Integrated design and operation of urban arterials with reversible lanes

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ABSTRACT
Reversible lane operation, an effective strategy to relieve traffic congestion in urban arterials, must interact with other conventional traffic management and control components in the arterial, including left-turn restriction, lane channelization, and signal timings. This paper develops a lane-based optimization model to guide the integrated setting of reversible lanes and other traffic management measures in an arterial to maximize its operational performance. The optimization problem is formulated as a multi-objective mix-integer non-linear programming model, which is then transformed into a single-objective mix-integer linear programming formulation for an optimal solution. Results from extensive numerical analyses have demonstrated the effectiveness of the proposed model.

Keywords: Reversible lanes; urban arterials; lane markings; capacity; traffic management and control
1. INTRODUCTION

High traffic demand coupled with unbalanced directional flows on roadways exacerbates the perennial problem of congestion. Reversible lanes, deemed by the Institute of Transportation Engineers [1] as one of the most effective methods to increase peak-hour capacities of roadways, could essentially accommodate the imbalanced traffic flows between two driving directions on a congested roadway section [2].

Lane reversal has been used for several decades and much has been investigated regarding its effectiveness, feasibility and safety. One of the earliest referenced usages of reversible roadways was in Los Angeles in 1928, with a convertible lane variant known as off-center lane movement [3]. Over the past decades, many different forms of reversible roadways have been used throughout the world to address a variety of needs [4]. Three major applications have been developed to accommodate the demand associated with frequent and predictable imbalanced peak-period travel times [5,6], special events such as those associated with large sporting events, concerts, and festivals [7-9], and emergency conditions such as evacuation [10-13]. The principle of reversible roadways is to configure the lanes of a roadway to match available capacity with traffic demand. The common idea among these designs is that they only change the direction of the reversible lanes during daily peak periods, before and after large events, or during emergency evacuations. For convenience of application, many professional transportation organizations have also developed guidelines for operating reversible lanes (AASHTO Green Book [14], ITE [15], JSCE [16], and FGSV [17]).

Several optimization models have been proposed to produce the best operational strategy for an arterial with reversible lanes. Most of them formulate the optimal decision on the reversible lanes as a network design problem and optimize a target system performance measure such as the total system travel cost [18]. Tuydes and Ziliaskopoulos [19] proposed a system-optimal dynamic traffic assignment-based optimal capacity reversibility model (SODTA-CR) to capture spatiotemporal changes in disaster conditions. Tuydes [2] proposed three extensions of SODTA-CR: lane-based capacity reversibility (SODTA-LCR), total-or-nothing capacity reversibility (SODTA-TCR), and budgeted capacity reversibility (SODTA-BCR). These were single-level models because the drivers and the evacuation manager share the same objective in minimizing total system travel time. For operational design, however, user equilibrium is considered as a more suitable principle to capture travelers’ route choice behavior. Therefore, bi-level programming models were proposed to capture different perspectives between authorities and travelers. In a bi-level programming model developed by Zhang and Gao [20], the upper level model was to minimize the total system cost and the lower level was a user equilibrium assignment. The model was solved using a particle swarm optimization technique. Wu et al. [21] introduced flow entropy in the upper level objective function to obtain symmetrical flows. The upper level of Wu’s model was to minimize the total system cost and flow entropy and the lower level was a stochastic user equilibrium assignment with an advanced traveler information system. This model was solved using a chaotic optimization algorithm. Xie et al. [22,23] discussed a dynamic evacuation network optimization problem that incorporated lane reversal and crossing elimination strategies. A bi-level network optimization model was formulated in which the upper level aimed at optimizing the network evacuation performance subject to the lane-reversal and crossing-elimination constraints and the lower level conveyed a cell transmission-based dynamic traffic assignment problem. An integrated Lagrangian relaxation and tabu search method was designed for approximating the optimal problem solutions. Karoonsoontawong and Lin [24] allowed time-varying reversibility with different reversibility durations for various candidate link
pairs in the bi-level program model, such that the optimal starting times and the optimal reversibility durations for candidate link pairs could be determined for peak-period traffic management on a daily basis. A genetic algorithm with a cell-transmission-based user-optimal dynamic traffic assignment was adopted to solve the problem.

In summary, most existing literatures on reversible lane operation focus on optimizing the number and the selection of lanes to be reversed. As a special type of traffic management strategy, however, implementation of reversible lanes must interact with other conventional traffic management and control strategies, such as left-turn restriction, lane channelization, and signal timing. Neglecting such interactions may result in non-optimal design results and unsatisfactory operational performance in the arterial. In previous studies [4,25], integration of these traffic management strategies was usually conducted sequentially, not simultaneously. Direction of reversible lanes can first be determined using discrete network design formulations, in which the effect of signalized intersections is simplified. Then, intersection signal timings are designed based on the turning restriction and lane channelization plans that have been determined. The above step-by-step design procedure also assumes relative independence among different traffic management strategies and therefore cannot reflect their interactions under different traffic flow patterns.

To remedy the above deficiency, researchers have developed the integrated design concept and applied it to isolated intersections. Several integrated models [26-30] have been established to combine the design of lane markings and signal timings for isolated signalized intersections. It was shown that substantial improvement in the intersection performance could be achieved by using the integrated model.

Despite the promising property of these integrated design models, only limited studies have been done regarding the integrated design and operation of an urban arterial with reversible lane settings, turning restrictions, lane channelization, and signal timing plans optimized in a unified framework. This can best demonstrate its effectiveness when there exist significant directional flow patterns in the arterial and the improvement of its operational performance is constrained by the available capacity at certain bottleneck intersections. In response to the above research needs, this paper develops a lane-based optimization model to simultaneously determine the lane assignments at roadway segments and intersections, left-turn restrictions, and signal timings in a target urban arterial.

The remainder of this paper is organized as follows. In Section 2, the model configuration and assumptions are described. The integrated optimization model is proposed in Section 3. The performance of the integrated model is evaluated through numerical analysis in Section 4. Conclusions and recommendations are given at the end of the paper.

2. MODEL CONFIGURATION AND ASSUMPTIONS

This study focuses on an arterial that includes both segments with reversible lanes and intersections along the arterial (see Figure 1). The median lanes in the internal segments are used as reversible lanes. The lane markings of all the approach lanes are also flexible and can be changed dynamically. The objective of this research is to develop an integrated model that can simultaneously optimize the number of lanes for each direction of the segment, the turning restriction strategies, the lane markings for each approach lane, and the signal timing for each intersection.
To ensure that the proposed model is tractable and reflects real-world constraints, this study has employed the following assumptions:

1. Traffic demand distribution in the target arterial is assumed to be given.
2. If a left turn at an intersection approach on the arterial is prohibited, the left turn movement will travel through the intersection and make a U-turn at the nearest downstream intersection at which a left turn is permitted.
3. The assigned direction of the reversible lanes within a road segment should be continuous.

3. THE INTEGRATED OPTIMIZATION MODEL

3.1 Notations

To facilitate the model presentation, notations and parameters used hereafter are listed in Table 1.

<table>
<thead>
<tr>
<th>Network representation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{N}$</td>
<td>Set of intersections</td>
</tr>
<tr>
<td>$r \in \mathcal{N}$</td>
<td>Index of signalized intersections in the target arterial (intersection $r$ located left of intersection $r+1$)</td>
</tr>
<tr>
<td>$\mathcal{S}$</td>
<td>Set of segments</td>
</tr>
<tr>
<td>$(r, r+1) \in \mathcal{S}$</td>
<td>The road segment between intersection $r$ and $r+1$</td>
</tr>
<tr>
<td>$\mathcal{A}_r$</td>
<td>Set of arms in intersection $r$</td>
</tr>
<tr>
<td>$i \in \mathcal{A}_r$</td>
<td>Index of intersection arms, $i = 1$ for east arm, $i = 2$ for south arm, $i = 3$ for west arm, and $i = 4$ for north arm, and the east and west arms are the arterial arms, the south and north arms are the cross-street arms, shown in Figure 1</td>
</tr>
<tr>
<td>$\mathcal{T}_i$</td>
<td>Set of turning movements in arm $i$</td>
</tr>
</tbody>
</table>
\( w \in T_i \) \quad \text{Index of turning movements in arm } i, w = 1 \text{ for } u\text{-turn and left-turn, } w = 2 \text{ for through movement, and } w = 3 \text{ for right-turn}

\( k \) \quad \text{Index of lanes, numbering from the left-most lane, as in Figure 1}

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_r )</td>
<td>Number of signalized intersections in the target arterial</td>
</tr>
<tr>
<td>( n_{af}^r )</td>
<td>Number of fixed approach lanes in arm ( i ) at intersection ( r )</td>
</tr>
<tr>
<td>( n_{ei}^r )</td>
<td>Number of fixed exit lanes in arm ( i ) at intersection ( r )</td>
</tr>
<tr>
<td>( n_{ai}^r )</td>
<td>Number of reversible lanes used for approach lanes in arm ( i ) at intersection ( r )</td>
</tr>
<tr>
<td>( n_{ei}^r )</td>
<td>Number of reversible lanes used for exit lanes in arm ( i ) at intersection ( r )</td>
</tr>
<tr>
<td>( n_{(r+1)},(r+1)r )</td>
<td>Number of reversible lanes in segment ( (r, r + 1) )</td>
</tr>
<tr>
<td>( e_{riw} )</td>
<td>Number of lanes on the exit that receives turning ( w ) on arm ( i )</td>
</tr>
<tr>
<td>( \delta_{riw} )</td>
<td>Permission of movement ( w ) in arm ( i ) at intersection ( r ) (1 - Yes, 0 - No)</td>
</tr>
<tr>
<td>( \gamma_{r(r+1)} )</td>
<td>Adjustment of direction of reversible lanes in segment ( (r, r + 1) ), if adjusted ( \gamma_{r(r+1)} = 1 ), if not adjusted ( \gamma_{r(r+1)} = 0 )</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Common flow multiplier for the target arterial</td>
</tr>
<tr>
<td>( \mu_r )</td>
<td>Common flow multiplier for intersection ( r )</td>
</tr>
<tr>
<td>( q_{riwk} )</td>
<td>Assigned flow of movement ( w ) on lane ( k ) in arm ( i ) at intersection ( r ) (veh/h)</td>
</tr>
<tr>
<td>( Q_{od} )</td>
<td>Demand flow from demand origin ( o ) to destination ( d ) (veh/h)</td>
</tr>
<tr>
<td>( