

**MODELING ARTERIAL SIGNAL OPTIMIZATION WITH ENHANCED CELL  
TRANSMISSION FORMULATIONS**

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**ABSTRACT**

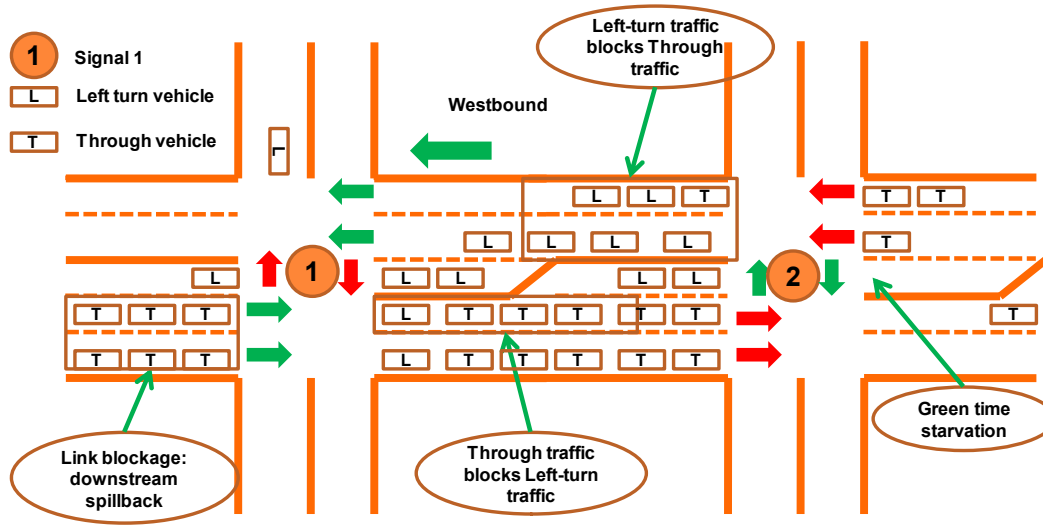
This study presents an arterial signal optimization model that is capable of capturing the queue blockage between intersection lane groups during oversaturated conditions. The proposed model is grounded on the original cell transmission concept proposed by Daganzo [1, 2], but enhanced with a new diverging cell for formulating the complex interactions of queue spillback between left-turn and through traffic flows. With the embedded formulations for forward wave, backward wave, and the horizontal queue, the proposed arterial signal optimization model can yield effective signal plans for both saturated and under-saturated intersections. To evaluate the performance of the proposed model, this study has conducted extensive simulation experiments with a segment of Georgia Avenue connected directly to Capital Beltway in Maryland. The analysis results in comparison with the signal plans from TRANSYT-7F (Release 10) have demonstrated the promising properties of the proposed model.

**Keywords:** lane blockage, signal optimization, cell transmission model, genetic algorithm

## 1 INTRODUCTION

Effectively contending with increasing congestion on urban arterials and saturated intersections has long been a challenge to transportation professionals. Despite the significant progress on this regard [3] over the past several decades, much remains to be done. For instance, consider the intersections shown in Figure 1, when queue spillback from downstream intersection blocks the upstream link traffic, the left-turn traffic may be blocked by the through traffic flows. Such complex interactions among movements in different lane groups, the bay length, and the link length between consecutive intersections very often incur gridlocks in urban networks.

At many congested intersections, there exist the following two different blockage patterns: the link spillback blockage and the movement blockage. The former occurs when the queue from the downstream intersection spills back, and thus blocks the upstream link traffic (see Figure 1). The latter may exist between different movements in the same approach. Figure 1 illustrates the types of left-turn traffic blocking the through flows, and the through blocking the left-turn vehicles. The green time starvation can be illustrated with the westbound left-turn traffic of Signal 2.



**Figure 1 the blockage and starvation at oversaturated intersections**

The arterial signal optimization studies in the literature generally fall into two major categories: bandwidth-based and delay-based models. The bandwidth-based programs, such as MAXBAND and PASSER, maximize the sum of bands for different directional progression. In contrast, the delay-based programs intend to minimize the network-wide delay or equivalent performance index.

Most existing bandwidth-based programs in the literature [4-9] assume to have a constant travel speed and no queue at the downstream intersection at the arrival of upstream platoons, which cannot realistically capture the blockage effects. The delay-based models for network signal optimization have employed various traffic flow models to capture interactions between vehicles, including the use of macroscopic [10] and mesoscopic simulations [11-13]. A detail review in this regard is available in the paper by Papageorgiou, Diakaki et al.[3].

Normally, the bandwidth-based model can just handle undersaturated traffic conditions since they cannot handle the queue condition. For the oversaturated conditions, it is well

recognized that it is fundamentally different from the undersaturated condition. Hadi and Wallace [14] propose enhancements to Transyt-7F to optimize signal-timing plans under congested conditions. Abu-Lebdeh and Benekohal [15] maximize the throughput by managing queue formation and dissipation under oversaturated traffic conditions. Park, Messer et al. [11] proposed their genetic algorithms (GA) for optimal signal timing and queue management based on Transyt-7F model. In 2000, to manage queue length, Lieberman, Chang et al. [16] propose a real-time traffic control policy for both undersaturated and oversaturated traffic conditions. Abu-Lebdeh, Benekohal [17] present a formulation and a genetic algorithm for a dynamic signal control and queue length management of oversaturated arterials. Stevanovic, Martin et al. [18] propose a VisSim-based genetic algorithm for optimizing signal timings. Katwijk [19] proposes a multi-agent look-ahead control strategy for adaptive signal control. However, the impact of potential lane blockage due to the spillback of some lane groups at one or more arterial intersections has not been addressed in the literature.

In recent years, some researchers have proposed the use of Cell Transmission Model (CTM) for signal control. CTM is a finite differential schema proposed by Daganzo [20] based on the LWR model [21, 22], which is capable of replicating kinematic waves, queue formation and dissipation. Lo [23, 24] is the first one to employ CTM to represent the traffic dynamics and reports some promising results for signal optimization. In a later study [25], they have developed an enhanced model to account for turning movements with the original CTM diverging cell, and solve the optimal signal timings with a genetic algorithm method. In 2004, Lo and Chow [26] extended the model to optimize the green splits without a constant cycle length. The most recent release of TRANSYT [27] has also included CTM as an alternative method to its embedded Platoon Dispersion Model (PDM). By using CTM, TRANSYT is capable of considering the spillback effects and the time-varying flow evolution. It, however, remains difficult to tackle the traffic conditions where some arterials intersections are oversaturated, and incur some blockages between lane groups.

