Traffic Signal Control with Partial Grade Separation for Oversaturated Conditions

Qing He\textsuperscript{ab1}, Ramya Kamineni\textsuperscript{a}, and Zhenhua Zhang\textsuperscript{a}

\textsuperscript{a}Department of Civil, Structural and Environmental Engineering
University at Buffalo, The State University of New York
Buffalo, NY 14260

\textsuperscript{b}Department of Industrial and Systems Engineering
University at Buffalo, The State University of New York
Buffalo, NY 14260

\textbf{Abstract:}
Increasing individual vehicular traffic is a major concern all around the world. This leads to more and more oversaturated intersections. Traffic signal control under oversaturated condition is a long-lasting challenge. To address this challenge thoroughly, this paper introduces grade separation at signalized intersections. A lane-based optimization model is developed for the integrated design of grade-separated lanes (e.g. tunnels), lane markings (e.g. left turns, through traffic, right turns, etc.) and signal timing settings. We take into account two types of lane configurations. One is conventional surface lanes controlled by signals, and the other is grade-separated lanes. This problem is formulated as a Mixed Integer Linear Program (MILP), and this can be solved using the regular branch-and-bound methods. The integer decision variables help in finding if the movement is on grade-separated or surface lanes, and also the successor functions to govern the order of signal display. The continuous variables include the assigned lane flow, common flow multiplier, cycle length, and start and duration of green for traffic movements and lanes. The optimized signal time settings and lane configurations are then represented in Vissim simulation. Numerical examples, along with a benefit-cost analysis show the good savings of the proposed optimization model for oversaturated traffic conditions. The benefit-cost ratio for installing 4 grade-separated lanes (as a tunnel) at a heavily oversaturated intersection (intersection capacity utilization rate equal to 1.57) exceeds 5.4.

\textbf{Keywords:} Traffic signal control; Oversaturated traffic; Partial grade separation; Mixed-integer programming;

\textsuperscript{1} Corresponding Author, Email: qinghe@buffalo.edu
1. Introduction

The traffic congestion index has been growing steadily over the past 20 years in most of the urban and suburban areas of United States, according to the 2012 Urban Mobility report (Schrank, Eisele, and Lomax 2012). In 1982, the average personal delay was 16 hours per year; by 2012 that figure had doubled, and the total delay for all travelers reached 38 hours. The amount of fuel wasted due to the idling engines in traffic jams was 2.9 billion gallons, and the total cost due to traffic congestion was more than 121 billion dollars and nearly 820 dollars for each commuter. Consequently, there will be an increase in vehicle hour delay by a number of folds which will cause the decrease in the level of service even after adding new road lines. Traffic congestion mitigation has been the primary task of the federal, state, and local transportation agencies. Intersections are vital nodal points in a transportation network, and the efficiency of their traffic signal control greatly influences the entire network’s performance. The evidence shows that more than 90% of the surface road congestion in an urban street network occurs at or near intersection areas. Traffic signal control is a fundamental element in the traffic control and management system and plays an important role in traffic operation and control. According to the Federal Highway Administration (FHWA), over 75% of the 350,000 traffic signals in the United States could be improved by updating the equipment or by simply adjusting the timing (Paulson 2002). Retiming traffic signals alone can produce a benefit-cost ratio as high as 40 to 1. That is, for every $1 invested in optimizing the timing of traffic signals, $40 is returned to the public in time and fuel savings (Sunkari 2004).

Traffic signal control under oversaturated conditions is a well-known challenging problem and has been studied over past decades (Gazis 1964; Daganzo 1996). However, very limited progress has been made for this challenge since the traffic demand exceeds intersection capacity too much in oversaturation. In this paper, the proposed solution to address this issue is to use grade separation. Grade separation increases roadway safety and mobility. The crossing traffic is removed from the intersection, thus eliminating the possibility of collisions between those streams of vehicles. Pedestrians are given greater protection from cars, as there will be only less number of traffic movements to cross and more refuge points can be provided at multiple locations. The Highway Safety Manual of American Association State Highway and Transportation Officials (AASHTO) reports that converting an at-grade, 4-leg intersection to a grade-separated interchange reduces injury crashes by 57%. Converting a signalized intersection into a grade-separated interchange reduces injury crashes by 28%.

Most importantly, intersections are a large cause of congestion on arterial streets. Signal time given to each direction dramatically decreases a road’s capacity, increasing the possibility of congestion and queues. This planned stop-and-go condition greatly increases travel time for all drivers. Tunneling one of the streets will reduce the conflict caused by intersecting roadways. The reduced interference will increase the road capacity. Grade-separated intersections substantially increase capacity by eliminating delay caused by the previous intersection. Traffic
moves freely, and any needed signal timing can be increased by the lack of a traditional intersection, as signals may only be necessary for accessing the exit and entrance ramps of the interchange. Removing at-grade intersections with heavy traffic substantially increases speed and throughput. Street traffic moves freely over interchange ramp or in tunnel, reducing wait times and increasing travel speed and capacity of the roadway.

In this paper, to mitigate oversaturated intersection while considering the cost of full grade separation, we resort to adding additional intersection capacity by introducing partial grade separation (PGS), which allows one or multiple lanes grade-separated from other surface lanes and prevents them from being controlled by signals. A typical PGS example is building a tunnel under intersections. In this case, the tunnel increases the throughput of the intersection permanently. Compared with traditional traffic signal control, signal control with PGS helps in smoothing traffic flow with fewer interruptions, achieving higher overall speeds, and also increasing the capacity of intersection by many folds. Further, we can adopt higher speed limits on grade-separated lanes. In addition, fewer conflicts between traffic movements reduce the risk of accidents. However, PGS will likely attract more volumes during peak hours. The demand elasticity of intersection design with PGS will be not considered in the scope of this paper. This paper aims to develop a mathematic model to design traffic signals with PGS and examine its long-term benefit.

The proposed partial grade separation (PGS) scheme has been widely implemented in practice (Meconstructionnews 2016; Shin et al. 2008; Hughes et al. 2010). However, no prior research has systematically modeled traffic signal control for PGS. The practice lacks a systematic tool to both design the intersection lane markings and signal timing under PGS and to evaluate the benefit/cost ratio in order to determine when the decision should be made to invest additionally for PGS on existing intersection. To fill this gap, this paper models the problem using a mathematic formulation, proposes new parameters to be considered, and assesses the benefit gained from the grade separation.

