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A Network Traffic Flow Model for Motorway and Urban Highways

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Abstract

The research reported in this paper develops a network level traffic flow model (NTFM) which is applicable for both motorway and urban roads. It forecasts the traffic flow rates, queue propagation at the junctions and travel delays through the network. NTFM uses sub-models associated with all road and junction types which comprise the highway. The flow at any one part of the network is obviously very dependent upon the flows at all other parts of the network. To predict the two-way traffic flow in NTFM, an iterative simulation method is executed to generate the evolution of dependent traffic flows and queues. To demonstrate the capability of the model it is applied to a small case study network and a local Loughborough-Nottingham highway network. The results indicate that NTFM is capable of identifying the relationship between traffic flows and capturing traffic phenomena such as queue dynamics. By introducing a reduced flow rate on links of the network then the effects of strategies employed to carry out roadworks can be mimicked.

Keywords: Pavement maintenance; Traffic flow models; Individual junction models; Iterative simulation method

Notations

$c_{i,j}$	flow capacity on the link between nodes *i* and *j* (passenger car unit (pcu)/hour)
$cp_{i,j}$	link capacitance, i.e. the maximum number of cars which can queue on the link from node *j* (pcu), which is obtained based on the full length from junction *j* to junction *i*
$sr_{i,j}(t_k)$	source flow entering the link in time t_k, for example, cumulative traffic joining the main road from an estate, i.e. housing estates or work places (pcu/hour)
$sk_{i,j}(t_k)$	sink flow leaving the link in time t_k, for example, cumulative traffic leaving the main road for an estate, i.e. housing estates or work places (pcu/hour)
$d_{i,j,l}(t_k)$	proportion of flow on the link choosing the outflow direction *l, l* is expressed either in direction left, right, ahead or in the ID of the destined node, i.e. *j*+1
$f_{i,j}(t_k)$	flow on the link in time t_k (pcu/hour)
$q_{i,j}(t_k)$	average number of vehicles queuing on the link in time t_k (pcu)
$q_i(t_k)$	average number of vehicles propagating back to the upstream links of node *i* in time t_k (pcu)

1 Introduction

In recent years highways agencies have turned their attention from construction of new pavements to the maintenance and rehabilitation of existing ones. According to the Annual Local Authority Road Maintenance Survey ((AIA) 2011), in England, the government has spent heavily on road maintenance in recent years. £2,240m was spent in 2006, £937m in 2007 and another £861m in 2008, an aggregate total of £6,867m from 2002 to 2008, in order to maintain the serviceability level of pavements. The survey also reports that a further £10.65b is currently required to bring the UK's roads to the required standard. In addition to the expenditure on carrying out the work, the travel delay cost to road users caused by maintenance is significant and expected to substantially exceed the corresponding cost of maintenance. Consequently, with the purpose of examining and understanding the travel delays which occur when maintenance is performed, the NTFM network traffic flow model has been developed. It predicts the traffic flows and queues build up in a road network. When roadwork is performed it will cause a restriction in the flow rate capacity of parts of the network. By comparing the flow and delay characteristics resulting from different maintenance strategies the best way of keeping the highways in a good state of repair can be established.

Typically, traffic flow models are categorised into two main groups: macroscopic models and microscopic models. Macroscopic traffic models are used to identify the aggregate behaviour of sets of vehicles, are generally easy to validate and ensure a good real-time quality, such as the fluid-dynamic traffic models (Lighthill and Whitham 1955; Richards 1956). Microscopic models are applied to model the travel behaviour of an individual vehicle which is recognised as a function of the traffic conditions in its environment (Cremer and Ludwig 1986; Nagel and Schreckenberg 1992). As drivers' behaviour in real traffic is difficult to observe and measure, microscopic models are difficult to validate accurately (Daganzo 1994). In addition, the computational effort required by microscopic models is significantly higher than that for macroscopic models, and the data required by microscopic models are more difficult to record. Due to the reasons, described above, and the suitability of macroscopic models for network-level analysis, a macroscopic model has been developed in this paper.

Many macroscopic traffic models have been constructed to identify traffic behaviour on motorways and urban roads. Lighthill and Whitham (1955) and Richards (1956) provided a pioneering flow-dynamic model (LWR model) to describe unidirectional traffic flow on highway networks. Based on the car-following model (Rothery 1997) that considering the driver's reaction time, Payne (1971) developed a second-order model (Wagner, Hoffmann et al. 1996) in which the dynamic flow phenomena are modelled. Daganzo (1994) proposed a cell transmission model (CTM) that adopted a convergent approximation to the LWR model to evaluate the traffic on a highway network with a single entrance and exit. Afterwards, more cell types are applied in CTM to broaden its applicability (Daganzo 1995; Lo 1999; Lo 2001; Lo, Chang et al. 2001). METANET (Messmer and Papageorgiou 1990) considered the situation of a motorway network based on the second-order model. Extensive research has been performed to improve METANET including the adoption of variable speed limits (Breton, Hegyi et al. 2002; Hegyi, Bart De et al. 2005), and the application of route guidance (Deflorio 2003; Karimi, Hegyi et al. 2004). Subsequently, Van den Berg, Hegyi et al. (2007) developed an integrated traffic control capability for mixed urban and motorway networks. However, priority junctions, i.e. T-junction and roundabout, are not considered in CTM and METANET, so the conflicting requirements of the traffic flows from competing directions cannot be captured. In Van den Berg, Hegyi et al. (2007), the urban traffic model assigns sub-queues for each turning direction on road link; thus, shared lanes are not taken into account where traffic heading to different directions might be mixed together.

To model priority intersections, gap acceptance theory and queuing theory have been widely presented and investigated. Gap acceptance models have been applied to estimate the critical gaps and capacities at priority intersections (Siegloch 1973; Cowan 1975; Plank and Catchpole 1984; Troutbeck and Brilon 1997; Brilon, Koenig et al. 1999; Ning 2001; Wu 2006; Guo and Lin 2011). Queuing theory is generally used to evaluate situations which involve average delays, average queue lengths, distributions of delays and queue lengths (Kremser 1962; Tanner 1962; Kremser 1964; Yeo and Weesakul 1964; Daganzo 1977; Poeschl 1983; Ning 2001). One disadvantage for the gap acceptance models is that they have failed to capture conflicts among the major streams (Ruskin and Wang 2002). Also the adjacent signalized intersections can have a significant impact on capacity and performance of priority intersections, which led to the variation of headways (Robinson, Tian et al. 1999; Tracz and Gondek 2000). Hence, gap acceptance theory no longer applies. Since queuing theory is also constructed based on headway distribution models, it suffers the same drawbacks of the gap acceptance theory. As gap acceptance theory and queuing theory mainly focus on investigating the traffic on single intersection, and are not accurate for modelling directional flow (Tian, Troutbeck et al. 2000), they are not capable of identifying the traffic characteristics at network level.

Considering the traffic interaction at both signalized and priority junctions, this paper describes a macroscopic traffic flow model the purpose of which is to provide a method for predicting the traffic flow and travel delay for each junction in the network. One novel feature of the model is that both motorway and urban networks are evaluated based on the same principle of considering a maximum capacity flow rate at the junctions where flows compete, balancing out the traffic flow in the network, and modelling traffic overflow through to the related junctions. Another novel feature is that two-way traffic flow along network links is investigated, when an iterative simulation method is utilised to generate the evolution of dependent traffic flows and queues. Models for a large variety of junctions, such as priority junctions, motorway roundabouts, etc. are introduced, and shared lanes for traffic heading to different directions are modelled, in order to model real situations on highway networks.

2 Road Network Model

The road network studied in NTFM is composed of nodes and links. Links represent roads, i.e. motorway links and urban road links, and nodes demonstrate junctions, including signalized intersections and T-junctions, etc. Also, parts of the same road with different characteristics such as flow capacity are separated by a node (e.g. when a dual carriageway reduces to a single traffic stream). Prior to the evaluation of the road network, the relationships between traffic flows and queue build up at junctions need to be specified. Models for junctions have links which enable the exit traffic from one junction to enter the second junction this will work in two directions as for these two junctions two-way traffic flow is deployed. In this way, all the junctions in the network are linked to each other.

From the network flow theory a network can have a number of source nodes and sink nodes, where a source node defines the flow into the network and a sink node defines the flow out of the network. Source and sink nodes can be used to model the edges of the network or include the rest of the network in the model of a sub-network. In addition, the links themselves can have source and sink nodes, which are used to model cumulative traffic entering/leaving the link. This can represent significant traffic flows to/from the network from such elements as housing estates, airports, railway stations or places of employment. In this way it is possible to avoid the inclusion of all minor roads on the network.

NTFM is based on the principle of the queue model. First of all, flows from the network source nodes are passed through the network to all the sink nodes, calculating the flow on each link. Then the flow on each link is compared with the flow capacity of the link, applying the general equations for the queue on the link and the models for the different types of junction, and the queue is calculated. If the queue exceeds the link capacitance, effects of the queue are propagated back through the network. Finally, in the following time steps, different flows from the network source nodes are propagated through the network, to represent situation such as the rush hour, and their effects are added to the queues present on the network from the previous time steps. If the flow through the network improves, for example, traffic flow rates from the source nodes decrease or traffic lights are adjusted to allow a better flow through the congested links, the queues can decrease and eventually the links can become clear of queues. In this manner the traffic characteristic for a given highway network throughout a day can be identified by NTFM. Detailed rules for calculating flows and queues on the link are described in Section 2.1.

2.1 Main principle of NTFM

Flow on the link *i-j* in time t_k is calculated as a sum of all the flows to node *i*, the flow entering the link and the negative flow leaving the link:

$$f_{i,j}(t_k) = \sum_{alls} d_{s,i,j}(t_k) f_{s,i}(t_k) + sr_{i,j}(t_k) - sk_{i,j}(t_k) \quad (1)$$

Once the flow on each link in time t_k is calculated (for the circumstances that there are no restrictions), the flow value and the queue value on the link *i-j* might need to be updated according to the flow capacity on this link $c_{i,j}$ and the link capacitance $cp_{i,j}$. The updated flow is expressed as $f'_{i,j}(t_k)$ and the updated queue is expressed as $q'_{i,j}(t_k)$. Two cases are considered:

(1) Flow on the link is higher than the flow capacity in time t_k:

$$\text{If } f_{i,j}(t_k) > c_{i,j}\text{, then } f'_{i,j}(t_k) = c_{i,j} \quad (2)$$

$$q'_{i,j}(t_k) = q_{i,j}(t_k) + \left(f_{i,j}(t_k) - c_{i,j}\right) \cdot t_k \quad (2^a)$$

$$\text{if } q'_{i,j}(t_k) > cp_{i,j}\text{, then } q'_{i,j}(t_k) = cp_{i,j} \text{ and } q_i(t_k) = q_{i,j}(t_k) + \left(f_{i,j}(t_k) - c_{i,j}\right) \cdot t_k - cp_{i,j} \quad (2^b)$$

(2) Flow on the link is lower than the flow capacity and there is a queue on the link in time t_k:

$$\text{If } f_{i,j}(t_k) \le c_{i,j}\text{, and } q_{i,j}(t_k) > 0\text{, then } f'_{i,j}(t_k) = c_{i,j} \text{ and} \quad (3)$$

$$q'_{i,j}(t_k) = q_{i,j}(t_k) + \left(f_{i,j}(t_k) - c_{i,j}\right) \cdot t_k \quad (3^a)$$

$$\text{if } q'_{i,j}(t_k) < 0\text{, then } f'_{i,j}(t_k) = c_{i,j} + q'_{i,j}(t_k) \text{ and } q'_{i,j}(t_k) = 0 \tag{3^b}$$

Once the queue is larger than the link capacitance, as described in the Equations 2^b, the queue at the end of the link, $q_i(t_k)$, is passed back to the connecting network, i.e. to the links that contributed to the build-up of the queue. This is done using the queue propagation algorithm. The general idea is that a proportion of the queue is passed to each link that contributed to the build-up of the queue. The proportion of the queue for each link is calculated as the proportion of the flow from that link contributing to the overall flow. For example, if a queue builds up on the link from *j* to *j*+1 and it exceeds the capacity of the link by the number of vehicles $q_j(t_k)$, it is proportionally distributed back to all the links that enter node *j*. This process is going to increase the size of the queue and decrease the flow on each link that enters node *j*:

$$q'_{i,j}(t_k) = q_{i,j}(t_k) + \frac{f_{i,j}(t_k)}{f_{j,j+1}(t_k)} \cdot q_j(t_k) \tag{4}$$

$$f'_{i,j}(t_k) = f_{i,j}(t_k) - \frac{f_{i,j}(t_k)}{f_{j,j+1}(t_k)} \cdot \frac{q_j(t_k)}{t_k} \tag{5}$$

If after this process the size of the increased queue, $q'_{i,j}(t_k)$, exceeds the capacity of the link, $cp_{i,j}$, the effects of the queue are passed back further through the network until a queue can be accommodated and does not exceed the capacity of the link. For example,

$$\text{if } q'_{i,j}(t_k) > cp_{i,j}\text{, then } q_i(t_k) = q'_{i,j}(t_k) - cp_{i,j} \text{ and } q'_{i,j}(t_k) = cp_{i,j} \tag{6}$$

$q_i(t_k)$ is passed to the upstream links that enter node *i*, etc.

If the queue is present in time t_k, i.e. $q'_{i,j}(t_k) > 0$, it is also present at the beginning of the modelling step t_{k+1}, i.e. $q_{i,j}(t_{k+1}) = q'_{i,j}(t_k)$, which then depends on the flow in time t_{k+1}, $f_{i,j}(t_k + 1)$, and the relevant equations are applied to update the flow and the queue on the link as necessary. More complexity is introduced in the junction models, when separate lanes are modelled on the links and the flow capacity and the capacitance on each lane are considered.

2.2 Sub-Models

In addition to the basic link model, the sub-models for each junction type are constructed to express the traffic interaction at junctions. The involved junction types are listed in Table 1.

Table 1: Junction types in NTFM

Junction groups	*Junction types*		
Signalized Junctions	Signalized T-junction	Signalized Intersection	Signalized Roundabout
Priority Junctions	T-junction	Urban Roundabout	Motorway Roundabout
One-way Junctions	On-ramp and Off-ramp	Merge and Diverge	Roadwork node

The traffic flow at a signalized junction is influenced by both the flow capacity of the entry arm and the green split time of the traffic signals (proportion of times the signals gives priority to flow in its direction), where the conflictions among competing traffic flows are eliminated owing to the application of traffic lights. For the group of one-way junctions where (except for the on-ramp of motorways), the entering traffic for the one-way junction is only characterized by the corresponding flow capacity. The on-ramp is also evaluated as a priority junction. For priority junctions, the traffic flow is based on right-of-way rules, where the entering traffic flow for each arm of the junction is restricted by the flow capacity and also by the traffic flows from competing arms. The underlying methodologies for the T-junction, urban roundabout, and motorway roundabout are described in detail to explicitly demonstrate these concepts.

2.2.1 T-junction model

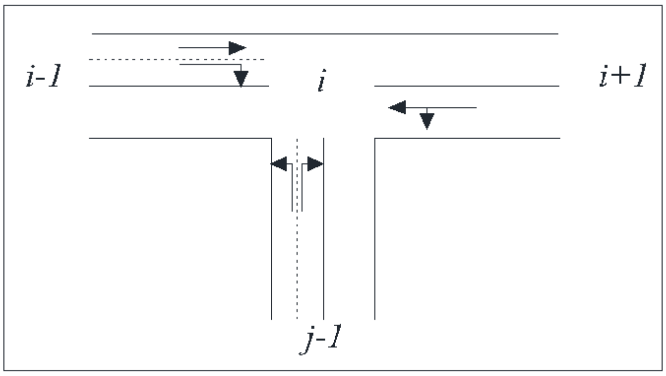

Figure 1: T-junction

This junction, shown in Figure 1, is controlled assuming that drivers obey the right-of-way rules. On the T-junction a vehicle travelling on the major roads has right-of-way and a vehicle approaching the major road must allow it to pass before joining the flow of traffic. Some roads to the intersection have a single lane, some have two lanes. Two lanes are used on the left part of major road, where lane 1 is used for going straight on and lane 2 is used for turning right and crossing the oncoming traffic on the major road. Also, two lanes are used on the minor road, lane 1 is used for turning left and lane 2 is used for turning right. The rest of the roads have a single lane. The junction specific data applied in this model is:

$f_{i-1,i,l}(t_k)$	flow at node *i* that coming from direction *i*-1 and going in lane *l*, i.e. 1 represents the left lane, in time t_k (pcu/hour)
$c_{i-1,i,l}$	node *i* flow capacity for the traffic coming from direction *i*-1 and going in lane *l*, depending on gaps between vehicles and vehicle speed (pcu/hour)
$cp_{i-1,i,l}$	link capacitance in lane *l*, i.e. the maximum number of cars which can queue in lane *l* of the link (pcu)
$q_{i-1,i,l}(t_k)$	average number of vehicles queuing on lane *l* of arm *i*-1 for node *i* at the beginning of t_k (pcu)

The T-junction is controlled by right-of-way rules and a priority is set for certain directions. Therefore, in order to calculate the queue for each direction on the junction, i.e. the major roads *i*-1 and *i*+1 and the minor road *j*-1, has to be considered separately.

2.2.1.1 The major road *i*-1

For the flow from direction *i*-1 to direction *i*+1, i.e. in lane 1, no conflicting traffic restriction on the flow exists. Therefore, a queue can only build up due to the flow capacity on the link after the junction, following the general rule described in Section 2.1.

