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METERING STRATEGIES APPLIED TO GRID NETWORKS

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CONTENTS

ABSTRACT

SHEPHERD, SP (1994). Metering strategies applied to grid networks. *ITS Working Paper **413***, Institute for Transport Studies, University of Leeds.

This paper describes the adaptation of traffic responsive metering strategies for use on grid networks. The study considers two hypothetical grid networks, a one-way and a two-way system with internal destinations.

The grids were simulated using the micro-simulation model NEMIS and were loaded in such a way that gridlock formed around the central square in both cases.

The adapted metering strategies were applied within the grid networks and were shown to be effective in preventing gridlock formation. The strategies also showed substantial savings in terms of time spent by vehicles in the system.

Section 1 gives a brief introduction, section 2 describes how the strategies were adapted for one-way grid networks and presents results and conclusions. Section 4 considers two-way metering and explains how the early cut-off approach introduced by Shepherd (1993) is required for a successful application of two-way metering.

KEY-WORDS:

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METERING STRATEGIES APPLIED TO GRID NETWORKS

1. INTRODUCTION

This paper describes the development and adaptation of method 1:MX and method 2:KX1 of the metering strategies described by Shepherd (1993) for use on grid networks.

The problem to be addressed by the metering strategies is the problem of very heavy flows such that gridlock occurs, whereby queues block upstream links around a square or loop until the original queue is also blocked.

The process of gridlock formation has been described and simulated by Roberg (1994) for a one-way grid system. This paper considers a similar one-way grid and also extends the study to a two-way grid network.

The metering strategies were adapted for use on grid networks by taking into account measures of congestion for all links immediately downstream of the gated link, weighted by an estimate of the turning percentage from the gated link. The method is extended further for use on two-way grids. In this case it is shown that a simple two stage system cannot prevent gridlock formation, but that a more complicated system of "Early Cut-off" stages can prevent gridlock when used in conjunction with the adapted metering strategies.

2. ONE-WAY GRIDS

The one-way grid simulated in this study consists of 16 signalised intersections. Each intersection has two entry links and two exit links; each link has two lanes, such that the vehicles can go straight ahead from both lanes but can only turn from one lane, left or right depending on the link. The capacity of each link is equal and determined in NEMIS by the number of lanes, as the car-following law does not contain any parameters which vary with lane width. All links in the network are 125 metres in length. The network nodes and link directions are depicted in figure 1.

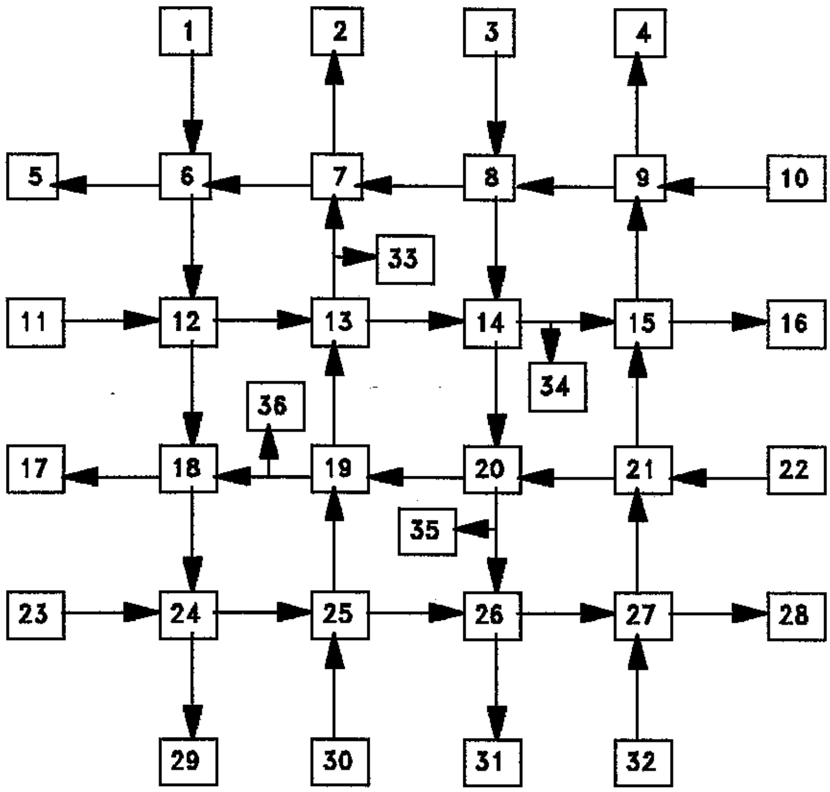


Figure 1: The one-way network

The network zones consisted of 8 external origins, 8 external destinations plus 4 internal destinations (nodes 33 to 36). Each intersection is signalised with two stages. Two fixed plans were tested for the one-way grid, a flow-dependent optimal plan based on equalising the degrees of saturation and a plan which caused gridlock with initial settings of 30 seconds of green followed by 5 seconds of amber for each stage, giving a common cycle time of 70 seconds. All the offsets were set to zero for both plans.

It must be pointed out that this second fixed plan is not an optimal plan, but one which causes a gridlock for the given demand in order to test the strategies. It will be shown later that for the one-way grid system the strategies respond to congestion and tend towards a plan similar to the optimal fixed plan.

The demand matrix used for all the simulations contained major flows towards the central destinations from all the origins to simulate a hypothetical morning peak period. The NEMIS static equilibrium assignment program described in the NEMIS manual was run before the simulation for each signal plan. This introduces the element of route choice into the NEMIS micro-simulation package. However it must be noted that the assignment does not change during the simulation so that vehicles do not respond to congestion in real-time.

The network plus initial gridlock formation can be seen in figure 2, taken from the simulation at time = 400 seconds.

The patterns formed by the gridlock are similar to those described by Roberg (1994) and Wright and Abbess (1991) for the one-way grid despite major differences in the two simulation models used. One major difference in the approaches was that Roberg caused the gridlock formation by placing an obstruction on one link, representing a loss in capacity due to a parked vehicle or incident whereas the NEMIS network contains internal destinations placed around the central square and no obstruction is required to produce a gridlock.

Similar conclusions were made about the conditions necessary to form gridlock. For example both studies found that as the percentage of turns within the "core" square increases then the likelihood of gridlock formation increased for the given signal plan. Another conclusion from both models was that once the gridlock had formed it was impossible to clear even if the demand was dropped to zero. This will be discussed later with reference to the assumptions in the blocking-back model incorporated in NEMIS for this study.