Here this paper considers the design problem of a signalized intersection with PGS, which adopts both the traffic signal system and grade separation, as shown in Figure 1. A partially grade-separated intersection would be more cost effective and also efficient than full grade separation. Except for grade-separated lanes, all other movements will be controlled by the signals. An optimization model is developed after a rigorous analysis in order to find out lane markings, signal timing settings like the green time, start of green cycle length. It will also assist in finding out lane settings to be adopted for grade separation. A detailed description of how this is developed is discussed later in this paper. A numerical example is provided to know the credibility of the developed optimization model.
The objective of this paper is to address the traffic signal control problem for oversaturated traffic conditions with partial grade separations. Here in this paper partial grade separation at an intersection is considered as a way to mitigate oversaturated intersection. A mathematic formulation for optimizing signal timing and lane configurations of an isolated intersection is developed. This model features a mixed integer programming approach that maximizes intersection throughput under real-time traffic demand. The algorithm optimizes background cycle length, splits, and phase sequence according to the projected traffic demand. In addition to signal control, the concept of grade separation is also included in the optimization model.

The remainder of this paper is organized as follows. In Section 2, a literature review is conducted to summarize previous work related to oversaturated signalized intersections and grade separation. Section 3 introduces the optimization model that finds out the best combination of lane settings, lane marking, signal timing settings. It will also help finding out lane settings to be adopted for grade separation. Section 4 focuses on the microscopic simulation, and the optimized settings are integrated into microscopic traffic simulation tool, and results are discussed. Section 5 discusses the benefit-cost analysis. Finally, the summary of findings and future research are given in Section 6.

2. Literature Review

The literature review for the research with two aspects is presented. One is previous studies related to traffic signal control for oversaturated intersections. The other aspect is alternative intersection designs. Previous studies in both at-grade design and grade-separated design are reviewed.

2.1. Traffic Signal Control for Oversaturated Conditions

Urban transportation networks have become more crowded and repeatedly develop into gridlock according to Liu (1988) and Gazis (1964). When a local queue spills back and spreads over the

Figure 1. Lane configuration with and without grade separation

(a) Conventional Intersection
(b) Intersection with partial grade separation (one eastbound lane is converted to a tunnel)
network, this traffic state often restricts traffic movements in all other directions (Daganzo 1996; Daganzo 2007; Schmöcker, Ahuja, and Bell 2008). Signalized intersections frequently become oversaturated due to the temporal and spatial variation in traffic flow. Under oversaturated traffic conditions, steady-state models (Koonce 2009) may break down when the vehicle arrival rate exceeds the intersection capacity, leading to the carryover of queues from one cycle to another. The design of an effective traffic signal timing plan for oversaturated traffic is more intricate than that for undersaturated traffic.

Some mathematical models have been proposed by many researchers on control variables in the signal time plan for oversaturated intersections. Part of important contributions in early days includes: the semi-graphical approach by Liu (1988) and (Gazis 1963) where, oversaturation has been characterized as “a stopped queue that cannot be completely dissipated during a green cycle” the work on verification of Dunne–Potts’s phase switching policy for oversaturated flow conditions conducted by (Green 1967); the so-called bang–bang two-stage timing method proposed by (Michalopoulos and Stephanopoulos 1977; Newell 1989); and the negative offset control strategy, which advances the downstream green in order to flush the residual queue ((Pignataro 1978; Rathi 1988).

Recently, most of the studies leveraged mathematical programming and optimization models for signal control at oversaturated intersections. Some researchers developed a large-scale optimization model maximizing throughput with constraints on downstream storage capability and green time utilization (Abu-Lebdeh and Benekohal 2000). Another study developed a mixed-integer linear programming approach for queue length control (Lieberman, Chang, and Prassas 2000). (Lo and Chow 2004) developed a dynamic intersection signal control optimization method for oversaturated condition based on cell-transmission model. (Li and Prevedouros 2004) presented a hybrid optimization and rule-based oversaturated control algorithm for isolated signals. (Chang and Lin 2000; Chang and Sun 2004) developed a discrete dynamic model and performance index approach to optimize signal parameters during the entire period of oversaturated conditions. (H. Liu, Balke, and Lin 2008) treated oversaturated signalized intersections as normal highway bottlenecks to greatly improve computational efficiency. (Y. Liu and Chang 2011) explicitly modeled physical queue evolution on arterial links by lane-group to capture the dynamic interactions of spillback queues. (Hu, Wu, and Liu 2013) proposed simple Forward–Backward Procedure (FBP) to derive the optimal maximum flow at oversaturated intersections. (Tong et al. 2015) developed a stochastic programming (SP) model to schedule adaptive signal timing plans that minimize the expected vehicle delay. (Sun, Wang, et al. 2015) built a quasi-optimal decentralized queue-based feedback control strategy (QUEUE) for a system of oversaturated intersections. QUEUE is applied cycle-by-cycle based queue sizes, but its overall result is able to approximate the optimal one derived from off-line studies.

Different with previous approaches, Ding et al. interviewed Traffic control agencies (TCAs), including police officers, firefighters or other traffic law enforcement officers, who can override automatic traffic signal control and manually control the traffic at an intersection (Ding, He, and Wu 2014). They modeled TCA-based manual traffic signal control and showed that such control
methods can mitigate non-recurrent oversaturated congestions very effectively (Ding et al. 2015).

2.2 Alternative Intersection Designs

The above studies share the common assumption that the geometry design of the intersection is conventional. Another branch of previous studies is alternative intersection design that aims to address the congestion issue with new lane configurations at intersections. We categorize alternative intersection design into two types: at-grade design and grade-separated design.

2.2.1 At-grade Design

The majority of the previous work falls into the category of at-grade design, which does not involve additional construction of bridges or tunnels. At-grade design aims to improve the capacity utilization at bottleneck intersections. The typical at-grade designs are tandem intersections, quadrant roadway intersections, displaced left-turn intersections, median U-turn intersections, etc. Tandem intersections separate the left-turn and through traffic in tandem by a pre-signal, so that all travel lanes are fully utilized for both left-turn and through traffic (Xuan, Daganzo, and Cassidy 2011). In a quadrant roadway intersection, all four left-turn movements at a conventional four-legged intersection are rerouted to use a connector roadway in one quadrant (Hughes et al. 2010).

Displaced left-turn (DLT) intersections are well studied in the last two decades. Two major DTL types are continuous flow intersection (CFI) (Goldblatt, Mier, and Friedman 1994; Jagannathan and Bared 2005; El Esawey and Sayed 2007; El Esawey and Sayed 2013; Hughes et al. 2010; Yang et al. 2013; Zhao et al. 2015) and parallel flow intersections (PFI) (Jagannathan and Bared 2004; Hughes et al. 2010; Parsons 2009). CFI relocates the left-turn movement to the other side of the opposing roadway by a pre-signal. Under this design, left-turn drivers have to first cross the opposing through lanes at a pre-signal in the upstream of the main intersection. While CFI allocates a turn pocket storage and transition area in the upstream of the intersection, PFI builds the transition area on the receiving leg of the left turn (Zhao et al. 2015). Both CFI and PFI requires installing additional sub-intersections. Sun, Wu, et al. (2015) developed a simplified continuous flow intersection (called CFI-Lite) design for arterials with short links. The new design enabled simultaneous move of left-turn and through traffic at bottleneck intersections, but does not need an installation of sub-intersections.