For the flow from direction *i*-1 to direction *j*-1, i.e. in lane 2, the conflicting flow is the flow from direction *i*+1 to *i*. A queue builds up if the flow in lane 2 or the conflicting flow is higher than the flow capacity in lane 2 through the intersection. The updated flow is expressed as $f'_{i-1,i,l}(t_k)$ and the updated queue is expressed as $q'_{i-1,i,l}(t_k)$. Five cases are considered:

(1) Flow on the link in lane 2 is higher than the flow capacity in lane 2 through the intersection, the conflicting flow from direction *i*+1 is lower than the flow capacity in lane 2 through the intersection, and there is no queue in the lane in time t_k:

$$\text{If } f_{i-1,i,2}(t_k) > c_{i-1,i,2}, \text{ and } f_{i+1,i}(t_k) \le c_{i-1,i,2} \text{ and } q_{i-1,i,2}(t_k) = 0, \text{ then} \quad (7)$$

$$f'_{i-1,i,2}(t_k) = c_{i-1,i,2} \text{ and } q'_{i-1,i,2}(t_k) = \left(f_{i-1,i,2}(t_k) - c_{i-1,i,2}\right) \cdot t_k \quad (7^a)$$

$$\text{if } q'_{i-1,i,2}(t_k) > cp_{i-1,i,2}\text{, then } q'_{i-1,i,2}(t_k) = cp_{i-1,i,2} \text{ and} \quad (7^b)$$

$$q_{i-1}(t_k) = \left(f_{i-1,i,2}(t_k) - c_{i-1,i,2}\right) \cdot t_k - cp_{i-1,i,2}$$

(2) The conflicting flow from direction *i*+1 is higher than the flow capacity in lane 2 through the intersection and there is no queue in the lane in time t_k:

$$\text{If } f_{i+1,i}(t_k) > c_{i-1,i,2} \text{ and } q_{i-1,i,2}(t_k) = 0\text{, then } f'_{i-1,i,2}(t_k) = 0 \text{ and} \quad (8)$$

$$q'_{i-1,i,2}(t_k) = f_{i-1,i,2}(t_k) \cdot t_k, \quad (8^a)$$

$$\text{if } q'_{i-1,i,2}(t_k) > cp_{i-1,i,2}\text{, then } q'_{i-1,i,2}(t_k) = cp_{i-1,i,2}\text{, and} \quad (8^b)$$

$$q_{i-1}(t_k) = f_{i-1,i,2}(t_k) \cdot t_k - cp_{i-1,i,2}$$

(3) Flow on the link in lane 2 is higher than the flow capacity in lane 2 through the intersection, the conflicting flow from direction *i*+1 is lower than the flow capacity in lane 2 through the intersection and there is a queue in the lane in time t_k:

$$\text{If } f_{i-1,i,2}(t_k) > c_{i-1,i,2}\text{, and } f_{i+1,i}(t_k) \le c_{i-1,i,2} \text{ and } q_{i-1,i,2}(t_k) > 0\text{, then} \quad (9)$$

$$f'_{i-1,i,2}(t_k) = c_{i-1,i,2} \text{ and } q'_{i-1,i,2}(t_k) = q_{i-1,i,2}(t_k) + \left(f_{i-1,i,2}(t_k) - c_{i-1,i,2}\right) \cdot t_k \quad (9^a)$$

$$\text{if } q'_{i-1,i,2}(t_k) > cp_{i-1,i,2}\text{, then } q'_{i-1,i,2}(t_k) = cp_{i-1,i,2}\text{, and} \quad (9^b)$$

$$q_{i-1}(t_k) = q_{i-1,i,2}(t_k) + \left(f_{i-1,i,2}(t_k) - c_{i-1,i,2}\right) \cdot t_k - cp_{i-1,i,2}$$

(4) The conflicting flow from direction *i*+1 is higher than the flow capacity in lane 2 through the intersection and there is a queue in the lane in time t_k:

$$\text{If } f_{i+1,i}(t_k) > c_{i-1,i,2} \text{ and } q_{i-1,i,2}(t_k) > 0\text{, then } f'_{i-1,i,2}(t_k) = 0\text{, and} \quad (10)$$

$$q'_{i-1,i,2}(t_k) = q_{i-1,i,2}(t_k) + f_{i-1,i,2}(t_k) \cdot t_k, \quad (10^a)$$

$$\text{if } q'_{i-1,i,2}(t_k) > cp_{i-1,i,2}\text{, then } q'_{i-1,i,2}(t_k) = cp_{i-1,i,2}\text{, and} \quad (10^b)$$

$$q_{i-1}(t_k) = q_{i-1,i,2}(t_k) + f_{i-1,i,2}(t_k) \cdot t_k - cp_{i-1,i,2}$$

(5) Flow on the link in lane 2 is lower than the flow capacity in lane 2 through the intersection, the conflicting flow from direction i+1 is lower than the flow capacity in lane 2 through the intersection and there is a queue in the lane in time t_k :

If $f_{i-1,i,2}(t_k) \leq c_{i-1,i,2}$, and $f_{i+1,i}(t_k) \leq c_{i-1,i,2}$ and $q_{j-1,i,1}(t_k) > 0$, then (11)

$f'_{i-1,i,2}(t_k) = c_{i-1,i,2}$ and $q'_{i-1,i,2}(t_k) = q_{i-1,i,2}(t_k) + \left(f_{i-1,i,2}(t_k) - c_{i-1,i,2}\right) \cdot t_k$ (11^a)

if $q'_{i-1,i,2}(t_k) < 0$, then $f'_{i-1,i,2}(t_k) = c_{i-1,i,2} + q'_{i-1,i,2}(t_k)$ and $q'_{i-1,i,2}(t_k) = 0$ (11^b)

2.2.1.2 The major road *i*+1

For the flow from direction *i*+1 to direction *i*-1 or direction *j*-1 no conflicting traffic requirement is present. Therefore, a queue can only build up due to the flow capacity on the link after the junction following a general rule described in Section 2.1.

2.2.1.3 The minor road *j*-1

For the flow from direction *j*-1 to direction *i*-1, i.e. in lane 1, the conflicting flow is the flow from direction *i*+1 to *i*-1. While for the flow from direction *j*-1 to direction *i*+1, i.e. in lane 2, the conflicting flow is the sum of the flow from direction *i*+1 to *i*-1 and the flow from direction *i*-1 to *i*+1. Both flows on minor road *j*-1 are evaluated as the flow in lane 2 from direction *i*-1.

2.2.2 Roundabout model

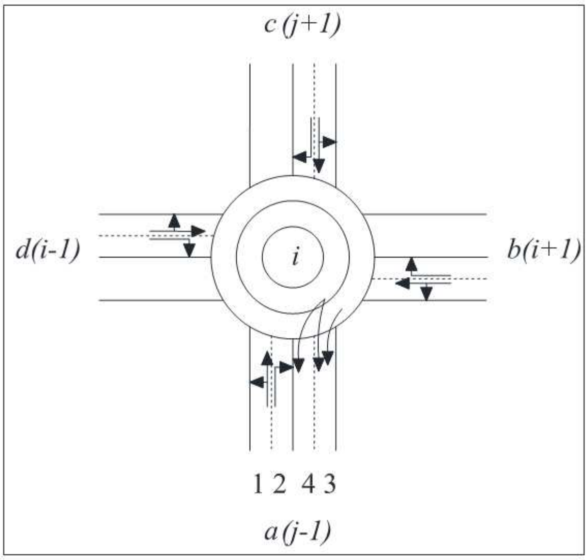

Figure 2: Roundabout

A roundabout is modeled in effect as a series of priority junctions with priority to traffic on the roundabout. As signalized roundabout is operated by signal control without consideration of conflicting flows, urban roundabout and motorway roundabout are investigated in this section.

Assume a roundabout with four entry arms *a, b, c* and *d* for roundabout *i*, illustrated in Figure 2, used to represent to upstream links j-1−i, i+1−i, j+1−i, i-1−i respectively. The order in which the traffic flow is calculated at the roundabout progresses clockwise round the roundabout starting at arm *a*: *a-d-c-b*. The flow from arm *a* will be dependent on the flow from arms *b* and *c*, this is because only parts of flows from arms *b* and *c* have to pass through the entrance of arm *a*, i.e. lane 1 and lane 2, to leave the roundabout, while the flow from arm *d* exits at the back of the entrance, i.e. lane 3 and lane 4 of arm *a*. The same for other arms, the inflow depends on preceding circulating inflows.

Each road to the roundabout is considered to have two lanes; lane 1 is used for turning left and going straight, and lane 2 for turning right. It assumes that the vehicles intending to make a u-turn and return in opposite direction along the road in which they approach the roundabout are sufficiently small that they can be ignored. Another assumption is that the traffic on lane 1 of each entry arm only takes the outer lane circulating the roundabout, while the inner lane is occupied by the traffic on lane 2.

2.2.2.1 Urban Roundabout model

The urban roundabout model assumes that vehicles are not allowed to queue on the roundabout. Because roundabout is usually symmetrically constructed, only the flow on arm *a* is analysed. For the flow from arm *a* to arm *d* and *c*, i.e. in lane 1, the conflicting flow includes the merged flow from arm *b* that is going straight on and the flow from arm *c* that is turning right:

$$cf_{a,i,1}(t_k) = \min(f_{b,i,d}, c_{b,i,1} \times \frac{d_{b,i,d}}{d_{b,i,a} + d_{b,i,d}}) + \min(f_{c,i,d}, c_{c,i,2}) \qquad (12)$$

$cf_{n,i,l}(t_k)$ conflicting flow for the flow on entry arm *n*, i.e. *a*, *b*, *c* and *d*, in lane *l*, i.e. 1 and 2 (pcu/hour)

$f_{n,i,m}$ flow from arm *n* to arm *m* (pcu/hour)

$c_{n,i,l}$ flow capacity for lane *l* of arm *n* (pcu/hour) (pcu/hour)

$d_{n,i,m}$ proportion of the traffic that going to arm *m* from arm *n*

The *min* formula is used to restrict the inflow from each arm. The first *min* formula in Equation 12, takes the minimum of: the first parameter which represents the traffic flow intending to move from arm *b* to arm *d*, and the second parameter which corresponds to the flow capacity for this traffic flow in lane 1 of arm *b*. The second *min* formula demonstrates the traffic flow from arm *c* to arm *d* that should be less than or equal to the corresponding flow capacity.

For the flow from arm *a* to arm *b*, the conflicting flow is the sum of the flows from arm *b* to arm *d* and *c* and the flow from arm *c* to arm *d*, described as:

$$cf_{a,i,2}(t_k) = \min(f_{b,i,d}, c_{b,i,1} \times \frac{d_{b,i,d}}{d_{b,i,a} + d_{b,i,d}}) + \min(f_{b,i,c}, c_{b,i,2}) + \min(f_{c,i,d}, c_{c,i,2}) \qquad (13)$$

The first term and the third term in Equation 13 are identical to Equation 12, as the conflicting flow for lane 1 of arm *a* also restricts the flow on lane 2 of arm *a*. The flow on lane 2 of arm *a* is further limited by the traffic from arm *b* to arm *c* that described as the second term. The evaluation of the two traffic flow on arm *a* follows the same rule in Section 2.2.1.1.

2.2.2.2 Motorway Roundabout model

The extension for this roundabout is that vehicles are allowed to queue on the roundabout. In addition to the restriction of inflows, outflows are also restricted according to the flow capacity of the out-going lanes for each arm. The results from urban roundabout are employed as inputs for the calculation of outflows of the motorway roundabout. It assumes that cars in the queue on the roundabout will leave gaps for entering and exiting the roundabout. Another assumption is that the out-going flow on the outer lane will only take the left lane as exit, while the traffic flow on the inner lane can take either as exit, as illustrated in Figure 2. As the roundabout investigated is assumed to be built symmetrically, the free spaces for each part of the roundabout are the same.

The additional junction data is employed in motorway roundabout:

$cp_{i,ot}$	capacitance for outer lane of roundabout *i* (pcu)
$cp_{i,in}$	capacitance for inner lane of roundabout *i* (pcu)
$f_{a,i,l}$	outflow for lane *l* of arm *a*, *l* includes 3 and 4 (pcu/hour)
$of_{b,i,a}$	outflow of roundabout *i* from arm *b* to arm *a* (pcu/hour)
$oq_{a,b}$	length of the queue formed in section *ab* of the outer lane of roundabout (pcu), as illustrated in Figure 3
$iq_{a,b}$	length of the queue formed in section *ab* of the inner lane of roundabout (pcu), as illustrated in Figure 3
$oqp_{a,b}$	queue propagation of queue for section *ab* of outer lane to other links (pcu)
$iqp_{a,b}$	queue propagation of queue for section *ab* of inner lane to other links (pcu)

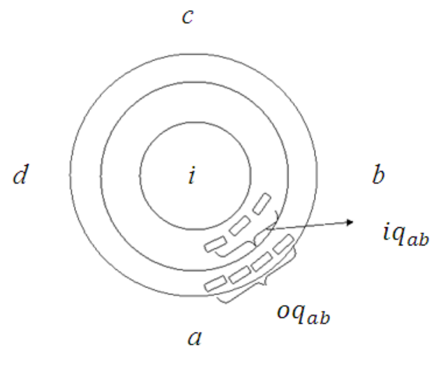

Figure 3: The formation of queue at the roundabout

The traffic flows from each arm will occupy their defined path through the roundabout; the mixed traffic flow at each component of the roundabout is represented in

Table 2.

Table 2: Composition of traffic flows

Components of roundabout	*Outer lane*	*Inner lane*
ab	$f_{b,i,a}$, $f_{b,i,d}$, $f_{c,i,a}$	$f_{d,i,a}$, $f_{c,i,d}$, $f_{b,i,c}$
bc	$f_{c,i,b}$, $f_{c,i,a}$, $f_{d,i,b}$	$f_{a,i,b}$, $f_{d,i,a}$, $f_{c,i,d}$
cd	$f_{d,i,c}$, $f_{d,i,b}$, $f_{a,i,c}$	$f_{b,i,c}$, $f_{a,i,b}$, $f_{d,i,a}$
da	$f_{a,i,d}$, $f_{a,i,c}$, $f_{b,i,d}$	$f_{c,i,d}$, $f_{b,i,c}$, $f_{a,i,b}$

The urban roundabout model is initially deployed as the first part of the motorway roundabout model. The results of urban roundabout model are then employed as inputs for the next calculation in the motorway roundabout model. Lane 3 and lane 4 for arm *a* (as in Figure 2) are analysed separately. The evaluation of the exiting traffic in lane 3 for arm *a* is described as follows:

(1) A queue builds up if flow on the link in lane 3 is higher than the flow capacity of lane 3 of arm *a*.

If $f_{b,i,a} + f_{c,i,a} > c_{a,i,3}$, $f_{a,i,3} = c_{a,i,3}$

For section *ab* of outer lane at the roundabout, the disturbed traffic for exiting traffic at arm *a*, i.e. $f_{b,i,a}$ and $f_{c,i,a}$ in time t_k is calculated as $(f_{b,i,a} + f_{c,i,a} - c_{a,i,3}) \times t_k$, further led to the blockage of flow $f_{b,i,d}$ derived as $(f_{b,i,a} + f_{c,i,a} - c_{a,i,3}) \times t_k \times \frac{f_{b,i,d}}{f_{b,i,a} + f_{c,i,a}}$ based on the flow proportions on section *ab* of outer lane. This is because these three directional traffic flows are mixed together on section *ab* of outer lane. As a result, the queue formed on section *ab* of outer lane is updated as:

$$oq'_{a,b} = oq_{a,b} + (f_{b,i,a} + f_{c,i,a} - c_{a,i,3}) \times t_k \times \frac{f_{b,i,a} + f_{c,i,a} + f_{b,i,d}}{f_{b,i,a} + f_{c,i,a}} \tag{14}$$

In addition, the variation of queue in *ab* is represented as:

$$\Delta oq_{a,b} = \min(oq'_{a,b}, \frac{cp_{i,ot}}{4}) - oq_{a,b} \tag{15}$$

Equation 15 is used to restrict the queue increment in section *ab*. The first term represents the updated queue length in *ab*, when it is greater than the capacitance, it is restricted as $\frac{cp_{i,ot}}{4}$.

Due to the traffic disturbance, the traffic flows that passing through section *ab* of outer lane are decreased by:

$$\Delta f_{b,i,a} = -\frac{\Delta oq_{a,b}}{t_k} \times \frac{f_{b,i,a}}{f_{b,i,a} + f_{c,i,a} + f_{b,i,d}}$$
$$\Delta f_{c,i,a} = -\frac{\Delta oq_{a,b}}{t_k} \times \frac{f_{c,i,a}}{f_{b,i,a} + f_{c,i,a} + f_{b,i,d}}$$
$$\Delta f_{b,i,d} = -\frac{\Delta oq_{a,b}}{t_k} \times \frac{f_{b,i,d}}{f_{b,i,a} + f_{c,i,a} + f_{b,i,d}} \quad (16)$$

If queue is less than the queue capacitance, $oq'_{a,b} \le \frac{cp_{i,ot}}{4}$, the queue is restricted in *ab*.

