

CELL-BASED SHORT-TERM TRAFFIC FLOW FORECASTING USING TIME SERIES MODELLING

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ABSTRACT:

The paper develops an efficient short-term traffic flow forecasting strategy merging the theoretical based and empirical based approaches. The empirical based time-series forecasting technique is integrated with the theoretical 'Cell-Transmission Model' (CTM) to effectively forecast the traffic demand downstream using upstream demand values. Traffic flow at the downstream is estimated using CTM, in which the traffic flow demands used are the time series forecasts obtained from seasonal ARIMA time-series models trained on historical loop-detector observations from the upstream junctions. Two junctions are chosen along a congested thoroughfare in the city centre of Dublin, Ireland. The traffic demands obtained on two other downstream junctions are compared with the loop-detector counts of that junction. Comparison shows that the simulated forecasts at downstream junctions deviate around 10% from the original observation. This approach can be utilised where no continuous data collection taking place. It can be considered as a real-time prediction and traffic signal control strategy which captures traffic dynamics such as queue spillback.

INTRODUCTION:

All the major and congested cities of the world are continuously facing the need of betterment of existing traffic control scenario. As there are bleak possibilities of major changes in capacities of existing transportation networks in developed cities, this betterment is only possible through Intelligent Transportation System (ITS). Short-term traffic flow forecasting is an important aspect of this technology.

Short-term forecasting attracted considerable research interest only in the last decade. With increases in computational and data collection facilities research in this field is evolving very fast. The forecasting methods can be broadly classified into two approaches [Van Arem et al., 1997]. One is the ‘empirical based’ approach and the other is the ‘theoretical based’ approach. The empirical methods are essentially heuristic approaches of modelling the traffic volume or other related parameters without referring to the theory behind the traffic movement. The empirical methods include different types of parametric and non-parametric regressions, neural networks, time series analysis and many other techniques. In time series modelling several techniques like the ‘Box & Jenkins techniques’ [Ahmed & cook, 1982], application of subset ARIMA model [Lee & Fambro, 1999], application of seasonal ARIMA model, exponential smoothing model [Williams 2003, Ghosh et al. 2005] etc. are applied by several researchers. The theoretical modelling can be physical as well as behavioural. The physical modelling can be modelling of the variables related to supply into the network using state-space model and Kalman filtering. Behavioural modelling includes different types of assignment models, like Dynamic Traffic Assignment (DTA). One of the most promising macroscopic modelling approaches in developing the underlying traffic behaviour of DTA is the Cell-Transmission Model [Daganzo, 1994 & 1995a]. Recently Lo [2001a & 2001b]

developed a cell-based dynamic network traffic control formulation called *Dynamic Intersection Signal Control Optimization* (DISCO). DISCO is based on the Cell Transmission Model developed by Daganzo [1994, 1995a]. CTM provides a convergent numerical approximation (first-order finite difference) of the well-known LWR (Lighthill-Whitham-Richards) model which is the basis of many existing traffic flow models.

The aim of this paper is to combine the ‘theoretical based’ and the ‘empirical based’ approaches of short-term traffic flow forecasting. This will develop a traffic behavioural basis for the empirical predictions and also strengthen the theoretical based approaches by making them more application oriented. The CTM traffic flow model is combined with the seasonal ARIMA time series forecasting technique. Lo [2001a] developed a real time application of the CTM for certain Hong Kong Streets with DISCO. While with DISCO, Lo always worked on manually collected traffic demand data. Most of the major cities of today’s world have some kind of automated data collection system to maintain an optimized traffic management system in conditions of severe congestion to free flow conditions. The traffic in the city of Dublin is controlled by a well known adaptive traffic control system called SCATS (Sydney Coordinated Adaptive Traffic System). Continuous data collections from almost all the major intersections are carried out using embedded inductive loop-detectors. The seasonal ARIMA model is used to model the loop-detector observations to obtain future predictions to be used for the CTM model as traffic demand input. Using the predictions, CTM model will help to find the traffic flows in Junctions where there is no continuous data collection taking place (Loop detectors are often not used for non critical Junctions). This approach can be used in real-time traffic flow prediction over a transportation network and traffic signal control while capturing traffic dynamics such as queue spillback

Overviews of CTM and Seasonal ARIMA models are given in Section 1 and 2 respectively. The next section (Section 3) describes the site selected for this modelling in the city centre of Dublin, Ireland and also describes the cell representation of the site. The following section deals with the observations collected from the site, along with their time series modelling. Validity of the predictions from the combined models is qualitatively and quantitatively discussed in section 5. Section 6 concludes the paper.