The U-turn intersection is another type of popular design. Typical U-turn intersections are Median U-turn Intersections (MUT) (Hughes et al. 2010) and Restricted Crossing U-turn Intersections (RCUT) (or called Superstreet Intersection) (Kim, Chang, and Rahwanji 2007). The key idea of U-turn intersections is to redirect left-turn movements on side streets by requiring drivers to turn right onto the main street and make a U-turn maneuver at a median downstream. However, U-turn intersections have some disadvantages for certain intersections where there are heavy through and left-turn volumes for the side street approaches. Also, the driver confusion is another concern. Other treatments of at-grade design involve Jughandle Intersection (New Jersey Department of Transportation 2015), Hamburger or Through-About Intersection (Hughes et al. 2010), green T-intersections (Litsas and Rakha 2013), two-stage pedestrian crossing (Wang and Tian 2010), and etc. Although at-grade designs have demonstrated the benefits in the previous studies, the extra gained capacity is still quite limited compared to grade-separated intersections.

2.2.2 Grade Separated Design
Intersections handling a high volume of traffic and pedestrians (and possibly railroads) limit the capacity of the approaching roads. Grade separation resolves these conflict points and allows an uninterrupted flow of traffic, while also eliminating the safety threat posed by trains, pedestrians, or other vehicles. However, grade-separated intersections are very costly (Shin et al. 2008). The critical question before adopting grade-separated design is to determine whether or not the construction of grade-separation is necessary. Schrader and Hoffpauer (2001) created a methodology to provide a consistent quantitative evaluation of potential locations. Three primary roadway improvement objectives are increased capacity, uninterrupted flow, and increased safety. Similarly, (Lang and Machemehl 1995) described a simple analysis for determining whether or not grade separation is warranted for intersections along urban arterial streets. This determination required the evaluation of user benefits attributable to operational and design improvements made to arterial intersections. Rymer, Urbanik, and others (1989) facilitated choosing proposed grade separation improvements on the basis of an evaluation of the reduced delay benefits to the cost of a grade separation. This methodology can assist decision-makers in determining when grade separations are appropriate. An economic analysis that presents the benefit/cost methodology for ranking a grade separation project was included.

Popular grade-separated designs include the single-point urban interchange (SPUI) (Bonneson and Messer 1989; Shin et al. 2008), center-turn overpass (CTO) (Kim, Chang, and Rahwanji 2007; Reid 2004), and echelon interchange (EI) (actually an intersection) (Miller and Vargas 1999). SPUI have been widely used for freeway interchanges, but the same design can be also applied for intersections. The SPUI separates straight-through traffic of the major road from all other traffic flow, which is controlled by a single signal on a different level. The proposed PGS design in Figure 1(b) becomes the SPUI design (see Figure 2), once all the EB/WB through lanes are converted into tunnels. The major shortcoming of SPUI is that SPUI still causes large congestion at the minor street when the two streets have similar traffic volumes (Shin et al. 2008). In a different approach, CTO and EI separate the left-turn movements. The CTO design elevates all the left-turn lanes to an upper level, thus separating left-turn vehicles from straight-through movements (Reid 2004). The EI removes left-turn and through conflicts through dividing movements by direction into two levels and adding a two-phase signal system (Miller and Vargas 1999).
All the previous grade-separated designs face the issues of flexibility since they cannot accommodate different traffic demand patterns for different locations. Further, the construction costs are very high. To our best knowledge, no prior work jointly optimize partial grade-separated lanes, lane markings and signal timings in a uniformed framework.

3. Methodology:

The methodology adopted for this paper includes three steps. First, an intersection is modeled in Vissim, a popular microscopic traffic simulation tool. The original intersection condition is simulated in Vissim. The second step involves creating the same scenario in Synchro to optimize the signal timings. These signal timings are adopted and implemented in Vissim model as the base scenario. The third step develops an optimization model to obtain lane markings, assignments and signal settings that are again developed and implemented in Vissim as the test scenarios. All of the test scenarios are compared to the base to verify the effectiveness of the proposed methods.

3.1 Optimization Model

3.1.1 General notation and terminology:

Table 1 lists the parameters used hereafter and the layout of a typical signalized intersection is shown in Figure 3 to facilitate the model presentation.

<table>
<thead>
<tr>
<th>Table 1. Symbols and Parameters</th>
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<tr>
<td>$x_{ijk}$</td>
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to arm \( j \) at lane \( k \), else it is zero.

\( y_{ijk} \)  
Permitted grade-separated movements, \( y_{ijk} = 1 \) if there is a grades separated lane for movement from arm \( i \) to arm \( j \) at lane \( k \), else it is zero.

\( r_{ik} \)  
Flow ratio for lane \( k \) in arm \( i \).

\( q_{ijk} \)  
Assigned flow capacity (veh/hr) for movement from arm \( i \) to arm \( j \) at lane \( k \).

\( \mu \)  
Common multiplier based on existing total demand

\( \xi \)  
Reciprocal of cycle length

\( \theta_{ij} \)  
Starts of green time for movements, normalized to the range \([0, 1]\) within a cycle.

\( \varphi_{ij} \)  
Duration of green for movements, normalized to the range \([0, 1]\) within a cycle.

\( \Theta_{ik} \)  
Starts of green for traffic lanes, normalized to the range \([0, 1]\) within a cycle.

\( \Phi_{ik} \)  
Duration of green for traffic lanes, normalized to the range \([0, 1]\) within a cycle.

\( \Omega_{ij,m} \)  
Order of signal phase. \( \Omega_{ij,m} = 0 \) if the start of green of signal group \((l,m)\) follows that of signal group \((i,j)\), and \( \Omega_{ij,m} = 1 \) if the opposite is true.

\( z_{ijk,lmn} \)  
Indicators for adjacent lanes of grade separation, \( z_{ijk,lmn} = 1 \) when 2 adjacent lanes \((i,j,k)\) and \((l,m,n)\) are both grade separation lanes, otherwise, \( z_{ik,lm} = 0 \)

**Data**

\( C \)  
Cycle length in seconds.

\( C_{\text{max}} \)  
Maximum cycle length in seconds.

\( C_{\text{min}} \)  
Minimum cycle length in seconds.

\( e \)  
The difference (seconds) between actual green signal time and effective green time.

\( g_{ij} \)  
Minimum duration (seconds) of green signal for movement from arm \( i \) to arm \( j \).