If $oq'_{a,b} > \frac{cp_{i,ot}}{4}$, part of the queue propagates back to upstream links, described as:

$$oqp_{a,b} = oq'_{a,b} - \frac{cp_{i,ot}}{4} \text{ and } oq'_{a,b} = \frac{cp_{i,ot}}{4} \quad (17)$$

As this queue propagation is contributed by traffic flows from arms *b* and *c*, it spills back to lane 1 of arm *b* and section *bc* of outer lane. The first part that induced by $f_{b,i,a}$ and $f_{b,i,d}$ is added to the queue in lane 1 of arm *b*, described as:

$$q'_{b,1} = q_{b,1} + oqp_{a,b} \times \frac{f_{b,i,a} + f_{b,i,d}}{f_{b,i,a} + f_{c,i,a} + f_{b,i,d}} \quad (18)$$

and the inflow from lane 1 arm *b* is decreased as:

$$f'_{b,i,1} = f_{b,i,1} - \frac{oqp_{a,b}}{t_k} \times \frac{f_{b,i,a} + f_{b,i,d}}{f_{b,i,a} + f_{c,i,a} + f_{b,i,d}} \quad (19)$$

If $q'_{b,1} > cp_{b,i,1}$, queue propagates back to the source links of arm *b*

$$qp_{b,1} = q'_{b,1} - cp_{b,i,1} \text{ and } q'_{b,1} = cp_{b,i,1} \quad (20)$$

The rest part spills back to section *bc* of outer lane, and the queue in section *bc* is updated as:

$$oq'_{b,c} = oq_{b,c} + oqp_{a,b} \times \frac{f_{c,i,a}}{f_{b,i,a} + f_{c,i,a} + f_{b,i,d}} \times \frac{f_{c,i,a} + f_{c,i,b} + f_{d,i,b}}{f_{c,i,a}} \quad (21)$$

The disturbed traffic of $f_{c,i,a}$ further resulted in the blockage of $f_{c,i,b}$ and $f_{d,i,b}$, as they are mixed in section *bc* of outer lane.

Consequently, the traffic that could exit the roundabout at arm *a* from arm *b* is computed as:

$$of_{b,i,a} = f'_{b,i,1} \times \frac{d_{b,i,a}}{d_{b,i,a} + d_{b,i,d}} + \Delta f_{b,i,a} \quad (22)$$

(2) Flow on the link in lane 3 is less than the flow capacity of lane 3 through the roundabout

If $f_{b,i,a} + f_{c,i,a} \le c_{a,i,3}$,

(2-a) If $q_{a3} = 0$, no queue.

$$f_{a,i,3} = f_{b,i,a} + f_{c,i,a} \quad (23)$$

(2-b) If $0 < q_{a3} \le \frac{cp_{i,ot}}{4}$, queue located in part *ab.*

$$f_{a,i,3} = c_{a,i,3} \quad (24)$$

$$oq_{d,a} = oq_{c,d} = oq_{b,c} = 0, oq_{a,b} = q_{a,3} \quad (25)$$

$$oq'_{a,b} = oq_{a,b} + (f_{b,i,a} + f_{c,i,a} - c_{a,i,3}) \times t_k \times \frac{f_{b,i,a} + f_{c,i,a} + f_{b,i,d}}{f_{b,i,a} + f_{c,i,a}} \quad (26)$$

Equation 26 is evaluated as Equation 14, which is based on the flow ratios on section *ab* of outer lane. Increment of flows due to clearance of queue is evaluated as:

$$\Delta oq_{a,b} = \max(oq'_{a,b} - oq_{a,b}, -oq_{a,b}) \quad (27)$$

This max formula is used to restrict the clearance of queue; the maximum value of queue reduction would be the previous queue length. As a result of queue clearance, the traffic flows that passing through part *ab* of outer lane are increased by:

$$\Delta f_{b,i,a} = -\frac{\Delta oq_{a,b}}{t_k} \times \frac{f_{b,i,a}}{f_{b,i,a} + f_{c,i,a} + f_{b,i,d}}$$

$$\Delta f_{c,i,a} = -\frac{\Delta oq_{a,b}}{t_k} \times \frac{f_{c,i,a}}{f_{b,i,a} + f_{c,i,a} + f_{b,i,d}}$$

$$\Delta f_{b,i,d} = -\frac{\Delta oq_{a,b}}{t_k} \times \frac{f_{b,i,d}}{f_{b,i,a} + f_{c,i,a} + f_{b,i,d}} \quad (28)$$

If $oq'_{a,b} \ge 0$, queue still exists in *ab.* If $oq'_{a,b} < 0$

$$f_{a,i,3} = c_{a,i,3} + oq'_{a,b} \times \frac{f_{b,i,a} + f_{c,i,a}}{f_{b,i,a} + f_{b,i,d} + f_{c,i,a}} \text{ and } oq'_{a,b} = 0 \quad (29)$$

Consequently, the traffic flows that passing through *ab* are updated as:

$$of_{b,i,a} = f_{b,i,a} + \Delta f_{b,i,a}, of_{b,i,d} = f_{b,i,d} + \Delta f_{b,i,d}, of_{c,i,b} = f_{c,i,b} + \Delta f_{c,i,b} \quad (30)$$

(2-c) If $q_{a3} > \frac{cp_{i,ot}}{4}$, queue located in part *ab* and some other parts. Queue clears from its end to *ab*. The methodology used above will be applied.

As for the lane 4 of arm *a*, the exiting traffic flow is computed as:

$$c'_{a,i,4} = c_{a,i,4} + \max(c_{a,i,3} - f_{a,i,3}, 0) \quad (31)$$

Equation 31 determines the outflow capacity for lane 4 arm *a*. As flow $f_{d,i,a}$ can exit the roundabout by either lane 3 or 4, the outflow capacity for $f_{d,i,a}$ is calculated as the sum of capacity of lane 4 and residual flow capacity of lane 3. The methodology, used to evaluate the traffic condition in lane 3 for arm *a*, is also applied to the outflow through the lane 4 for arm *a*.

3 Network Solution Routine

In performing the network level analysis, the inflows at each junction result from the outflows of its upstream junctions and entries to the network; whereas, its outflows are functions of the inflows for the junction. Thus the whole system of traffic flows is interconnected and dependent. It is of vital importance to determine the sequence of node evaluations for traffic flow. These will start from the original node, progress round the network and end at the same node. The simulation of these nodes is processed iteratively until a convergence has been reached when all out profiles are effectively unchanged by further iterations. As for the first iteration, the unknown inputs for each junction in the model are supposed to be zero, which will be updated by the outcomes of its upstream links in the same iteration and applied to the next iteration. Except for the traffic flows from source nodes, traffic flows for each simulation iteration are updated as the inputs for the next iteration. It is worth noting that at the beginning of each iteration queues formed in the network are reset to the condition at the end of previous time period so as to conserve the amount of traffic in the network. For instance, queues are initialized to zero for the simulation iterations at the first time step, since there was no traffic in the network previously.

The evaluation of traffic conditions for a highway network falls into two main steps. The first step is to calculate the entering flows, exiting flows and queues for each junction iteratively until those parameters reach a stable state. The next step is to identify the effect of vehicles that propagating back to their upstream links, which makes the traffic condition even more severe. Consequently, the traffic condition for the highway network at the current time step is obtained, and then this in turn is utilised as the initial traffic condition at next time step. By this means the traffic condition state for a highway network over a time period is evaluated.

The NTFM software is programmed in Visual C++, in which a class is constructed for each junction, studied in the NTFM, and it is used to describe the type and the flow capacity of the junction, and to store its inflows, outflows and queues. The software is used to model the traffic on the network throughout a day.

4 Data Sources

NTFM requires a comprehensive list of inputs which specify the geographical characteristics of the road network along with the traffic flows through it at different parts of the day. Included in the geographical network features are: the length for each link and the flow capacity for each arm of the junctions. In addition, the traffic entering each link of the network at all points of the day are required, along with the proportion of vehicles leaving each junction on each of the exit arms and the signal control inputs at each time interval. In the NTFM traffic flows and turning movements are constant over each time interval.

The available traffic inputs on the highway network, used in this study, were the number of cars per hour, which had been collected at various locations on trunk roads and at various junctions over the last couple of years. Such traffic data were obtained from the Highways Agency and

Nottingham County Council for the majority of the roads, and were directly applied in the NTFM to model two-way traffic flow during a day. However, if the traffic data at some points during a day were unavailable, they were derived using the linear extrapolation between two data points. For the road sections on the local network where the data were not recorded in the database, data collection was carried out by the authors to obtain some traffic information during a typical day to be used in the NTFM.

5 Model Application

5.1 Case Study 1

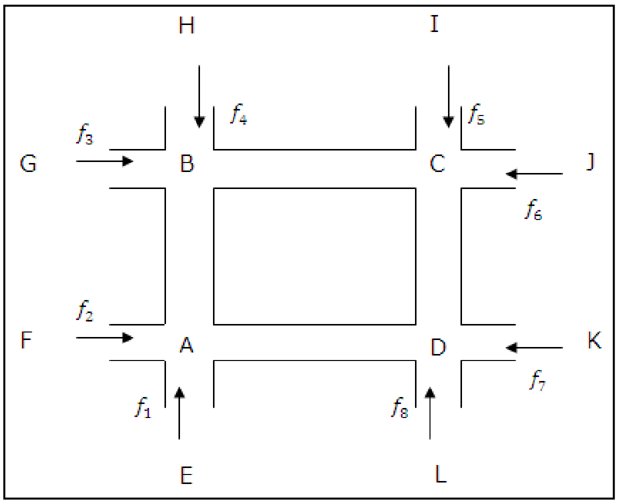

Figure 4: The case study network

For ease of exposition, a simple network in Figure 4 is provided to illustrate the properties of NTFM. This road network is composed of 4 signalized intersection and 12 dual 2-lane links. The flow capacity for each intersection is defined as 1500 pcu/hour; the capacitance for each inner link is 1000 pcu; the turning ratios for each arm of each junction are defined as 0.3, 0.4 and 0.3 (turning left, going straight, turning right); the green time split for traffic that turning left and going straight is set to 0.5, and 0.3 for right turning traffic. As *EA*, *FA*, *GB*, *HB*, *IC*, *JC*, *KD* and *LD* are external links, their capacities are assigned as infinity to avoid queue propagation. In order to illustrate the formation of queue in the network, relatively high traffic flows are employed. The inflows for f_1 to f_8 are 1000, 1000, 1200, 1200, 1400, 1400, 1600, 1600 pcu/hour, respectively. The modelling horizon in this case study is set to 2 time steps, one time step is defined as one hour. Additionally, f_{AB} is used to denote the flow from node *A* to node *B*, and q_{AB} represents the queue that formed at node *B* and extended to node *A*, which is recognised as a product of f_{AB}.

5.1.1 Network Simulation

The sequence for the evaluation of the nodes in this network is defined as *A-B-C-D-A*. For each iteration the traffic flows in the network are evolved with respect to the following rule until convergence is obtained:

- Junction A, f_1, f_2, f_{DA} and f_{BA} are used to calculate the outflows f_{AB}, f_{AD}, f_{AE} and f_{AF}
- Junction B, f_3, f_4, f_{AB} and f_{CB} are used to calculate the outflows f_{BC}, f_{BA}, f_{BG} and f_{BH}
- Junction C, f_5, f_6, f_{BC} and f_{DC} are used to calculate the outflows f_{CD}, f_{CB}, f_{CJ} and f_{CI}
- Junction D, f_7, f_8, f_{CD} and f_{AD} are used to calculate the outflows f_{DA}, f_{DC}, f_{DK} and f_{DL}

It should be noted that f_{DA}, f_{BA}, f_{CB} and f_{DC} are initialised as 0 on the first iteration. After the values of these variables remain steady, queue propagation through the network is evaluated. As a result of this, the traffic condition at current time step is obtained. Queues formed at this time step are recorded as the initial traffic condition at next time step. In this approach, the traffic condition for this network over the planning span is evaluated. It takes around 1 second for NTFM to model the traffic characteristics on this network during two time steps.

5.1.2 Evaluation of Traffic Condition

At first, the model is fed with the initial traffic states, i.e. inflows, turning ratios for junctions and signal control inputs. The initial traffic condition for the network is depicted in Table 3:

Table 3: Initial traffic condition in time 1

Junctions	*Initial traffic condition in time 1*			
A	q_{AE}	q_{AD}	q_{AB}	q_{AF}
	0	0	0	0
B	q_{BA}	q_{BC}	q_{BH}	q_{BG}
	0	0	0	0
C	q_{CD}	q_{CJ}	q_{CI}	q_{CB}
	0	0	0	0

D				
	q_{DL}	q_{DK}	q_{DC}	q_{DA}
	0	0	0	0

As for each iteration for time 1, the initial traffic condition states for each junction should be reset according to Table 3, so as to keep the balance between traffic inputs and outputs. In order to obtain a stable traffic condition state, the evaluation of the network is run iteratively until convergence is reached, the evolution of traffic for each junction are represented in Table 4:

Table 4: Evolution of the traffic condition for the case study network in time 1

Junction		*Traffic condition states in time 1*											
		Entering flow (pcu/hour)				Exiting flow (pcu/hour)				Queue length (pcu)			
A	Iteration	f_1	f_{DA}	f_{BA}	f_2	f_{AE}	f_{AD}	f_{AB}	f_{AF}	q_{AE}	q_{AD}	q_{AB}	q_{AF}
	0	1000	0	0	1000	300	700	700	300	0	0	0	0
	1	1000	1061	789	1000	933	937	1018	962	0	0	0	0
	2	1000	1070	1044	1000	1039	1013	1021	1041	0	0	0	0
	3	1000	1070	1110	1000	1050	1021	1021	1061	0	0	27	0
	4	1000	1070	1110	1000	1050	1021	1021	1061	0	0	27	0
B	Iteration	f_{AB}	f_{CB}	f_4	f_3	f_{BA}	f_{BC}	f_{BH}	f_{BG}	q_{BA}	q_{BC}	q_{BH}	q_{BG}
	0	700	0	1200	1200	789	960	601	570	0	0	90	90
	1	1018	849	1200	1200	1044	1055	983	1005	0	0	90	90
	2	1021	1170	1200	1200	1110	1056	1081	1095	0	69	90	90
	3	1021	1170	1200	1200	1110	1056	1081	1095	0	69	90	90
	4	1021	1170	1200	1200	1110	1056	1081	1095	0	69	90	90
C	Iteration	f_{DC}	f_6	f_5	f_{BC}	f_{CD}	f_{CJ}	f_{CI}	f_{CB}	q_{CD}	q_{CJ}	q_{CI}	q_{CB}
	0	0	1400	1400	960	1038	705	708	849	0	230	230	0
	1	1089	1400	1400	1055	1066	1070	1167	1170	12	230	230	0
	2	1160	1400	1400	1056	1067	1091	1166	1170	62	230	230	0
	3	1183	1400	1400	1056	1067	1099	1166	1170	78	230	230	0
	4	1185	1400	1400	1056	1067	1099	1166	1170	80	230	230	0
D	Iteration	f_8	f_7	f_{CD}	f_{AD}	f_{DL}	f_{DK}	f_{DC}	f_{DA}	q_{DL}	q_{DK}	q_{DC}	q_{DA}
	0	1600	1600	1038	700	946	1042	1089	1061	400	400	0	0
	1	1600	1600	1067	937	1029	1145	1160	1070	400	400	0	0
	2	1600	1600	1067	1013	1052	1175	1183	1070	400	400	0	0
	3	1600	1600	1067	1021	1054	1179	1185	1070	400	400	0	0
	4	1600	1600	1067	1021	1054	1179	1185	1070	400	400	0	0

Examining Table 4, the traffic condition for this network reached a steady state after 5 iterations, as it is quite a small network that only requires a little computational effort. Also we found that queues formed at all the four junctions, this is because entering traffic flow exceeds the corresponding flow capacity. For instance, in terms of the turning ratios for arm BA of junction *a*, f_{BA} is divided into two sub-flows for each lane, i.e. 777 pcu/hour, turning left and going straight, in lane 1, and 333 pcu/hour, turning right, in lane 2. Considering the green splits, the entering flow capacities for these two lanes are 750 pcu/hour and 450 pcu/hour, respectively. As the entering traffic in lane 1 is higher than its entering flow capacity, the portion of the vehicles that exceeds the flow capacity, i.e. 27 pcu, is disturbed in lane 1. For other junctions, because they experienced more traffic than junction A, more serious traffic congestions suffered.

As for the next time step, the entering flows for the network remains, the only difference is that there are few queues presented. The initial traffic condition for the network in time step 2 is described in Table 5, which is received from the traffic condition at the end of time 1.

Table 5: Initial traffic condition in time 2

Junctions	*Initial traffic condition in time 2*			
A	q_{AE}	q_{AD}	q_{AB}	q_{AF}
	0	0	27	0
B	q_{BA}	q_{BC}	q_{BH}	q_{BG}
	0	69	90	90
C	q_{CD}	q_{CJ}	q_{CI}	q_{CB}
	80	230	230	0
D	q_{DL}	q_{DK}	q_{DC}	q_{DA}
	400	400	0	0

The initial traffic condition on each iteration in time 2 should be reset according to Table 5. The same process is conducted as time 1 and the traffic condition for the network at the end of time 2 is shown in Table 6:

Table 6: Traffic condition for the case study network in time 2

Junction		*Traffic condition states in time 2*											
		Entering flow (pcu/hour)				Exiting flow (pcu/hour)				Queue length (pcu)			
A	Iteration	f_1	f_{DA}	f_{BA}	f_2	f_{AE}	f_{AD}	f_{AB}	f_{AF}	q_{AE}	q_{AD}	q_{AB}	q_{AF}
	3,4	1000	1070	1110	1000	1050	1021	1021	1061	0	0	54	0
B	Iteration	f_{AB}	f_{CB}	f_4	f_3	f_{BA}	f_{BC}	f_{BH}	f_{BG}	q_{BA}	q_{BC}	q_{BH}	q_{BG}
	3,4	1021	1170	1200	1200	1110	1056	1081	1095	0	138	180	180
C	Iteration	f_{DC}	f_6	f_5	f_{BC}	f_{CD}	f_{CJ}	f_{CI}	f_{CB}	q_{CD}	q_{CJ}	q_{CI}	q_{CB}
	3,4	1185	1400	1400	1056	1067	1099	1166	1170	160	460	460	0
D	Iteration	f_8	f_7	f_{CD}	f_{AD}	f_{DL}	f_{DK}	f_{DC}	f_{DA}	q_{DL}	q_{DK}	q_{DC}	q_{DA}
	3,4	1600	1600	1067	1021	1054	1179	1185	1070	800	800	0	0

In comparison to traffic condition in time 1, the entering traffic flows and exiting traffic flows are the same, while the length of all queues in the network are doubled. This is because the traffic inputs for the network remained, which resulted in the weak links suffering more severe congestion.

