Applying Cell Transmission Model for Solving Urban Traffic Jams

Y.S. HUANG, C.C. Ho and B.Y. Xie

Abstract—Cell transmission model (CTM) is useful for evaluating the performance of urban traffic networks due to its mathematical formalism. This work explores an extend traffic control policy for dispersing the problem of the incident-based traffic jams. For this purpose, the authors employ CTM to analyse of an urban traffic jam problem. CTM is useful for evaluating the performance of urban traffic networks due to its mathematical formalism. In this paper, the MATLAB platform is used to design a traffic simulation tool based on CTM, which successfully simulates the propagation and dispersion of traffic congestion caused by an accident. This work explores the application of CTM to develop control strategies for dispersion accident-induced traffic jams and evaluates the efficiency of these strategies.

Keywords— Cell transmission model, traffic jam, and traffic safety.

I. Introduction

TRAFFIC congestion is a growing problem in many big cities because a growing number of vehicles are used. With more and more vehicles, the transportation delay and traffic congestion on urban arterials are increasing throughout the world. Hence, it is essential to possess strategic analysis methods for increasing the efficiency of transportation. Intelligent transportation system (ITS) can play an important role in improving transportation system efficiency and safety. Naturally, ITS technologies are applied in traffic congestion issues, such as traffic accident detection and verification [1]-[3], accident response logistics [4], and accident wireless communication [5]. Besides, Figueiredo *et al.* [6] analyze the freeway traffic via a simulator of ITSs. On the other hand, the problem of traffic congestion has become a major issue, particularly when a car crash occurs in an urban area. Car accidents can cause traffic jams that spread over large tracts of an urban network. Consequently, one demands to study the process of traffic jam formation and growth. We understand that a traffic jam can be caused by one of the following three reasons [7]: (1) a temporary obstruction, (2) a permanent capacity constraint, and (3) a stochastic fluctuation in the demand. Here, we only pay attention to traffic congestion caused by a grid network accident that might be categorized under (1) or (2). Qi et al. [8] pointed out that accident-based congestion is a kind of traffic jam. If the accident is not cleared in time, it may lead to large-scale congestion of upstream traffic. Much research work has been discussed with various accident-based jam issues, such as Wright and Roberg [9] proposed a simple analytical model and Roberg [10] proposed accident simulation models, are based on accident-based jam formation and growth. Additionally, Roberg *et al.* [11] mentioned that the accident-based control strategy can be divided into static prevention and dynamic control strategies. The static prevention strategy issues on how the road layout features can be employed to diminish the jam spreading. The dynamic control strategy can be hired to slow the jam propagation. Daganzo [12] proposed CTM for analyzing network traffic and the method can be applied to solve the problem of traffic jams. Recently, Long *et al.* [13] stated that CTM can simulate network-wide traffic flow in a more realistic manner than traffic flow in one-way networks [14-17]. Especially, they have extended CTM and employed it to simulate accident-based jam propagation in two-way grid networks. Moreover, two-way roads are more commonly found in urban traffic networks than one way ones [18]. Nevertheless, Qi *et al.* [8] also proposed control strategies for dispersion accident-induced traffic jams and evaluated the efficiency of these strategies. On the other hand, Roberg-Orenstein *et al.* [11] have developed various strategies to solve traffic congestion issues.

A lot of work has been invested into developing various traffic signal control strategies to improve traffic efficiency. They are divided into three categories: (1) fixed-timed, (2) traffic responsive and (3) predictive control strategies. The first one is widely adopted in most existing urban transportation systems because it is easy to implement and manage. However, the drawback of fixed-timed is based on historical traffic flow data rather than real-time data. The first is widely adopted in most existing urban transportation systems because it is easy to implement and manage. However, the disadvantage of fixed timing is based on historical traffic flow data rather than real-time data. The second one, such as SCATS [19] and SCOOT [20], is based on measured traffic states in time and has

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been widely used in many cities throughout the world [21]. The third one is an optimal control strategy that predicts the future traffic behavior of the network [22].