\( M \)  
A large positive number.

\( N_T \)  
Number of arms.

\( N_g \)  
Number of grade-separated lanes.

\( Q_{ij} \)  
Existing traffic demand (veh/hr) from arm \( i \) to arm \( j \).

\( s_{ik} \)  
Saturation flow rate (veh/hr) for lane \( k \) at arm \( i \).

\( \beta_{ij} \)  
Number of exit lanes of the movement from arm \( i \) to arm \( j \).
<table>
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<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$\alpha_i$</td>
<td>Number of approach lanes in arm $i$.</td>
</tr>
<tr>
<td>$\omega_{ij,lm}$</td>
<td>Minimum clearance time for mutually incompatible signals between movement $(i,j)$ and $(l,m)$.</td>
</tr>
<tr>
<td>$S$</td>
<td>Savings for a pair of adjacent grade separation lanes.</td>
</tr>
<tr>
<td>$W$</td>
<td>The weights assigned to savings as compared to total intersection capacity.</td>
</tr>
<tr>
<td>$\Psi_{ij,lm}$</td>
<td>Set of all mutually incompatible signals between movement $(i,j)$ and $(l,m)$.</td>
</tr>
<tr>
<td>$\Gamma_{ijk,lmn}$</td>
<td>Set of all adjacent lanes $(i,j,k)$ and $(l,m,n)$.</td>
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**Figure 3.** Numbering convention for destination arms in an example junction. Arm $i$ is the notation for “from arms”, and arm $j$ for “to arms”. For each arm $i$, arm $j$ is defined as 1, 2, and 3 clockwise from the left side of the flow direction.

3.1.2 Objective Function:
Because the ultimate objective of operating oversaturated intersections is to accommodate more cars, capacity maximization is employed as the objective of the integrated optimization model. The concept of reserved capacity is used to formulate a linear model. Conventionally, the concept of reserve capacity has been applied to individual signal-controlled intersections, and is measured by the greatest common multiplier ($\mu$), based on existing total demand ($\sum_{i=1}^{N_I} \sum_{j=1}^{N_T-1} Q_{ij}$) (Wong and Wong 2003; Ma, Head, and Feng 2014; Wong and Heydecker 2011). The objective also takes into account the potential savings ($S$) for building adjacent grade-separated lanes ($Z_{ijklmn}$). In this paper, we assume the additional construction cost of the intersection with PGS is linearly correlated to the number of grade-separated lanes. Rostami et
al. (2013) fitted a regression curve between unit cost of a tunnel (y) and the diameter (x) given 12 observations of highway tunnels. They found the regression line is very close to a line, as shown in Figure 4. Given this assumption, the total cost of building a 4-lane tunnel is approximately equivalent to 60% of the total cost of building 2 separate 2-lane tunnels.

![Figure 4. Unit cost vs. diameter for conventional highway tunnels (Rostami et al. 2013).](image)

The model is subject to approach capacity constraints, cycle time and minimum green constraints and others. Based on the commonly used assumption that the traffic flows for the turning movements in the intersection would increase in proportion to the demand matrix. See Table 1 for the notations of decision variables and data. The intersection capacity maximization problem can be effectively formulated as an MILP as shown below:

Max $\mu \sum_{i=1}^{N_T} \sum_{j=1}^{N_T-1} Q_{ij} + \sum_{(i,j,k,l,m,n)\in\Gamma} z_{ijklmn}SW$

where the first component is to maximize common multiplier ($\mu$), which indicates the number of times of design capacity compared to the total demand $\sum_{i=1}^{N_T} \sum_{j=1}^{N_T-1} Q_{ij}$. The second component is to increase the savings by allocating adjacent grade-separated lanes. These two objectives are competing each other. According to the previous work (Rostami et al. 2013), the construction cost of building a 2-lane tunnel is about 80% of the cost of a 4-lane tunnel. Therefore, the savings of allocating adjacent grade-separated lanes are significant. And the major objective of this model is to select the design with maximal savings. So the second component should dominate the objective. In this case, we choose an appropriate $W$ so that $\sum_{(i,j,k,l,m,n)\in\Gamma} z_{ijklmn}SW$ is much greater than $\mu \sum_{i=1}^{N_T} \sum_{j=1}^{N_T-1} Q_{ij}$. In this paper, we set $W=1$ and $S = 1,000,000$. The values of $W$ and $S$ could be adjusted according to a variety of practical considerations.
3.1.3 Constraints:
All constraints are listed as follows,

(1) Minimum number of permitted movements on traffic lanes: each traffic lane must permit at least one turning or through movement as either a surface lane or a grade-separated lane (e.g. a tunnel), which can be specified as

\[ \sum_{j=1}^{N_T-1} (x_{ijk} + y_{ijk}) \geq 1, \text{for all } i = 1, \ldots, N_T; k = 1, \ldots, \alpha_i \] (2)

(2) Maximum permitted movements at exit: due to safety and operational considerations, for each turning movement from arm \( i \), the number of exit lanes in the corresponding exit arm should always be at least as many as the total number of lanes assigned to permit such a movement.

\[ \beta_{ij} \geq \sum_{k=1}^{\alpha_i} (x_{ijk} + y_{ijk}), \text{for all } i = 1, \ldots, N_T; j = 1, \ldots, N_T - 1 \] (3)

(3) Mutual exclusive lanes: The lanes used for commute should either be surface lanes or grade-separated lanes but not both at the same time. Each lane must be specified its type.

\[ (x_{ijk} + y_{ijk}) \leq 1, \text{for all } i = 1, \ldots, N_T; j = 1, \ldots, N_T - 1; k = 1, \ldots, \alpha_i \] (4)

(4) Flow rate constraints: if \( x_{ijk} + y_{ijk} = 0 \), the movement \( j \) on lane \( k \) in arm \( i \) does not have right of way so the assigned lane flow \( q_{ijk} \) will be 0. This can be realized in following inequality:

\[ M(x_{ijk} + y_{ijk}) \geq q_{ijk} \geq 0, \text{for all } i = 1, \ldots, N_T; j = 1, \ldots, N_T - 1; k = 1, \ldots, \alpha_i \] (5)

(5) Conflict avoidance with an arm: for any two adjacent traffic lanes, \( k \) (left-hand) and \( k+1 \) (right-hand) lanes from arm \( i \), if the traffic movement of turning \( j \) is permitted on lane \( k+1 \), then traffic movements of all other turns, \( j+1, \ldots, N_T - 1 \), should be prohibited on lane \( k \) to forbid potential internal-cross conflicts within an arm. This can be specified by below

\[ 1 - x_{ij(k+1)} \geq x_{imk}, \text{for all } i = 1, \ldots, N_T; j = 1, \ldots, N_T - 2; m = j+1, \ldots, N_T - 1; k = 1, \ldots, \alpha_i - 1 \] (6)

\[ 1 - y_{ij(k+1)} \geq y_{imk}, \text{for all } i = 1, \ldots, N_T; j = 1, \ldots, N_T - 2; m = j+1, \ldots, N_T - 1; k = 1, \ldots, \alpha_i - 1 \] (7)

