A graphical representation of the strategy is provided in Fig. 4.

A variation of the *Diamond Re-routing Strategy* has also been devised, in which the vehicles are not re-routed but simply queued outside the envelope of vehicle-bans. This strategy is referred to as the *Diamond Gating Strategy*.

5.3. A combined approach

Applying the *Core* and either of the *Diamond* strategies in parallel, seems to offer the promise of quick and effective dispersal of jams on the idealised network. The *Diamond Strategy* protects the emerging jam from excessive demand whilst the simple or compound *Core Strategies* are applied directly to irreversible knots at the heart of the jam. The shielding of the cordon minimises the tendency of the cores to reform at nearby locations and the reduction in the overall jam size and delay time can be dramatic within a few time slices of the simulation process.

5.4. Notation and assumptions

The traffic jam has been dispersed by employing different control strategies. In some situations all the control strategies have provided positive results, whilst in others only a partial level of success has been achieved. Table 1 summarises the strategies which have been considered for this part of the research. The parameter j in the definition *Diamond*(j) describes the size of the cordon.

The model assumes that the propensity of turning does not change as a result of an incident. In practice, drivers will react to congestion and may alter their original route. However, in the isotropic network which has been presented in this paper, it is not clear how drivers would react because they do not have any previous knowledge or details of the short cuts in the network. Hence diversion activities will be compensatory in a collective sense. In applying the strategies to non-idealised networks, the problem of self-diversion will have to be addressed specifically.

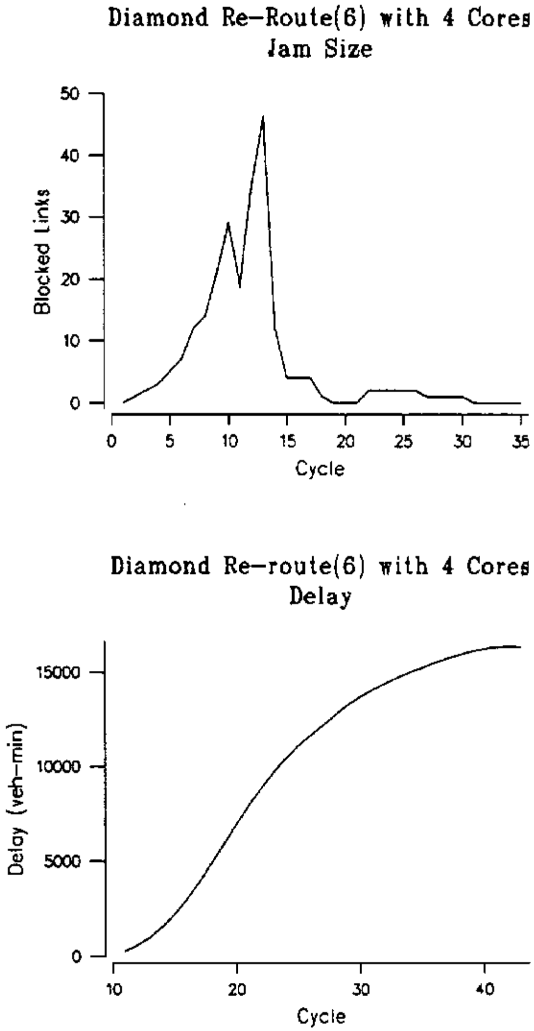

Fig. 5. The decay process of a traffic jam using B_4C_6 strategy.

6. Results

Fig. 5 shows two perspectives of the jam decay process using the B_4C_6 strategy. The top half of Fig. 5 describes the dispersion pattern via the number of blocked links incorporated in the structure. When the number of blocked links reaches zero, and no banning mechanisms are present on the network, the system is defined to be clear. The bottom half of Fig. 5 shows the delay incurred as a result of congestion.

Simulation experiments of various ban-patterns have been conducted under a range of network conditions. The study has found that the application of vehicle-bans may lead to the elimination of the traffic jam although this outcome is not always guaranteed. Tables 2, 3 and 4 summarise the results of the simulation trials. It can be seen that a number of the control strategies force the locking core to migrate to other locations in the network, and in some cases, the intervention strategies fail to clear the traffic jam.

Table 1
Strategies in intervention: definition and notation

Strategy type	Strategy definition	Reference
	Remove Obstacle Only	A
Nucleus	Core	$B_i\ i \in \{1,3,4\}$
Boundary	Diamond(j) re-route	$C_j\ j \in \{4,6,8\}$
Boundary	Diamond(j) gating	$Q_j\ j \in \{4,6,8\}$
Combination	Core and Diamond(j) re-route	B_iC_j
Combination	Core and Diamond(j) gating	B_iQ_j

In situations like these, the total delay incurred by drivers can be seen as infinite as it increases each time-slice with no bound. This situation has been denoted by the ∞ symbol.

6.1. Increasing demands

The results shown in Table 2 confirm that with each increase in the level of demand, it becomes more difficult to disperse the resultant traffic jam. (The figures appearing in parentheses represent the number of time-slices required until the road network returns to its original steady state. These figures are required in order to compute the average delay experienced by a single driver in the system.) The numerical entries along the rows of the table, outline that with each increase in demand, the effectiveness of a particular control strategy is either reduced ,as shown by the increasing delays, or rendered useless, as shown by the ∞ symbol. As the network approaches saturation levels, it is no longer possible to dissolve the queue structures using the selection of strategies described in the this paper.

By considering each column of entries it is possible to compare the effect of the various types of strategy on the overall delay. In situations of low demand, the simple expedient of removing the obstruction is sufficient to clear the traffic jam. The implementation of more complicated strategies does not invoke considerable relief, on the contrary, intervention,(particularly the gating strategy) usually induces unnecessary delay.

With average levels of demand, the removal of the obstruction, may no longer be a sufficient measure and more detailed intervention is required to control the jam and thus minimise the total delay. The control measures are initially directed at the irreversible knots which have formed near the location of the original obstruction. Repeated simulations have shown that delay can be reduced further, if *compound* core strategies are applied in conjuction with an appropriate boundary re-routing strategy.

With higher levels of demand, the application of core strategies on their own is no longer an appropriate feasible solution as the rate of growth of the traffic jam is more rapid, and the jam assumes an area wide structure. The *core* strategies operating at the nucleus of the jam cannot cope with the excessive demand caused by the large number of queues in the structure. A shielding mechanism is required so that vehicles are deflected away from the congested area for a limited time period. During this time period the *core* strategies may be applied to the nucleus of the jam, and the cordon placed around the jam acts as a barrier so that the traffic jam structure may be dissolved.

The cordon can be set up so that it neatly encompasses the jam at whatever node it originates. The cordon can be altered in size and is context sensitive. Invariably, a larger cordon implies a higher number of restrictions being imposed on the network, so that the overall aim is to define a cordon which is as small as possible which will in turn invoke as few delays as possible. As with the *core strategies* care must be exercised when fitting cordons to emerging jams. An ill-fitting cordon which does not capture the complete jam produces irreversible gridlock cores along the boundary of the cordon. This tendency occurs if the cordon is left in place for too many cycles of the simulation and is heightened in situations of severe demand.

In the experiment, two versions of boundary intervention have been employed. The first involves re-routing of vehicles away from the congested area whilst simultaneously barring entry into the traffic jam, whilst the second simply holds back traffic from entering the congested area. The results in the table

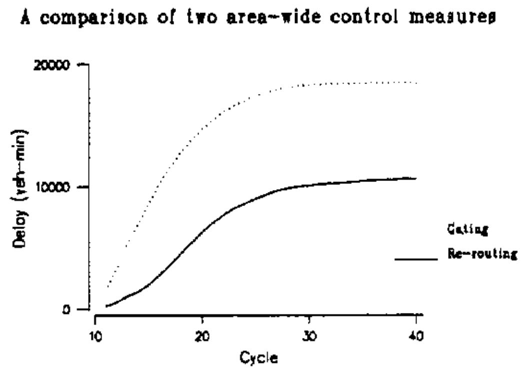

Fig. 6. Re-routing vs Gating strategy: a comparison of delay times.

show that the the re-routing technique is the more efficient of the two and in most cases, the total delay incurred is half that of the gating mechanism.

This implies that the gating option involves heavier delay to drivers caught in the congestion. However, re-routing takes drivers away from their destinations. In reality they would drive around until allowed to go where they wanted and the delays might be large. In the current model, if vehicles are displaced from their original route they cannot drive around to get back where they originally planned. In order to tackle this problem, we propose to modify the post dispersal phase by computing the amount of vehicles which have been forced to turn away from their planned route, and then increase the propensity of turning in the network to compensate for the affected vehicles. We expect the total delay to increase as a result of the modification and the success of the strategy overall will need to be re-evaluated.

A graphical comparison of the delays incurred by the respective re-routing and gating strategies is provided in Fig. 6.

6.2. Increasing turning proportions

The effectiveness and applicability of the various methods of intervention has also been measured for different turning proportions. Table 3 examines how the proportion of turning vehicles within the system effects the dispersability of a traffic jam for a fixed level of demand. The proportion of turning vehicles varies from nine to forty-two percent. The remaining percentage go straight-on.

Table 2
Total delay(veh-min): increasing demands

Parameters						
μ	**18**	**20**	**23**	**25**	**27**	**29**
$\bar{W}$	6035.4	6598.6	7483.2	8000.2	8487.7	9663.5
s_w	42.4	47.1	58.2	53.9	62.7	86.7
Strategy	Total delay					
A	2550.2	5403.6	∞	∞	∞	∞
	(14)	(19)				
B_1	2550.2	5788.8	17123.0	∞	∞	∞
	(14)	(27)	(33)			
B_3	2581.2	5767.2	16455.1	∞	∞	∞
	(15)	(27)	(33)			
C_6	2847.2	5258.4	∞	∞	∞	∞
	(11)	(14)				
Q_6	5925.6	10444.8	∞	∞	∞	∞
	(20)	(32)				
B_3C_4	2882.9	5460.0	9982.0	∞	∞	∞
	(11)	(15)	(28)			
B_3C_6	2950.2	5409.6	9376.6	19915.0	49450.5	∞
	(11)	(14)	(28)	(35)	(99)	
B_3Q_6	6354.4	10821.6	18354.0	38801.0	∞	∞
	(19)	(27)	(28)	(46)		
B_3C_8	2514.6	4827.2	9569.8	24052.5	49236.7	∞
	(11)	(14)	(28)	(45)	(99)	

The results in Table 3 outline the fact that turning proportions do contribute to the dissipation characteristics of traffic jam structures. Generally, as turning proportions increase, it becomes more difficult to force the resultant structures apart.

The effect of the turning proportion, p, on the performance of the control strategies cannot be easily explained. The results generally show that increasing the turning proportion reduces the performance of the control strategies.

Careful analysis of the results has shown that the turning proportion of vehicles has a crucial effect on the dispersal process. The control strategy is more effective and induces smaller delays when p is low. As p assumes higher values, the control strategy is less successful and often fails to eliminate the jam. For values of p occurring between these two upper and lower bounds, the total delay incurred during the dispersal period does not follow a systematic trend. Instead, the total delay is extremely sensitive to changes in p and changes markedly with each variation. It is not possi-

Table 3
Total delay (veh-min): increasing turning

Turning	Smooth value	Strategies				
p	$\bar{w} \pm s_w$	A	B_4	B_4C_4	B_4C_6	B_4C_8
0.09	9035.3 ± 59.6	13717.0 (58)	12928.0 (64)	15008.0 (64)	20064.0 (64)	25798.5 (63)
0.13	9037.7 ± 88.7	∞	36382.5 (99)	29304.0 (99)	17250.0 (46)	14448.0 (28)
0.17	8699.8 ± 55.7	∞	16038.0 (44)	14042.0 (28)	12465.0 (30)	13146.0 (28)
0.20	8188.1 ± 63.3	∞	28681.0 (46)	30452.0 (46)	16560.0 (45)	15120.0 (35)
0.23	8000.2 ± 53.9	∞	31525.0 (50)	∞	19602.0 (33)	17935.5 (33)
0.26	7630.1 ± 65.6	∞	50341.5 (99)	∞	34020.0 (81)	30294.0 (81)
0.29	7975.6 ± 95.1	∞	∞	∞	14658.0 (28)	15624.0 (28)
0.31	7394.9 ± 263.1	∞	∞	∞	33056.0 (64)	33824.0 (64)
0.33	7373.7 ± 46.7	∞	∞	∞	14742.0 (27)	17145.0 (27)
0.35	7283.9 ± 63.4	∞	∞	∞	∞	∞
0.38	6574.6 ± 53.3	∞	∞	∞	34228.0 (86)	32720.0 (80)
0.40	6919.7 ± 68.9	∞	∞	∞	∞	∞
0.42	6330.6 ± 42.1	∞	∞	∞	∞	∞

ble to predict how the pattern of fluctuations will vary with respect to changes in the turning proportion.

This non-smooth behaviour may be linked with the discrete nature of the software, in which the variable for vehicular flow always remains integer. Thus, certain values of p, when associated with other parameters, such as the level of demand, may induce the dispersing jam into one critical state, whereas another combination may produce a different, albeit related state. Each state will exhibit similar yet distinct patterns of delay.

6.3. Channelisation

The results in Table 4 show that for a particular control strategy, the queue storage configuration of a link can dramatically affect the delay incurred during congestion. However, care must be exercised when changing the allocations between ahead and turning proportions. The results show that as p assumes higher values, it would be unwise to increase the value of α beyond 0.50. The reason for this is that allocating more space to the ahead traffic simultaneously reduces the amount of space available for turning movements. When turning proportions are high, spillback can be triggered more rapidly, thus inducing a premature onset of gridlock type phenomena. This would make dispersal more difficult.

With this particular control strategy, B_4Q_6, the delays involved are relatively high. Looking across the first few rows of the table, the numerical entries suggest that the overall delay can be reduced and often minimised by slightly changing the link storage configuration. The sensitivity of this change is demonstrated in the entries along the first row of the table. The results show that the total delay is minimised by setting $\alpha = 0.75$. In this example, the turning proportion is vey low, ($p = 0.09$), and the majority of vehicles at a particular intersection will move ahead. The optimal exploitation of the road link storage capacity would be one which allocates a higher proportion of space to the ahead queues. However, care must be ex-

Table 4
Variation in total delays (veh-min) using B_4Q_6 for various channelisation regimes

Turning	Smooth value	Channelisation:α			
p	$\overline{w} \pm s_w$	**0.50**	**0.66**	**0.75**	**0.80**
0.09	9037.8 ± 68.0	36525.0 (58)	17127.0 (33)	14794.5 (21)	22606.5 (21)
0.13	9015.8 ± 87.2	44148.0 (156)	33320.0 (85)	35870.0 (85)	40247.5 (85)
0.17	8695.0 ± 53.8	23264.0 (32)	21551.0 (23)	25800.0 (30)	∞
0.20	8186.8 ± 65.6	43004.0 (52)	29620.5 (39)	∞	∞
0.23	7998.4 ± 53.9	36850.0 (50)	30172.0 (38)	∞	∞
0.26	7630.1 ± 65.6	55826.0 (103)	∞	∞	∞
0.29	7975.6 ± 95.1	26864.0 (46)	∞	∞	∞
0.31	7394.9 ± 263.1	45152.0 (64)	∞	∞	∞
0.33	7373.7 ± 46.7	26610.0 (30)	∞	∞	∞
0.35	7273.9 ± 63.4	∞	∞	∞	∞
0.38	6574.6 ± 53.3	51112.5 (87)	∞	∞	∞
0.40	6919.7 ± 68.9	∞	∞	∞	∞

ercised when changing the link storage configuration, as can be seen in the final entry in the first row. Here, too little space has been devoted to the turning movement so that spillback is more rapid and the total delay increases as a result of interference.

7. Conclusions

This study examined the process of traffic jam dispersal under a variety of network conditions. Experiments with the control of traffic jams were conducted on a one-way grid network, but the principles can be applied to less idealised layouts.

The work established that two elements were generally necessary for controlling gridlock-based congestion. These included the fragmentation of the gridlock cores at the centre of the traffic jam using turn bans whilst simultaneously restricting the flow into the congested region via a re-routing or gating policy. Under appropriate circumstances, certain combinations of these control measures were found to have an appreciable impact on jam development and dispersion. This was measured in terms of the total delay incurred by the network.

The performance of the proposed control strategies was analysed under a variety of road network conditions. Simulation experiments confirmed that it becomes more difficult to disperse traffic jams when the level of demand and the proportion of turning vehicles increased. Furthermore, the dispersion mechanism appeared to be rather delicate and interference with the queue storage configuration was found to be damaging. The results also showed that changes in the queue storage configuration often limited the performance of the control strategies.

The use of gating instead of re-routing caused queues to propagate along the jam boundary. The longer the restrictions remained in place, the more likely that the queues themselves formed cores of new traffic jams. This implies that the gating option involves heavier delay to drivers caught in the congestion. However, re-routing takes drivers away from their destinations. In reality they would drive around until allowed to go where they wanted and the delays might be large. Gating therefore reflects more realistically what might happen in real life.

8. Application of results

In this paper we have described a simulation model which has been used to investigate the underlying mechanism of queue propagation and dispersion in an idealised grid network. However, the network and the demand pattern are both not very representative of reality. A more flexible model, which can deal with features such as different link lengths, variable turning proportions, capacity constraints and junction control is required in order to translate the idealised model into a research tool for investigating jam formation on real networks.

A detailed study [8] which considered the suitability of commercially available traffic assignment models for this purpose, concluded that whilst the models were capable of simulating the patterns of congestion, they could not adequately represent the underlying mechanism of congestion, and in particular, they were deficient in describing the dispersal process of area-wide traffic jams.

We have recently constructed a real network prototype which applies some of the modelling techniques which have been employed on the idealised network to a particular region of the Leicester network in the UK. The model incorporates network specific information such as O-D patterns, traffic-signal timings and coordination, demands and queue storage arrangements. The model has been extended to cope with variable junction layouts and control as well as uneven turning proportions and demand levels.

When studying the patterns of congestion and dispersal in the context of this model, it will be necessary to address a number of issues including, the effect of obstruction location on the ensuing severity of congestion and the relationship between the traffic conditions on the network and the shape of the traffic jam structure. The traffic locking mechanism is likely to be substantially different than the simple patterns we have simulated and the implementation of control strategies of the type described in this paper must be tailored accordingly. In addition, the problem of vehicles being forced away from their chosen route will need to be assessed particularly in view of the fact that drivers will try ultimately to get back on their route when forced to deviate from it by the control mechanisms.

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Appendix

The algorithm which has been used to estimate the total delay, Δ_i^*, is described in this section.

In a 20×20 one-way road network there are 40 entry points. During each time slice, the sum of the vehicles arriving at each entry point represents the system input for that time slice. The system input over all entry points at time slice j is denoted by u_j. The corresponding system output over all entry points is denoted by v_j.

Let $E(U) = \nu$ and $\nu = 40\mu$ where μ is the mean demand per entry point defined by the demand parameter. The mean value of input will remain close to the steady state throughout the simulation.

Let w_i be the observed number of vehicles in the system at time slice i and let w_0 be the total number of vehicles in the system just before the obstruction is placed. We assume that in the steady state (i.e. at the end of RUNUP) W is normally distributed with mean ω and standard deviation σ_w. $\bar{w}$ will be used as an estimator of ω and s_w will estimate σ_w.

Then the number of vehicles in the system at the end of time slice i will be given by:

$$w_i = w_0 + \sum_{j=1}^{i} u_j - \sum_{j=1}^{i} v_j.$$

This can be approximated by:

$$w_i \simeq \omega + i\nu - \sum_{j=1}^{i} v_j.$$

Rewriting and approximating again we obtain:

$$w_i - \bar{w} \simeq \sum_{j=1}^{i} (\nu - v_j).$$

Since $\delta\Delta_i = \tau \sum_{j=1}^{i} (\nu - \nu_j)$ it follows that the contribution to the total delay **from** time slice i is:

$$\delta\Delta_i \simeq \tau(w_i - \bar{w}).$$

Hence the total delay in the system **at** time slice i is given by:

$$\Delta_i \simeq \tau \sum_{j=1}^{i} (w_j - \bar{w}) \quad (\text{veh} - \text{min}).$$

If the implementation of a control measure in time slice s successfully treats the traffic jam so that the system recovers its steady state at time slice i, it is possible to compute the total delay incurred from time slice s to i via the definition that follows. (The total delay in this case has been computed relative to time slice s and is hence denoted by Δ_i^*).

$$\Delta_i^* = \tau \sum_{j=s}^{s+i} (w_j - \bar{w}) \quad (\text{veh} - \text{min}).$$

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