The development and dispersal of area-wide traffic jams

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The development and dispersal of area-wide traffic jams is a matter of considerable social concern. Work at Middlesex University has enabled the construction of a simulation model with greater geographical scope than most conventional congestion simulation models. This paper proposes a simulation model which 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 shown that the uncontrolled growth of the traffic jam is both rapid and potentially irreversible. Attempts to disperse the traffic jam appear to be hampered by 'gridlock' phenomena. The paper describes a number of strategies which could be exploited to achieve a controlled dispersion of traffic jams.

1. INTRODUCTION

The development of area-wide traffic jams over an idealised network can be analysed as a spatial phenomenon which involves the propagation of queues from one traffic stream to another. The queues branch out to form a structure possessing near-regular geometric features, superimposed on the network of streets through which the vehicles are attempting to pass. This research is concerned with deepening the understanding of the formation of traffic jams as well as controlling their dispersal.

2. AIMS OF STUDY

To gain an insight into the inherent properties of traffic-jam structures, the research has concentrated on constructing an ideal model which would provide a holistic view of traffic jam formation in a setting of isotropic flow[1]. In addition to focusing attention on the features of congestion growth and decay, a conceptual approach allows for the development of a model with greater geographical scope than most conventional models.

The simulation model described in the context of this research seeks to embody the overall situation of a composite system which is governed by many interactions. In this way, the effect of actions may be observed in detail and a long-term assessment into the effectiveness of certain strategies be analysed.

3. BACKGROUND TO THE SIMULATION MODEL

3.1. The environment

An idealised network of evenly-spaced one-way streets intersecting at right-angles has been chosen as a starting-point for the modelling of the growth of a traffic jam. The system of streets forms a grid-like structure typical of some town centres, New York's busy Manhattan being a particular example. A sequence of alternating sources and sinks has been constructed at the edges of the square grid.

Arrival of vehicles at the sources is determined by a Poisson model, reflecting the demand for access to the network of roads. The expected mean of the demand at each access point is described by μ, the model's parameter. A fixed value of μ is used to help create an isotropic flow of vehicles through the system as a whole.

The mechanism of vehicle movement, known as the release mechanism, mimics simple traffic control. Vehicles are partially segregated into traffic lanes and the release mechanism allows vehicles to progress subject to vehicle space downstream, capacity constraints at junctions and interactions between queueing vehicles. Vehicles can either maintain their ahead direction or turn in prescribed directions. The propensity of a vehicle turning is controlled by a fixed probability value which is the same for each intersection. The proportion of vehicles turning is determined at the time of release and is fixed according to simple numerical rounding.

3.2. Queue propagation and spillback

The propagation of queues throughout a road network can be described in relatively simple terms[2]. Consider a one-way road link which is divided into two distinct zones: a downstream queue storage area where vehicles are organised into separate movements; and an upstream reservoir where the turning movements are mixed. At one end of the link there will be a junction with one or more approaches that feed traffic into the link. At the downstream end there will be a junction with one or more exits through which the traffic can leave the link. If a particular exit becomes blocked (say, the left-turning exit), vehicles intending to turn left will form a queue that will spread along the link, eventually spreading across all the lanes and blocking all the traffic. Traffic feeding into this particular blocked link will be barred entry, causing a queue to form on the link upstream. This pattern repeats itself, creating a system of queues to evolve around the original source of obstruction.

The movement of individual vehicles within the system is not recorded. Instead, vehicles are assembled into queues, throughout the system, whose states are continually being reviewed. Traffic queues are maintained along all links in the network and are characterised by the segregated area and the reservoir area — that portion of a link devoted to vehicles whose queueing discipline (turn or ahead) has yet to be determined by the program.

3.3. Vehicular movement

Vehicles located on the network's links can only progress in two possible directions — these being ahead or turning, as described above. Vehicles are introduced at the entry-points and progress through the network according to the regulations imposed on the system. Upon arrival at exit-points, vehicles are lost to the system. Whilst still in the system, vehicles are assigned to links whose queues are updated reflecting the movement of vehicles away downstream. Although temporarily at rest, the vehicles would normally be moved on during the next time-slice, though some vehicles may be retained for more than one cycle of the simulation. During the assignment process the possibility of the downstream link becoming full may arise. This means that there is no available space for the temporary placement of extra queueing vehicles. Under these circumstances the link becomes blocked, and further movement of vehicles into this link is not allowed. The link remains blocked until vehicles begin to discharge at the front, thus creating space to accommodate a new set of