(6) Lane separation constraints: For an arm with both surface lanes and grade-separated lanes, we always allocate the grade-separated lanes in the left side (for right-hand traffic) of all surface lanes. This is because grade-separated lanes usually have higher speed limits than surface lanes. In this case, high-speed traffic will be allocated to the left side of the road.

\[ 1 - x_{ijk} \geq \sum_{m=1}^{N_T-1} y_{imn}, \text{for all } i = 1, \ldots, N_T; j = 1, \ldots, N_T - 1; k = 1, \ldots, \alpha_i - 1; n = k+1, \ldots, \alpha_i \] (8)
(7) Flow ratio constraints: The flow ratio of a lane is the ratio of the flow rate to the saturation flow rate, as given by the following equation:

\[ r_{ik} = \frac{\sum_{j=1}^{N-1} q_{ijk}}{s_{ik}}, \text{ for all } i = 1, \ldots, N_T; k = 1, \ldots, \alpha_i \] (9)

For all approach lanes, including both surface lane and grade-separated lanes, it is required that the flow ratios must be identical to the pair of adjacent lanes that have a common lane marking. This constraint can be specified by the following equations:

\[ M(2 - x_{ijk} - x_{ij(k+1)}) \geq r_{i(k+1)} - r_{ik} \geq -M(2 - x_{ijk} - x_{ij(k+1)}), \text{ for all } i = 1, \ldots, N_T; j = 1, \ldots, N_T-1; k = 1, \ldots, \alpha_i \] (10)

(8) Flow conservation: Assume that the traffic demand matrix \( Q \) is multiplied by a common flow multiplier \( \mu \) to represent the maximum amount of traffic increase that would still allow the junction to perform reasonably well. With the increased demand, the flow conservation constraints can be set as follows.

\[ \mu Q_{ij} = \sum_{k=1}^{\alpha_i} q_{ijk}, \forall j = 1; \ldots; N_T-1; i = 1; \ldots; N_T \] (11)

(9) Each grade-separated lane is exclusive for one turn. Multiple lane markings are not allowed for grade-separated lanes.

\[ \sum_{j=1}^{N_T-1} y_{ijk} \leq 1, \text{ for all } i = 1, \ldots, N_T; k = 1, \ldots, \alpha_i \] (12)

(10) Surface turns and grade-separated lanes cannot co-exist for lane \( k \) at arm \( i \).

\[ \sum_{j=1}^{N_T-1} x_{ijk} \leq (1 - \sum_{j=1}^{N_T-1} y_{ijk}) \cdot M, \text{ for all } i = 1, \ldots, N_T; k = 1, \ldots, \alpha_i \] (13)

(11) Budget constraint to build a total number of grade-separated lanes. Suppose the limit is \( N_g \).

\[ \sum_{i=1}^{N_T} \sum_{j=1}^{N_T-1} \sum_{k=1}^{\alpha_i} y_{ijk} \leq N_g \] (14)

(12) Determine if grade-separated lanes are adjacent. \( z_{ijk,lmn} = 1 \) when two adjacent lanes \( (i,j,k) \) and \( (l,m,n) \) are both grade-separated lanes, otherwise, \( z_{ik,ln} = 0 \)

\[ z_{ijk,lmn} \leq y_{ijk} \quad \forall ((i;j,k); (l;m,n)) \in \Gamma \] (15)

\[ z_{ijk,lmn} \leq y_{lmn} \quad \forall ((i;j,k); (l;m,n)) \in \Gamma \] (16)

\[ 1 \geq z_{ijk,lmn} \geq 0 \] (17)

(13) Signal timing constraints:

\[ \frac{1}{C_{\text{min}}} \geq \xi \geq \frac{1}{C_{\text{max}}} \] (18)
\[ 1 \geq \theta_{ij} \geq 0 \quad \forall j = 1; \ldots; N_T - 1; \ i = 1; \ldots; N_T \]  
(19)

\[ 1 \geq \varphi_{ij} \geq \zeta g_{ij} \quad \forall j = 1; \ldots; NT - 1; \ i = 1; \ldots; N_T \]  
(20)

The following constraints define the order of two incompatible signal groups \((i,j)\) and \((l,m)\). \(\Omega_{ij,lm} = 0\) if the start of green of signal group \((l,m)\) follows that of signal group \((i,j)\), and \(\Omega_{ij,lm} = 0\) if the opposite is true.

\[ \Omega_{ij,lm} + \Omega_{lm,ij} = 1, \quad \forall \ ((i; j); (l;m)) \in \psi \]  
(21)

The following constraints make sure there is no overlap between any pair of incompatible movements, and the clearance time between the two has to be greater than \(\omega_{ij,lm}\).

\[ \theta_{lm} + \Omega_{ij,lm} + M(2-x_{ijk}-x_{lmk}) \geq \theta_{ij} + \varphi_{ij} + \zeta \omega_{ij,lm}, \quad \forall \ ((i; j); (l;m)) \in \psi \]  
(22)

(13) Lane signal timings: if a lane is shared by more than one movement, these movements must receive identical signal indications to avoid ambiguity.

\[ M(1 - x_{ijk}) \geq \Theta_{ik} - \theta_{ij} \geq M(1 - x_{ijk}) \]  
(23)

\[ M(1 - x_{ijk}) \geq \Phi_{ik} - \varphi_{ij} \geq M(1 - x_{ijk}) \]  
(24)

(14) Flow capacity constraints subject to green time at lane \(k\) in arm \(i\)

\[ \Phi_{ik} + e \xi \geq \eta_{ik} - (\sum_{j=1}^{N_T-1} y_{ijk}) M \text{ for all } i = 1,\ldots, N_T \ ; \ k = 1,\ldots,a_i \]  
(25)

(15) Flow capacity constraints for each lane designed as either surface or grade separation:

\[ \sum_{j=1}^{N_T-1} q_{ijk} \leq s_{ik} \text{ for all } i = 1,\ldots, N_T \ ; \ k = 1,\ldots,a_i \]  
(26)

The optimization model above is used for different demand scenarios to test its effectiveness and to derive conclusion for a given scenario. The discussion about this is continued in the next section.