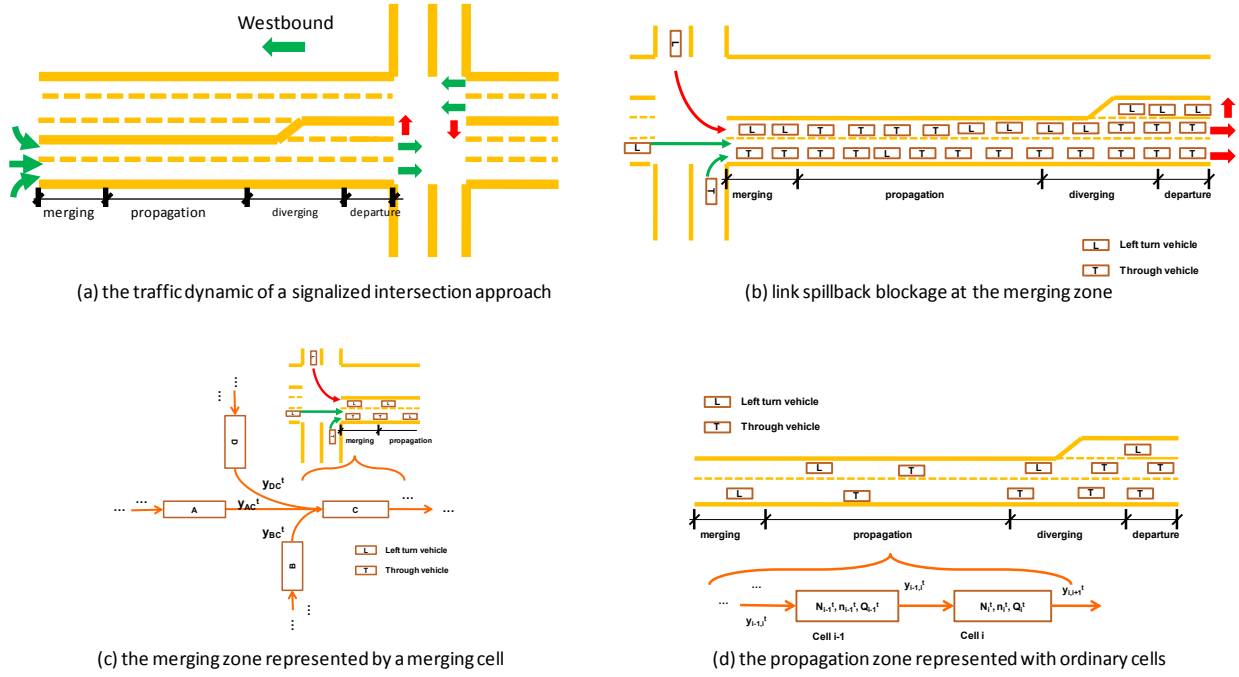
This study intends to address this critical lane-blockage issue on arterial signal optimization with enhanced formulations for the CTM diverging model. The proposed model takes full account of the lane channelization effects to turning traffic, and captures the movement blockage between lanes. Based on the enhanced formulations for lane blockage, the study will present an arterial signal optimization model that can account for oversaturated conditions at some arterial intersections.

The remaining part of this paper is organized as follows. Section 2 will discuss the modeling methodology for signal optimization. Section 3 will focus on the GA-based solution algorithm. A case study and its experimental results will be presented in Section 4, and conclusions are summarized in Section 5.

## MODELING METHODOLOGY

To model the temporal and spatial interactions of traffic flows at a signalized intersection, one can conceptually divide each link into the following four zones: the merging, propagation, diverging and departure zones (see Figure 2(a)). Vehicles entering such a link will move over these four zones and then bound to their respective destinations. Notably, vehicles for left-turn and through movements may block each other due to spillback if the bay length and signal timings are not properly designed in response to the time-varying traffic demand. The queue caused by lane-blockages may spill back to the upstream intersections under saturated traffic

1 conditions.



**Figure 2 the traffic dynamic of arterial link and the representations by cells**

To provide the optimal signal times for arterials experiencing lane-blockage conditions at some intersection, this study first employs the Cell Transmission concept to formulate the flow interactions in the above four zones. The Cell Transmission Model (CTM) [1, 20] is a finite difference approximation of the traffic flow model by Lighthill and Whitham [21] and Richards [22]. Its core concept is to divide the target roadway into homogeneous sections (cells), whose lengths equal the distance traveled by a vehicle in the free flow speed during one unit interval.

The states of the traffic system at any time instant is tracked by the number of vehicles in each cell, denoted as  $n_i^t$ . In addition, the following parameters are commonly used in the CTM model illustration, where time  $t$  represents the time interval  $[t\tau, (t+1)\tau]$  and  $\tau$  is the predefined constant time interval duration:

- $N_i^t$  is the buffer capacity, defined as the maximum number of vehicles that can be presented in cell  $i$  at time  $t$ , which is the product of cell length multiplied by the jam density;
- $Q_i^t$  is the flow capacity in time  $t$ , and defined as the maximum number of vehicles that can flow into cell  $i$ , which can be computed as the product of the cell's saturated flow multiplied by the length of time interval;
- $y_{ij}^t$  is defined as the number of vehicles leaving cell  $i$  and entering cell  $j$  in time  $t$ .

There are three types of cell defined in the CTM model: the ordinary cell, the merging cell and the diverging cell. The ordinary cell has just one upstream cell and one downstream cell; the merging cell has more than one upstream cell and one downstream cell; the diverging cell has only one upstream cell and more than one downstream cell. The recursive relationship of the CTM model can be expressed as follows:

$$n_i^{t+1} = n_i^t + \sum_{k \in \Gamma^+(i)} y_{ki}^t - \sum_{j \in \Gamma^-(i)} y_{ij}^t \quad (1)$$

Equation ( 1 ) represents the flow conservation relationship at the cell level, which means that the vehicle number of a cell in the next time interval equals the vehicle number of this interval and the difference between all entering and departing vehicles. Note that the second and third terms in Equation ( 1 ) will vary with the cell category, where  $y_{ij}^t$  needs to be computed with a traffic flow-density relationship. We will detail how to apply the core CTM concept in formulating traffic flow interactions in these four identified intersection vehicle moving zones.