5.2 Case Study 2

To illustrate the performance of the NTFM on a real highway network, a case study based on the Loughborough-Nottingham highway network has been presented, which includes both urban road links and motorway links. The topology of this highway network is illustrated in Figure 5. There are three main routes from Loughborough to Nottingham, which are A60-A52 (*A-B-C-D*), A6-A453-A52 (*A-J-G-K-C-D*) and A512-M1-A52 (*A-H-G-F-D*).

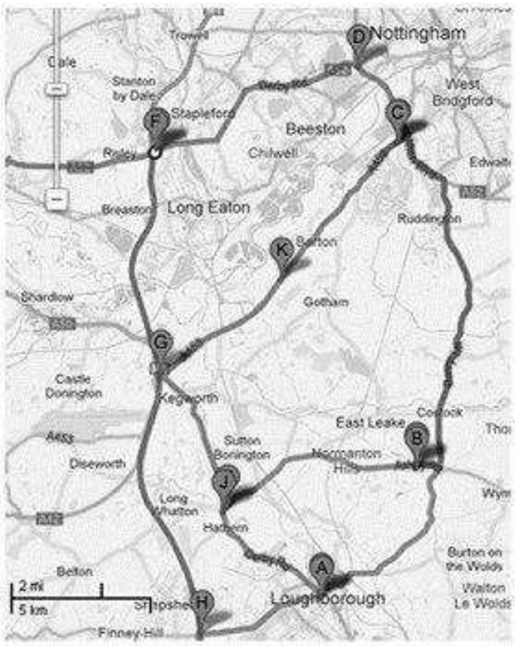

Figure 5: Loughborough-Nottingham highway network

Only trunk roads and roads between major junctions are retained in the network, as shown in Figure 6. Some symbols, e.g. M1 and A52, denote the road class and road number of the road links, where M represents a motorway and A - a trunk road. Other symbols represent the type and ID of a junction, for instance, a "diverge" junction in Loughborough is named D2. There are 47 junctions modelled in the network, including 8 roundabouts (R), 3 signalised roundabouts (SR), 5 diverge junctions (D), 3 merge junctions (MG), 12 off-ramps and 12 on-ramps (both denoted by S), 2 signalised T-junctions (ST), and 2 signalised intersections (SI). (Insert the number of links!)The sequence of the evaluation of these junctions is determined as: SR1-SR2-SR3-R6-R7-R8-R2-R5-MG1-D5-MG3-D6-MG2-R4-R1-SI2-R3-SI1-ST2-D2-ST1. The on-ramps and off-ramps are evaluated at the same time as the junctions, that they are connected to. The traffic data for this network are obtained from the Highways Agency and Nottingham County Council (HA 2011), and applied to the traffic flow model in the form of two-way hourly traffic flow. Where such data were unavailable, the number of cars per hour were estimated, as discussed in Section 4.

The focus of this study is to predict the outflow and queue length for each junction/link in this real highway network, and to identify the weak links/junctions that experienced severe traffic congestion. There are 16, one hour, time steps used to model the highway network, which represents the modelling duration from 7:00 am to 11:00 pm per day. The computational time for NTFM to simulate this network during the defined planning period is 10 seconds. On the basis of the results obtained, it was concluded that roundabouts R1, R6 and R7 suffered the worst traffic congestion during the morning and evening peak periods, as they are connected to the places with large traffic flows, i.e., the motorway, the city centre and some residential areas; while other junctions can accommodate their input flows without causing any queues.

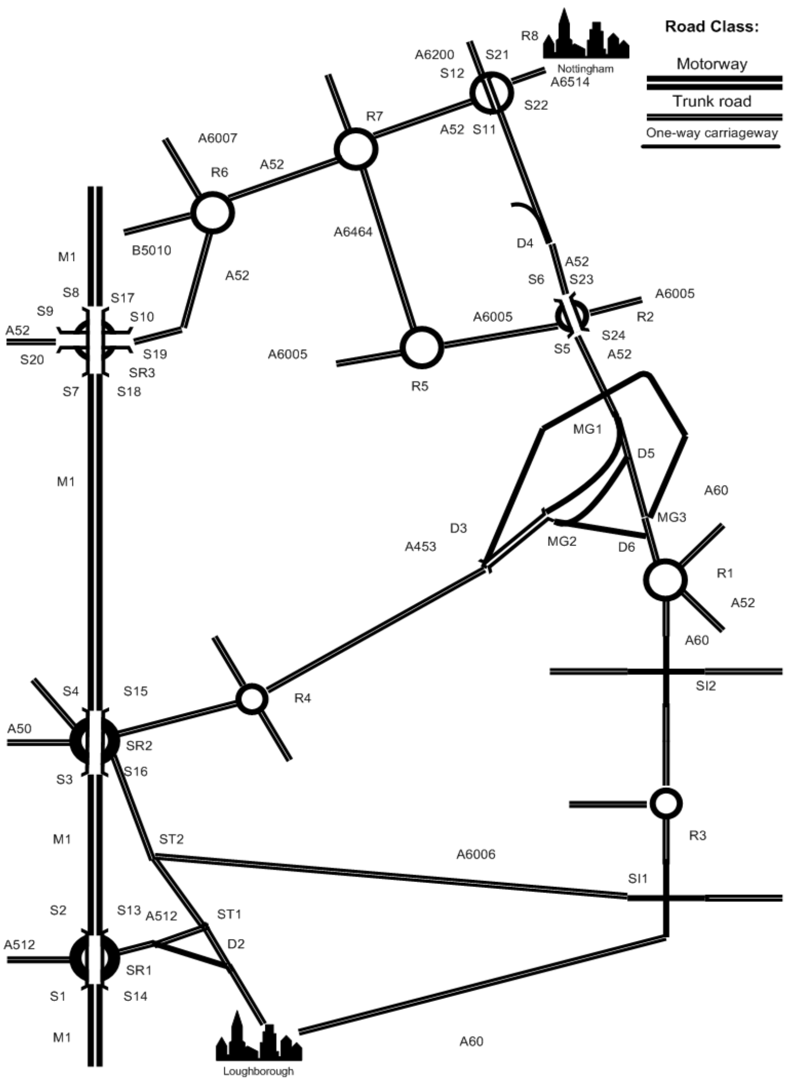

Figure 6: Loughborough-Nottingham modelled highway network

The numerical solution of this highway network through a typical day is demonstrated in Figure 7. On the left hand side of Figure7 the total flow into the network and out of the network has been presented, with the expected increase at peak times. On the right hand side the sum of all the queues formed in the network throughout the day is presented. It can be seen that the highway network experienced heavy traffic congestion during the peak times, i.e. between 8:00 and 11:00 and between 17:00 and 20:00. When the flow capacity on the links with queues is higher than the entering traffic flow, the queues reduce and eventually the network becomes clear of queues, as illustrated between 11:00 and 16:00.

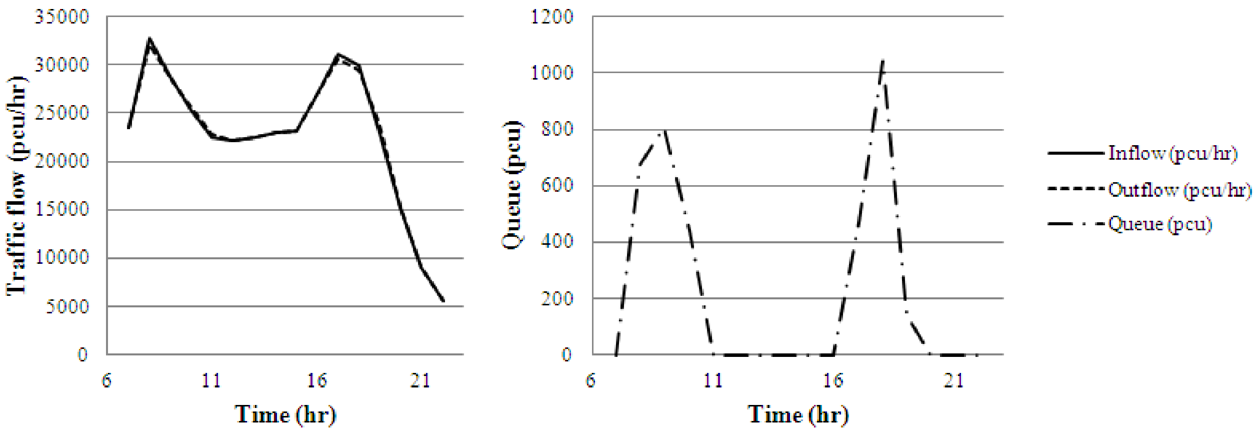

Figure 7: Traffic condition of the example network under normal condition

5.3 Discussion

Based on the results above, the inflow and outflow for each junction and the queue stored on each link in the simple example network are obtained. In the light of these parameters, the total exiting traffic flow and aggregate queue length in the network can be derived by summing up the outflows of all the exits of the network and by summing up the length of queues formed in the network, respectively. The total exiting traffic flow and aggregate queue length are used to measure the transportability of the network, the higher the exiting traffic flow, the better the network transportability, while aggregate queue length is in indirect proportion to the network transportability. In addition, the daily performance of a local real network in the Loughborough-Nottingham area, which is composed of both urban and motorway road sections, is presented. Using this model in addition to the normal road conditions, maintenance actions can be implemented in the network. NTFM can be deployed to calculate the resulting flow rates in the network when maintenance is performed and to compare them with the flow rates without maintenance. When road maintenance is carried out additional delay queue length can be evaluated in order to obtain the cost to road users. Afterwards, by comparing the effects of various maintenance actions on the road network and road users, the best option that resulted in the least maintenance and road user costs can be found.

5 Conclusions

In this study, we have proposed a macroscopic network level traffic flow model and its associated junction models, which are in consistent with the queue model and right of way rules. The model calculates the flows through the network junctions and the queues which build up and disperse at different points during the day. The modelling capability developed provides advances on the previously developed alternatives in the following features:

i. It accounts for both motorway and urban roads in the same road network reflecting the interactive nature of the two systems.
ii. It copes with two-way traffic flow by employing iterative simulation method to determine the value of the dependent traffic flows in the network.
iii. The models feature enables entry and exit points for traffic flow along each urban network section link (road). This simulates traffic exiting/joining the network at housing estates or work place locations.
iv. It deploys shard lane, i.e. a lane that is occupied by traffic that is turning left and going straight, to illustrate the traffic interaction among mixed directional traffic flows.

The results showed that this model has the capability to describe the evolution of dependent traffic flows and forecast the traffic movement and queue dynamics through a real mixed highway network that consists of both urban and motorway links. Also, it is expected that after the initial study of the processing time, the NTFM is suitable to model real highway networks and the effects of maintenance works at network level.

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REFERENCES

(AIA), A. I. A. (2011). Annual Local Authority Road Maintenance Survey

Breton, P., A. Hegyi, et al. (2002). "Shock wave elimination/reduction by optimal coordination of variable speed limits." Intelligent Transportation Systems, 2002. Proceedings. The IEEE 5th International Conference.

Brilon, W., R. Koenig, et al. (1999). "Useful estimation procedures for critical gaps." Transportation Research Part A: Policy and Practice, **33**(3–4): 161-186.

Cowan, R. J. (1975). "Useful headway models." Transportation Research **9**(6): 371-375.

Cremer, M. and J. Ludwig (1986). "A fast simulation model for traffic flow on the basis of boolean operations." Mathematics and Computers in Simulation **28**(4): 297-303.

Daganzo, C. F. (1977). "Traffic Delay at Unsignalized Intersections: Clarification of Some Issues." TRANSPORTATION SCIENCE **11**(2): 180.

Daganzo, C. F. (1994). "The Cell Transmission Model - a Dynamic Representation of Highway Traffic Consistent with the Hydrodynamic Theory." Transportation Research Part B-Methodological **28**(4): 269-287.

Daganzo, C. F. (1995). "The Cell Transmission Model .2. Network Traffic." Transportation Research Part B-Methodological **29**(2): 79-93.

Deflorio, F. P. (2003). "Evaluation of a reactive dynamic route guidance strategy." Transportation Research Part C: Emerging Technologies **11**(5): 375-388.

Guo, R. J. and B. L. Lin (2011). "Gap Acceptance at Priority-Controlled Intersections." Journal of Transportation Engineering-Asce **137**(4): 269-276.

HA (2011). Traffic Information Database, Highways Agency.

Hegyi, A., S. Bart De, et al. (2005). "Optimal coordination of variable speed limits to suppress shock waves." Intelligent Transportation Systems, IEEE Transactions on **6**(1): 102-112.

Karimi, A., A. Hegyi, et al. (2004). "Integration of dynamic route guidance and freeway ramp metering using model predictive control." American Control Conference, 2004. Proceedings of the 2004.

Kremser, H. (1962). "Ein Zusammengesetztes Wartezeitproblem Bei Poissonschen Verkehrsströmen (A Complex Problem of Delay with Poisson-Distributed Traffic Flows)." Osterreichisches Ingenieur-Archiv **16**.

Kremser, H. (1964). "Wartezeiten Und Warteschlangen Bei Einfadelung Eines Poissonprozesses in Einen Anderen Solchen Prozess (Delays and Queues with One Poisson Process Merging into Another One)." Österreichisches Ingenieur-Archiv **18**.

Lighthill, M. J. and G. B. Whitham (1955). "On Kinematic Waves. II. A Theory of Traffic Flow on Long Crowded Roads." Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences **229**(1178): 317-345.

Lo, H. K. (1999). "A novel traffic signal control formulation." Transportation Research Part A: Policy and Practice **33**(6): 433-448.

Lo, H. K. (2001). "A Cell-Based Traffic Control Formulation: Strategies and Benefits of Dynamic Timing Plans." Transportation science **35**(2): 148-164.

Lo, H. K., E. Chang, et al. (2001). "Dynamic network traffic control." Transportation Research Part A: Policy and Practice **35**(8): 721-744.

Messmer, A. and M. Papageorgiou (1990). "METANET: A macroscopic simulation program for motorway networks." Traffic Engineering and Control **31**(9): 466-470.

Nagel, K. and M. Schreckenberg (1992). "A cellular automaton model for freeway traffic." Journal de Physique I **2**(12): 2221-2229.

Ning, W. (2001). "A universal procedure for capacity determination at unsignalized (priority-controlled) intersections." Transportation Research Part B: Methodological **35**(6): 593-623.

Payne, H. J. (1971). "Models of freeway traffic and control." Simulation Council Proceeding 1: ch6: 51-61.

Plank, A. W. and E. A. Catchpole (1984). "A general capacity formula for uncontrolled intersection." Traffic Eng. Control **25**: 327-329.

Poeschl, F. J. (1983). "Die Nicht Signalgesteuerte

Nebenstrassenzufahrt Als Verallgemeinertes M/G/ 1- Warteschlangensystem (The Unsignalized Minor Street Entry as a Generalized M/G/1 Queueing System)." Zeitschrift für Operations Research **27B**.

Richards, P. I. (1956). "Shock Waves on the Highway." Operations Research **4**(1): 42-51.

Robinson, B. W., Z. Tian, et al. (1999). "Extensions of theoretical capacity models to account for special conditions." Transportation Research Part A: Policy and Practice **33**(3–4): 217-236.

Rothery, R. W. (1997). "Car-following models." In Traffic flow theory: A state of the art report - revised monograph on traffic flow theory, N. H. Gartner, C. Messer and A. K. Rathi, Eds., Oak Ridge, Tennessee, Oak Ridge National Laboratory.

Ruskin, H. J. and R. Wang (2002). Modeling Traffic Flow at an Urban Unsignalized Intersection. Proceedings of the International Conference on Computational Science-Part I, Springer-Verlag**:** 381-390.

Siegloch, W. (1973). "Die Leistungsermittlung an Knotenpunkten ohne Lichtsignalsteuerung g (Capacity determination at intersections without traffic signals)." Schriftenreihe Strabenbau und strabenverkehrstechnik **154**.

Tanner, J. C. (1962). "A Theoretical Analysis of Delays at an Uncontrolled Intersection." Biometrika **49**(1/2): 163-170.

Tian, Z. Z., R. Troutbeck, et al. (2000). "A further investigation on critical gap and follow-up time " TRansportation Research Circular E-C108: 4th International Symposium on Highway Capacity 397-408.

Tracz, M. and S. Gondek (2000). "Use of simulation to analysis of impedance impact at unsignalized intersections." Transportation Research Circular(E-C018): 471-484.

Troutbeck, R. J. and W. Brilon (1997). "Unsignalized intersection theory."

Van den Berg, M., A. Hegyi, et al. (2007). "Integrated traffic control for mixed urban and freeway networks: A model predictive control approach." European Journal of Transportation and Infrastructure Research **3**(3): 223-250.

Wagner, C., C. Hoffmann, et al. (1996). "Second-order continuum traffic flow model." Physical Review E **54**(5): 5073.

Wu, N. (2006). "A new model for estimating critical gap and its distribution at unsignalized intersections based on the equilibrium of probbailities." Proceeding of the 5th International Symposium on Highway Capacity and Quality of Service, Yokohama, Japan.

Yeo, G. F. and B. Weesakul (1964). "Delays to Road Traffic at an Intersection." Journal of Applied Probability **1**(2): 297-310.