Moreover, two traffic light strategies are proposed for single-intersection control and network-wide control, such as minimizing the queue lengths described by an optimal traffic light switching scheme model [23] and applying the network-wide traffic control in large-scale [24]-[30]. Unfortunately, most of the existing control strategies are only suitable for low/middle traffic flow and stable conditions. Note that an accident can quickly invalidate the above control strategies due to traffic congestion. In order to solve the problem of urban traffic jams based on accidents, mostly prevented methods are adopted traffic flow diversion with the help of the traffic police. This work employs a CTM-based method to analyze the problem of traffic jams according to the number of vehicles contained in each cell.

The rest of the paper is organized as follows: Section II provides the definitions of CTM via a compact way. Section III depicts the simulation results. Conclusions will be explained in Section IV.

II. Preliminaries

This section aims to introduce the notations of CTM [37] and describe the definitions of TPNs [30]. To the best of our knowledge, Daganzo [38][39] proposed the original CTM to improve the Lighthill-Whitham-Richards (LWR) model [40][41] by adopting the following relationship between traffic flow q and density k as shown in Fig. 1:

$$q = min\{vk, q_{max}, w(k_j - k)\}, 0 \le k \le k_j \tag{1}$$

where v is the free flow speed and w is the speed of all backward moving waves, and q_{max} and k_j denote maximum allowable inflow and jam density, respectively.

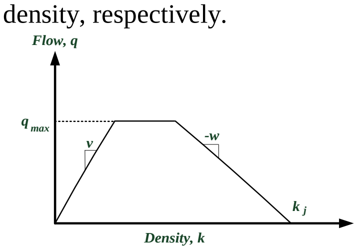

Fig. 1. The relationship of flow-density for the generalized CTM [42].

In this study, we employ an 8×8 two-way grid network $G = (C, A)$ to demonstrate simulation results by our traffic jam control policies. C is defined as the set of nodes, A is the set of links; $a = (l, m)$ is the link formed of nodes l and m; A_l denotes the set of links heading to node l; B_m denotes the set of links leaving to node m. Here, each link is discretized into λ cells and time is partitioned into intervals such that the cell length by free-flow traffic in one time interval δ. As shown in Fig. 2, Link a is divided into two distinct zones [37]: a downstream queue storage area where vehicles are organized according to their turning movements, and an upstream reservoir where the turning movements are mixed. For a particular cell, i.e., 9th cell, the downstream queue storage area consists of three divisions, i.e., q_L, q_S and q_R, which form the segregated queuing areas. For convenience, we introduce CTM [37] by a compact way. The details of the CTM will be described as follows.

$$y_i(t) = \min\{n_{i-1}(t), Q_i(t), w\big(N_i(t) - n_i(t)\big)/v\} \tag{2}$$

$$n_i(t+1) = n_i(t) + y_i(t) - y_{i+1}(t) \tag{3}$$

where $y_i(t)$ is the number of vehicles that flow into cell i during time interval t, $n_i(t)$ is the number of vehicles in cell i before t, $N_i(t)$ denotes the maximum number of vehicles that can be contained in cell i during t, and $Q_i(t)$ denotes the inflow capacity in cell i during t.

Here, the inflow formulation can be classified into three categories: inflow of upstream reservoir (i = 1), inflow of upstream cells (1< i≤8), and inflow of channelized downstream queue area (i = λ). We consider the influence of traffic flow lane changing behavior to illustrate the designed traffic light strategy. The inflow formulation is presented as follows:

1) *Inflow of upstream cells*

Inflow of upstream cells can be calculated by:

$$y_a^i(t) = \min\{n_a^{i-1}(t), Q_a^i(t), w(N_a^i(t) - n_a^i(t)/v\}, 1 < i \le 8 \tag{4}$$

From Eq. (4), we have

$$y_{ab}^i(t) = \emptyset_{ab} y_a^i(t), i = 9 \tag{5}$$

2) *Inflow of the channelized downstream queue area*

Here, we employ the definition of $\tilde{y}_{ab}(t)$ as the up bound of inflow of the downstream queues area for vehicles travelling from link a to link b. Hence,

$$\tilde{y}_{ab}(t) = \min\{\emptyset_{ab} Q_a^i(t), w(\emptyset_{ab} N_a^i(t) - n_{ab}^\lambda(t))/v\} \tag{6}$$

Because of interference between turning vehicles and ahead vehicles, the total inflow of channelized queues area can be formulated as follows.

