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Traffic Jam Simulation

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Abstract: This research is concerned with the properties of incident-induced traffic jams on rectangular grid networks and possible measures for preventing and controlling them. However, while most conventional traffic management measures aim to increase capacity and hence postpone the onset of gridlock, this research develops several alternative strategies for protecting networks from gridlock and dissipating traffic jams once they have formed. The treatment focuses on the installation of bans at specific network locations. Turn bans are imposed on selected links to break gridlock cycles at the centre of the traffic jam. By contrast, ahead bans are implemented around the traffic jam envelope to reduce input into critical sections of the road.

The control strategies have been tested using a simulation model and some general control principles have emerged. While not immediately applicable to real networks, since they incorporate simplifying assumptions, they point to certain general characteristics of traffic jam growth and dispersal which would not be accessible in any other way.

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1. Introduction

In urban areas, vehicles can interact with their environment in many different ways. Movement of the traffic stream is interrupted by signals, give-way lines, crossing pedestrians, parked vehicles, and so on. During the last decade, planners have been increasingly concerned about congestion. A queue on any particular link can propagate to other links upstream, so that a jam will spread out over an area of network and continue to grow until either the demand falls away or the obstruction is removed. Area-wide congestion is difficult to observe or measure in a scientifically precise manner, but colleagues at Middlesex University have used a combination of theoretical analysis and computer simulation to reveal some unexpected features of jam propagation for idealised grid networks.

In the paper, we consider the overall pattern of jam development. The network is an idealized uniform grid network with an inelastic pattern of traffic demand. Dynamic effects of the type generated by traffic signals are deliberately omitted and there is no underlying origin-destination matrix, allowing one to observe more clearly the underlying spatial structure, unobscured by local variations in network geometry and traffic flow. This has also led to the development of simple control mechanisms which have been tested using a simulation model and some general control principles have emerged. While not immediately applicable to real networks, since they incorporate simplifying assumptions, they point to certain general characteristics of traffic jam growth and dispersal which would not be accessible in any other way.

We begin with a brief discussion of other work in the area. This leads to a description of the key features of traffic jam development which is drawn from earlier results and previous work (Sections 2 and 3). In Section 4, we introduce a distinctive set of guidelines for dispersing gridlock-based traffic jams and the discussion thereof offers a more comprehensive conclusion to the problem of area-wide traffic jam control in general.

2. Background

Over the past few decades, traffic modelling has evolved along two paths: theory and simulation. Theoretical models concentrate on the mathematical analysis of a specific problem which is often stated in simplified terms. Computer simulations are employed when the dynamics of the problem are too complex to handle. The two approaches can thus be seen as complementary processes. Our research considered several theoretic traffic models, (Edie, 1974; Lighthill and Whitham, 1955; Vaughan and Hurdle, 1992; Newell, 1993; Daganzos, 1995; Holden and Risebro, 1995 and Wilson, 1995) and their suitability for representing traffic congestion in urban networks. However, these models were mainly concerned with traffic flow whereas our work deals specifically with what happens after flow has already broken down.

This led to the simulation approach, in particular to the work by Biham et al., 1992, who applied a cellular automaton model to model the evolution of traffic on urban networks. Their work deals specifically with the onset of ‘gridlock’ which the authors define as a loop of locked vehicles which can occur at any density of vehicles. A number of subsequent analyses (D’Souza, 2005; Holroyd, 2005), have been developed using this approach to determine a critical density p, which leads to this breakdown or the transition from free-flow to the jammed state. These models assume that a single vehicle occupies an intersection and do not study queue propagation properties which arise in the jammed state. This is the starting point for our work.

3. Traffic Jam Characteristics

3.1 Queue Propagation

If a blockage is placed, for example, on an east-west link within a one-way rectangular grid network, a queue will tail back initially until it reaches the previous upstream junction. A secondary queue will then form at right-angles to it, and from that point onwards, the two queues will propagate simultaneously. These two queues will then generate further branches in turn. Figure 1 shows the structure of a jam several minutes after the flow is obstructed by a blockage on an E-W road link near the centre of the grid. This mechanism reflects a 'horizontal' queuing approach.