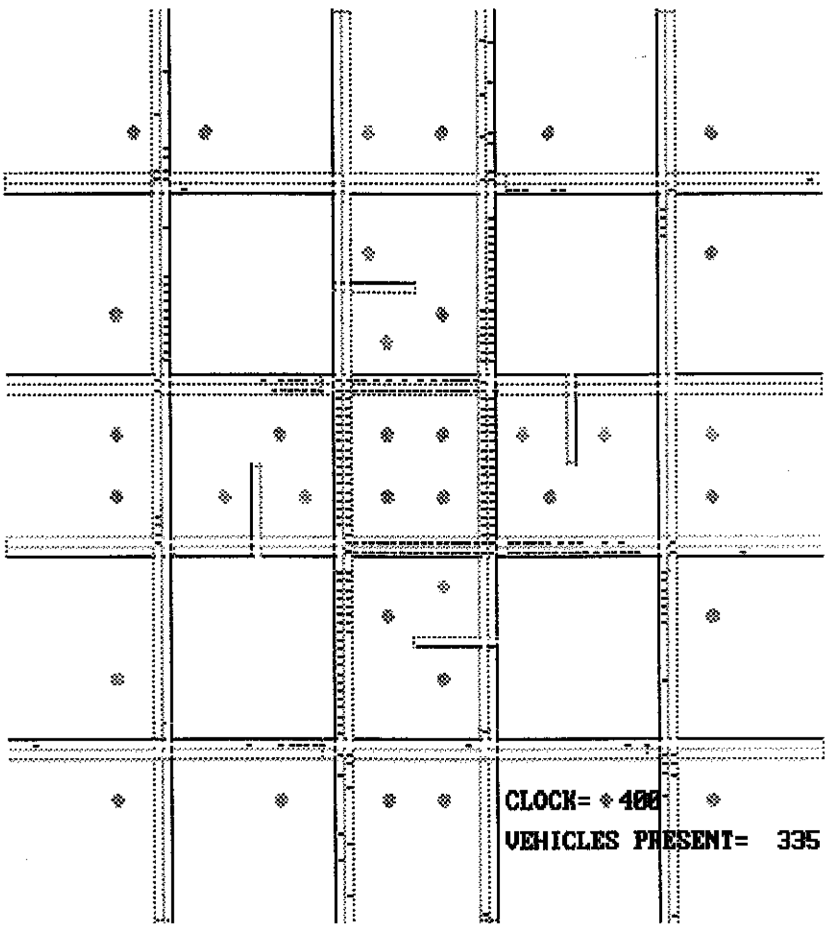


Figure 2: Initial Gridlock formation for the one-way grid.

2.1 ADAPTING THE METERING STRATEGIES

This study adapted methods 1 and 2 described by Shepherd (1993) namely the MX and KX1 methods respectively.

Both methods used the platoon dispersion model by Cremer and Schoof (1989) to give a measure of congestion on the immediate downstream links. The first step in adapting the strategies was to calibrate this dispersion model to the above grid network. Under normal conditions without gridlock, this could be done quite easily by adjusting the average travel time for a link and the assumed saturation flow at the end of the link. However when the link was blocked by a downstream link in periods of heavy congestion or gridlock the Cremer and Schoof model diverged from the NEMIS modelled queues and flows.

This effect is due to the model assuming that the departure rate during green time was equal to the saturation flow provided that there is a queue to maintain the flow. In NEMIS however the flow out of a link is reduced due to downstream conditions.

This error in the platoon dispersion model affects the modelled value of average density compared to the true value by always producing an under-estimate. Tests for this network showed that the model under-estimates the average density during gridlock by a constant amount, due to the fact that no vehicles enter or leave the core links and the model assumes the same amount leave per cycle. The modelled value is about 70% of the true value. This can be taken into account when setting the parameters in the metering strategies.

2.2 METHOD 1, THE MX STRATEGY

The strategy was adapted to take account of all downstream links and percentage turns as follows:-

$$g^{i}(k) = \frac{[g^{i}_{des}(k) + 2g^{i}(k-1) + 2g^{i}(k-2) + g^{i}(k-3)]}{6} \quad (1)$$

where

$$g^{i}_{des}(k) = Max\,(Min(\frac{g_{max}\sum_{i=1}^{n} P_{ij}X_{j}(k)}{X_{c}}, g_{max}), g_{min}) \quad (2)$$

$g^i(k)$ is the green time for link i at cycle k
$g_{des}{}^i(k)$ is the desired green time for link i cycle k
g_{min} is the minimum permissable green time
g_{max} is the maximum permissable green time
$X_j(k)$ is the percentage average space left on the downstream link j during cycle k
X_c is the critical average space left downstream
P_{ij} is the average turning percentage from link i to link j
n is the number of immediate downstream links

This formulation of the strategy calculates the length of the green times for both stages at each controlled junction. This has the effect of varying the splits, cycle and offsets within the network in a distributed manner according to downstream conditions only.

2.3 METHOD 2, THE KX1 STRATEGY

The KX1 algorithm was adapted in a similar manner to take account of percentage turns and all downstream links as follows:-

$$g_i(k+1) = Max(Min(\frac{q^i_{desout}\ (k+1)\ g_i(k)}{q^i_{out}(k)}\ ,\ g_{max}),\ g_{min}) \tag{3}$$

where

$$q^i_{desout}(k+1) = q^i_{out}\ (k) - K \sum_{j=1}^{n}\ [P_{ij}\ \bar{\rho}_j(k) - \bar{\rho}^d_j] \tag{4}$$

$g_i(k)$	is the green time for link i at cycle k
$q_{out}{}^i(k)$	is the modelled number of vehicles leaving link i in cycle k
$q_{desout}{}^i(k)$	is the desired number of vehicles to leave link i during cycle k
$\bar{\rho}_j(k)$, $\bar{\rho}_j{}^d$	are the average density on link j over cycle k and the desired average density for link j
K	is a gain feedback which determines the response of the control
P_{ij}	is the average turning percentage from link i to link j
n	is the number of immediate downstream links

Again this method was applied for both stages at each controlled intersection resulting in variable cycles.

3. RESULTS FOR THE ONE-WAY GRID

All simulations were performed with a constant demand from time zero to 600 seconds; this caused gridlock at around t = 400 seconds as shown in figure 2 with the fixed plan. At 600 seconds, the demand was dropped to zero to test the recovery of the network. The first tests were conducted for method 1:MX strategy applied to the four central junctions only, the idea being to meter the traffic into the core loop which caused the gridlock.

The graphs in figures 3 and 4 show the resulting green times for the set of links which feed the central square and the set of links which form the central square (i.e. where vehicles can leave the square or turn within the square). The value used for X_c is 60%, which is higher than those previously used to take account of the error in the modelling described earlier.