1. CELL TRANSMISSION MODEL:

The cell transmission model (CTM) is a first order finite difference based numerical approximation of the Lighthill-Whitham-Richards (LWR) model. The LWR model [Lighthill & Whitham, 1955, Richards, 1956] or the hydrodynamic theory of the traffic flow underlies most of the present day macroscopic traffic operation models.

This model includes-

1. The quasi-linear hyperbolic conservation equation (*Equation of continuity*)

$$\frac{\partial q}{\partial x} + \frac{\partial k}{\partial t} = 0 \quad [1]$$

2. Relationship between flow and density (*Equation of state*)

$$q = S(k(x,t), x, t) \quad [2]$$

Here q is the flow, k is the density and $S(\cdot)$ is a function of k , x and t .

The solution to the quasi-linear hyperbolic differential equations (of LWR model) is classically computed using the method of characteristics. This apparently simple and continuous solution method becomes very complicated and laborious if a shock wave is formed. Newell and Daganzo [Newell, 1993; Daganzo, 1995a] suggested some approaches to

deal with these problems. Daganzo suggested an alternative way (consistent with the LWR theory) for predicting traffic behaviour for a single link as well as a network, by computing flows at a finite number of carefully selected intermediate points, including the entrance and exit. [Daganzo, 1994 & 1995b].

Though CTM can be applied to any flow-density relation (figure1a), a particular trapezoidal flow-density function is generally used (figure1b). According to the flow-density curve used for CTM, there is a constant free-flow speed (higher speed) at low densities and constant shockwave speed (always less than the free-flow speed) at high densities. Empirically it can be shown that the free-flow speed decreases mainly while the density approaches the flow capacity and otherwise it is fairly constant over a wide range of low densities.

CELL REPRESENTATION FOR A SINGLE LINK [Daganzo, 1994]: For CTM the single link is assumed to be divided into a number of cells of equal length. The length of each cell is the distance traversed in one tick of clock by a single vehicle travelling at free-flow speed.

To define the characteristics of a cell,

- $n_i(t)$: the number of vehicles in any cell i at time instant t
- $N_i(t)$: the maximum number of vehicles that can be present (holding capacity) in cell i at time instant t
- $Q_i(t)$: the maximum vehicle flow possible to cell i while clock ticks from t to $t+1$.
- $Y_i(t)$: vehicles ready to enter cell I at time step t .

$$N_i(t) = (k_j) \times n_l \times L$$

where, k_j is the jam density [veh/km-lane];

n_l is the number of lanes in the cell;

L is the length of the cell [km];

The whole CTM for a single link (figure 2) can be expressed by two equations:

1. The equation of state:

$$Y_{i+1}(t) = \min\{ n_i(t), Q_{max}, \delta[N_{i+1}(t) - n_{i+1}(t)]\} \quad [3]$$

where,

$Y_{i+1}(t)$ is the inflow to cell $i+1$ at any instant t ;

Q_{max} is the maximum number of vehicles that can enter cell $i+1$ at any single tick of clock;

$N_{i+1}(t) - n_{i+1}(t)$ is the available space in cell $i+1$;

δ is the ratio of shockwave speed to free-flow speed (w/v);

This equation covers both the congested and uncongested situation. In the case of uncongested flow, the situation in the upstream cell i.e. the first term determines the flow; whereas in the congested situation downstream conditions i.e. the third term determines the flow. The middle term acts as the constraint in the case of bottlenecks.

2. The conservation equation:

$$n_i(t+1) = n_i(t) + Y_i(t) - Y_{i+1}(t) \quad [4]$$

This equation updates the flow in consecutive cells at each time step. According to the equation the number of vehicles present in cell i at time instant $t+1$ is the number of vehicles present in the cell before the time step, plus the inflow to the cell minus the outflow from the cell during this time step.

If the cells are signalized (Lo, 1999a & b), then the maximum holding capacity $Q_i(t)$ of any cell i varies as follows-

$$Q_i(t) = \begin{cases} Q_{max} & \text{if } t \in \text{green phase} \\ 0 & \text{if } t \in \text{red phase} \end{cases} \quad \text{where, } i \text{ is a signalized cell;}$$

CELL REPRESENTATION FOR A NETWORK: A network consists of an ensemble of directed links and nodes. Each of the links can be modelled for CTM using the technique described for a single link. The only improvements are required while modelling the nodes attached with multiple links. Daganzo [1995b] suggested the allowed topologies (merges and diverges) in a network and their representation in CTM. For a signalized network Chang [1998] further developed these representations for ‘*signalized merges*’ and ‘*turning lane diverges*’ case. Here the network topologies used in the paper are discussed.

Merges are one the most important movements to be modelled while dealing with a network. According to Daganzo [1995b], there are three types of merge conditions possible.

MERGES:

There can be three possible types of merging scenarios:

1. Forward: If flows from both the merging approaches (here, cells) depend on the conditions upstream (both approaches flowing freely).
2. Backward: If flows from both the merging approaches/cells depend on the conditions downstream (both approaches are congested).
3. Mixed: If the flow from one merging approach depends on downstream conditions while the other on upstream conditions (when the priority crowds out traffic on complementary approach)

Boundary conditions used here to get the CTM form are similar to those for two merging pipes carrying a compressible fluid. Figure 3 shows a ‘merge’ manoeuvre.

$$Y_B(t) = \text{mid} \{ S_B, R_E - S_C, p_B R_E \} \quad [5a]$$

$$Y_C(t) = \text{mid} \{ S_C, R_E - S_B, p_C R_E \} \quad [5b]$$

$$\text{if, } R_E < S_B + S_C \quad [5c]$$

where, S_B and S_C are maximum possible outflow from the two sending cells **B** and **C** respectively while R_E is the maximum possible inflow to cell **E**; Y_B and Y_C are the emitting flows from the cells **B** and **C**. p_B and p_C are the proportions of R_E coming from the cells and **C** respectively.

The equations 5(a) to 5(c) are the generalised form of equation 3 used for ‘merges’ in a network. Using the equation 4 the flows can be updated.

Unsignalised and Signalised Merges: From figure 3, both the cells **B** and **C** flow into the cell **E**. In case of both signalised and unsignalised junctions, the three equations 5(a) to 5(c) are to be used. Only the constants p_B and p_C will be different for signalised and unsignalised junctions. These constants are to be determined while designing any intersection which captures this kind of merging manoeuvre.

The set of equations 5(a, b & c) will remain in the same form for unsignalised junctions.

Only it is to remember always that $p_B + p_C = 1$.

In the case of a signalised intersection, cell **B** and cell **C** don’t flow in the same time to cell **E**. Under these circumstances, where a maximum of one cell can flow at a time, the constants p_B and p_C will be either 1 or 0. The set of equations 5(a, b & c) will simplify to,

$$\begin{aligned} Y_B(t) &= 0, \text{ if, } p_B(t) = 0; \\ Y_B(t) &= \min\{S_B, R_E\} \text{ if, } p_B(t) = 1; \end{aligned} \quad [6]$$

DIVERGES:

To accurately model a network Daganzo [199x] introduced the idea of modelling diverging manoeuvres. In the case of the one way street system modelled here, this diverging applies to the through and turning movement of vehicles from any one way street, sharing the same green time. In the same way as used by Lo [2001], the time variant turning properties are

used here. As shown in figure 4, with this option, vehicles from a single cell (here cell **B**) can flow to two different destination cells (here, cell **E** and cell **C**) in two different directions. Considering that the turning proportions are known from beforehand, the inflow to each cell is,

$$Y_C = \beta_C S_B(t) \quad \text{and,} \quad Y_E = \beta_E S_B(t) \quad [7]$$

where, Y_C : the inflow to cell **C**

Y_E : the inflow to cell **E**

$S_B(t)$: the outflow from cell **B** at time instant t

and, β_C & β_E are the proportions going to cells **C** and **E** respectively. As both cells **C** and **E** are considered as destinations of the outflow from cell **B**, if any of them is unable to accommodate the allocated inflow then the entire outflow is restricted. This is to maintain FIFO (first in first out) principle. Hence,

$$S_B(T) = \min \left\{ \begin{array}{c} n_B(t) \\ Q_B(t) \\ \min\{Q_E(t), \delta[N_E(t) - n_E(t)]\} / \beta_E \\ \min\{Q_C(t), \delta[N_C(t) - n_C(t)]\} / \beta_C \end{array} \right\} \quad [8]$$

2. SEASONAL ARIMA MODEL:

A simple ARIMA model constitutes three parts, ‘AR’, i.e. autoregressive part; ‘I’, i.e. differencing part; ‘MA’, i.e. moving average part; ‘Differencing’ is essentially a tool to eliminate trends in time series data.

The 'first difference' y'_t of any time-series data is, $y'_t = y_t - y_{t-1}$ [1a]

In an 'auto regressive' process, each time-series observation ' y_t ' is defined in terms of its

predecessors, ' y_s ', for $s < t$, by the equation, $y_t = \sum_{i=1}^p \alpha_i y_{t-i} + Z_t$ [1b]

where, $\alpha_1, \alpha_2, \alpha_3, \dots, \alpha_p$ are the coefficients of the auto regressive process of the order p .

A 'moving average' process is simply a finite linear filter applied to a white noise sequence

$\{Z_t\}$, of the form $y_t = Z_t + \sum_{j=1}^q \beta_j Z_{t-j}$ [1c]

where, $\beta_1, \beta_2, \beta_3, \dots, \beta_q$ are the coefficients of the moving average process of the order q .

Combining these three components and using the 'backshift operator', B , the equation

representing an ARIMA (p, d, q) model is,

$$\phi(B)(1-B)^d y_t = \theta(B)Z_t \quad [1d]$$

where, Z_t is a white noise sequence;

ϕ is a polynomial of degree p , i.e. $\phi(B) = (1 - \alpha_1 B - \alpha_2 B^2 - \alpha_3 B^3 - \dots - \alpha_p B^p)$ and θ is a

polynomial of degree q , i.e. $\theta(B) = (1 - \beta_1 B - \beta_2 B^2 - \beta_3 B^3 - \dots - \beta_q B^q)$. [1e]

In ARIMA (p, d, q), p denotes the order of the AR process, d denotes the order of differencing and q denotes the order of MA process.

Seasonality and ARIMA Process

[Fuller, 1996]

If the time-series data to be fitted in an ARIMA model has some intrinsic periodicity, then instead of a simple ARIMA, a seasonal ARIMA model can be used.

There are two types of seasonal models, *additive* and *multiplicative*. Here the

multiplicative seasonal ARIMA model $(p, d, q)(P, D, Q)_s$ is used. In the *multiplicative*

model the non-seasonal part (p, d, q) and the seasonal part (P, D, Q)_s part are multiplied together. The equation used for the multiplicative seasonal ARIMA model is as follows:

$$\phi(B)\Phi(B^S)(1-B)^d(1-B^S)^D y_t = \theta(B)\Theta(B^S)Z_t \quad [1f]$$

where, ϕ, θ have the same significance as described in the earlier section and Φ, Θ are their seasonal counterparts, S denotes the seasonality. The centred traffic data is used for ARIMA modelling using Box and Jenkins [Box and Jenkins, 1970] methodology. Following the three steps of this methodology, *Identification, Estimation and Diagnostics checking* a few seasonal ARIMA models are fitted.

3. TRAFFIC NETWORK USED:

The traffic network used here for modelling using a combined CTM and time series forecasting approach is a part of the busy city centre of Dublin (figure 5). Considerable queue formation and congestion can be encountered in this site during the peak hours. The main thoroughfares are Tara Street and the Quays, which carry one-way traffic throughout. Two crossings of Tara Street with Pool beg Street and the Quays are considered here. Two un-signalised side streets from the quays are also considered within the network. All of the crossroads carry one-way traffic as well as the main streets. Ireland has a left-hand drive system with no protected turning movements in this site. Junction TCS183 and TCS184 has two phased signals, but the two downstream junctions have multi-phased (>2) signal plans.

3.1 DATA COLLECTION FOR CTM MODELLING:

The traffic management in the city of Dublin is done using SCATS. The traffic demand data are collected using the loop-detectors used by SCATS. Signal timings (from adaptive signal

control) are obtained from the SCATS database as well. Other required constants for the CTM model are,

- Free flow speed [60 dataset]
- Saturation Flow [40 dataset]
- Shockwave speed [30 dataset]

Other than these for the turning movement (which is not obtained from the loop-detectors), 16sets of data from each lane, used for both through and turning movements, are collected. Using this manually counted data and the loop detector volumes, turning ratios and the merge ratios are calculated.

3.2 CTM REPRESENTATION AND CALIBRATION OF THE NETWORK:

The links are divided into equal length cells (whose length is governed by the free flow speed and the space discretisation criteria). The possible movement in and out of the cell are represented by directional arrows. Figure 6 shows a figurative representation of the network. Turning movements along with merges and diverges are modelled as can be seen from figure 6. The capacity of each approach or more precisely each lane is decided judging the site conditions and past traffic demands.

4. TIME-SERIES MODELLING OF LOOP OBSERVATIONS

The traffic demands used in the CTM model are the predicted demands from the time series modelling of the existing and past traffic demand data. The traffic demand of the four roads (Tara Street, Poolbeg Street, Butt Bridge and the Quays) used in modelling

are obtained from the inductive loops of those streets. The data used for modelling were recorded from 16th May 2005 early morning to 30th June 2005 early morning, excluding the weekends and bank holidays. 96 observations are obtained in each day. [The total number of observations is 2592 are obtained from each data source.](#) The data show definite seasonality in pattern over a period of 24 hours. This leads to the idea of fitting a seasonal time-series model. As this site is the same as (or very similar) to that of the paper by Ghosh et al.[2005], more or less the same seasonal ARIMA models are used in modelling the observations. All the seasonal ARIMA models fitted to each origin traffic demand data are given in table 2.

5. COMPARISON OF CTM RESULTS WITH REAL TIME FLOW:

Although it was expected that there would be manual errors during data collection, most of the predictions were within 10% of the actual observations. The mean absolute percentage of the 1 hour prediction data set (table 3) is only 4.4% in Junction TCS 17 and 10.6% in TCS 196. The error has two parts; one is due to CTM simulations and one related to using the time-series forecasts as input traffic demand instead of real observations.

The possible reasons of the error or discrepancy seems to lie in the erroneous data used for the model. The loop-detector data are often erroneous owing to the fact that some of the inductive loops in any big network are regularly faulty. The signal timing plan (table 4) used from the SCATS system in Dublin really follows a fixed cycle time approach in Junction TCS 184 and TCS 183. But in Junction TCS 17 and TCS 196, the cycle length

was not exactly fixed and the phase times were varying in the order of $\frac{1}{2}$ seconds 0.5 seconds??. But as the pedestrian phases are not recorded by the SCATS system, the average fixed cycles of 120 second were to be assumed. Due to this average cycle time over 4:00pm to 5:00pm of 30th, June, 2005 are used, instead of an exact signal time plan and accurate cycle lengths as used for Junction TCS 183. This error in the order of $\frac{2}{3}$ seconds may be attributed to a considerable percentage to the final error values.

6. CONCLUSION:

The empirical based time-series forecasting technique is integrated with the theoretical 'Cell-Transmission Model' (CTM) to effectively simulate the traffic demand at two downstream junctions at the city centre of Dublin using traffic demand of two upstream junctions. The simulated traffic demands are actually based on the time-series forecasts at the origins. Instead of a single site time-series model, this model can capture the effect of neighbouring sites by capturing phenomenon like queue spillback. In the two junctions considered here, the simulated traffic demands vary differently. The variation is mainly due to lane changing, which cannot be captured by this model. In cases where lane changing is not significant, the model performs well. So, this technique can be used very effectively for junctions where no data collection is taking place. Again, this model is used to simulate traffic demands in the future unlike other CTM based simulation technique and hence, can be used for real time online traffic signal control.

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Table 1

ROAD NAME	FREE FLOW SPEED	SHOCKWAVE SPEED	SATURATION FLOW
<i>TARA STREET</i> (From Origin till TCS 184)	9.78m/s	3.7m/s	1783.67vphpl
<i>TARA STREET</i> (TCS 184 to TCS 183)	9.78m/s	3.7m/s	1783.67vphpl
<i>BUTT BRIDGE</i>	9.78m/s	3.7m/s	1783.67vphpl
<i>POOLBEG STREET</i>	9.78m/s	3.7m/s	1783.67vphpl
<i>BURGH QUAY & GEORGE QUAY</i>	9.78m/s	3.7m/s	1783.67vphpl

Table 2

ORIGIN	LOOP-DETECTOR	SEASONAL ARIMA MODEL
OR1	Loop 7, Junction TCS 183	(2,0,1)(0,1,1) ₉₆
OR2	Loop 5 & 6, Junction TCS 183	(2,0,1)(0,1,1) ₉₆
OR3	Loop 6, Junction TCS 184	(2,0,1)(0,1,1) ₉₆
OR4	Loop 5, Junction TCS 184	(1,0,1)(1,1,1) ₉₆
OR5	Loop 1, Junction TCS 184	(2,0,1)(0,1,1) ₉₆
OR6	Loop 2,3 & 4, Junction TCS 184	(2,0,1)(0,1,1) ₉₆

Table 3

TIME	TCS17 observations	TCS17 forecasts	Abs RMSE error	TCS196 observations	TCS196 forecasts	Abs RMSE error
16:15	453	485.1431	0.070956	374	329.3304	0.119437
16:30	452	424.0489	0.061839	314	342.8294	0.091813
16:45	451	470.2962	0.042785	367	322.9775	0.119952
17:00	418	416.9537	0.002503	313	342.8294	0.095302

Table 4

Junction	Street Name	Phase	Offset	Green Effective	Red Effective
TCS 183	<i>Tara Street</i>	A	0	69sec	51sec
	<i>Burgh Quay & George Quay</i>	B	72sec	45sec	75sec
TCS 184	<i>Tara Street</i>	A	0	93sec	27sec
	<i>Poolbeg Street</i>	B	96sec	21sec	99sec

Figure 5: The Figurative Diagram of the Junctions

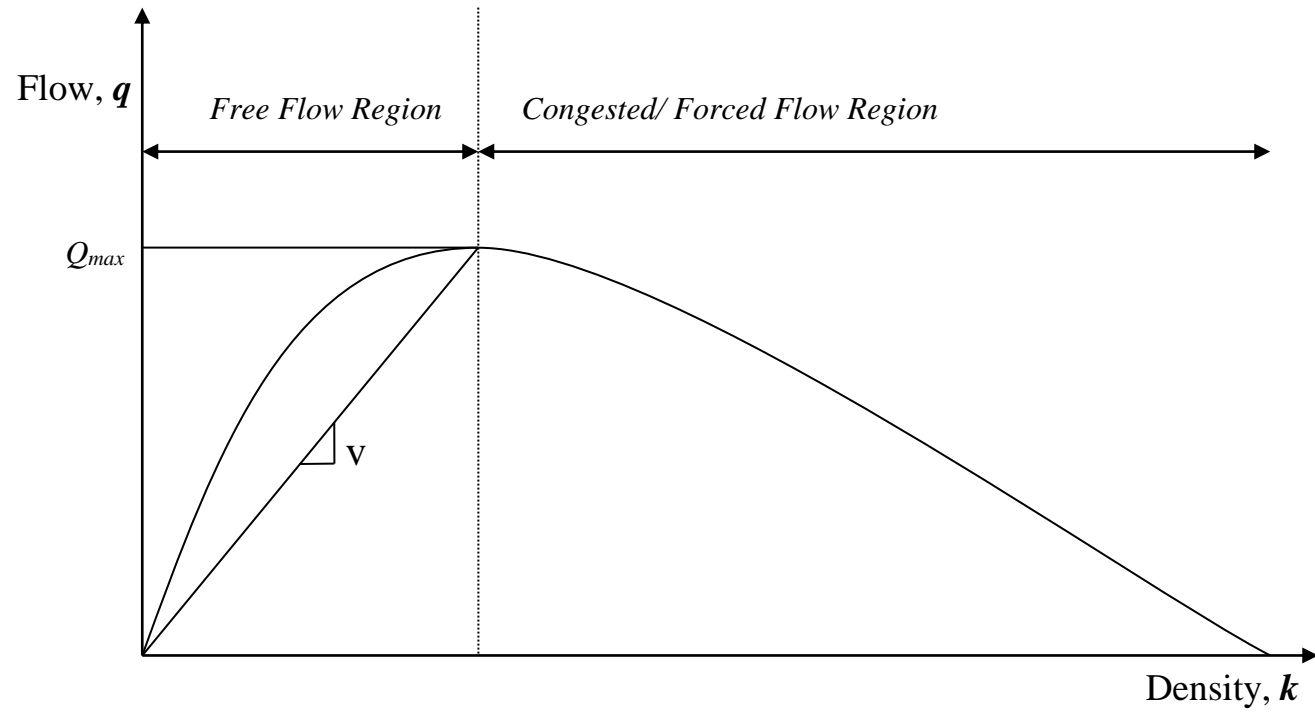


Figure 1a: The Fundamental Flow-density Diagram

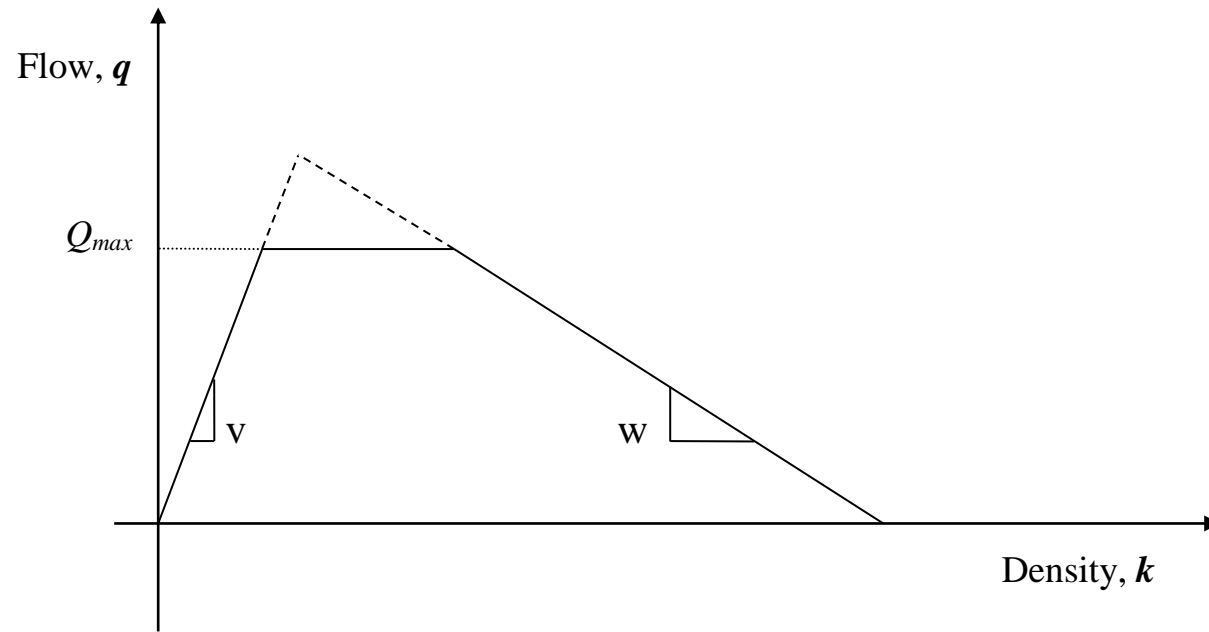


Figure 1b: The Flow Density Relationship Used in CTM

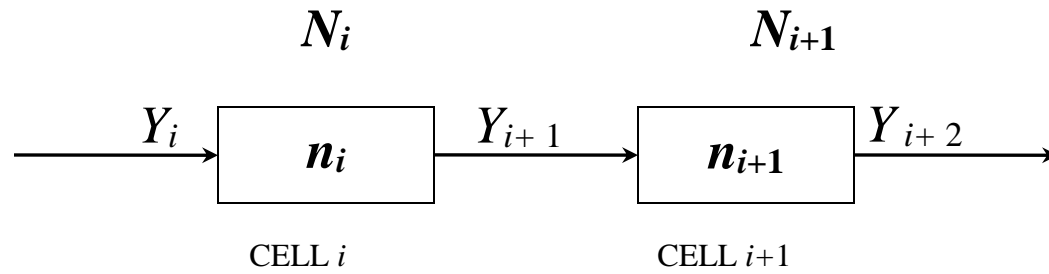


Figure 2: The Basic CTM Model for Single Link with Two Cells
Ref: Lo & Chan (2001a)

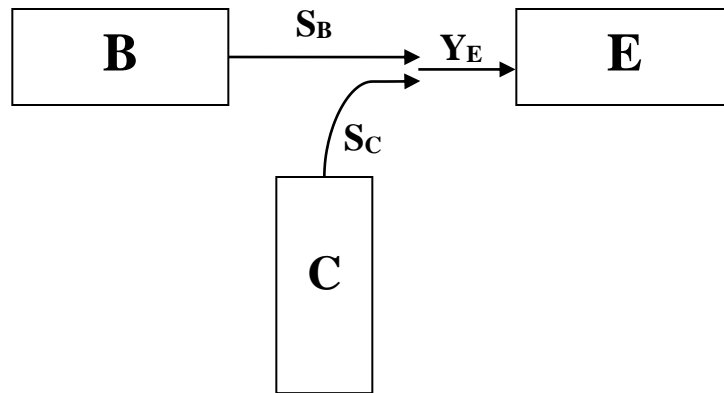


Figure 3: A Signalised Merge
Ref: Lo & Chan (2001a)