Each link in the model contains two segregated queue storage areas terminating at the downstream stopline: one for the 'ahead' movement and one for the 'turning' movement. Each segregated area is of constant width: it may contain one or more lanes, but there are no shared lanes. Upstream of the segregated region, there is an upstream 'reservoir' which feeds into them both. It occupies the full width of the road. One can visualize the 'reservoir' as being channelized (ie, it may possess lane markings), but within this area, vehicles are allocated positions regardless of their intended direction of movement at the downstream junction. The 'reservoir' may be of zero length, allowing simulation with 'perfect' lane discipline everywhere.

3.2 Fractal structure

During the early stages of formation, the jam appears to have a boundary that is roughly diamond-shaped. But queue propagation does not take place at a uniform rate within that boundary, for two reasons. First, during the early stages, streets leading away from the core of the jam are unaffected by the initial blockage, so that on those links, traffic can continue to move normally. This can be seen in Figure 1, where roughly half the streets inside the boundary are empty of queues. As the jam grows in size, a secondary mechanism comes into play: many links become 'starved' of vehicles that are trapped elsewhere in stationary or slow-moving queues, and the shape of the boundary itself takes on a distinctive fractal structure.

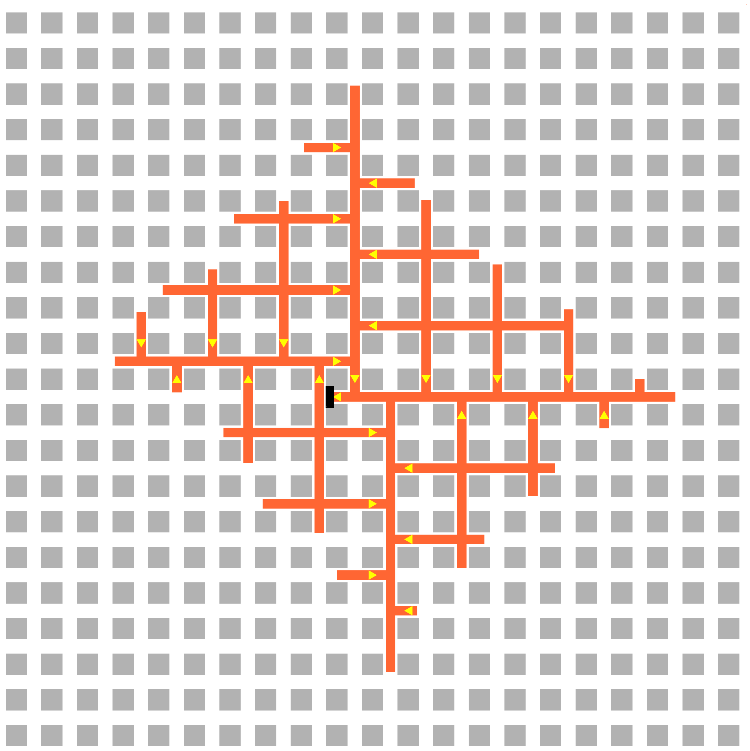

Figure 1 Simulated traffic jam on an idealised one-way grid network (after Wright and Roberg-Orenstein, 1999).

1. The traffic origins and destinations are arranged along the fours sides of the grid, with identical flow inputs on all inbound streets. The proportion of turning traffic is the same at all junctions.
2. Streets are one-way, with direction of traffic flow alternating between adjacent streets.
3. Each junction is treated as a traffic signal, with right-of-way given alternately to eastbound/westbound traffic, then northbound/southbound traffic.
4. The traffic jam was triggered by an obstruction marked by the black rectangle. The red bars represent stationary traffic queues propagating away from the core. Not shown are moving vehicles, or transioent queues that occur at uncongested junctions during each signal cycle.

Using a high-speed simulation technique in which randomised traffic flows are injected into the edges of a rectangular one-way grid, Roberg and Abbess (1995, 1996) have explored the evolution of traffic jams on very large networks roughly equivalent in size to that of Greater London. The results of one particular simulation are shown in Figure 2, which reveals indentations on each of the four sides of the jam. The indentations separate the queue system into four distinct ‘leaves’, coloured alternately green and orange in the diagram. Free of queues, they would in principle allow vehicles to penetrate close to the heart of the jam in a series of diagonal zig-zag movements. The indentations are repeated on successively smaller scales within each leaf, creating a frond-like appearance rather different from a 'solid' mass of traffic that one might expect. The fronds closely resemble those that occur in the microscopic accumulation of dust particles, a process referred to as 'Diffusion-Limited Aggregation' or DLA. The traffic jam shown in Figure 2 was initiated in the same way as with Figure 1, by placing an obstruction at the jam centre. The difference between the simulations is the grid size. In Figure 1, we used a 20x20 grid to demonstrate the queue development process in detail. In Figure 2, we used a 256x256 grid in order to obtain a "birds-eye" view of the developing traffic jam. The links that became blocked were colored (orange for N-S, and green for E-W), whereas the links that became starved of vehicles were left blank. In this way, we were able to highlight the gaps that form both along and inside the outer boundary of the traffic jam which lend a fractal characteristic to the developing traffic jam.

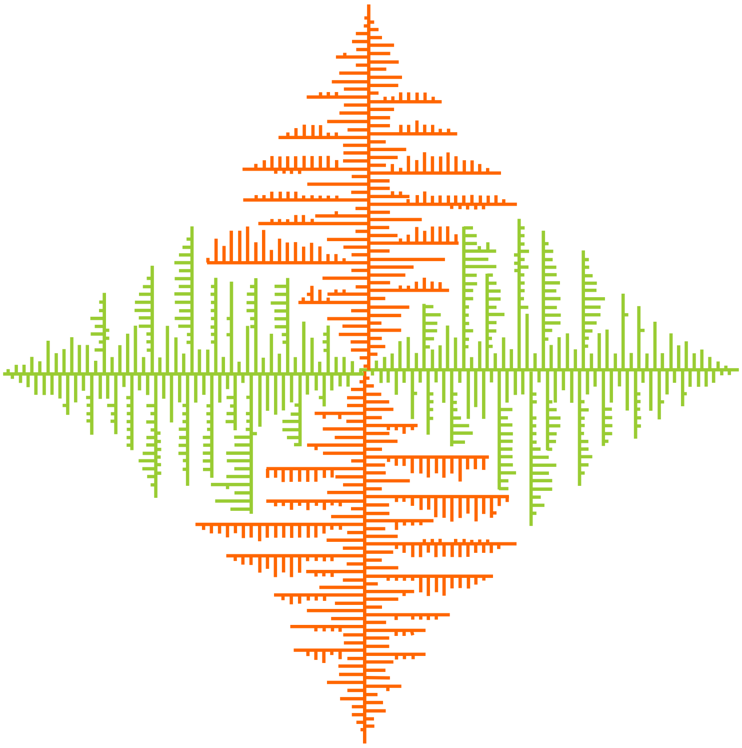

Figure 2 Simulated traffic jam on a one-way rectangular grid network roughly the size of Greater London.

4. Practical implications

There are two approaches for controlling traffic queues. The first, considers how features in the road layout, such as the allocation of queue storage space between ahead and turning vehicles, can be exploited to curb the rate of traffic jam expansion and to delay the onset of gridlock phenomena. These measures are *static*, i.e., road markings and street furniture that cannot easily be re-configured in response to traffic events. Several *static* countermeasures for delaying the onset of a traffic jam, or reducing its rate of growth once it has formed are suggested in (Wright and Roberg-Orenstein, 1999).

By contrast, *dynamic measures* include responsive measures which can alleviate congestion in response to traffic congestion. Here, we focus on a set of *dynamic* countermeasures and discuss their applicability to effective traffic jam dispersal.

It is convenient to consider the recovery from gridlock in three stages, each of which leads on to the next. The stages are *detection, treatment and evaluation*. The detection stage includes establishing the cause of congestion (for example using cellular phone callers, detectors linked to specialized software that can reliably diagnose queues, ANPR cameras and the like), ascertaining its severity and determining whether gridlock has occurred. An appropriate control scheme may then be implemented to treat the affected regions which is followed by an evaluation stage during which the effectiveness of the treatment is monitored and assessed.

4.1 Counter-measures for traffic jam control

The form of a traffic jam in a simple, idealized, one-way road network is characterized by gridlock cycles that develop at specific locations within the jam area. These cycles persist even when traffic demand falls away at the end of the peak period. External measures are required to break the interlocking queues apart and thereby restart vehicular movement.

The strategies involve the application of vehicle bans at a number of critical junctions in the network. The bans come in two forms: turn or ahead. Turn bans are imposed on selected links to break up gridlock cycles at the nucleus of the traffic jam. Ahead bans are used around the traffic jam envelope to reduce input into critical sections of the road.

If the demand is fairly light, or if the traffic jam is in its early stages of development, it is sufficient to ban a small number of critical turning movements (block-strategy) to clear the whole jam. However, experiments have demonstrated, (Roberg-Orenstein, 1994), that this expedient often forces the original gridlock cycle to move to a new location, close by in the network. This is known as *traffic jam migration*. Traffic jam migration can be dealt with by using multiple block strategies with increasing success. But, when demand increases, and the traffic jam has already assumed area-wide proportions, more extensive intervention is required. This set of measures (referred to as the *envelope strategy*) sets a cordon of ahead bans around the periphery of the traffic jam. Vehicles can either be queued outside the congested region (known as gating), or else re-routed away from the traffic jam. As far as this model is concerned, the simulated vehicles do not have specific destinations, they have no memory and do not care where they end up. Thus the re-routing technique is only useful in the short term. The gating approach is a safer concept in the context of this work.

Applying the *block* strategy and either of the *envelope* strategies in parallel (*an integrated control scheme*) provides a quick and effective mechanism to disperse traffic jams on the idealized network. Figure 3 graphically illustrates a particular arrangement of bans used in this scheme. Note how the *envelope* strategy (green squares) protects the emerging jam from excessive demand, whilst the single or multiple *block* strategies (red squares) treat the affected regions at the centre of the traffic jam. The shielding of the cordon minimizes the effects of traffic jam migration and the reduction in jam size and delay time can be dramatic within a few time-slices of the simulation process.

4.2 Numerical Results

Choosing an appropriate control scheme can lead to quantifiable gains in terms of the time it takes for the jam to clear and the total delay experienced in the network as a whole. Without appropriate control, the queues extend over the network and the total delay increases without bound. By implementing the turn bans at the jam centre a measure of reduction can be achieved, but only up to a point. Once the jam has achieved area-wide proportions, more extensive intervention is required, and the jam must be shielded from incoming traffic using ahead bans to re-route (or gate) the traffic away from the congested region and bring the network back to its original free-flow state.

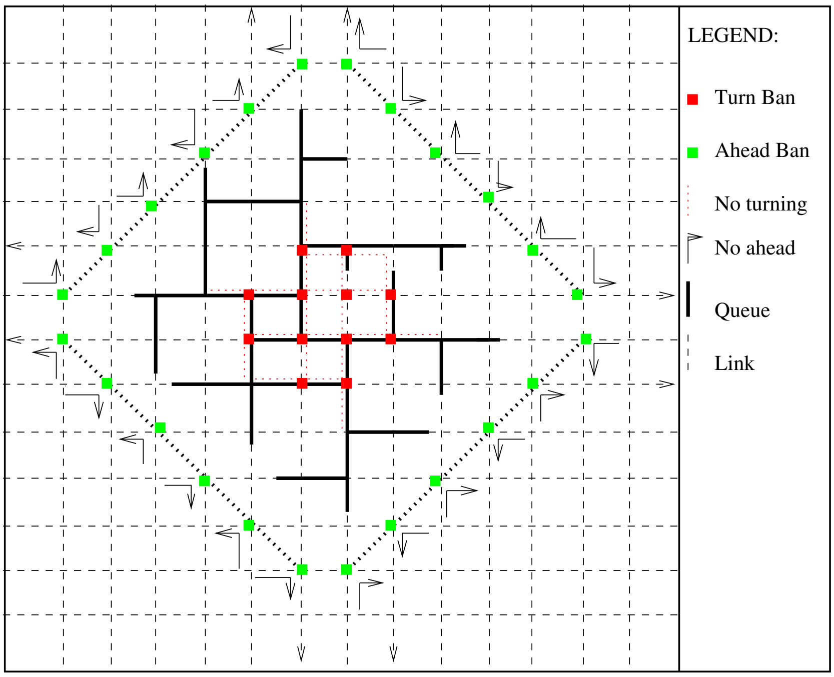

Figure 3 An integrated control scheme.

Table 1 provides some data to support this observation. Due to space limitations, the detailed calculations of delay are not provided in this paper. These can be found in (Roberg-Orenstein, 1997). Instead, we provide two performance measures to compare the relative efficiency of the different strategies in clearing the traffic jam. The first is cycle time: the number of cycles (each of one minute length) it takes to clear the traffic jam from the time when the obstruction was removed and control was implemented. The second is the increase/reduction in the total delay as a result of control.

For example, with a demand of 23 vehicles per minute, per entry point, a traffic jam clears by the thirty-fifth cycle, using a series of turn bans placed only at the jam centre. Each time slice lasts for one minute. But the simulation also calculates the total delay and if the re-routing strategy is applied in tandem with the turn bans at the jam centre, as opposed to turn bans on their own without shielding, the network delay is reduced by a factor of 36% (Column 4). The comparison in terms of cycle time shows a similar pattern: the time taken for the jam to clear is also reduced by a factor of 17% (Column 3). From a controller's perspective, both these savings can be significant.

However, if the demand is increased to 25 vehicles per minute per entry point, and the remaining jam parameters remain unchanged, the traffic jam fails to clear using the *block strategy* only and a shielding cordon of ahead-bans is required.

When using a gating mechanism (as opposed to a re-routing mechanism) at the jam periphery, simulation has shown that the total delay is approximately doubled. This is to be expected, as the gated vehicles must wait until being allowed to proceed, whereas the re-routed vehicles may continue, albeit under certain restrictions, towards a destination, not necessarily their intended one. We can also observe that implementing unnecessary bans (demand=18), can shorten the overall time it takes for the jam to clear (56% less), but the total delay increases by 9% because of the additional bans.

Demand (Veh. per minute)	**Turn Bans at jam centre only; block strategy (mins)**	**Turn Bans at jam centre with shielding cordon of ahead bans; integrated control scheme (mins)**	**% reduction in terms of time to clear**	**% change in total delay (veh-min)**
18	16	7	-56	9
20	16	9	-43.75	-18
23	35	29	-17	-36
25	FAIL	45	N/A	N/A
27	FAIL	84	N/A	N/A
29	FAIL	FAIL	N/A	N/A

Table 1. Time taken (measured in number of simulation cycles each of length one minute) to clear a traffic jam using two control strategies. The total delay experienced for each combination of demand and control strategy is not shown, instead the relative improvement using the strategies is provided in column 4. Note that under these levels of demand, the traffic jam fails to clear without control strategies even if the original obstruction has been removed (infinite delay). We do not perform any relative calculations for situations when traffic jams fail to clear.

Effective control implies selecting an *appropriate* measure for the congested situation. While the data in Table 1 relates to idealized traffic jams, nevertheless it is indicative of the impact of different strategies. We have used these indicators in formulating the results provided in Table 2.

Table 2 describes a set of guidelines for clearing gridlock-based traffic jams which may be used by the controller in selecting a suitable form of control.

Simulation experiments involving various strategies (including the *integrated control scheme*) found that dispersal was more difficult under increasing levels of demand and turning proportions and that it was best to allocate stopline widths between ahead and turning vehicles in proportion to the respective turning movements. A detailed sensitivity analysis analyzing the delay incurred using the *integrated control scheme* can be found in, (Roberg-Orenstein, 1995).

Detection
1. Identify and remove source of obstruction.
2. Locate and identify gridlock cycles.
3. Determine the extent of their development.
Treatment
4. Separate any interlocking turning movements (gridlock cycles) using ahead only restrictions.
5. Define a cordon which encloses the currently developed traffic jam.
6. Reduce the incoming flow into the congested region using an appropriate system of gates or diversion mechanisms.
7. Identify all potential friction points
8. Tackle friction points individually from the centre of the jam outwards using mechanism similar to criterion 4.
Evaluation
9. Remove the cordon of gates once congestion at centre has dissolved.
10. Remove internal restrictions and continue to monitor events until system has returned to original free-flow state.

Table 2.Guidelines for clearing gridlock-based traffic jams: dynamic control.

5. Conclusions

Our research has revealed a number of interesting traffic jam dispersal phenomena which point out the difficulty in selecting appropriate dynamic measures for traffic jam control. Unlike, the growth process, which develops in a predictable way, traffic jam dispersal phenomena are less straightforward. We can summarize the different outcomes as follows:

1. Traffic jam clears completely within a short time.
2. Traffic jam expands and contracts at regular intervals. The period of oscillation is followed either by dispersal or resumed growth. The fluctuations are due to the migration of the original gridlock cycle to a nearby vicinity: thus congestion may sometimes be transferred and not eliminated.
3. Traffic jam assumes static nature: it does not expand or contract.

4. Traffic jam migrates to new location.
5. Single traffic jam splits into two (or more) mini-jams which:
    - Resonate until one dies out followed by the other; or
    - Resonate until one grows and other dies out; or
    - Resonate until both become gridlocked and extend over the network
6. Traffic jam continues to grow regardless of counter-measures.
7. Traffic jam develops over network without and obstruction ever having been present (the spontaneous traffic jam).

We described an *integrated control strategy* for clearing one-way traffic jams. The strategy involved the application of turn bans at the jam centre to treat gridlock cycles there, together with a cordon of ahead bans applied at the jam boundary to reduce flow to the congested area, either via a gating mechanism, or via re-routing the vehicles away from the traffic jam.

The effects of boundary queuing may be reduced by replacing the gating mechanism with a re-routing option. However, in the simulation model, once re-routed, vehicles do not adhere to their original planned routes (since there is no underlying O-D matrix). This implies that the queuing option involves heavier delays to drivers caught in congestion. However, re-routing takes vehicles away from their destinations. In reality they would drive around until allowed to go where they wanted and delays might be large. But this effect was not simulated and hence not accounted for in the results. Hence the results from the queuing option might reflect more realistically what might happen under the assumptions made. This is a possible area of future research.

While in certain situations the proposed control mechanisms dispersed the traffic jams, they did not always work. This was mainly due to a mismatch between the selected control strategy and the traffic jam structure being cleared. In some cases, the traffic jam appeared to clear, but later on, it recurred elsewhere in the network (traffic jam migration). The complexity of such phenomena highlighted the importance of monitoring the effects on a local level while maintaining a long-term perspective. Thus, in some cases, *reactive control* was sometimes insufficient for treating traffic jam migration problems, whereas advance implementation of control measures (*proactive control*), treating potential gridlock cycles before they had formed completely was found to be more effective.

In this context one needs to address the issue of whether the measures we have proposed merely encourage more traffic demand and if such schemes are simply making things worse in the long term. A planning authority might want to consider limiting the amount (i.e. vehicle numbers and network length) of motorised transport on the roads, and instead, use the freed up road space to promote non-vehicular traffic (i.e., pedestrianisation, or reserved bus lanes). This is a possible direction for this research.

Building on the results of the study for one-way jams, we have extended the simulation model to deal with two-way idealized grid networks and to a lesser extent irregular road networks (Roberg-Orenstein, 1997). The general principles of traffic jam growth and dispersal have emerged but we have not yet applied any of the control principles from the one-way study to tackle such traffic jams. In theory, the mechanism would be to treat the internal parts of the traffic jam, whilst simultaneously reducing the flow into the congested region. However, the practical implementation of these control principles would need to be tailored according to the traffic jam under consideration. This represents a future goal for this research.

With the increase in popularity of wireless technology and the explosion of devices (cellular phones, pagers, notebooks, in-vehicle GPS systems and the like) one could implement dynamic countermeasures which would be responsive to up to date traffic conditions. Before doing this, more research is required to bridge the gap between the theoretical study and its application to real traffic situations. However, this topic is now feasible in view of the communication revolution that has occurred in the past ten years. The application of this theoretical research to real-traffic scenarios when coupled with the wireless information aspect is a fertile area for future research.

Software

Software for this project was written by the authors. A graphical simulation model for the simulation of the traffic jams discussed in this paper is available at http://wicat.poly.edu/faculties/penina/thesis.html, under the software download tab.

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