### Merging zone

In the merging zone, the vehicles from different upstream approaches will join together to form a traffic stream. During oversaturated traffic conditions, the queue can spillback and block the upstream traffic as shown in Figure 2(b).

The merging cell is best suited for modeling the traffic flow interactions in the merging zone. As illustrated in Figure 2(c), Cell C represents the merging zone; Cell A, B, D represents the upstream through, right-turn and left-turn approaches. At signalized intersections, since the entering traffic stream will be given different priorities to enter the merging zone based on the signal phasing plan, one can then use Equations ( 2 ) to capture such relations.

$$y_{ic}^t = \min\{n_i^t, Q_i^t, \delta[N_c - n_c^t]\}, i = A, B, D \quad (2)$$

Where  $\delta = 1$ , if  $n_i^t \leq Q_i^t$ , and  $\delta = \frac{w}{v}$ , if  $n_i^t > Q_i^t$ , in which  $w$  represents the backward propagating speed of the disturbances; and  $v$  is the free flow speed. When the merging zone represented by cell C is full (i.e., the vehicle number in cell C,  $n_c^t$ , equals to its buffer capacity,  $N_c^t$ ), no vehicle can enter the merging zone (i.e.,  $N_c^t - n_c^t = 0$  which implies  $y_{ic}^t = 0$ ).

### Propagation zone

In the propagation zone, the interactions between vehicles increase with the traffic volume. From the aggregate perspective, such interactions can best be represented with the flow-density relationship. Hence, to compute the optimal signal plan for an arterial, one needs to best formulate the temporal and spatial relations of vehicles evolving over the link between neighboring intersections.

For such needs, this study employs the ordinary cell to capture these vehicle interactions in the propagation zone. As illustrated in Figure 2(d), the number of cells in the propagation zone may vary with the link length. For each ordinary cell, there exists one upstream cell and one downstream cell. The number of vehicles which can exit cell  $i$  and enter cell  $i+1$  in time  $t$  ( $y_{i,i+1}^t$ ) can be determined with Equation ( 3 ), a simplified flow-density relationship proposed by Daganzo [1] that can capture the traffic dynamics under various traffic conditions.

$$y_{i,i+1}^t = \min\{n_i^t, Q_i^t, \delta[N_{i+1} - n_{i+1}^t]\} \quad (3)$$

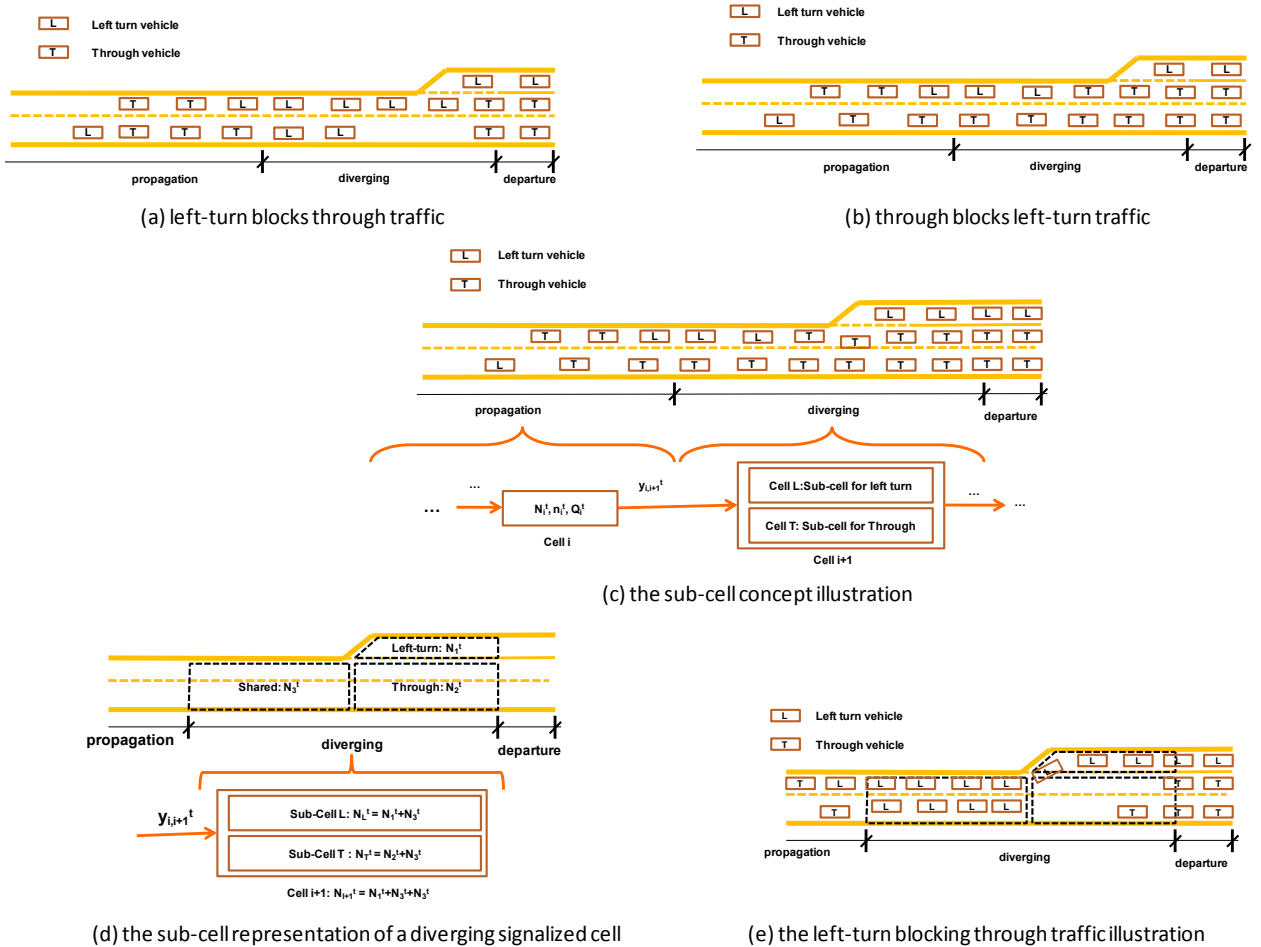
If one defines  $S_i^t (= \min\{Q_i^t, n_i^t\})$  as the sending capacity, and  $R_i^t (= \min\{Q_i^t, \delta(N_i^t - n_i^t)\})$

as the receiving capacity of cell  $i$ , then Equation ( 3 ) naturally evolves to Equation ( 4 ).