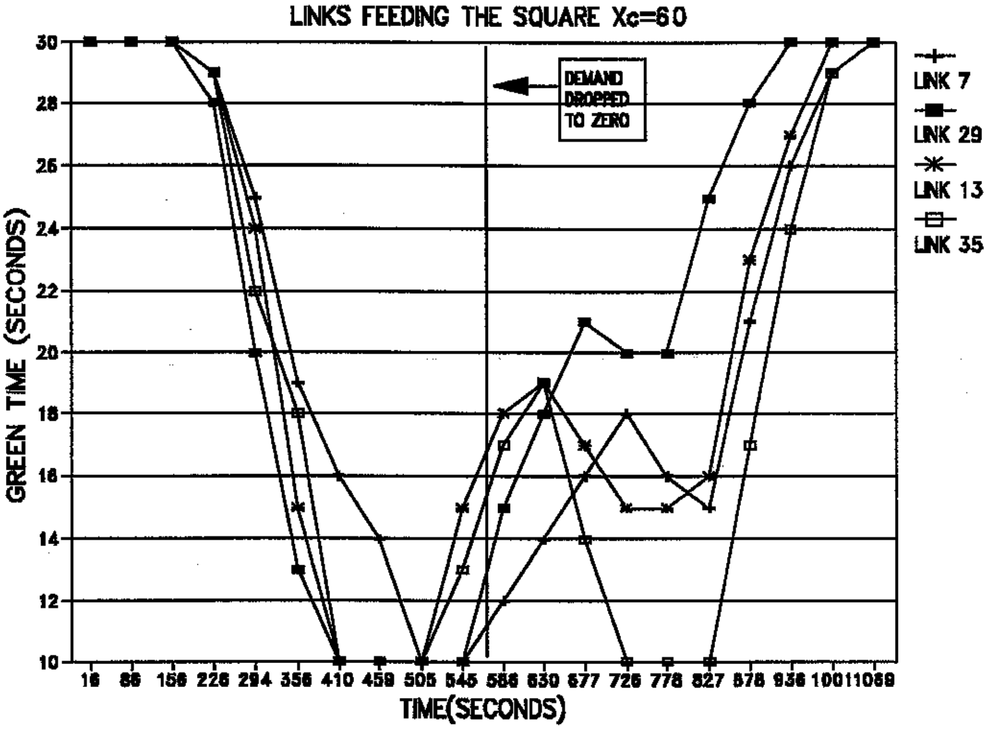


Figure 3: Green times for links feeding the square.

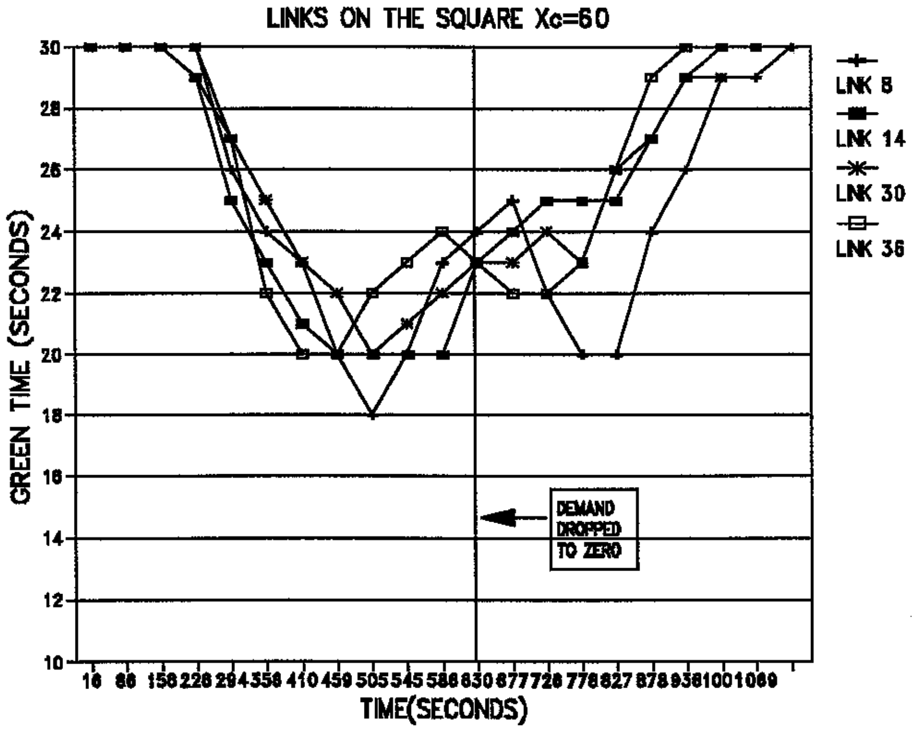


Figure 4: Green times for links on the central square.

Notice that the green times respond to congestion at around t = 200 seconds and that the green times recover to the maximum value as the congestion clears. An important feature is that the green times for the links on the square are longer than for those feeding the square; they dip to 20 seconds compared to the minimum value of 10 seconds reached by links feeding the square. This effect is due to the values of the turning percentages i.e. a higher proportion of vehicles are heading towards a congested link from the feeder links than from the square links. Taken together these timings have the effect of preventing gridlock and being able to recover from congestion.

Unfortunately it is impossible to compare the usual indicators such as travel time and delay in the system to the no control case (or fixed plan). This is because in the no control case the gridlock formed and trapped the vehicles in the network even when the demand was dropped to zero. These travel times cannot be collected by NEMIS as it only collects information about vehicles as they leave each link.

One measure of how the strategy has performed is to look at the number of vehicles present in the network over the simulation period shown in figure 5.

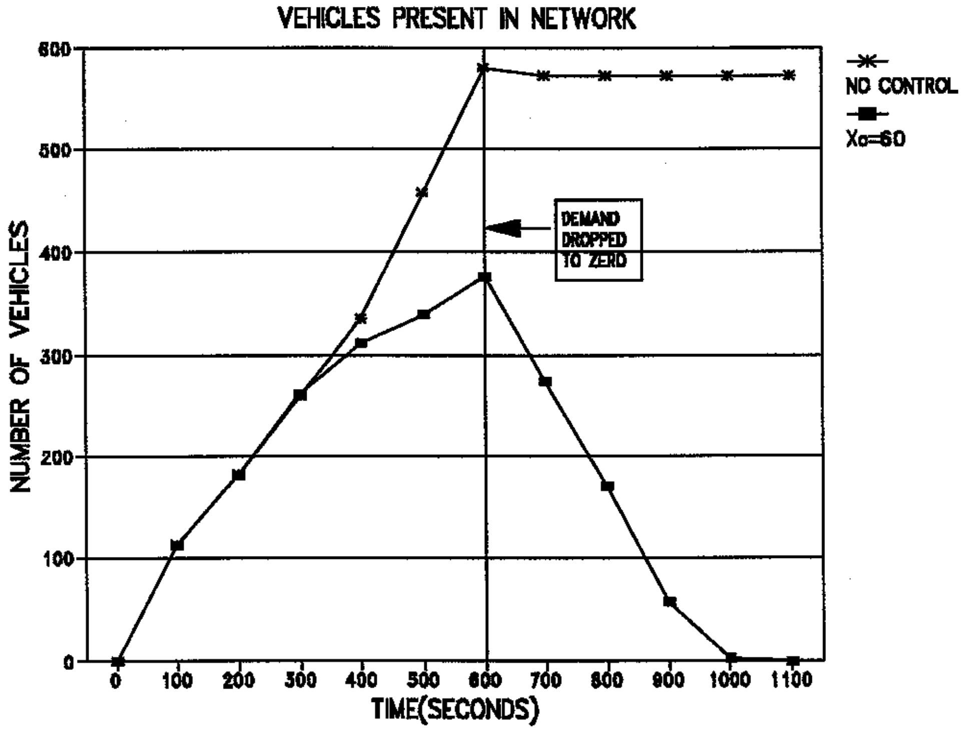


Figure 5: One-way grid method 1:MX : vehicles present in the network

It can be seen from figure 5 that as the strategy comes into action, the number of vehicles present in the network drops away from the no control case; this indicates more vehicles are leaving the network than in the no control case. At t = 400 seconds there is a marked increase in the slope of the no control case; this indicates the onset of gridlock and the fact that few vehicles are leaving the network. At t = 600 seconds the demand was dropped to zero to test recovery from the jam, the horizontal line in the no control case indicates gridlock is not recoverable, while with the strategy the vehicles can exit the network. The benefit of having the strategy could be said to be equal to the difference in areas under these two lines i.e. the integral of vehicles present gives total time in the system.

It was thought however that the "trapping" of vehicles in the system for ever more was unrealistic and that the effect of the blocking-back model incorporated in NEMIS may be too harsh. In effect the blocking-back model gives an upper bound for the benefits due to the strategy. A lower bound to the gridlock effect might be found by running the same simulations but without the blocking-back modelled i.e. cross traffic is not blocked and can in fact drive across a blocking vehicle.

Both the no control case and the $X_c = 60$ case for method 1:MX were run again without the blocking-back modelled. Figure 6 shows the vehicles present for all four cases. It can be seen that for no control, no blocking-back (NO CON NO BB) gridlock did not occur and that the network recovered. However, both cases with control produce very similar results in terms of the number of vehicles present in the network and both are better than the no control case without blocking-back. In fact these cases can now be compared as all the vehicles have left the network. The control cases are 11% better in terms of total time in the system over the no control case. This is a lower bound on the benefits as the true effect of blocking back is likely to be somewhere in between the two cases.

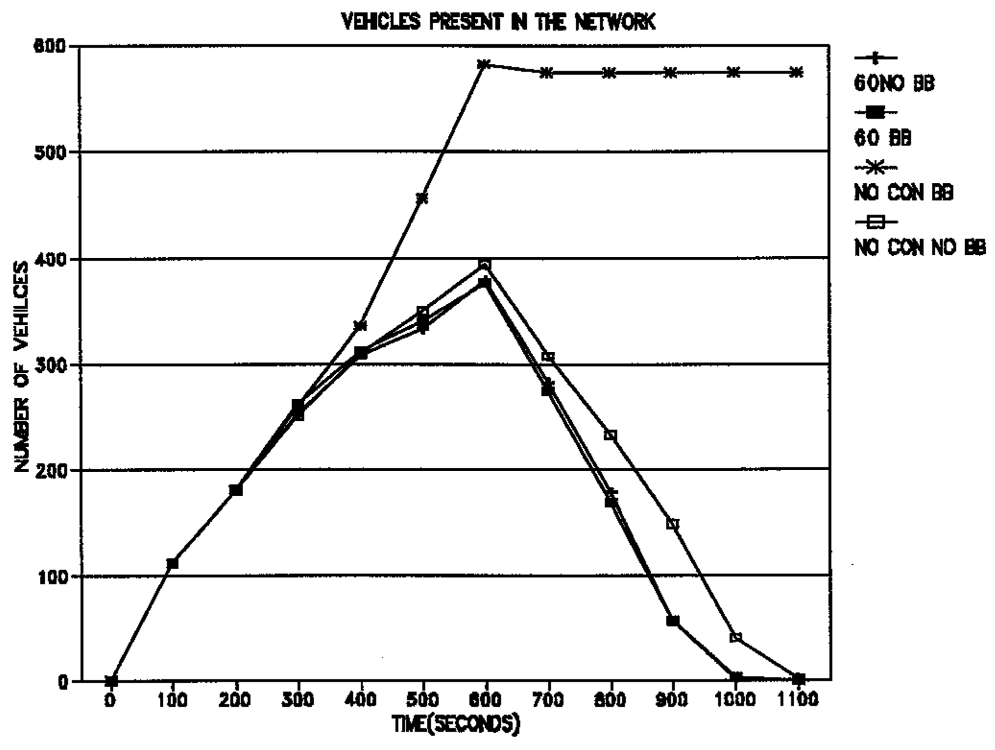


Figure 6: The effect of modelling blocking-back on vehicles present in the network

3.1 METERING AT ALL INTERSECTIONS

In the previous case, where only the four central junctions were controlled, it was noted that queues on the metered or gated links could block-back and interfere with the upstream junctions. To counter this effect all junctions were controlled by the strategy. Both method 1:MX and method 2:KX1 were simulated in this way for various values of critical percentage space and desired density respectively. Figures 7 and 8 show the number of vehicles present over time for the two methods, compared to the no control case without blocking-back modelled. Table 1 shows the percentage reduction in travel time for each method over the no control case without blocking-back modelled.

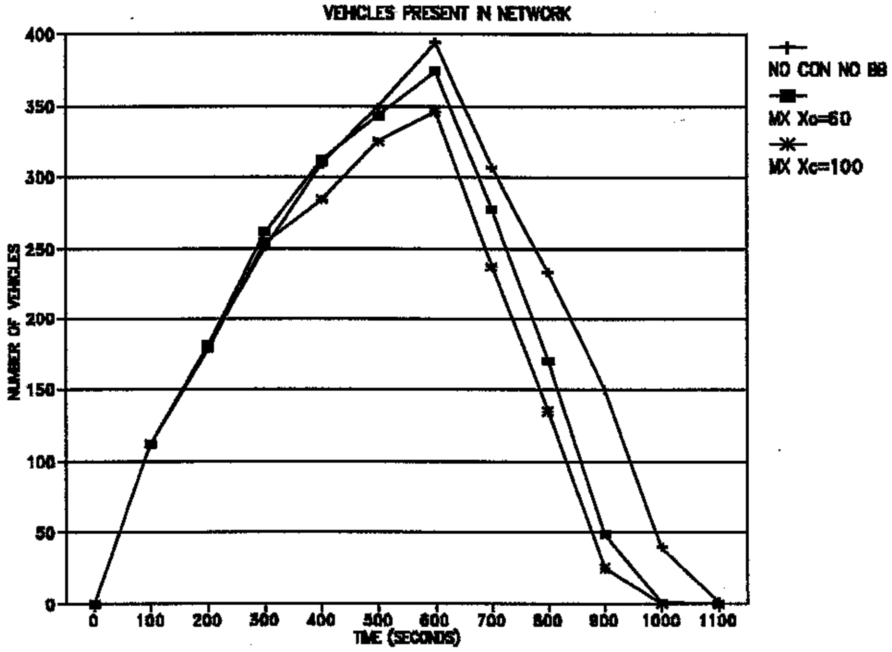


Figure 7: Method 1:MX metering all intersections : vehicles present in the network

Table 1: Percentage reduction in travel time

	Method 1:MX		Method 2:KX1 (K = 1)	
Percentage Reduction in travel time	$X_c = 60$	$X_c = 100$	$\bar{\rho}^d = 40$	$\bar{\rho}^d = 0$
	11%	19%	12%	20%

Note that the values of the parameters used in both methods seem far harsher than in the arterial case reported by Shepherd (1993). This is partly due to the under-estimates of congestion as explained earlier and also because the method is now considering all downstream links from a node, some of which may be free-flowing. Both methods show substantial benefits even though the above figures are only a lower bound on the benefits.

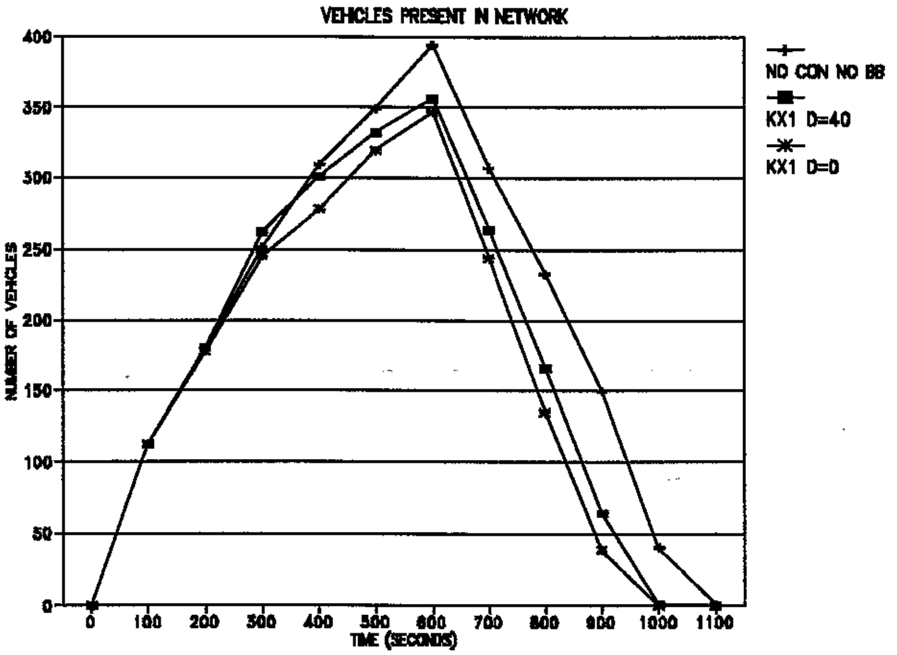


Figure 8: Method 2:KX1 metering all intersections : vehicles present in the network

3.2 SENSITIVITY TESTS

In order to get an idea of the difference between the upper and lower bounds on the benefits it was decided to perform a sensitivity test on the effect of the blocking-back model.

The basic assumption in the blocking-back model is that when the next link or lane for a vehicle is blocked downstream or a cross link is blocking the vehicle's path, then the vehicle will be forced to wait at the stop line until the path is clear. The model was intended to work in a similar fashion to a yellow box junction, i.e. vehicles only proceed if the way is clear. The current method for determining if a link is "blocking" is to check for the existence of a queue within the last 5 metres of a lane. If there is a queue then any vehicle wishing to cross or turn into this lane is blocked and will not set off from the stop line until the condition is cleared.

The value of 5 metres was varied and the simulations for the no control case run again. The values used were 2, 5, 10 and 15 metres; all gave the same result in that gridlock formed and could not be cleared. In the extreme case of gridlock it seems that the blocking-back model is insensitive to variations in the above parameter. It was therefore concluded that the simulations should be compared to the case without blocking-back modelled and the benefits be stated as a lower bound.

The effect of cycle times was also investigated. Three sets of fixed cycles were used, namely 30, 70 and 110 seconds which correspond to green times of 10, 30 and 50 seconds in each stage with inter-greens of 5 seconds. In all cases the two stages received equal green times. In all three cases if blocking-back was modelled then gridlock formed and could not be cleared, i.e. varying the cycle time did not prevent gridlock formation.

As mentioned earlier the previous base plan was used to test the strategy in gridlock conditions. It is possible, for the one-way grid network at least, to prevent gridlock by using a different fixed plan. If the plan is selected according to the usual equisaturation policies then the resulting plan gives similar results to the two metering strategies applied above. In fact the optimal plan consists of similar green times at the four central junctions to those obtained from applying the two strategies, i.e. it gives less green time to those links entering the core loop than to those which are leaving or turning within the loop.

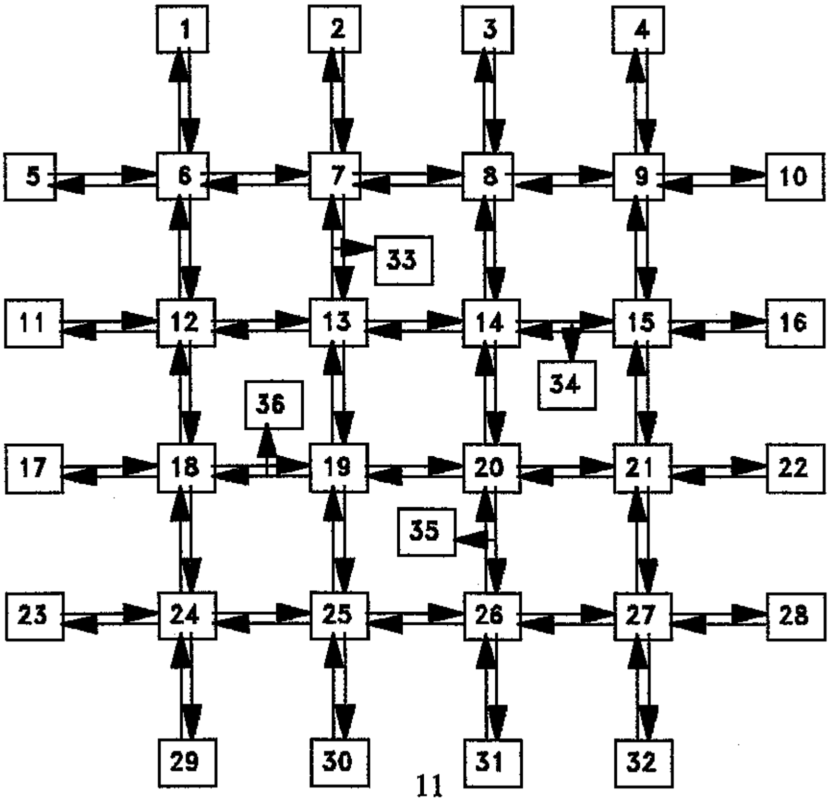
3.3 ONE-WAY GRID CONCLUSIONS

Both methods 1:MX and 2:KX1 have been proven to be effective means of preventing gridlock formation and provided substantial benefits to the system in terms of total travel time. The method of implementing the strategies goes completely against current UK practice in that it results in varying splits, cycles and offsets within a tight region compared with the usual common cycle times and co-ordinated offsets. The signal settings have been determined in a distributed manner paying no attention to co-ordination between intersections and yet have tended to move the signals towards the optimal plan. For one-way grids it seems that an optimal fixed time plan, i.e. without gating, can be constructed to avoid the problems of gridlock. It will be shown that this is not the case for the two-way grid network. The aim of the metering strategies has been to prevent those conditions whereby junctions disrupt not only each other but also the model used in the system.

4. RESULTS FOR THE TWO-WAY GRID

The two-way grid consists of 16 signalised intersections, 16 external origin and destination nodes and 4 internal destination nodes as shown in figure 9.

Figure 9: The two-way grid network



Each intersection is again controlled by two stages with all turning movements possible from each link. Each link consists of two lanes 125 metres in length with straight ahead movements allowed from either lane and turning movements allowed from the left or right lane as appropriate. A snap-shot of the two-way grid graphics is shown in figure 10 with an extensive jam at t = 600 seconds. The symmetric demand matrix used for the study has major flows from the external origins to the internal destinations. The optimal fixed plan based on equi-saturation is to give equal green times to each stage due to the symmetry of the grid and demand pattern used. It should be noted that even with this optimal plan a gridlock formed and could not be cleared. A sensitivity analysis of the assumptions about the optimal fixed plan was carried out using TRANSYT and will be discussed in section 4.4.

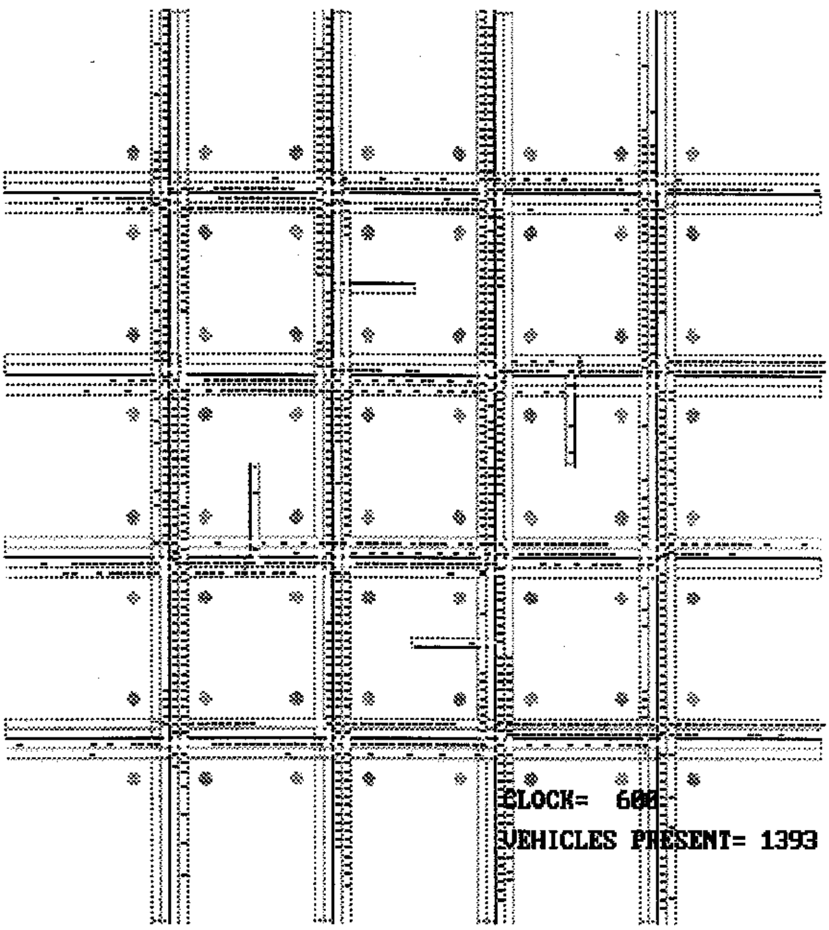


Figure 10: Initial gridlock formation for the two-way grid

Again the three sets of cycle times 30, 70 and 110 seconds were tested with the same results, i.e. if blocking-back is modelled then all three caused gridlock. If blocking-back was not modelled then gridlock still formed for the 70 and 110 second cycles, but the 30 second cycle managed to clear the network when the demand was dropped to zero. This is an indication that the problem of gridlock is more severe for a two-way grid system. The shorter cycle time provides some protection against gridlock as it naturally meters the area due to the greater percentage of lost time per cycle.

4.1 TWO-WAY METERING

When applying the metering strategies to a two-way grid, both directions must be considered for each stage. If one direction is to be "gated" or shortened according to the strategy, then the opposite direction is also gated. This is a direct consequence of using a simple two stage cycle. When the metering strategies were applied in this manner the onset of gridlock was delayed but it was not prevented totally.

Figure 11 helps to explain the reaction of the gating system under two-way operation.

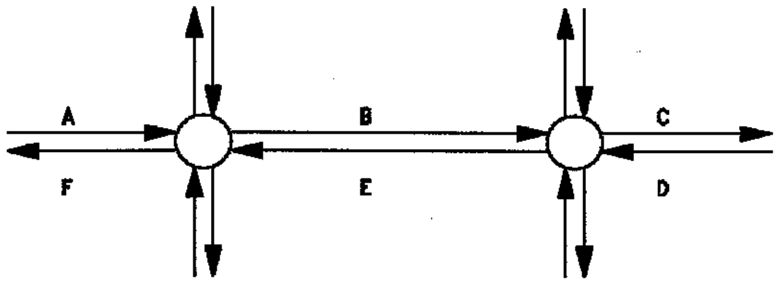


Figure 11: Gating under two-way operation

Suppose that link B is congested, then the green time for link A will be reduced as a direct response to the congestion on link B. However this implies that the green time for link E must also be reduced (as it is in the same stage). This in turn causes congestion on link E. In response the green time for link D is reduced which also reduces the green time for link B thus making the situation worse.

In fact it was seen that for junctions on the central loop both stages were reduced at a similar rate until the minimum values were reached. This was equivalent to using a fixed plan with a cycle time of 30 seconds and, as explained earlier, this caused gridlock when blocking-back was modelled.

It became obvious from the above argument that some form of gating was required which could be implemented without upsetting the outbound or opposing traffic. The "Early Cut-Off" approach used in the arterial network study described by Shepherd (1993) was therefore adapted for use on the two-way grid. The early cut-off approach inserts extra stages which cut-off one direction whilst allowing the other to continue. These stages are often used to aid turning movements with filter stages. In the case of figure 11. a stage would be called after the main stage which cuts off link A in response to congestion on link B but which allows traffic to exit link E. Both methods were implemented for all junctions using the above early cut-off approach.

4.2 METHOD 1:MX RESULTS

Both methods were compared to the optimal fixed plan with a 30 second cycle with no blocking-back modelled, as this was the only fixed plan which could recover from the jam and hence give a comparison. The early cut-off approaches were implemented within a cycle time of 70 seconds which meant that there was a maximum green time of 30 seconds for any one link per cycle. Figure 12. shows the graph of vehicles present over the simulation period for the fixed plan and two cases, $X_c = 60$ and $X_c = 100$ for method 1:MX. The 70 second cycle fixed plan which caused gridlock is also shown to give an idea of the extent of the gridlock.

In terms of total travel time in the system both cases gave a reduction of the order of 35-37% over the optimal fixed plan based on a 30 second cycle with no blocking-back modelled, i.e. the only plan which could recover.

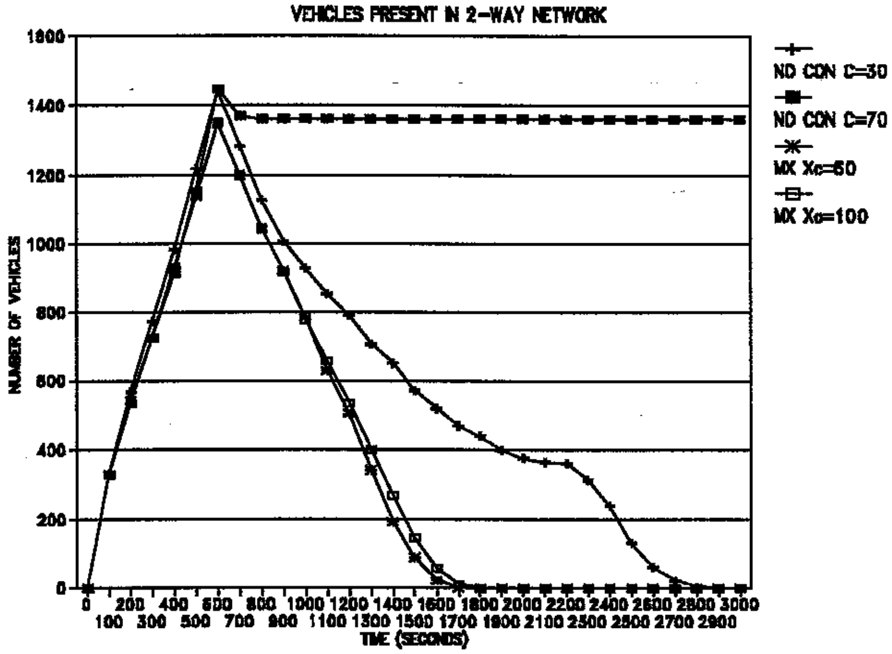


Figure 12: Method 1:MX two-way results : vehicles present

4.3 METHOD 2:KX1 RESULTS

This method was simulated for two cases with the same parameters as used in the one-way grid scenario. Figure 13 shows graphically the number of vehicles present in the network over the simulated period, again compared to the optimal fixed plan with a 30 second cycle (no blocking-back modelled) and the fixed plan with a 70 second cycle. Again in terms of total travel time in the system both cases gave a reduction of the order of 38-39% over the optimal fixed plan.

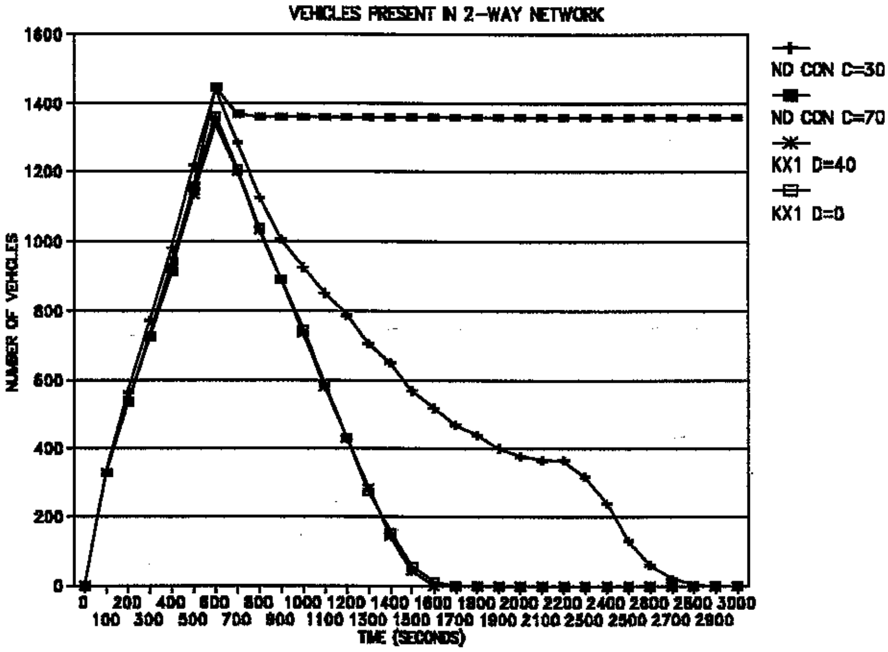


Figure 13: Method 2:KX1 two-way results : vehicles present

4.4 SENSITIVITY TESTS

The optimal fixed plan used as a base case was derived by equalising the degrees of saturation at each node and testing the responses via simulation for various cycle times as described in section 4. However these plans assumed zero offsets between the junctions, i.e. all stage ones started at the same time. This assumption was tested by running TRANSYT for various demand factors. Although TRANSYT gave different offsets from those assumed it gave the same green splits, and the difference in the performance index between assumed and optimal settings was only of the order of 1%. The TRANSYT optimised plan was simulated using NEMIS giving very similar results to the zero offset plan in terms of travel time and gridlock formation. It was concluded from these results that the previous base plan could be used as an optimal base case. This lack of sensitivity to the offsets was due partly to the oversaturation but mainly to the symmetry of the network, the symmetry of the flows and the fact that the central square is acting like a two-way signalised roundabout. This lack of sensitivity will not necessarily be reproduced for other networks.

The effect of implementing the strategies at various demand levels was also investigated using NEMIS and TRANSYT. Figure 14. shows the demand versus travel time curve resulting from NEMIS simulations for the fixed plan and Method 2:KX1 with desired densities of $\bar{\rho}^d$=40 and $\bar{\rho}^d$=0 percent.

It can be seen from figure 14. that the demand at which the travel time line rises suddenly is where gridlock occurs. For the fixed plan this is for a factor of 0.7, for $\bar{\rho}^d$=40 the gridlock is delayed to f=0.9 and for $\bar{\rho}^d$=0 it is possible to clear the network for f=1.1. This is because with $\bar{\rho}^d$=0 the metering is harsher and basically the vehicles are forced to queue up at the entrances to the network. There are no adverse effects from running the strategies at lower flows, as the strategies do not act until there is a problem. Note that all previous results were for a demand factor of f=0.8. where gridlock occured for the fixed plan.

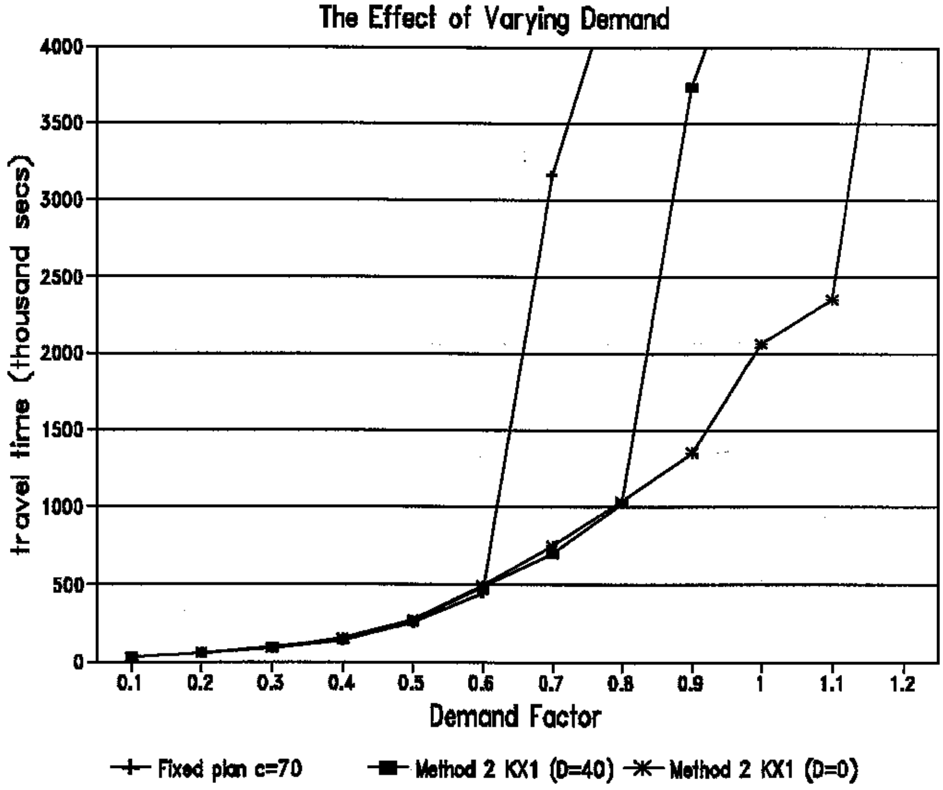


Figure 14: Varying demand in NEMIS $(D=\bar{\rho}^d)$

The effect of varying the demand in TRANSYT can be seen in figure 15. which gives the TRANSYT performance index for each demand factor from 0.1 to 1.0. The graph steepens from f=0.6 onwards due to the over-saturation delay plus random delay modelled in TRANSYT, but the effect is not as marked as the simulation results from NEMIS when gridlock occurs.

The difference between the two graphs basically occurs at the point of gridlock formation. This is due to the way in which the models simulate interaction between flows on different links. In TRANSYT the flows are independent of each other, i.e. there is no blocking-back of upstream junctions, whereas in NEMIS the blocking-back is modelled through individual vehicle simulation and results in gridlock formation. This indicates that TRANSYT is not well suited to modelling such over-saturated conditions and that as demand exceeds capacity metering signal strategies can outperform TRANSYT fixed plans.

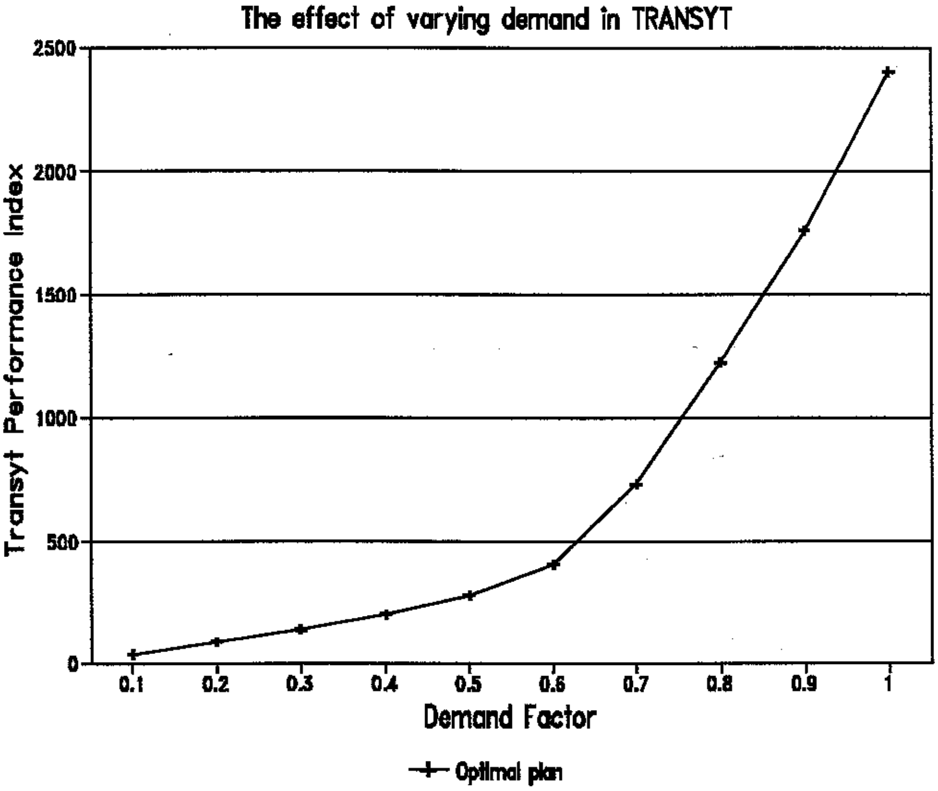


Figure 15: Varying demand in TRANSYT

4.5 CONCLUSIONS FOR TWO-WAY GRIDS

First of all it must be pointed out that for the two-way grid the optimal plan based on flows was to give equal green durations to both stages at each junction. This was due to the symmetry of the network, the equal saturation flows and the symmetry of the demand matrix used. This optimal plan caused gridlock for all three sets of cycle times tested when blocking-back was modelled.

Secondly the gridlock formation was similar to that of the one-way grid, in that the central square became blocked on all sides. This implied that an effective means of preventing gridlock would be to use shorter stages feeding the central square than those leaving the central square. However this is not possible for a two-way grid with a simple 2-stage sequence at each junction, as each stage contains both a feeding and a leaving link.

It was shown that a 2-way metering system could be effective if an early cut-off approach was introduced, thus enabling the above arrangement of green times. In effect the introduction of these cut-off stages makes the two-way grid temporarily imitate a one-way grid system.

5. GENERAL CONCLUSIONS

It may be concluded from the above study that metering strategies are an effective tool for delaying the onset of gridlock formation and for dealing with highly saturated grid networks in general.

It should also be noted that a one-way grid contains properties which make it less susceptible to the formation of jams, given the correct signal plan. It is the topology of the one-way grid which gives the traffic signal plan far more flexibility. The two-way grid system can imitate a one-way system if early cut-off stages are used.

As the strategies have been implemented with no concept of co-ordination or common cycle times between junctions, further research should be conducted into the question of whether common cycle times should be maintained under all conditions.

6. REFERENCES

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