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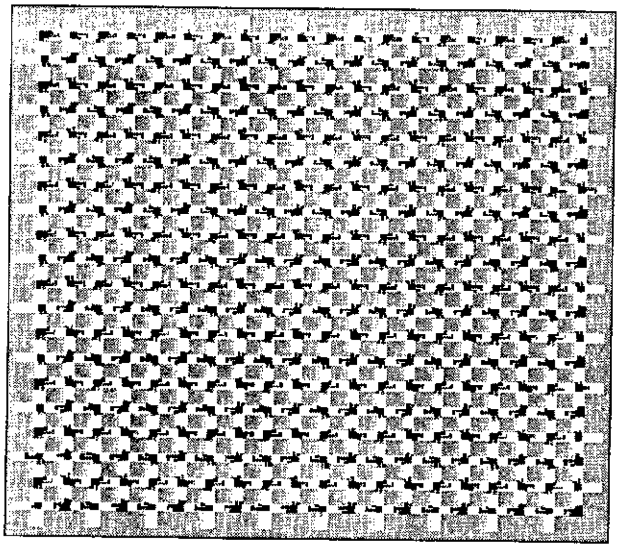


Fig 1.1. Traffic simulation network: Isotropic road network.

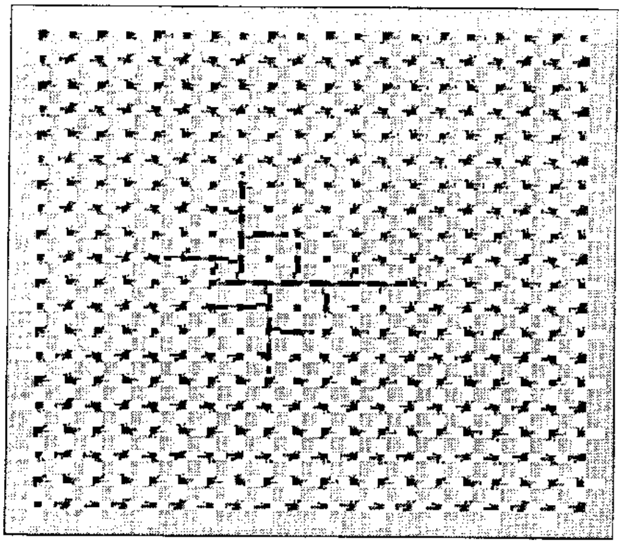


Fig 1.2. Traffic simulation network: Traffic jam evolution — Obstruction core formation.

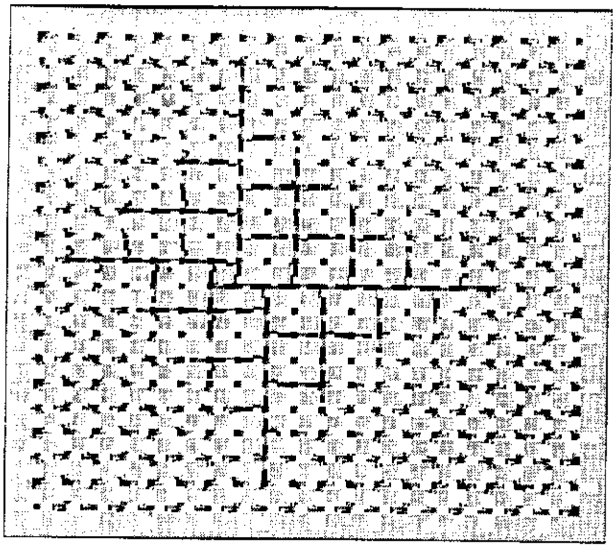


Fig 1.3. Traffic simulation network: Traffic jam evolution — Diamond envelope.

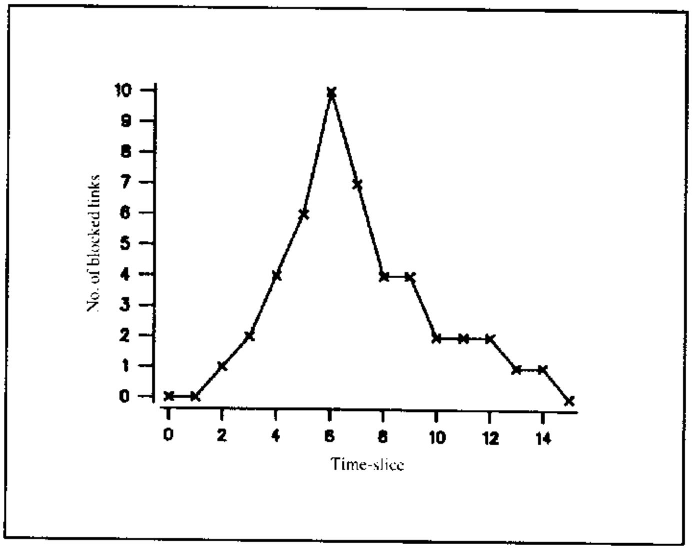


Fig 2.1. Dispersal mechanisms of traffic queues: Traffic jam decays — no obstruction present.