$$y_a^\lambda(t) = \min_{b \in B_m}\{\tilde{y}_{ab}(t)/\emptyset_{ab}\} \tag{7}$$

Here, let ϕ'_{ab} denote the proportion of vehicles traveling from link a to link b. When a ban/warning signal is displayed for direction a, direction b or c can be considered as the direction in which the vehicle can select the right/left turn. We have

$$\phi'_{ab} = \phi_{ab}(1 - d_x), \phi'_{ac} = \phi_{ac} + \phi_{ab}(d_x/2), \text{and}$$
$$\phi'_{ad} = \phi_{ac} + \phi_{ab}(d_x/2), \text{where } x \in \{A,B,C\} \tag{8}$$

The total inflow of the channelized queues area can be obtained via Eqs. (4)-(7), where $\phi_{ab} = \phi'_{ab}$ is computed by Eq. (8). Inflow of each direction can be calculated by Eq. (9), gives

$$y_{ab}^\lambda(t) = \min\{\emptyset_{ab} y_a^\lambda(t), \phi'_{ab} n_a^{\lambda-1}(t)\} \tag{9}$$

Hence, the update of the number of vehicles contained in each cell is formulated as follows.

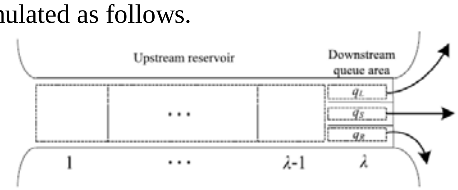

Fig. 2. Components of link a in two-way grid network.

III. Simulation And Analysis

We employ the MATLAB platform to design a traffic simulation environment for traffic jam propagation and dispersion using a time-step method. The simulation environment is based on CTM and can capture realistic traffic dynamics in detail. For convenience, we construct a two-way 8

× 8 grid traffic network (i.e., Fig. 3) to demonstrate traffic jam propagation while an accident is happening and how the traffic jam is dispersed while our control policy is active.

For convenience, the parameters for the extended CTM are set as the same as [8] and [37]. They are shown below:

1) The length of each time interval δ: 5*s*;
2) Jam density: 133 *vehicles*/*km* (i.e., 7.5 *m* for every vehicle);
3) Free-flow speed: 54 *km/h* (i.e., 15 *m/s*), and backward shock-wave speed [8]: 21.6 *km/h* (i.e. 6 *m/s*);
4) Number of lanes: 2 ;
5) Flow capacity: 1800 *vehicles/h/lane* (i.e. 2.5 *vehicles/time interval/lane*) ;
6) The length of each cell is 75 *m*, and the holding capacity of each cell is 20 vehicles;
7) The number of cells of each link: 9 (i.e. the length of every link is 675 *m*);
8) We define the concept of a jammed cell which can occur if the density of a cell in the upstream 'reservoir' is greater than 0.9*N*; or if

the density of a cell in any direction of the downstream channelized area is greater than $0.9k_j$;

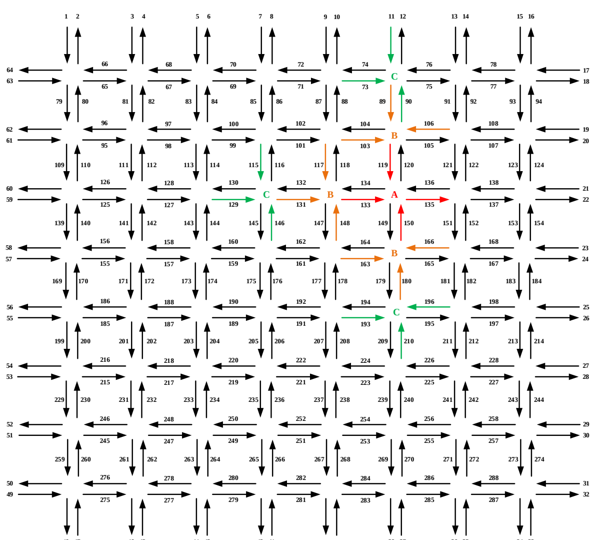

Fig. 3. A two-way 8 × 8 grid traffic network.

Example 1: we use no strategy (regular control strategy) to observe the formation of traffic jams. To facilitate the observation of traffic jam propagation, we assume that the accident occurs at the 301st time interval and it is cleared at the 1000th time interval. In this case, the simulation results of traffic jam formulation and dispersion are shown in Fig. 4. We can obtain the maximal of jammed cell is 58 at 1000th time interval.