4. Simulation Results

The intersection of Sheridan Drive and Niagara Fall Boulevard in the City of Buffalo is modeled using Vissim with its original intersection layout (See Figure 5). The PM peak volume counts on each lane in all directions were collected from Greater Buffalo-Niagara Regional Transportation Council (GBNRTC) (GBNRTC 2015). We scale the PM peak volume proportionally to a traffic volume called “100% volume” in this paper. We use the intersection capacity utilization (ICU) to represent the demand level as compared with the intersection capacity (Husch and Albeck 2003).
Scenarios with ICU greater than 1 have the oversaturated traffic. In “100% volume” scenario, the ICU value equals 0.97, representing a near-saturated traffic condition. By increasing the saturated volume we can see how the intersection is impacted in each scenario during oversaturated conditions. The most important aspect of our intersection is grade separation. The grade separation in here is achieved by removing the signal head for the grade-separated route and defining separate lanes for them so that the traffic can flow smoothly.

![Figure 5. Original intersection layout for the test site.](image)

**Table 2.** Demand matrix

<table>
<thead>
<tr>
<th>from arm (i)</th>
<th>100%, ICU* = 0.97 to arm (j)</th>
<th>150%, ICU=1.57 to arm (j)</th>
<th>200%, ICU=2.05 to arm (j)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 (left-turn)</td>
<td>2 (through)</td>
<td>3 (right-turn)</td>
</tr>
<tr>
<td>1 (WB)</td>
<td>453</td>
<td>1458</td>
<td>344</td>
</tr>
<tr>
<td>2 (NB)</td>
<td>0</td>
<td>1164</td>
<td>285</td>
</tr>
<tr>
<td>3 (EB)</td>
<td>635</td>
<td>1180</td>
<td>5</td>
</tr>
<tr>
<td>4 (SB)</td>
<td>304</td>
<td>889</td>
<td>479</td>
</tr>
<tr>
<td></td>
<td>1 (left-turn)</td>
<td>2 (through)</td>
<td>3 (right-turn)</td>
</tr>
<tr>
<td></td>
<td>680</td>
<td>2187</td>
<td>516</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1746</td>
<td>428</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>953</td>
<td>1770</td>
</tr>
<tr>
<td></td>
<td>953</td>
<td>1770</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>1334</td>
<td>608</td>
<td>1778</td>
</tr>
<tr>
<td></td>
<td>719</td>
<td>1778</td>
<td>958</td>
</tr>
</tbody>
</table>

*: ICU represents intersection capacity utilization defined in Synchro.

Synchro, a popular tool for off-line signal optimization, is used for obtaining optimized signal timings for the base scenario. Table 2 presents the demand matrix for Sheridan Drive and Niagara Fall Boulevard under three different cases, representing the different percentage of the
saturated volume that is 100% (case I), 150% (case II) and 200% (case III). Note that arm $i$ represents the arm ID, whereas arm $j$ always indicates the turns corresponding to $i$.

The ICU from Synchro can be regarded as a practical indicator of intersection oversaturation. As one can see, the 150% case and the 200% case are oversaturated with ICU 1.57 and 2.05, respectively. The new volumes are induced in the model for each case, and the signal timing is optimized by both Synchro and proposed MILP model. The Synchro optimized signal timings are used in Vissim simulation model as the base scenario.

This paper considers two levels of the budget: allowing 2 grade-separated lanes (Ng-2) and 4 grade-separated lanes (Ng-4). Three different Vissim models are created which depict three scenarios: base, Ng-2 and Ng-4. The base scenario is the original intersection before grade separation, while Ng-2 and Ng-4 represent the case of grade separation with 2 lanes and 4 lanes, respectively. So total six cases are studied: The first three cases allow 2 grade-separated lanes with 100%, 150%, and 200% volumes, respectively. The next three cases have 4 grade-separated lanes with the same three levels of volumes.

The maximum cycle length considered is 180s and the minimum 45s. The difference between actual and effective green signal time ($e$) is set as zero. The minimum green time is 5s. The number of arm $N_T$ is 4. The minimum clearance time for mutually incompatible signals is considered 4s and we assume a constant saturation flow rate as 1650 vehicles per hour (Roess, Prassas, and McShane 2010). The optimization model is implemented and solved in IBM iLOG CPLEX 12.6 on a personal laptop with Intel(R) Core(TM) i7-2.9GHz CPU and 8GB RAM.

<table>
<thead>
<tr>
<th>Results</th>
<th>Base</th>
<th>Ng-2</th>
<th>Change%</th>
<th>Ng-4</th>
<th>Change%</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICU</td>
<td>0.97</td>
<td>0.81</td>
<td>-16.49%</td>
<td>0.65</td>
<td>-32.99%</td>
</tr>
<tr>
<td>Total travel time [h]</td>
<td>135.28</td>
<td>95.40</td>
<td>-29.48%</td>
<td>86.25</td>
<td>-36.24%</td>
</tr>
<tr>
<td>Number of vehicles</td>
<td>7112.00</td>
<td>7145.40</td>
<td>0.47%</td>
<td>7149.60</td>
<td>0.53%</td>
</tr>
<tr>
<td>Average delay time[s]</td>
<td>34.67</td>
<td>14.85</td>
<td>-57.17%</td>
<td>10.29</td>
<td>-70.32%</td>
</tr>
<tr>
<td>Average stops</td>
<td>0.69</td>
<td>0.48</td>
<td>-31.28%</td>
<td>0.37</td>
<td>-47.22%</td>
</tr>
<tr>
<td>Average speed [km/h]</td>
<td>25.33</td>
<td>35.97</td>
<td>42.03%</td>
<td>39.82</td>
<td>57.21%</td>
</tr>
<tr>
<td>Average stopped delay</td>
<td>26.30</td>
<td>9.09</td>
<td>-65.42%</td>
<td>5.65</td>
<td>-78.53%</td>
</tr>
<tr>
<td>Total delay time [h]</td>
<td>69.77</td>
<td>29.85</td>
<td>-57.22%</td>
<td>20.68</td>
<td>-70.36%</td>
</tr>
<tr>
<td>Number of Stops</td>
<td>5020.60</td>
<td>3447.00</td>
<td>-31.34%</td>
<td>2647.40</td>
<td>-47.27%</td>
</tr>
<tr>
<td>Total travel time [h]</td>
<td>135.28</td>
<td>95.40</td>
<td>-29.48%</td>
<td>86.25</td>
<td>-36.24%</td>
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<td>7112.00</td>
<td>7145.40</td>
<td>0.47%</td>
<td>7149.60</td>
<td>0.53%</td>
</tr>
<tr>
<td>CPLEX Computational time(s)</td>
<td>N/A</td>
<td>13.85</td>
<td>N/A</td>
<td>6.96</td>
<td>N/A</td>
</tr>
<tr>
<td>Common multiplier ($\mu$)</td>
<td>N/A</td>
<td>1.48</td>
<td>N/A</td>
<td>1.72</td>
<td>N/A</td>
</tr>
</tbody>
</table>
The base represents the case where the existing real-world intersection layout is considered at the current intersection. So this scenario will not have any grade-separated lanes but it has optimized signal settings by Synchro. For our proposed MILP model, the optimized lane configurations and signal timings are implemented in Vissim and results are obtained from simulation accordingly.

We have conducted 10 simulation runs for each scenario with different random seeds. The average results of evaluation from each scenario are presented in Table 3-5. As we can see from each scenario, the savings in disutility are remarkable after adding grade-separated lanes.
Considering case I that is 100% volume scenario, shown in Table 3, we have a 29% and 36% decrease in travel time for 2 (Ng-2) and 4 (Ng-4) grade-separated lanes respectively. We can also see from the table that there is a significant amount of decrease in terms of the number of stops for this scenario. In terms of intersection capacity, Ng-4 provides 1.72 ($\mu$) times as much as the 100% demand, whereas Ng-2 1.48. Figure 6 validates $\mu$ with ICU under different scenarios. In case I, the ICU for Ng-2 and Ng-4 is only 0.81 and 0.65, respectively.

Table 4 illustrates the results of case II, which is 150% volume scenario. As we can see from the table, there is a significant change in travel time values in this case compared to the base case, which comes out to be 58% and 60% for Ng-2 and Ng-4, respectively. The average speed is also increased by a great amount with a percentage as high as 153% for Ng-4. The number of stops in this case decreases by 72%. Both average delay reduction and speed increases are among the highest in case II. The common multiplier ($\mu$) is close to 1 with Ng-2 (0.99), which means that the capacity of intersection design with 2 grade-separated lanes barely meets the 150% of peak demand.

The results of case III, which represents an extremely oversaturated case with twice as much as 100% demand, are presented in Table 5. Greatly improved by 4 grade-separated lanes, the throughput for Ng-4 increases by 42% and the speed (17.92 km/h) obtained is 67% higher than the speed (10.73 km/h) in the base case. However, under case III, the common multipliers ($\mu$) for Ng-2 and Ng-4 are 0.74 and 0.86, respectively, meaning that the demand can not be totally accommodated by the new intersection design.

Comparisons of performance in throughput and average delay are further illustrated in Figure 7 and Figure 8, respectively. As one can see in Figure 7, the throughput increases for each Ng-4 case. There is only a 0.5% increase for the original 100% volume case compared to the base, since it is not an oversaturated condition. The percent change increases around 30% for both the Ng-2 and Ng-4 cases under the 150% volume. The throughput for the case III comes out to increase by an amount of 42% from 8075 to 11459 under the Ng-4 scenario. The results show that 2 grade-separated lanes obtain desirable results similar as 4 grade-separated lanes in mitigating traffic congestion under medium oversaturated conditions (ICU=1.57). However, the design with 4 grade-separated lanes performs better under very heavily oversaturated traffic conditions (ICU=2.05), compared to 2 grade-separated lanes. However, the highest delay reduction is achieved (76%) under 150% volume, shown in Figure 8.
Figure 6. The Intersection Utilization Capacity (ICU) compared with different scenarios; Scenarios with ICU greater than 1 have the oversaturated traffic.

Figure 7. The intersection throughput changes compared with the base scenario.

Figure 8. The intersection delay changes compared with the base scenario.
The lane settings and configurations are very critical in the design of an intersection to maximize the possible throughput. The lane configurations for Ng-2 cases can be found in Figure 9. As one can see, there are 2 grade-separated lanes allocated in the northbound approach. In this case, except for northbound right-turn, all northbound traffic has been accounted by grade separation because no northbound left-turn demand exists. Therefore, the signal timing settings could simply “neglect” northbound traffic.

The lane configuration for a Ng-4 intersection can be seen in Figure 10. The same convention can be followed to obtain the lane configurations for northbound traffic. In addition, another 2 grade-separated lanes are added in southbound approach to take into account all the through traffic for southbound. As a result, grade-separated lanes provide full capacity for through traffic in both northbound and southbound. Therefore, no green phase is needed for northbound and southbound through traffic. Saved green time can be allocated to increase the green split-cycle ratio for the eastbound and westbound traffic. It is worth noting that all 4 grade-separated lanes are adjacent in the middle of Niagara Fall Boulevard (in north and south direction). So only one tunnel is needed to accommodate all 4 grade-separated lanes.

Figure 9. Lane configuration diagram for a grade separated intersection with 2 grade separated lanes (Ng-2) for different levels of volume.
The obtained signal timing settings for Ng-2 and Ng-4 are presented in Figure 11. This helps in manipulating the traffic without any changes to the intersection geometry if used properly. The signal timing settings here have a start of green at zero. The signal timing duration and its values are represented in the diagram in green bars. Shaded bars represent the grade-separated movements. Here in this diagrams, the “from” arms are designated as 1, 2, 3 and 4. The “to” arm is numbered 1, 2, and 3 clockwise corresponding to each “from” arm. So “to” arm 1 represents left turns, 2 represents through movements and 3 right turns. Since permissive right turn is allowed, “to” arm 3 is not plotted in Figure 11. The signal timings for each turning movement can be obtained from the figure. The optimized signal timing settings for all cases are with a cycle length of 180 seconds. For both cases, it is found that all three cases have very similar green splits due to proportional demand increase at all movements. Therefore, only the signal timing plans for 100% volume are presented. As one can see, comparing Ng-2 with Ng-4, the green time for arm 4 is significantly reduced from 48.3s to 28.4s. Such result is reasonable since all the through traffic demand on arm 4 are carried by grade-separated lanes. These timings are used for obtaining the results by importing the values into Vissim.

Figure 10. Lane configuration diagram for a grade separated intersection with 4 grade-separated lanes (Ng-4) under different levels of volume; Note that only one tunnel is needed for these 4 grade-separated lanes.
Figure 11. Traffic signal timing settings for at (a) Ng-2, (b) Ng-4 for 100% volume; Note that other volume levels have very similar timing plans due to proportional demand increase at all movements. The solid green bars represent green time, and the shaded bars represent the grade-separated movements.

5. Benefit-Cost Analysis

Benefit-cost analysis (BCA) is conducted to evaluate the economic benefits of implementing the traffic signal system with partial grade separation in place of traditional traffic signal system. BCA is often used by governments and other organizations, such as private sector businesses, to appraise the desirability of a given policy. It is an analysis of the expected balance of benefits and costs, including an account of foregone alternatives and the status quo. BCA helps predict whether the benefits of a policy outweigh its costs, and by how much relative to other alternatives (i.e. one can rank alternative policies in terms of the benefit-cost ratio). Generally, accurate BCA identifies choices that increase welfare from a utilitarian perspective. Assuming an accurate BCA, changing the status quo by implementing the alternative with the highest benefit-
cost ratio can improve efficiency. An analyst using BCA should recognize that perfect appraisal of all present and future costs and benefits is difficult, and while BCA can offer a well-educated estimate of the best alternative, perfection in terms of economic efficiency and social welfare are not guaranteed.