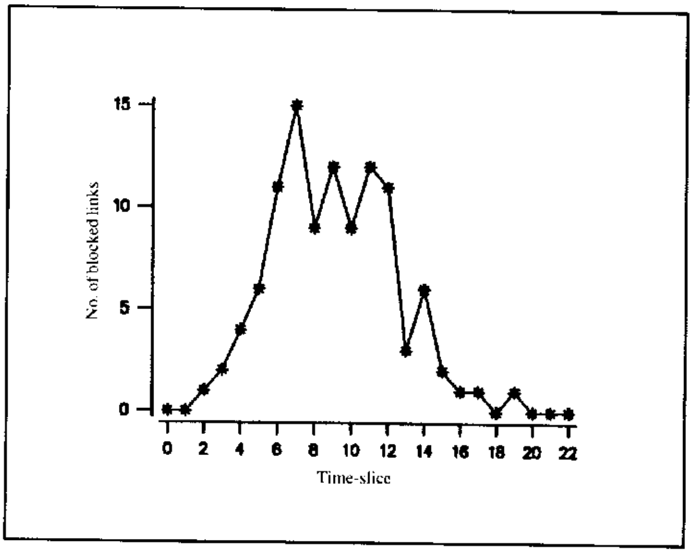


Fig 2.2. Dispersal mechanisms of traffic queues: Traffic jam including oscillatory phase.

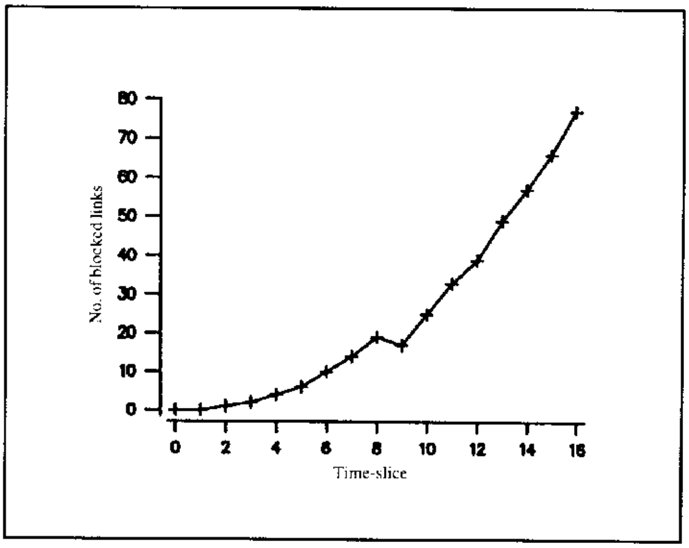


Fig 2.3. Dispersal mechanisms of traffic queues: Traffic jam grows — no obstruction present.

queueing vehicles. A record of blocked links is maintained and updated throughout the simulation. The extent of a traffic jam can be analysed by combining information about the number of blocked links with details about the total number of vehicles that pass through the whole system. These figures are assessed in the context of the graphical output obtained from the simulation.

The movement of vehicles via the release procedure for links is implemented in two phases. All the east-west movements are processed in the first phase, whilst the north-south movements are realised in the second phase. This encourages a slight asymmetry, reflected by slightly larger queues on the east-west road system in comparison with the north-south counterpart. This asymmetry is due to the relative position of the image in relation to the simulation time-slice.

4. THE STAGES OF THE COMPUTER SIMULATION

The Traffic Simulation Network has been implemented using the PASCAL programming language for an IBM 386 PC-compatible microcomputer. The modelling of congestion growth and its subsequent decay has been achieved by dividing the simulation into three stages[3]. The stages can be described as a 'RUNUP' period, a Jam Evolution period and an optional Dispersion stage.

4.1. RUNUP stage

In the RUNUP stage, vehicles progress through a system in which no obstruction is present. The total input to the road network is recorded at the beginning of each time-slice, as is the total output corresponding to the end of each time-slice. The difference between the input and output to the system forms a sequence which can be tested for stationarity using time-series methods[1]. Once the system has achieved its steady state, the RUNUP stage is terminated.

4.2. Jam Evolution stage

Once a steady-state flow is in operation, the growth of a traffic jam may be initiated simply by installing an obstruction on the network. Although in the model traffic incidents can effectively be introduced anywhere in the network, the research shall investigate the situation of a single obstacle placed towards the centre of the grid. The result of such an incident causes the traffic jam to evolve. Queues will begin to form, with one vehicle waiting behind another; and, depending on the severity of the original obstruction, a pattern of interlocking queues will begin to emerge. The accelerated growth of the traffic jam with time is presented in an animated visual form.

4.3. Dispersion stage

At any time during the Jam Evolution stage the cause of the obstruction may be removed, and the results of this action are also displayed graphically. In addition to eliminating the cause of the traffic jam, options are included to enable the controlled dispersion of the traffic jam, by employing a degree of external intervention. The long-term effectiveness of a chosen strategy may be observed.

5. QUEUES AND DISPERSALS: A CLASSIFICATION

Although in principle all traffic jams involve a sequence of vehicles waiting to proceed to their respective destinations, research[4] has shown that the queue formations can be divided into three distinct categories:

- — traffic queues on one or more links, but effectively independent;
- — queues which begin to tail-back, causing interference with the flow through the junction (queues begin to interact); and
- — queues which encircle the original source of congestion, creating a core of locked vehicles.

Following the onset of the third phase of the growth of a traffic jam, a pattern of four primary queues begins to emerge. These queues branch out into secondary queues which themselves extend to form larger centres of interlocking queues. The evolution of the traffic jam and its eventual shape can be seen in Figs 1.1, 1.2 and 1.3 respectively. The resultant traffic-jam image is defined by a characteristic diamond-shaped envelope, as shown in Fig 1.3.

The elimination of the original traffic incident leads to a change in the growth of the traffic jam. The variation is determined by the timing at which the extraction occurs. Again, one can classify the effect of removing the obstacle in the following way:

(1) Queues begin to disperse at varying rates.

(2) Queues cease to grow and begin to disperse after a short delay.

(3) Queue length fluctuates, causing the traffic-jam growth to accelerate or decelerate at regular intervals. Following the oscillatory period, the queues will either dissolve or grow.

(4) Queues continue to grow following an initial small reduction in queue lengths. This reduction, albeit temporary in nature, is due to the redistribution of the vehicles within the jam caused by the limited amount of extra space made available by the extraction of the obstacle.

Figures 2.1, 2.2 and 2.3 respectively demonstrate the differing characteristics of dispersal patterns. The nature of a dispersal is described by the number of blocked links included in the traffic-jam structure: the larger the number, the more extensive the jam.

Figure 2.1 exhibits the acceleration of growth caused by the presence of the obstruction. The removal of the obstruction, in the sixth cycle of the simulation, brings about an almost immediate reduction in the number of blocked links, and the eventual elimination of the traffic jam.

Figure 2.2 displays the third case of the classification for dispersals. The obstruction is eliminated in the seventh cycle of the simulation, resulting in an oscillatory phase, which is followed by the subsequent decay of traffic-jam growth.

The third graph, Fig 2.3, portrays the growth of the traffic jam up and till the obstacle is extracted. The extraction occurs in the eighth cycle of the simulation. Thereafter follows a re-arrangement of the vehicles within the queues, causing a temporary reduction in the number of blocked links which precedes the continuation of the growth of the traffic jam. This re-arrangement appears to be due to the additional space made available when the cause of obstruction is eliminated.

To qualify traffic-jam dispersal phenomena in terms of the above broad classification system is by no means an easy task. In simple terms, a traffic jam will either dissolve or else continue to evolve in some shape or form. The difficulties arise when trying to determine which type of congested situation is under consideration. The above framework is intended as an initial guide in helping to predict the outcome of traffic jam phenomena.

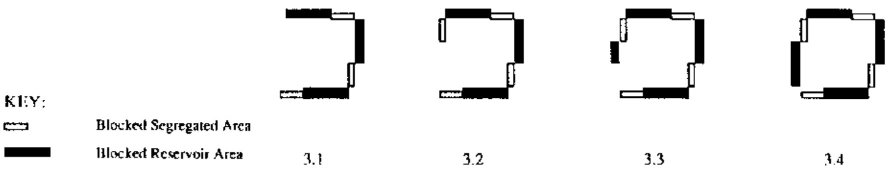
6. TRAFFIC-JAM EVOLUTION

To tackle the dispersal of traffic queues, it is first necessary to comprehend the underlying growth pattern of a traffic jam. An insight into the developmental stages of a traffic jam will enable the suggestion of two possible approaches solving this complex problem.

6.1. Developmental stages

A traffic jam can be described as an intricate system governed by many interactions. The form of a traffic jam involves a pattern of interlocking queues at various levels of severity. Having installed an obstruction on a link in the network, the movement of vehicles using this link is restricted. As a result a queue will propagate along the segregated portion of the link and will eventually spread across the whole width of the road, creating a blocked link. Following this, vehicles wishing to proceed via this link (either by turning or by maintaining an ahead direction) will be barred entry. Additional queues will now form on the links feeding the original blocked link, creating a sequence of interconnecting blocked links. This pattern repeats itself in a recursive manner and effectively creates cores of interlocking queues which tail-back along four sides of one or more city blocks. The stages are displayed in Figs 3.1 to 3.4 respectively. The formation of the initial cores around a single city block can be viewed as the onset of gridlock. This core will be referred to as the *obstruction core*. The examples in Figs 3.1 to 3.4 describe a core of vehicles formed by vehicles wishing to turn right. The corresponding core of vehicles requiring a left-turning movement can be defined intuitively.

Fig 3. Stages in the development of the initial obstruction core.



6.2. Anti-queues and jams

A secondary feature of the traffic jam is the starvation effect caused by the formation of the jam itself. Vehicles that under unobstructed conditions could access certain links are barred entry due to the fact that these links have become surrounded by blocked links. This phenomenon leads to unoccupied areas that are propagated from one link to another in much the same way as queues[2]. One can view the free links as anti-queues that link together to form an anti-jam that is complementary to the jam itself. The prevalence of empty space seems to play an important rôle in the decomposition of traffic-jam formations.

6.3. Attempts at dispersal

Simulation experiments have revealed that the formation and eventual closure of the obstruction core represent important stages in terms of queue development and dispersal. Two approaches can be considered when attempting to dislodge a traffic jam. The first is to allow the traffic jam to free naturally, whilst the second requires a degree of human intervention. The extent of the intervention depends on the severity of the situation. With both approaches a considerable amount of care is needed. This is largely due to the possible difficulties which may arise as a result of the removal of the original obstruction. This action does not bring about the immediate dispersal of a traffic jam. In some cases, eliminating the cause of the traffic jam will be the only action required. The queues will begin to dissipate in the reverse order to which they were formed, leaving the road network in an uncongested, free-flow state.

However, a frequent occurrence is the situation of a migrating traffic jam. Removing the obstacle in circumstances like these results in the original obstruction core being forced apart and subsequently freed. Whilst the initial core has been eliminated, a second core (and sometimes more) forms in nearby locations, creating fresh traffic-jam phenomena to arise. In such situations, extracting the obstruction does not result in the controlled dispersion of a traffic jam, but effectively moves the obstruction-core problem elsewhere.

Once the closure of the obstruction core has been achieved, removing the original obstacle will not be a sufficient measure. Although causing a temporary shift in the arrangement of the vehicles in the queues, the traffic queues are firmly lodged in each other, preventing them being forced apart. In such conditions, a degree of external intervention is required. Strategies in queue management represent the second approach.

7. SELF-RECOVERABILITY OF TRAFFIC QUEUES

The previous section has highlighted the different approaches in treating congested networks. The first approach, namely that of removing the original obstruction without any other form of intervention, is naturally to be preferred. This raises the question as to whether a threshold can be defined for the number of blocked links a network can sustain, yet still free without the application of external measures. Although the limit would relate specifically to the particular parameters of the simulation, it may be possible to utilise the information gained from the understanding of the principles of traffic-jam growth.

Repeated simulations have shown that the growth process of the traffic jam does not change radically when varying the parameters of the simulation. The parameters seem to govern the direction and rate at which the traffic queues propagate[2]. Essentially, however, the underlying growth pattern remains unchanged by the variations in the simulation parameters.

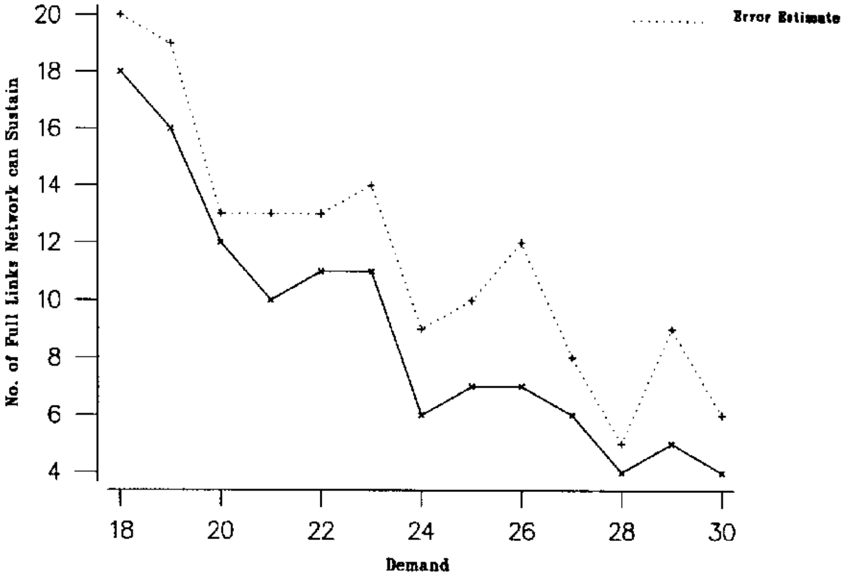


Fig 4. Upper bounds for self-recovering traffic queues.

7.1. Contributing factors

To extract information about the factors which contribute in a direct manner to a traffic jam's ability to disperse naturally, a suitable experiment was formulated. The experiment consisted of repeated runs of the simulation in which all the parameters were fixed, bar the level of demand. The experiment was replicated using a variety of set-up parameters. The aim was to discover the number of blocked links a particular network could sustain, yet still free once the obstruction had been removed. This figure was recorded along with a second number of blocked links, which represented the identical simulation run (achieved by replicating the sequences of random numbers), the only difference being the timing at which the obstacle had been removed. For this second figure, the extraction of the blockage was delayed one time-slice, resulting in the traffic jam losing its ability to disperse naturally. (Effectively the second figure describes an error estimate on the first figure.)

The simulation results have confirmed that the value of the threshold follows a downward trend, with each increase in the demand level. In addition, high levels of turning contribute to tighter interlocking structures whose *self-recovering* ability appears almost non-existent. The results are exhibited in Fig 4.

7.2. Interpretation

By repeating the simulation, varying only the level of demand, a network's self-regulating threshold can be determined. The results have been plotted along with an error estimate, as seen in Fig 4.

The experiment has confirmed the hypothesis that higher turning proportions result in a larger number of interactions. An increase in the propensity to turn causes a more rapid onset of 'gridlock' as well as traffic-jam formations which become increasingly difficult to dislodge. This idea is reflected by the value of the system's threshold. With high probability of turning the bound is relatively low, implying that the spectrum of self-controlling traffic jams is small. Once the traffic jams distribute themselves over larger areas the increase in the number of interactions means that the queues lose their ability to recover naturally. Conversely, low probability of turning allows for higher values of the upper bound, and a more extensive collection of self-recovering traffic jams.

The above experiment has drawn attention to the fact that a feature of most traffic-jam formations is an ability to recover naturally to an originally free-flow situation, once action had been taken in removing the obstruction. The extent of this ability is governed by the particular configuration which generates the traffic jam. Furthermore, there exists a critical point in the evolution of a traffic jam up until which a congested situation can recover its original free-flow state by the extraction of the incident which caused the congestion. Once this threshold has been reached the traffic jam loses its ability to free naturally — the strategy of eliminating the original obstruction is no longer deemed effective, and more active intervention is required.

8. COUNTERMEASURES FOR TRAFFIC QUEUE CONTROL

The nature of self-controlling traffic jams has led to the consideration of a dispersal strategy which has essentially tackled the problem from the angle of inhibiting traffic-jam growth. By preventing the onset of gridlock, it has been possible to dislodge most traffic-jam formations. However, it is often the case that traffic-jam phenomena reach more devastating proportions. In such circumstances, a preventive approach is of little use. What is required is a strategy that will alleviate the situation as it stands. The additional ingredient of gridlock contributes an expected degree of unpredictability. This makes the formulation of a coherent strategy a more difficult task. The objectives, on the other hand, remain simple. Assisted by a degree of external intervention, the aim remains to attempt to disperse traffic-jam formations which continue to grow even though the original obstacle has been extracted.

Detailed analysis of self-recovering traffic jams has shown that the disintegration of the original obstruction core plays a key rôle in enabling the dispersion of the traffic queues. One method of intervention focuses on forcing the core apart, thus reducing the interactions between the four primary queues. As a result, the traffic formation alters its shape. If successful, the traffic jam shrinks in size and eventually disappears. This method and its extension are essentially tactical in nature. The strategy locates the nucleus of the problem, and operates within this field.

8.1. Turn and ahead bans

One of the available alternatives within the computer simulation model involves the systematic application of turn (or ahead) bans along certain links of the network. Prior to the installation of bans, vehicles are able to turn in a prescribed direction or maintain an ahead direction. When a ban is set in place, the vehicles moving through the restricted link can only continue in an ahead direction for a turn ban and *vice versa* for an ahead ban. This research is concerned chiefly with the application of *turn bans* at specific road junctions in a prescribed pattern. One particular pattern will be referred to as the *core strategy*. A natural extension of this strategy which aims to tackle the traffic-jam migration phenomenon will also be described in this Section.

8.2. The core strategy

The core strategy is aimed at forcing apart the nucleus of the traffic jam. Initially, the nucleus is represented by the obstruction core, but in some cases the strategy must be directed to additional cores which may form as a consequence of the removal of the original obstruction. In circumstances like these, the operative field of the strategy must be extended.

The core strategy involves the installation of turn bans along the four links which comprise a core of obstruction, such as the one depicted in Fig 3.4. The relative position of a typical such core within the traffic jam can be seen in Fig 1.3. Introducing a set of bans effectively lessens the degree of interaction within the four primary interlocking queues. The effect of implementing this phase of the simulation is graphically displayed, with particular attention drawn towards the banned links. Figure 5 exhibits the consequences of applying the core strategy. The first graph describes the situation in which the traffic jam continues to grow even after having removed the original obstruction, this having occurred in the sixth cycle of the simulation. The second graph represents the identical situation, but the controlled dispersion of the same traffic jam has been achieved by introducing the core strategy in the twelfth cycle of the simulation. Both traffic jams continue to grow after extracting the cause of the jam, but the second traffic jam is successfully treated via the simple version of the core strategy.

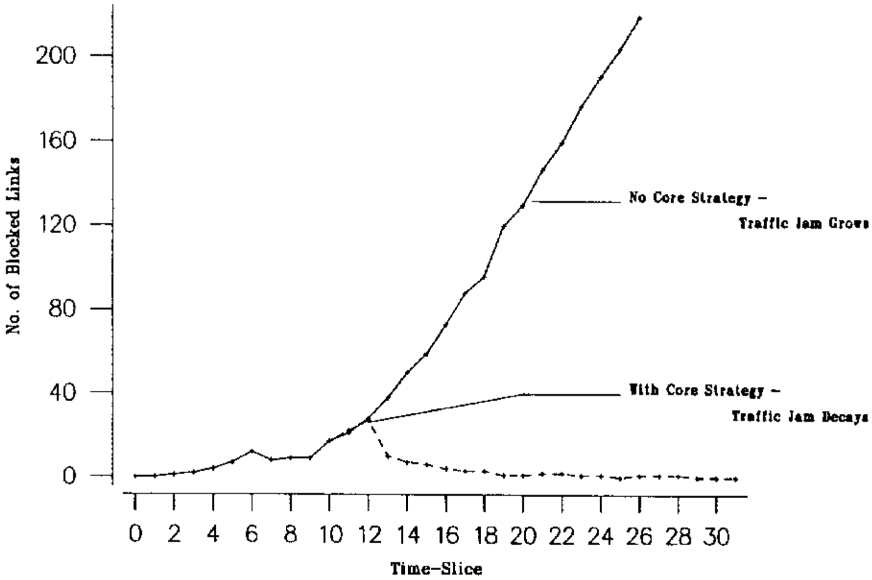


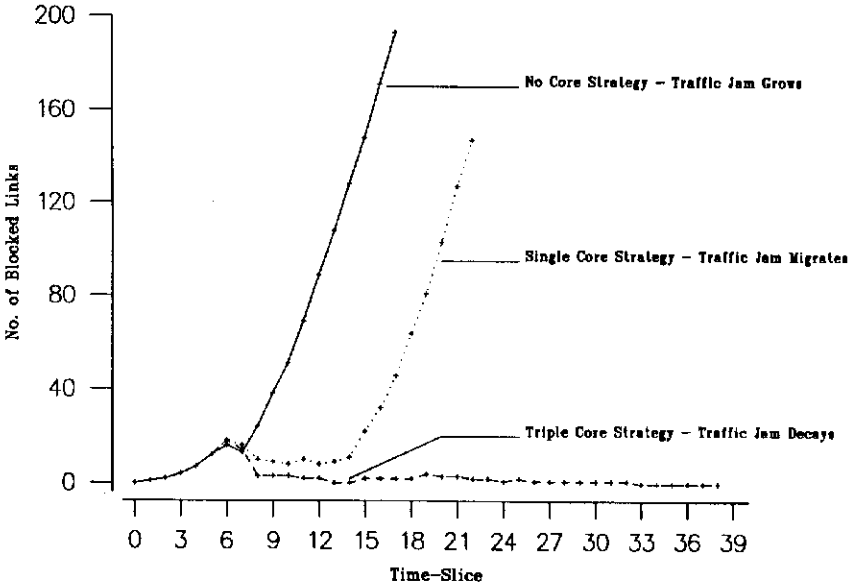
Fig 5. The core strategy.

8.3. Traffic-jam migration

The *core strategy* is not difficult to implement, and in addition it incorporates some of the knowledge gained from analysing traffic-jam phenomenon. However, as with all of the proposed strategies, an element of caution is required. As can be expected, one of the problems associated with the core strategy is the phenomenon of traffic-jam migration.

In certain situations, applying a set of turn bans to the original *obstruction core* often induces additional cores to form in nearby locations. The implications of such situations are fairly obvious. Whilst having dealt successfully with the original core, the prevalence of nearby cores often means that the emphasis of the traffic jam has simply been shifted elsewhere. In real networks, it is often the case that when vehicles are forced to go straight ahead at one junction, they will turn at the next available opportunity. The advantage of the graphical display becomes apparent when faced with such situations, and can be utilised to extend the power of the simple version of the core strategy. Instead of limiting the strategy to the obstruction core, when implementing the system of bans one can predict the possible nearby locations in which additional cores may form, and introduce similar cores of banned links. Figure 6 portrays this idea graphically. Applying the core strategy to the initial obstruction core brings about temporary relief to the traffic jam. Effectively the initial core has been

Fig 6. Obstruction core migration.



forced apart, but as a result two additional cores have formed nearby. When one of these cores becomes locked the situation is irretrievable and the traffic jam grows at the same rate as before the treatment was applied. However, the implementation of the *triple core strategy* has the desired effect. Instead of installing a single system of bans, the strategy has been extended to deal with the 'core shift'. The single system of bans has been replicated in the two areas where the traffic jam appears to migrate, resulting in the controlled dispersion of this situation.

9. CONCLUSIONS AND RECOMMENDATIONS

The research has established that the evolution of traffic queues over a rectangular grid network is a delicate process governed by numerous contributing factors. The formation of the initial obstruction core has been identified as a crucial stage in both the development and dispersal of traffic queues.

The potential self-recovering nature inherent in traffic-jam structures has highlighted two approaches for the successful control of traffic queues. The first considers traffic patterns which discourage the onset of gridlock and emphasises the limits involved in this technique. The second suggests practical measures aimed at alleviating congested situations of more extensive proportions. The measures attempt to tackle the problems associated with dispersion from a tactical angle (*core strategy*), and it is envisaged that future work will consider the problem from a distributed viewpoint.

The successful implementation of dispersal strategies is not always guaranteed. The use of an area-wide model enables the effectiveness of the strategies to be assessed both on the local level whilst simultaneously maintaining a long-term perspective. The results, particularly with respect to the core strategy, have demonstrated that as the network approaches saturation the system of queues becomes increasingly more sensitive to forms of intervention. The scope of operation and effectiveness of each strategy needs to be defined, to enable a more accurate assessment of the respective control measures to be prepared.

It would be desirable to expand the selection of available control strategies to include other forms of congestion regulation. In particular, it is expected that the development of metering and gating procedures[5] will contribute, in ways similar to the banning mechanisms proposed in this paper, to the controlled dissipation of interlocking traffic queues.

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REFERENCES

[1] ROBERG, P. and C. R. ABBESS. Fractal structure o traffic-jam images. *Proc., IMA Conference Complex Stochastic Systems and Applications*, 1993 (to appear).

[2] WRIGHT, C. C. and C. R. ABBESS. Queues an anti-queues: The evolution of traffic jams o rectangular grid networks. 1992 (unpublished).

[3] ROBERG, P. Traffic Simulation Network — Use Guide for Simulation Model. 1991 (unpublished).

[4] HUDDART, K. W. and C. C. WRIGHT. Catastrophi congestion, and some ways of preventing it *Proc., TRAFFEX 89 Conference: Congestio Control and Parking Enforcement*, PTRC London, 1989.

[5] SHEPHERD, S. P. Metering strategies applied t signalised networks. *Proc., ASCE 3rd Int Conf. on ATT, 1993*. pp.177-183.