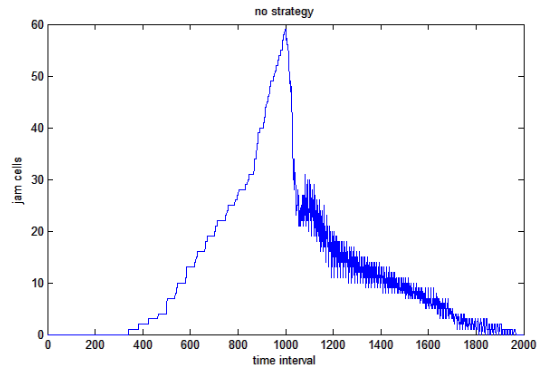

Fig. 4. All traffic jammed cells in regular control strategy.

For convenience, we use the same parameters as Qi *et al.* [8] in our simulation environment. They constructed a ban signal strategy that works at intersection *A* while the warning signal strategy works at intersection *B*. In this study, we employ d_A, d_B and d_C to represent the percent of vehicles headed in that direction will change their routes at the intersections *A*, *B* and *C*, *respectively*.

Example 2: In this example, an accident occurs from the 301st time interval to the 1000th time interval. Our control strategy starts at 301th time interval. Here, d_1 =0.9; d_2 =0.3 (d_2 =0.5) with t_d = 0.5. Two cases simulation results are shown in Fig. 5 and Fig. 6, d_2 =0.3 and d_2 =0.5, respectively.

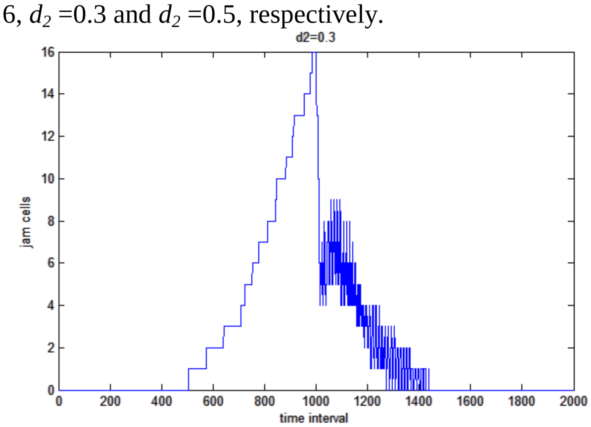

Fig. 5. Traffic jam propagation and dispersion under d_1 =0.9, d_2 =0.3 with t_d = 0.5.

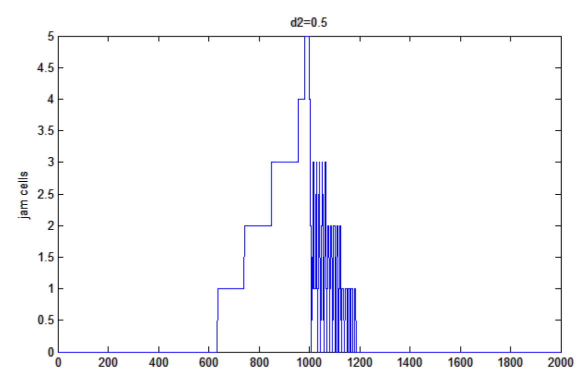

Fig. 6. Traffic jam propagation and dispersion under d_1 =0.9, d_2 =0.5 with t_d = 0.5.

According to the simulation results, the performance of traffic jam dispersion under d_1 = 0.9 and d_2 = 0.5 is better than d_1 = 0.9 and d_2 = 0.3. Case II needs only 350 time intervals for traffic jam dispersion.

IV. CONCLUSIONS

In this paper, the MATLAB platform is used to design a traffic simulation tool based on CTM, which successfully simulates the propagation and dispersion of traffic congestion caused by an accident. In order to effectively disperse the traffic congestion caused by an accident, our effective control strategy is able to adjust the duration of traffic lights that depends entirely on the location of the accident is presented. More importantly, our control strategy only uses traditional traffic lights in intersections adjacent to the accident site at the scene of the accident to prevent traffic from flowing to the direction of the accident.

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