As an example, we conduct BCA analysis for 150% volume with 4 grade-separated lanes (Ng-4). Several assumptions are made as follows:

- The tunnel construction cost is assumed to be 12 million dollars, the same as building an SPUI intersection (Shin et al. 2008). Further, we assume the construction cost of a 2 lane tunnel is $9.6 million, according to Figure 4 (Rostami et al. 2013).
- The delay savings in both peak hours and off-peak hours are only represented by six peak hours in a weekday, and 260 weekdays in a year (Park and Chen 2010).
- The value of travel time is $16.79 per hour (Schrank, Eisele, and Lomax 2012).
- The vehicle fuel consumption savings are calculated with the following formula from major traffic signal optimization tools (TRANSYT-7F and SYNCHRO) (Hale 2005; Stevanovic et al. 2009).

\[ F = k_1 \times VMT + k_2 \times D + k_3 \times N_s \]

Where

- \( F \) = fuel consumption (gallon)
- \( k_1 = 0.075283 - 0.0015892 \times S + 0.000015066 \times S^2 \)
- \( k_2 = 0.7329 \)
- \( k_3 = 0.0000061411 \times S^2 \)
- \( S \) = cruise speed (mph)
- \( VMT \) = vehicle miles traveled (veh-mile)
- \( D \) = total signal delay (h)
- \( N_s \) = total stops (veh/h).

- Due to lack of accident data at intersections with PGS, the accident savings are not considered in this paper. However, an early study showed that 82% annual accident cost reduction has been found for fully separated interchanges (Witkowski 1988).
- The annual traffic volume increases by 2%.
- The tunnel maintenance cost is 169 thousand per year (Weisskoff and Fauth 2003).

Now the BCA is conducted using the data mentioned above. The results can be seen in Table 6. As one can see, with the expected additional maintenance cost for the tunnel and delay savings for the next 10 years, the benefit-cost ratio reaches 5.42, which is higher than the ratio of urban fully grade-separated interchanges 2.5–3.5 (Witkowski 1988). The benefit-cost ratios for other scenarios are summarized in Table 7. One can see that benefit-cost ratio increases with the oversaturated rates of the intersection. When the traffic is nearly saturated (100%), the benefit-cost ratio is around 1 for both Ng-2 and Ng-4. When the traffic is medium oversaturated (150%), the benefit-cost ratio exceeds 5 for both Ng-2 and Ng-4. When the traffic is extremely oversaturated (200%), the benefit-cost ratio decreases back to 4.20 and 4.87 for Ng-2 and Ng-4, respectively. Because of relatively low additional construction cost, the scenarios with 4 grade-
separated lanes have higher benefit-cost ratio than 2 grade-separated lanes across different scenarios. The intersection with 4 grade-separated lanes under medium heavy oversaturated intersections (ICU=1.57) achieves the highest ratio.

Table 6. Benefit-cost analysis results for 150% volume with 4 grade-separated lanes (Ng-4)

<table>
<thead>
<tr>
<th>Category</th>
<th>Base</th>
<th>150%&amp;Ng-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel construction cost (million $)</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>Annual cost of maintenance for tunnel (million $)</td>
<td>0.169</td>
<td></td>
</tr>
<tr>
<td>Net present value (NPV) of cost of maintenance over 10 years</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Total cost (million $)</td>
<td></td>
<td>13.5</td>
</tr>
</tbody>
</table>

Table 7. The benefit-cost ratio for different scenarios

<table>
<thead>
<tr>
<th>Volume levels</th>
<th>Ng-2</th>
<th>Ng-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case I: 100% volume (ICU=0.97)</td>
<td>0.98</td>
<td>1.00</td>
</tr>
<tr>
<td>Case II: 150% volume (ICU=1.57)</td>
<td>5.20</td>
<td>5.42</td>
</tr>
<tr>
<td>Case III: 200% volume (ICU=2.05)</td>
<td>4.20</td>
<td>4.87</td>
</tr>
</tbody>
</table>

6. Conclusions
In this paper, a mixed-integer linear program (MILP) has been developed for the integrated design of partial grade separation (PGS), lane markings and signal settings for oversaturated intersections. The capacity maximization has been considered as the objective. This study fills the research gap in joint consideration of grade separation and traffic signal control for a signalized intersection.

Numerical examples have been given to demonstrate the effectiveness of the proposed method in a real-world intersection. There is a good saving in delay for all three cases. The first two cases, with 0.97 and 1.57 of intersection capacity utilization (ICU), respectively, of 2-lane grade separation (Ng-2) has a 57% and 60% savings in the delay. The case III (ICU=2.05) has a delay saving of 36%. But the case with 4 grade-separated lanes (Ng-4) has more delay savings compared to the Ng-2 case that sums up to be 70% for case I, 76% for case II and 50% for case III. There is also a significant increase in throughput for Ng-4. Initially for case I, it increases only by 0.5% for under-saturated traffic. But for case II it increases by 32% and for case III it is as high as 42%. From the benefit-cost analysis, we derive the benefit-cost ratio for Ng-4 with case II, which obtains the highest benefit-cost ratio 5.42 among all the scenarios. The benefit-cost ratio for intersection with PGS is found to be higher than the ratio of urban fully grade-separated interchanges 2.5–3.5 (Witkowski 1988). Further, the benefit-cost ratio of Ng-4 is typically higher than Ng-2 due to relatively low additional construction cost. It is also found that the intersection with PGS under nearly saturated traffic conditions has benefit-cost ratio 1. Therefore, adding grade-separated lanes for under-saturated traffic is not beneficial.

In future, the proposed optimization model can be extended for a series of intersections on an arterial. The goal is to maximize the flow capacity along an oversaturated corridor. One possible application is to apply the intersection with PGS for traffic signal control under emergency evacuation (Asamoah and He 2015).

Since most of the oversaturated intersections suffer from the competition among multiple travel modes, there is also a need to extend proposed optimization model for multi-modal traffic, which includes buses, light rail, and pedestrians (He, Head, and Ding 2011; He, Head, and Ding 2012; He, Head, and Ding 2014).

One more thing to address in future research is the location of grade-separated intersection. The location is an important aspect for adopting a grade separate lane because it is influenced by the traffic volumes. Also, if it is a residential area grade separation might cause land use impact, and increase in volumes in the neighborhood due to grade separation. So addressing those cases will further help solve the problem. At last but not least, the proposed model shall be further validated by field tests for the actual performance.

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