$$y_{i,i+1}^t = \min\{S_i^t, R_{i+1}^t\} \quad (4)$$

## Diverging zone – a new set of formulations

In the diverging zone, vehicles bound to different destinations may join different queues. Under over-saturated conditions, the blockage between different movements could occur. For instance, depending on the bay length, the left-turn queue could spillback and block the through traffic. For convenience of illustrating the modeling concept, let us consider only the interactions between left-turn and through vehicles. However, the concepts presented in this section can be extended to other types of lane blockage. It is noticeable that an intersection approach with left-turn and through lanes may incur two possible types of lane blockage as shown in Figure 3 (a) and Figure 3 (b), respectively.



**Figure 3 diverging zone**

The diverging movements in Figure 3 (a) and Figure 3 (b) are typically modeled with a diverging cell in the literature [2] as there exists multiple exiting movements. However, the original CTM diverging cell proposed in the literature does not account for the blockage effect between lanes, which is quite common under over-saturated conditions. To realistically capture the queue and blockage effect between neighboring movements, this study has proposed the following enhanced diverging model that employs the sub-cell concept to represent each type of

1 movement.

2 As shown in Figure 3 (c), the diverging zone link is presented with a diverging cell, Cell  
3  $i+1$ , which is further divided into two sub-cells, sub-cell L for left-turning and sub-cell T for  
4 through traffic.

5 The diverging zone can be further divided into the following three subzones as illustrated  
6 in Figure 3 (d). Where Zone 1, denoted by  $N_1^t$ , is the space exclusively reserved for left-turn  
7 traffic; Zone 2,  $N_2^t$ , is the space used only for through traffic; and Zone 3,  $N_3^t$ , is the space shared  
8 by left-turn and through traffic. The buffer capacity of each sub-cell can be computed with  
9 Equations ( 5 ) and ( 6 ).

$$N_L^t = N_1^t + N_3^t \quad (5)$$

$$N_T^t = N_2^t + N_3^t \quad (6)$$

$$N_{i+1}^t = N_1^t + N_2^t + N_3^t \quad (7)$$

10 Where Equation ( 7 ) captures the physical buffer capacity of the diverging cell  $i+1$ . Note that  
11 one can divide these zones based on the channelization at a signalized approach. The buffer  
12 capacity of these sub cells explicitly reflects the turning bay effects. The flow capacity of each  
13 sub-cell can be computed with its lane number and the lane saturation flow rate.

14 Based on the above definitions, the status of these sub-cells can be updated with  
15 Equations ( 8 ), ( 9 ), and ( 10 ).

$$w_i^t = \min\{S_i^t, R_{i+1}^t, R_L^t/r_L^t, R_T^t/r_T^t\} \quad (8)$$

$$y_{iL}^t = w_i^t \times r_L^t \quad (9)$$

$$y_{iT}^t = w_i^t \times r_T^t \quad (10)$$

16 Where  $w_i^t$  is the vehicle number entering the diverging cell from its upstream cell (cell  $i$ ), which  
17 is the minimum of the following four terms: the sending capacity of cell  $i$ , the receiving capacity  
18 of the diverging cell as a whole, the left-turn receiving capacity, and the through receiving  
19 capacity;  $y_{iL}^t$  is the left-turning vehicle number entering the diverging cell; and  $y_{iT}^t$  is the through  
20 vehicle number entering the diverging cell. The left-turn receiving capacity is defined as the  
21 available space for left-turn vehicle ( $R_L^t$ ) dividing by the left-turn turning ratio ( $r_L^t$ ). The through  
22 receiving capacity is defined in the same manner. The underlying assumption of Equation ( 8 ) is  
23 that the traffic will try to occupy the shared zone (Zone 3 in Figure 3 (d)) whenever its exclusive  
24 zone is occupied. For instance, as depicted by Figure 3 (e), when the left-turn queue spillback  
25 occurs, the left-turn vehicles may eventually occupy all the shared zone space if its volume  
26 continues to increase.

27 The new diverging model presented in this section offers the capability to explicitly  
28 model the effect of the turning bay, and capture some lane blockage relations as shown with  
29 Equations ( 8 ), ( 9 ), and ( 10 ). In the illustrative scenario of left-turn blocking through traffic



condition, the third term in the parenthesis of Equation ( 8 ) will be the minimum of these three terms, which implies  $w_i^t = R_L^t / r_L^t$  according to Equation ( 8 ). By substituting it to Equations ( 9 ) and ( 10 ), one can deduce that  $y_{iL}^t = R_L^t$  and  $y_{iT}^t = R_L^t \times r_T^t / r_L^t$ . If  $R_L^t$  decreases,  $y_{iL}^t$  and  $y_{iT}^t$  will also decrease. When  $R_L^t = 0$ , it indicates that left-turn vehicles have blocked through traffic completely. For the scenario of through blocking left-turn traffic, one can perform the same analysis.

### Departure zone

The segment in the departure zone is modeled with a signalized cell. Its flow capacity  $Q_i^t$  as a dependent variable, and is defined as follows:

$$Q_i^t = Q_{i,\max} g_i^t \quad (11)$$

Where  $g_i^t$  is the green time in time interval  $t$  and can be determined by signal timing associated with the downstream node;  $Q_{i,\max}$  is the saturated flow rate.

### Objective functions

Depending on the traffic conditions, one can set the control objective function as maximizing the total system throughput or minimizing the total delay. Using the above cell transmission based formulations, its objective function of maximizing the system throughput can be expressed as follows:

$$\text{Max (Throughput)} = \sum_{t=0}^T \sum_{j \in S} \sum_{i \in \Gamma^-(j)} y_{ij}^t \quad (12)$$

Where  $S$  is the sink cell set,  $\Gamma^-(j)$  is the upstream cell set of cell  $j$ , and  $T$  is total operation time period.

In CTM, the length of each cell is set to be the free-flow travel distance over a pre-specified unit, which means that the vehicles at each unit time in each cell can either stay or move to the downstream cells. Hence, one can approximate the delay as the difference between a vehicle's actual travel time and its free speed travel time over a given travel distance. For instance, if some vehicles staying in the same cell over  $n$  consecutive unit intervals, then it implies that they all have experienced  $n$  unit delay times. More specifically, one can define the delay over each cell for time interval  $t$  as  $d_i^t = (n_i^{t-1} - \sum_{j \in \Gamma(i)} y_{ij}^t) \times \tau$ , where  $\Gamma(i)$  is the downstream cell set of cell  $i$  and  $\tau$  is the time period length. Thus, one can propose an alternative objective function of minimizing the total system delay as follows:

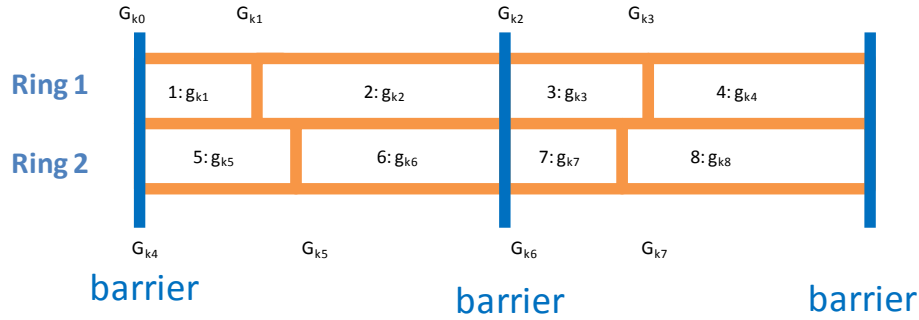
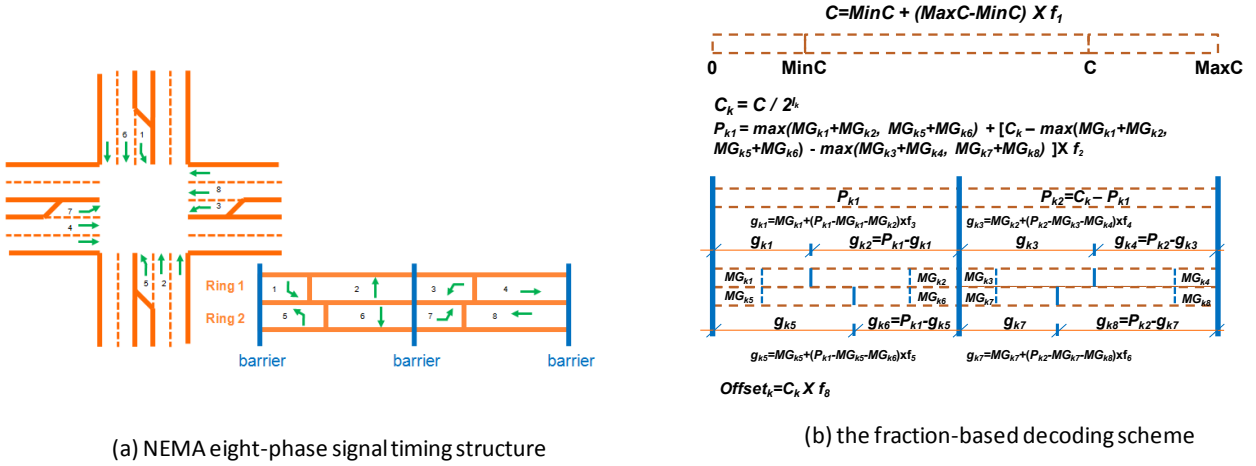
$$\text{Min [total delay]} = \tau \sum_{t=0}^T \sum_i (n_i^t - \sum_{j \in \Gamma(i)} y_{ij}^t) \quad (13)$$

As  $\tau$  is a constant, the objective function of minimizing the system delay can further be stated as:

$$\text{Min } Z = \sum_{t=0}^T \sum_t \sum_{j \in \Gamma(i)} (n_i^t - y_{ij}^t) \quad (14)$$

# Signal timing operation

- Figure 4 illustrates a typical four-leg intersection and the NEMA eight-phase structure. The right-turn on red is assumed to be permitted in this study.



**Figure 4 NEMA eight-phase signal timing structure and the fraction-based decoding scheme**

The two-ring eight-phase structure illustrated by Figure 4 (a) can be modeled with the following equations.

$$g_{k1} + g_{k2} = g_{k5} + g_{k6} \quad (15)$$

$$g_{k3} + g_{k4} = g_{k7} + g_{k8} \quad (16)$$

$$g_{k1} + g_{k2} + g_{k3} + g_{k4} = C_k \quad (17)$$

$$C_k = C/2^{h_k} \quad (18)$$

$$h_k = \begin{cases} 1, & \text{signal } k \text{ has half common cycle length} \\ 0, & \text{otherwise} \end{cases} \quad (19)$$

$$g_{kj} \geq MG_{kj}, j = 1, \dots, 8 \quad (20)$$

$$MinC \leq C_k \leq MaxC \quad (21)$$

$$0 \leq offset_k < C_k \quad (22)$$

$$g_{kj}, C_k, offset_k \text{ are integers} \quad (23)$$

Where  $g_{kj}$  is the green time for phase  $j$  of signal  $k$ ,  $C_k$  is the cycle length of signal  $k$ ;  $MG_{kj}$  is the minimum green time of signal  $k$  phase  $j$ ;  $MinC$  is the minimum cycle length;  $MaxC$  is the maximum cycle length;  $C$  is the common signal cycle length;  $h_k$  is a binary variable that indicates whether signal  $k$  has a half common cycle length as defined by Equation (19); and  $offset_k$  represents the offset of signal  $k$ . Equations (15) and (16) indicate the existence of the signal barrier. Equations (17) and (18) enforce the cycle length constraints. Equation (20) confines that the green time of each phase cannot be less than its minimum green time, and Equation (21) specifies a user-defined minimum and maximum cycle lengths. Equation (22) requires that the offset of signal  $k$  lies between 0 and its cycle length.

To compute the green time for each interval  $t$  of the departure cell, the green time of each phase should first be converted to time in a signal cycle.

$$G_{k0} = G_{k4} = 0; G_{ki} = \sum_{j=0}^{i-1} g_{kj}, \text{ for } i = 1, 2, 3 \quad (24)$$

$$G_{ki} = \sum_{j=4}^{i-1} g_{kj}, \text{ for } i = 5, 6, 7 \quad (25)$$

Where  $G_{ki}$  is the time in the signal cycle as illustrated in Figure 4 (c). If departure cell  $i$  is associated with signal phase  $j$  of signal  $k$ , the following equations will compute the green time of time interval  $t$  for cell  $i$ .

$$v_i^t = (t\tau + offset_k) \bmod C_k \quad (26)$$

$$g_i^t = \begin{cases} \max\{\min\{G_{k,j-1} + g_{kj}, v_i^t + \tau\} - \max\{G_{k,j-1}, v_i^t\}, 0\}, & v_i^t + \tau \leq C_k \\ \max\{\min\{G_{k,j-1} + g_{kj}, C_k\} - \max\{G_{k,j-1}, v_i^t\}, 0\} & \\ + \max\{\min\{G_{k,j-1} + g_{kj}, v_i^t + \tau - C_k\} - \max\{G_{k,j-1}, 0\}, 0\}, & v_i^t + \tau > C_k \end{cases} \quad (27)$$

Where  $v_i^t$  is the start time of time interval  $t$  in a signal cycle.

#### SOLUTION ALGORITHM

In the proposed model, the decision variables are the cycle length, green time split, and the offset of each signal. This study proposes a GA-based solution method for the proposed model, which can obtain a near optimal signal timing plan. GA is a search technique based on the mechanics of natural selection and evolution. Recently, GA has been successfully applied to optimize signal timings under various traffic conditions [11, 17, 18, 26, 28-31]. To efficiently reach convergence, this study employs the elitist selection method [32].

#### The fraction-based encoding scheme of signal timing

The most critical part of developing a GA-based algorithm is to derive a good encoding scheme, i.e., how to represent possible solutions of the target problem by a gene series of 0-1 bits. This study employs an encoding scheme which includes the constraints (15)-(23), i.e., the signal timing decoded from the scheme will be feasible to constraints (15)-(23). The fraction-based decoding scheme (by Park, Messer et al.[11]) based on the NEMA phase's structure can satisfy all the constraints except (18). This study has enhanced this schema by including the half common cycle length for certain signals.

A detailed description of the original scheme can be found in the literature [11]. As illustrated in Figure 4 (b), the proposed scheme sets the cycle length of signal  $k$  to half common cycle length if the half-cycle binary variable,  $I_k$ , is 1. Otherwise, the cycle length is set to be the full common cycle length.

#### AN ILLUSTRATIVE CASE STUDY

##### The case study site

To evaluate the performance of the proposed model, this study has selected a segment of Georgia Avenue (MD97) in Washington D. C. Beltway region for the experimental study. As shown in Figure 5, the target site includes four signalized intersections from Forest Glen Rd (MD192) to Seminary Pl. Using the actual volume as the base line, this study has varied the distribution of traffic volume for each approach and generated three possible levels of traffic conditions for performance evaluation (see Table 1).

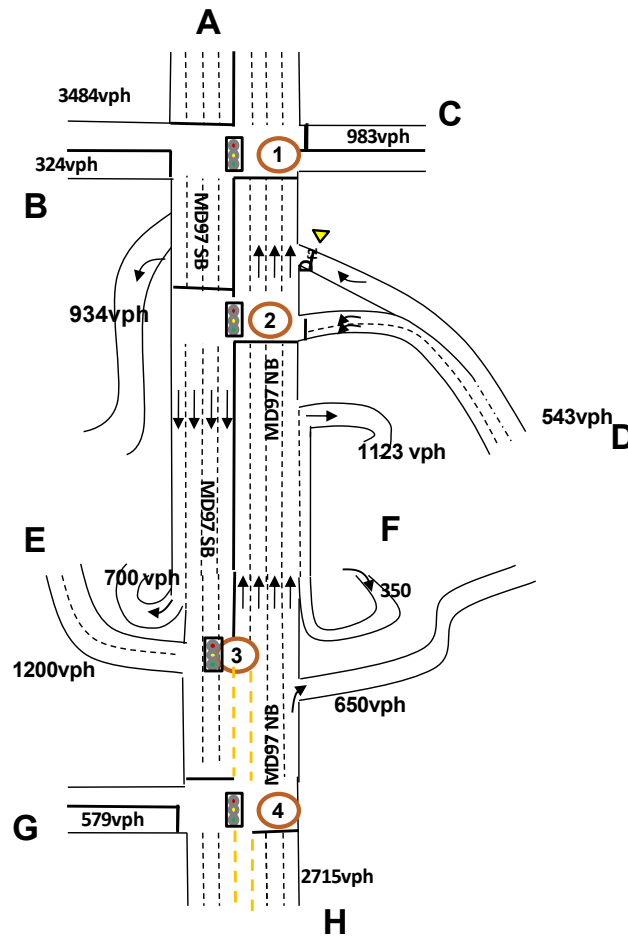


Figure 5 Case Study Site Sketch

In the case study site, approach C and approach D have two left-turn pocket lanes; where B and G have only one left-turn pocket lane.

The signal plans generated from the proposed model are used to compare with those generated by TRANSYT-7F (release 10), which is one of the most advanced programs for both research and practice. Transyt-7F (release 10) offers two optimization algorithms, the hill-climb algorithm and the GA algorithm. For a fair comparison, the GA method in Transyt-7F (release 10) has been used to optimize signal timings for the case study. Both GA optimizers take 200 generations with a population size of 50, a crossover probability of 0.3, and a mutation probability of 0.01. All the simulation runs in the signal optimizers are performed for 15 min as recommended by *Highway Capacity Manual 2000*. The network initialization process of 3 minutes is used for all programs.

Table 1: Demands for the case study site (vehicle per hour)

| Entrance | Movements | Demand Scenario |        |        |
|----------|-----------|-----------------|--------|--------|
|          |           | Low             | Medium | High   |
| A        | Through   | 3,044           | 3,382  | 3,720  |
|          | Right     | 101             | 112    | 123    |
| B        | Left      | 40              | 44     | 48     |
|          | Through   | 91              | 101    | 111    |
|          | Right     | 161             | 179    | 197    |
| C        | Left      | 536             | 596    | 656    |
|          | Through   | 306             | 340    | 374    |
|          | Right     | 42              | 47     | 52     |
| D        | Left      | 284             | 315    | 347    |
|          | Right     | 204             | 227    | 250    |
| E        | Right     | 1,080           | 1,200  | 1,320  |
| F        | Right     | 315             | 350    | 385    |
| G        | Left      | 498             | 553    | 608    |
|          | Right     | 23              | 25     | 28     |
| H        | Through   | 2,444           | 2,715  | 2,987  |
| Total    | -----     | 9,167           | 10,186 | 11,204 |

For comparison, a microscopic simulation, CORSIM, is employed as the performance index provider. The comparison results from simulation are presented in the following section.

#### Experimental results

The simulation results from CORSIM for one hour are presented in this section. The network-wide total delay, total queue delay, and system throughput, for each case based on the average of 50 simulation runs, are listed in Table 2. The results presented in Table 2 indicate that the proposed model outperforms the TRANSYT-7F for all three volumes at the system level. The 95% confidence intervals indicate that the improvements are statistically significant. The improvement with respect to delay increases with the congestion level, which implies that the proposed model is especially applicable for optimizing signals under congested conditions.

Table 2: Overall model performance comparison

| Demand Scenarios |                                   | Simulation Results from CORSIM (One hour) |             |              |                   |                       |
|------------------|-----------------------------------|-------------------------------------------|-------------|--------------|-------------------|-----------------------|
|                  |                                   | The Proposed Model                        | TRANSYT -7F | Improvement* | Improvement * (%) | Improvement (95% CI*) |
| Low              | Total Delay (vehicle-hour)        | 122.34                                    | 178.50      | 56.16        | 31%               | [28.8,83.5]           |
|                  | Total Queue delay (vehicle-hour)* | 63.26                                     | 105.73      | 42.47        | 40%               | [24.4, 60.5]          |
|                  | Total Throughput (vehicle)        | 9107.36                                   | 8990.10     | 117.26       | 1%                | [54.5, 180.0]         |
| Medium           | Total Delay (vehicle-hour)        | 174.20                                    | 276.01      | 101.81       | 37%               | [68.6,135.1]          |
|                  | Total Queue delay (vehicle-hour)  | 100.41                                    | 167.10      | 66.69        | 40%               | [42.8, 90.6]          |
|                  | Total Throughput (vehicle)        | 10047.50                                  | 9870.52     | 176.98       | 2%                | [78.1, 275.8]         |
| High             | Total Delay (vehicle-hour)        | 259.11                                    | 426.14      | 167.03       | 39%               | [135.7,198.3]         |
|                  | Total Queue delay (vehicle-hour)  | 157.99                                    | 272.24      | 114.25       | 42%               | [95.6, 132.9]         |
|                  | Total Throughput (vehicle)        | 10846.28                                  | 10192.18    | 654.10       | 6%                | [567.7, 740.5]        |

\* Delay improvement = TRANSYT-7F Delay – The Proposed Model Delay

Throughput improvement = The Proposed Model Throughput - TRANSYT-7F Throughput

Delay Improvement (%) = (TRANSYT-7F Delay – The Proposed Model Delay) / the Proposed Model Delay × 100%

Throughput Improvement (%) = (The Proposed Model Throughput - TRANSYT-7F Throughput) / TRANSYT-7F Throughput × 100%

C.I. = confidence Interval

Queue delay = Delay calculated by taking vehicles having acceleration rates less than 2 feet per second<sup>2</sup> and speed less than 9 feet per second. If a vehicle's speed is less than 3 feet per second, it will be included every second. Otherwise it will be included every two seconds[33].

The total delay for the four intersections, MD 97 SB, and MD 97 NB are presented in Table 3. For the low demand scenario, the proposed model favors the congested intersection (intersection 1), but increases the delay at other intersections. However, the proposed model reduces the total delay experienced by the traffic in MD 97 SB. For the medium and high demand levels, the proposed model can improve the performance of the congested intersections, and the improvement increases with the demand level. For the other intersections, the difference decreases with traffic demand.

The total delay for MD 97 southbound (SB) and northbound (NB) shows that the proposed model reduces the total delay of MD 97 SB at all three volume levels. For MD 97 NB, the two models provide comparable performance. Since the traffic demand of MD 97 SB is much heavier than that of MD 97 NB, the proposed model yields the optimal signal timing to reduce the delay experienced by SB traffic.

1 Table 3: Total delay comparison by intersection (vehicle minutes)

| Demand Scenarios |                | Simulation Results from CORSIM (One hour) |            |              |                   |                                       |
|------------------|----------------|-------------------------------------------|------------|--------------|-------------------|---------------------------------------|
|                  |                | The Proposed Model                        | TRANSYT-7F | Improvement* | Improvement * (%) | Improvement (95% confidence interval) |
| Low              | Intersection 1 | 2242.41                                   | 6112.78    | 3870.37      | 63%               | [5483.4, 2257.4]                      |
|                  | Intersection 2 | 588.20                                    | 443.24     | -144.95      | -33%              | [-109.1, -180.8]                      |
|                  | Intersection 3 | 1815.50                                   | 1703.63    | -111.87      | -7%               | [-32.1, -191.7]                       |
|                  | Intersection 4 | 1235.07                                   | 1064.19    | -170.88      | -16%              | [-67.5, -274.2]                       |
|                  | MD 97 SB       | 3951.1                                    | 7207.9     | 3256.8       | 45%               | [1668.9, 4844.7]                      |
|                  | MD 97 NB       | 1475.1                                    | 1637.7     | 162.6        | 10%               | [101.4, 223.7]                        |
| Medium           | Intersection 1 | 3771.26                                   | 9376.52    | 5605.26      | 60%               | [7742.7, 3467.9]                      |
|                  | Intersection 2 | 537.45                                    | 640.41     | 102.97       | 16%               | [161.3, 44.6]                         |
|                  | Intersection 3 | 1992.82                                   | 2183.95    | 191.13       | 9%                | [277.0, 105.2]                        |
|                  | Intersection 4 | 2318.74                                   | 1960.66    | -358.09      | -18%              | [-221.3, -494.8]                      |
|                  | MD 97 SB       | 4261.0                                    | 11943.5    | 7682.5       | 64%               | [5843.2, 9521.8]                      |
|                  | MD 97 NB       | 2011.0                                    | 2010.3     | -0.7         | -0%               | [-84.7, 83.3]                         |
| High             | Intersection 1 | 5967.06                                   | 16664.37   | 10697.31     | 64%               | [12008.3, 9386.3]                     |
|                  | Intersection 2 | 964.92                                    | 895.53     | -69.39       | -8%               | [284.9, -423.7]                       |
|                  | Intersection 3 | 2992.88                                   | 2779.33    | -213.55      | -8%               | [57.8, -484.9]                        |
|                  | Intersection 4 | 2689.92                                   | 2590.17    | -99.75       | -4%               | [-8.0, -191.5]                        |
|                  | MD 97 SB       | MD 97 SB                                  | 6671.8     | 17109.8      | 10438.0           | 61%                                   |
|                  | MD 97 NB       | MD 97 NB                                  | 2854.6     | 2961.3       | 106.7             | 4%                                    |

2 \* Delay improvement = TRANSYT-7F Delay – The Proposed Model Delay

3 Delay Improvement (%) = (TRANSYT-7F Delay – The Proposed Model Delay) / the Proposed Model Delay × 100%

4 C.I. = confidence Interval

6 Table 4 summarizes the total queue delay for each intersection, MD 97 SB, and MD 97  
7 NB. It is notable that the proposed model reduces the total queue delay for the most congested  
8 intersection (Intersection 1) at all three demand levels. For other intersections, the proposed  
9 model's performance improves with the demand level. For the congested corridor (MD97 SB),  
10 the proposed model can produce less queue delay than TRANSYT-7F. For the opposite direction  
11 (MD97 NB), the total queue delays from both models are comparable, as the traffic volume is  
12 relatively low.



1 Table 4: Total Queue delay comparison by intersection (vehicle minutes)

| Demand Scenarios |                | Simulation Results from CORSIM (One hour) |            |              |                   |                                       |
|------------------|----------------|-------------------------------------------|------------|--------------|-------------------|---------------------------------------|
|                  |                | The Proposed Model                        | TRANSYT-7F | Improvement* | Improvement * (%) | Improvement (95% confidence interval) |
| Low              | Intersection 1 | 1189.05                                   | 3945.16    | 2756.11      | 70%               | [3859.2, 1653.0]                      |
|                  | Intersection 2 | 374.54                                    | 317.19     | -57.35       | -18%              | [-29.1, -85.6]                        |
|                  | Intersection 3 | 1288.58                                   | 1290.17    | 1.59         | 0%                | [68.1, -64.9]                         |
|                  | Intersection 4 | 746.68                                    | 617.89     | -128.78      | -21%              | [-33.1, -224.5]                       |
|                  | MD 97 SB       | 1779.9                                    | 4156.2     | 2376.3       | 57%               | [1288.7, 3463.8]                      |
|                  | MD 97 NB       | 521.6                                     | 747.5      | 225.9        | 30%               | [187.5, 264.3]                        |
| Medium           | Intersection 1 | 2308.33                                   | 9376.52    | 7068.19      | 75%               | [9187.7, 4948.6]                      |
|                  | Intersection 2 | 288.21                                    | 640.41     | 352.21       | 55%               | [407.2, 297.2]                        |
|                  | Intersection 3 | 1442.18                                   | 2183.95    | 741.77       | 34%               | [820.4, 663.2]                        |
|                  | Intersection 4 | 1676.67                                   | 1960.66    | 283.99       | 14%               | [399.6, 168.4]                        |
|                  | MD 97 SB       | 1708.8                                    | 7027.8     | 5319.1       | 76%               | [4034.5, 6603.6]                      |
|                  | MD 97 NB       | 875.1                                     | 926.3      | 51.2         | 6%                | [-7.3, 109.8]                         |
| High             | Intersection 1 | 3870.18                                   | 16664.37   | 12794.19     | 77%               | [14114.8, 11473.5]                    |
|                  | Intersection 2 | 594.79                                    | 895.53     | 300.73       | 34%               | [560.6, 40.9]                         |
|                  | Intersection 3 | 2218.65                                   | 2779.33    | 560.68       | 20%               | [796.8, 324.5]                        |
|                  | Intersection 4 | 1895.93                                   | 2590.17    | 694.24       | 27%               | [767.1, 621.4]                        |
|                  | MD 97 SB       | 3049.8                                    | 10181.0    | 7131.2       | 70%               | [6090.4, 8172.0]                      |
|                  | MD 97 NB       | 1379.7                                    | 1464.1     | 84.4         | 6%                | [-54.1, 223.0]                        |

\* Delay improvement = TRANSYT-7F Queue Delay – The Proposed Model Queue Delay

Delay Improvement (%) = (TRANSYT-7F Queue Delay – The Proposed Model Queue Delay) / the Proposed Model Queue Delay × 100%

C.I. = confidence Interval

For all the three demand levels, the proposed model provides better performance than TRANSYT-7F with respect to the total system delay and total system throughput. The improvement seems to increase with the demand level. That is the advantage of tracking the movement blockage since the probability of its incurrence increases with demand. By tackling the traffic dynamics in a more accurate way, the proposed model reduces the total delay experienced by the traffic in MD 97 SB, and MD 97 NB. The results demonstrate that the proposed model is promising for oversaturated traffic conditions.

## CONSLUSIONS

This study has presented an enhanced Cell-Transmission Model for optimizing signal timings on congested arterials. The proposed model with its innovative sub-cell model is capable of capturing lane-blockage between neighboring lane groups due to queue spillback under high

volume conditions. The signal optimization model reported in the paper can optimize the cycle length, split, and offset, under the presence of the link blockage and lane group blockage.

Extensive simulation experiments with a field segment of four congested intersections have demonstrated that both the total delay and throughput resulted from the proposed model are far better than those with TRANSYT-7F under a wide range of traffic conditions, especially under the high volume level. Hence, the proposed model is ready for use in practice as illustrated by the case study, especially under oversaturated conditions.

Further research along this line should include the model performance evaluation in field operations, enhancing the CTM formulation to account for the shared lane traffic dynamic, right turn on red, and the permitted left-turn controls.

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