An urban traffic flow model to capture complex flow interactions among lane groups for signalized intersections

Marco Tiriolo a*, Ludovica Adacher a, Ernesto Cipriani b

a Department Of Computer Science And Automation, University of Roma Tre, Via della Vasca Navale 79, I-00146 Roma, Italy
b Department Of Science Of Civil Engineering, University of Roma Tre, Via della Vasca Navale 79, I-00146 Roma, Italy

Abstract

This paper presents a traffic flow model, based on cell transmission concept, to capture urban traffic dynamics taking into account complex flow interactions among lane groups at upstream of signalized intersections. This model is a simple and versatile simulation framework designed to simulate, at macroscopic level, more realistically the dynamic interaction of queues among neighboring lanes and intersections for large scale urban network. Model validation has been undertaken by comparing with Vissim results obtained in different scenarios that have been tested.

Keywords: Macroscopic simulation traffic flow; Cell transmission model; Queue interactions ; Urban road network

1. Introduction

The activity of urban traffic network remains a challenge in Intelligent Transportation Systems (ITS) due to the intrinsic complexity of traffic systems. An updated, possibly in real-time and reliable urban traffic flow prediction is the foundation of traffic management and control in urban context.

Papageorgiou et al. (2003) argued that despite the significant progress done by different traffic-control measures aimed at reducing the level of urban network congestions, the cost associated with the problem has been constantly increasing in the past decades. In the last years the research has shown that application of ITS can accomplish decrease of congestion (Viti 2006) but the technology solution is based on capacity to estimate accurately the travel time prediction. Van Hinsbergen et al. (2007) provided an overview on short-term traffic
prediction models highlighting the need of an efficiency model for larger scale. Liu et al. (2008) proposed the first neural network method for predict travel time and draw some conclusions.

Macroscopic model for traffic flows in urban arterials are frequently proposed in literature. Van den Berg et al. (2003) present a macroscopic model based on the model developed by Kashani (1983) for mixed urban and freeway traffic networks. A dynamic macroscopic model proposed by Chevallier and Leclercq (2007), for unsignalized intersections, accounts for time-limited disruptions in the minor stream flow, even in free-flow conditions when the mean flow demand is satisfied. Abu-Lebdeh et al. (2007) designed models that can represent the traffic output of intersections under congested flow conditions and, in particular, considered the interactions among traffic streams at successive signals. Tonguz (2009) proposed a new cellular automata approach to formulate an urban traffic mobility model. He has shown that different control mechanisms used at intersections such as cycle duration, green split, and coordination of traffic lights have a considerable effect on intervehicle spacing distribution and traffic dynamics.

In literature the Cell Transmission Model (CTM) is identified as a macroscopic simulation method with specific features quite close microscopic capabilities (Flöteröd and Nagel 2005). Therefore, it is suited for real-time application at large network scale, because the model doesn't have a complex formulation and is robust. In the present paper we proposed an CTM extension with the objective to capture the characteristics of traffic flows on urban roads in simulation.

The CTM proposed by Daganzo (1994, 1995), based on the hydromechanical theory, is a discrete approximate model of the Lighthill and Whitham (1955), and Richards (1956) (LWR) model. Through important features such as queue formation, queue dissipation and kinematic waves, the CTM can represent the realistic traffic dynamics. Recently, some researchers have proposed traffic simulation models based on cell transmission model (CTM). In 2006, Laval and Daganzo proposed a hybrid implementation of the kinematic wave theory to account for lane-changing in traffic streams, so improving CTM accuracy. Ishak et al. (2006) proposed different extensions to the original CTM formulation to account for variable cell length, non-integer movements between cells and more realistic representation of merging and diverging junctions. In this way, the applicability of CTM for operational analysis of large-scale traffic networks is refined.

Many researches have investigated the applicability of CTM in different transportation areas. Gomes et al. (2008) analyzed and validated the effectiveness of CTM in ramp metering management. Long et al. (2011) show that LWR model and the network version of CTM can simulate jam propagation and dissipation in grid networks. Lin et al. (2004), Juri et al. (2007), Van Hinsbergen et al. (2008), and Szeto et al. (2008) used CTM as a freeway traffic flow modelling tool in developing various travel time prediction methods.

Despite the results obtained in literature, some critical issues remain to be addressed. First, most dynamic queue models do not integrate the multiple signal phases. In second place, the spillback phenomena has not been explicitly modeled during congested conditions. For this reason, this paper presents a traffic flow prediction model, based on cell transmission concept, to capture urban traffic dynamics taking into account complex flow interactions among lane groups at upstream of signalized intersections. In this work we define a traffic simulation model that: i) provides a good trade-off between accuracy and computational complexity with respect to the microscopic model; ii) makes short-term prediction of traffic flow on the large traffic network; iii) captures spillback effect and queues dissipation for lane; and iv) represents flow interactions of queues among neighboring lanes and intersections.

2. Background model

The hydrodynamic theory of traffic flow can be used to represent the dynamic behavior of traffic, including the formation, propagation, and dissipation of queues. As it is well known, the classic continuity equation for flow conservation plays the key role of the hydrodynamic theory of traffic flow: it defines the relationship between flow ($\Phi$) and density ($\rho$) over time and space in the following form:
The speed is a function of density, \( v = v(\rho) \). The flow function \( \Phi(\rho) = \rho(v(\rho)) \), called the fundamental diagram, is assumed to be concave. \( \Phi \) is defined for \( \rho \in [0, \rho_j] \). At jam density \( \rho_j \), flow is zero because the vehicles are not moving. The maximum flow corresponds to the critical density \( \rho_c \). If \( v \geq \Phi(\rho_c)/\rho_c \) the speed is called free flow speed \( (v_f) \), i.e. the speed with which a vehicle can travel in optimal conditions. When the density exceeds the critical value, the road becomes congested and speed falls below free flow.

Let \((x, t)\) be the distance along a freeway at time \(t\), the flow can be reformulated as: \( f(x, t) = \rho(x, t) \cdot v(x, t) \). To describe the flow in a road section, it is possible rewrite (1) in integral form:

\[
dt \int_{x_{out}}^{x_{in}} \rho(x, t) dx = \Phi(\rho(x_{in}, t)) - \Phi(\rho(x_{out}, t)) \tag{2}
\]

According to the relationship existing between speed and density, and taking into account the discretization steps to cope with traffic propagations reported in Kurzhanskiy (2008), we obtain:

\[
f_i(k+1) = \begin{cases} 
\min_{\rho_i \leq \rho \leq \rho_{i+1}} \Phi(\rho), & \text{if } \rho_i \leq \rho_{i+1} \\
\min_{\rho_{i+1} \leq \rho \leq \rho_i} \Phi(\rho), & \text{if } \rho_i \geq \rho_{i+1}
\end{cases} \tag{3}
\]

that represents the average flow crossing from cell \(i\) to cell \(i+1\) during the time interval \([k\Delta t, (k+1)\Delta t]\). It is a conservative Godunov (1959) scheme with the property to converge to the solution without oscillations in case of discontinuity and with accuracy of the first order; it keeps in consideration the change of direction of flow by approximating piecewise the state, namely the density, at each time step in each cell of the spatial grid.

The CTM is a special case of the Godunov scheme for a triangular fundamental diagram. For such a diagram with capacity \( F \), free flow speed \( v > 0 \) and congestion wave speed \( -w < 0 \) the Godunov scheme simplifies very much:

\[
\rho_i(t+1) = \rho_i(t) + \frac{\Delta t}{\Delta x_i} (f_{i-1}(t) - f_i(t)) \tag{4}
\]

where \( \Delta t \) is the sampling period, \( \Delta x_i \) is the length of the \(i\)th cell, and \( \Delta f_i \), the flow from cell \(i\) to cell \(i+1\), is calculated by

\[
f_i(t+1) = \min \{v \rho_i(t), w(\rho_j - \rho_i(t)), F\} \quad \text{if } f_i = \min \{v \rho_i, F\} \quad \text{or in congested mode}
\]

Consequently, cell \(i\) operates either in free flow mode if \( f_{i-1} = \min \{v \rho_{i-1}, F\} \), or in congested mode if \( f_{i-1} = w(\rho_j - \rho_i) \).

In this paper we have attempted to increase the level of detail extending CTM and exploiting by simulation all the practical benefits. We have proposed a new model for online simulation suitable for the urban environment.

3. CTM-UT formulation

We have been developed a generic model for applications of CTM in an urban network with signalized intersections in Matlab. It has the potential to accommodate the typical dynamic of flows and road conditions for
urban context. The software is focused on the representation of traffic movements and signal phases. Specifically, it models capacity reduction due to flow conflicts, queue spillback effects and overflow for lane.

Cell Transmission Model for Urban Traffic (CTM-UT) is a CTM based model which takes inspiration from formulation presented in Long et al. (2011). In the proposed version, the process of traffic flow propagating along the arterial link and network road is described by three sets of formulations: propagation into network, propagation into link (divided in upstream arrivals, merging zone, downstream channelized zone, channelized zone), and flow conservation. As shown in Fig. 1, link $a$ is divided into two distinct zones: a downstream queue storage area where vehicles are split into specific lanes dedicated to different turning movements, and an upstream merging zone where the turning movements are mixed. For a particular cell, the downstream queue storage zone consists of three divisions which form the segregated queuing areas. Let $N$ and $I$ (see Table 1), the number of cells in the merging zone is $N - I$.

![Fig. 1. Traffic zone of link $a$](image)

### 3.1. Model Parameters and Variables

In Table 1 all parameters and variables notations are reported.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>number of cells</td>
<td>dimensionless</td>
</tr>
<tr>
<td>$I$</td>
<td>number of cells belong to merging zone</td>
<td>dimensionless</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>sampling period (time step)</td>
<td>hours ($h$)</td>
</tr>
<tr>
<td>$\Delta x_i$</td>
<td>cell length</td>
<td>miles ($m$)</td>
</tr>
<tr>
<td>$v_i$</td>
<td>free flow speed</td>
<td>$mph$</td>
</tr>
<tr>
<td>$w_i$</td>
<td>congestion wave speed</td>
<td>$mph$</td>
</tr>
<tr>
<td>$\bar{\rho}_i$</td>
<td>jam density</td>
<td>vpm</td>
</tr>
<tr>
<td>$\rho_i^c$</td>
<td>critical density</td>
<td>vpm</td>
</tr>
<tr>
<td>$k$</td>
<td>period number</td>
<td>dimensionless</td>
</tr>
<tr>
<td>$f_i^a(k)$</td>
<td>flow into cell $i$ of link $a$ in period $k$</td>
<td>vph</td>
</tr>
<tr>
<td>$f_i^{ab}(k)$</td>
<td>flow into cell $i$ of link $a$ and direct to link $b$ in period $k$</td>
<td>vph</td>
</tr>
<tr>
<td>$\rho_i^k(k)$</td>
<td>density into cell $i$ of link $a$ in period $k$</td>
<td>vpm</td>
</tr>
</tbody>
</table>
where
\( \rho_{ab}^i(k) \) is density into cell \( i \) of link \( a \) and direct to link \( b \) in period \( k \) (vpm)
\( V_i(k) \) is actual speed in cell \( i \) in period \( k \) (mph)
\( \text{TT}(k) \) is travel time in period \( k \) (h)
\( \text{MTT} \) is mean travel time (h)
\( G = (V, A) \) is road network (dimensionless)
\( V \) is set of nodes (intersection) (dimensionless)
\( A \) is set of links (dimensionless)
\( a = (l, m) \) is link between node \( l \) and \( m \) (dimensionless)
\( A_l \) is set of links leading node \( l \) (dimensionless)
\( B_m \) is set of links leaving node \( m \) (dimensionless)
\( n_i^a(k) \) is number of vehicles contained in cell \( i \) of link \( a \) in period \( k \) (vp\( \Delta t \))
\( n_i^{ab}(k) \) is number of vehicles contained in cell \( i \) of link \( a \) and direct to link \( b \) in period \( k \) (vp\( \Delta t \))
\( y_i^a(k) \) is flow into cell \( i \) of link \( a \) in period \( k \) \( \cdot \left( f_i^a(k) \cdot \Delta t \right) \) (vp\( \Delta t \))
\( y_i^{ab}(k) \) is flow into cell \( i \) of link \( a \) and direct to link \( b \) in period \( k \) \( \cdot \left( f_i^{ab}(k) \cdot \Delta t \right) \) (vp\( \Delta t \))
\( n_i^a(k) \) is number of vehicles contained in cell \( i \) of link \( a \) and direct to link \( b \) in period \( k \) (vp\( \Delta t \))
\( Y_i^a(k) \) is maximum number of vehicles that can flow into cell \( i \) of link \( a \) in period \( k \) (vp\( \Delta t \))
\( F_i^a(k) \) is total capacity of cell \( i \) of link \( a \) in period \( k \) (storage capacity) (vp\( \Delta t \))
\( \Phi^{ab} \) is proportion of vehicles traveling from link \( a \) to link \( b \) \( \in [0, 1] \) (dimensionless)
\( \alpha^{ab} \) is proportion of stopline width devoted to vehicles traveling from link \( a \) to link \( b \) \( \in [0, 1] \) (dimensionless)
\( \sigma^{ab}(k) \) is binary value indicating whether signal phase devoted to lane \( b \) of link \( a \) is green or not in period \( k \) (0 or 1). (dimensionless)

For convention, in formulation \( y_{N+1} \) has been used to define the outflow of the terminal cells.

### 3.2. Propagation into network

Outflow from link \( a \) and direct to link \( b \)

\[
y_{ab}^{N+1}(k) = \min_1 \left\{ n_i^{ab}(k), \alpha^{ab} Y_i^a(k), y_i^a(k), \frac{w(F_i^b(k) - n_i^b(k))}{v} \right\} \tag{4a}
\]

if outflow from \( a \) leaves the road network by fictitious node (with infinity capacity), we use the following equation:

\[
y_{af}^{N+1}(k) = \min_1 \left\{ n_i^{ab}(k), \alpha^{ab} Y_i^a(k), \infty, \frac{w(\infty - n_i^b(k))}{v} \right\} \tag{4b}
\]

Inflow of link \( a \)

\[
y_i^a(k) = \min_1 \left\{ n_i^{l,a}(k), Y_i^a(k), \frac{w(F_i^a(k) - n_i^a(k))}{v} \right\} \tag{5}
\]
Total outflow by link $a$

$$y_{N+1}^a(k) = \sum_{b \in B_a} y_{N+1}^{ab}(k)$$  \hspace{1cm} (6)

The number of vehicles from the upstream links can be calculated by Eqs. (4a) and (5).

### 3.3. Propagation into link

**Upstream arrives** for $i = 1$ the inflow into the first cell of link $y_1^a(k)$ is calculated by Eqs. (4a). While the $y_1^{ab}(k)$ is calculated from Eqs. (8).

Inflow of the cells belongs to the merging zone of link $a$ can be described with the following equation

$$y_i^a(k) = \min \left\{ n_i^a(k), Y_i^a(k), \frac{w(F_i^a(k) - n_i^a(k))}{v} \right\}, \hspace{1cm} 1 < i \leq N - I$$  \hspace{1cm} (7)

and for estimate flow into cell $i$ of link $a$ and direct to link $b$ we have:

$$y_i^{ab}(k) = \Phi_{ab} y_i^a(k), \hspace{1cm} 1 < i \leq N - I$$  \hspace{1cm} (8)

When $i = N - I + 1$, max flow of downstream channelized zone can be calculated by

$$\bar{y}^{ab}(k) = \min \left\{ \Phi_{ab} n_{N-I}^a(k), \alpha_{ab} Y_{N-I}^a(k), \frac{w(\alpha_{ab} F_{N-I+1}^a(k) - n_{N-I+1}^{ab}(k))}{v} \right\}$$  \hspace{1cm} (9)

Because of conflict between turning vehicles and ahead vehicles, the total inflow of channelized zone can be formulated as follows

$$y_{N-I+1}^a(k) = \min_{b \in B_m} \left\{ \frac{\bar{y}^{ab}(k)}{\alpha_{ab}} \right\}$$  \hspace{1cm} (10)

Inflow of each direction can be calculated by Eq. (10), gives

$$y_{N-I+1}^{ab}(k) = \Phi_{ab} y_{N-I+1}^a(k)$$  \hspace{1cm} (11)

*Channelized zone*, for $N - I + 1 < i \leq N$ the inflow of each cell can be represented as follows

$$y_i^{ab}(k) = \min \left\{ n_{i-1}^{ab}(k), \alpha_{ab} Y_i^a(k), \frac{w(\alpha_{ab} F_i^a(k) - n_i^{ab}(k))}{v} \right\}, \hspace{1cm} N - I + 1 < i \leq N$$  \hspace{1cm} (12)

After applying the Eqs. (12) for each $b \in B_m$ we can calculate the total inflow of cell $i$ as

$$y_i^a(k) = \sum_{b \in B_m} y_i^{ab}(k), \hspace{1cm} N - I + 1 < i \leq N$$  \hspace{1cm} (13)

### 3.4. Flow conservation

The flow conservation equation used for CTM-UT is expressed as the difference between the inflows and the outflows of the earlier time interval. The following formulation allows to update the number of vehicles contained in each cell. The follows formulation allows to update the number of vehicles contained in each cell

$$n_i^a(k+1) = n_i^a(k) + y_i^a(k) - y_{i+1}^a(k), \hspace{1cm} 1 \leq i \leq N$$  \hspace{1cm} (14)
\[ n_{i}^{ab}(k+1) = n_{i}^{ab}(k) + y_{i}^{ab}(k) - y_{i+1}^{ab}(k), \quad 1 \leq i \leq N \] (15)

3.5. Vehicular conflict of upstream channelized zone

To access in the channelized zone, vehicles direct to different turns may obstruct each other. For this cause, in oversaturated conditions, their behavior could block different movements. For example, depending on its length, the left-turn queue could spill back and, therefore, block the through traffic. In the following simple case, let us consider only the interactions between left-turn (L) and through (T) movements as pictured in Fig. 1. In such a case, in the model proposed by Long, the queue of a spilling back turning movement, exceeding the length of its lane (of the channelized zone), strongly affects the neighboring lane, even if in free flow condition: the inflow value of the neighboring lane is largely reduced. In order to realistically capture vehicular conflict occurring between neighboring turning movements when entering the channelized zone, the present paper proposes a formulation based on the inflow of the blocking movement: specifically, this conflict is assumed to be proportional to the difference of the values of blocking inflow when passing from the merging zone to the channelized one. For \( i = N - 1 = 3 \), if through queue spills back from cells belonging to channelized zone, the inflow of left-turn is calculated as follows:

\[ \gamma_{3}^{al}(k) = \min \left\{ \gamma_{3}^{al}(k), \left[ 1 - \left( \frac{\gamma_{2}^{al}(k) - \gamma_{3}^{al}(k)}{\gamma_{2}^{al}(k)} \right) \cdot \left( 1 - \Phi^{al} \right) \cdot \left( 1 - \alpha^{al} \right) \right] \cdot \Phi^{al} \cdot n_{2}^{a}(k), \alpha^{al} \cdot Y_{3}^{a}(k) \right\} \] (16)

It considers the maximum flow given by Eqs. (9) and substitutes (10) and (11) in model formulation. Moreover, capacity and supply constraints must be respected. Comparison between the CTM-UT and the Long model has been conducted on a link with four cells and two lanes, where the through queue spills back and, therefore, reduces the left-turn traffic. The values of main variables have been set as follows:

- \( F_{3}^{a} = 20, y_{2}^{at} = 2.44, n_{2}^{a} = 6.64, n_{3}^{at} = 5.58, n_{3}^{al} = 1.87 \) [vpm\( \Delta t \)];
- \( v = 33.56, w = 11.29 \) [mph];
- \( \Phi^{al} = \Phi^{at} = 0.5, \alpha^{al} = \alpha^{at} = 0.5 \).

\( \Phi^{al} \) and \( n_{2}^{a} \) assume ranging values in the figures reported below.

![Fig. 2. CTM-UT vs Long: left turn inflow entering the channelized zone for different proportions of left turn demand](image)

The tests results show that the Long model underestimates the left turn inflow penalizing it with respect to the capacity of the turning lane.

The Fig. 2 shows that when proportion of demand ranges between 0.8 and 0.9, the Long formulation decreases the inflow value. In the interval up to \( \Phi^{al} = 0.4 \), the value of \( y_{3}^{al} \) given by CMT-UT stabilizes around its
maximum value irrespective of any additional increase of $\Phi^{aL}$. Also the results of Fig. 3 confirms previous assertions.

![Fig. 3. CTM-UT vs Long: left turn inflow entering the channelized zone for different number of vehicles (supply traffic)](image)

4. Model Validation

In the previous chapter, a new model formulation is introduced for CTM-UT. The aim of this model is to capture complex flow and queue propagation through signal controlled intersections. To validate the proposed model two different traffic scenarios, representing various levels of downstream congestion within a signal controlled intersection, have been simulated. A comparison between CTM-UT and VISSIM, one of the most important microscopic traffic flow simulation software, is done.

We are interested in studying the accuracy of travel time prediction obtained by CTM-UT. Namely, we have tested if the simulation of our macroscopic model is comparable with the microscopic one.

4.1. Case study: a signal controlled intersection

In this case study, CTM-UT and VISSIM are configured to simulate one approach in a hypothetical three-way signal controlled intersection. The approach is 0.1863 m (300 meter) in length and has two lanes. A signal is placed to control the movements: left-turn and through movements. Different movements through this intersection are tested, and two signal phase combinations are defined (Table 2).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>T Signal Phase</th>
<th>L Signal Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Green: 30 Red: 30 [sec]</td>
<td>Permanent Green</td>
</tr>
</tbody>
</table>

The simulation longs 18 minutes. Five travel demand levels have been simulated, 1000, 2000, 2500, 3000, 3600 vehicles/hour respectively. The cell capacity and demand are split over the two lanes fifty-fifty. The flow capacities for links is 3600 and for lanes 1800 vehicles/hour respectively.

A typical application of traffic simulation models estimates total system travel time. It can be expressed as follows:

$$TT(k) = \sum_{\text{link} \in A} \sum_{i=1}^{N} \frac{\Delta x_i}{V_i^a(k)}$$

(17)
The mean travel time is calculated:

$$MTT = \frac{\sum_{k=1}^{\text{tot step}} TT(k)}{\text{tot step}}$$ (18)

where \text{tot step} is the final value of index \( k \) at the end of simulation, so we have tested the model capacity to predict the average travel time through a signal controlled intersection.

In the first scenario, the simulation shows that CTM-UT underestimated mean travel time when the flow demand is low respect to arterial capacity (see Fig. 4). While, when the travel demand and the relative congestion level increased the results between software approaching.

In the second scenario, the arterial upstream of signal is under congestion conditions. In particular, the signal phase decreases the capacity of outflow for left-turn of the 75% respective to previous scenario. The results presented in Fig. 4b indicate that CTM-UT is more consistent in predicting travel time when left-turn is congested causing a movement blockages and queue in the intersection. Under medium and high traffic flows CTM-UT overestimates mean travel time around 4%.

As demonstrated through the results the proposed model have a good capacity to simulate oversaturated traffic conditions. On the base of test cases, the CTM-UT produces acceptable travel time prediction for medium and high congestion conditions and reproduces VISSIM simulation results with consistency. The relative errors of all simulation results are about 2%. The proposed model well simulates the lane blocking effects and shared lanes.

5. Conclusions

This paper presents a short-term traffic flow prediction model. The CTM-UT captures urban traffic dynamics approach based on the CTM of Daganzo. The macroscopic model provides a reasonably accurate and fast platform for modeling large-scale networks. The traditional intersection traffic model is extended to take into account some real aspects of traffic conditions, such as the proportion of turning and lane width to different movements. This allowed to improve both flexibility and realism of the model for urban context. Our model is designed to capture complex flow interactions among lane groups. The experiments compared with macroscopic model proposed by Long, indicate that the model can better predict the realism of vehicular conflict at upstream channelized zone.

The accuracy of an urban traffic flow simulation model fundamentally depends on its ability to realistically predict travel time in traffic networks with signal controlled intersection. Therefore, two case scenarios are
designed to evaluate the capabilities of the CTM-UT to predict travel time through a signal controlled intersection under various demand and downstream congestion levels. The experiments compared with VISSIM indicate that, for simple scenarios, the model can predict the short-term traffic flow promptly and with precision.

In the future study, we will test the performance of the proposed model through case studies using a real traffic data. The CTM-UT is under testing to improve the representation of traffic flow on hybrid networks of both interrupted flows (e.g., signalized intersections) and uninterrupted flows (e.g., unsignalized intersections).

References