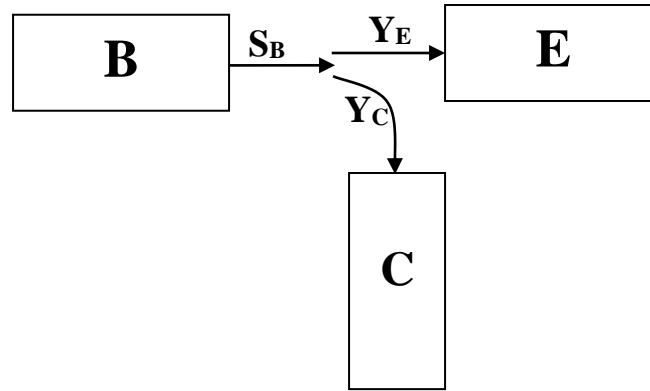


Figure 4: A Diverge Manoeuvre
Ref: Lo & Chan (2001a)

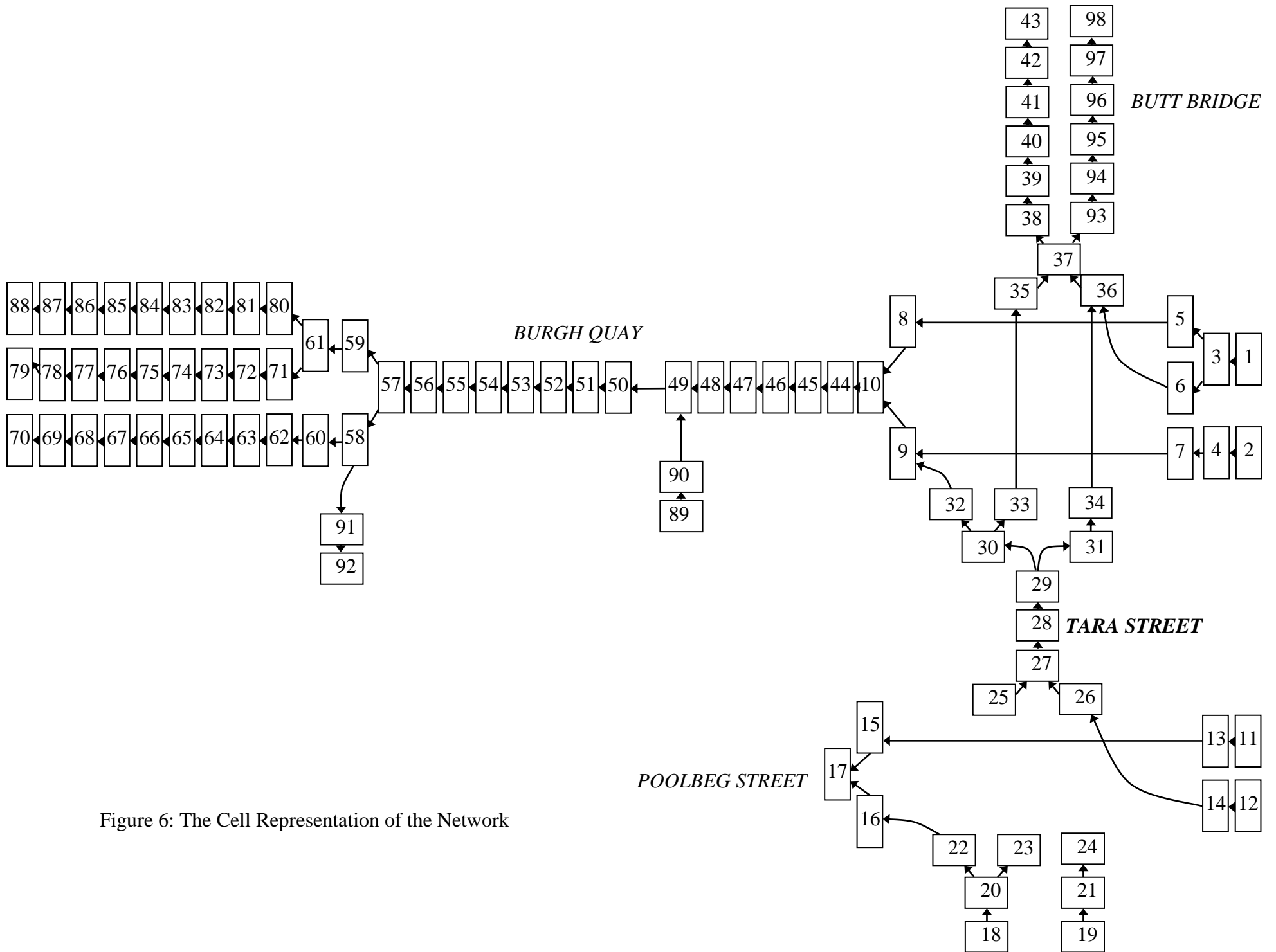


Figure 6: The Cell Representation of the Network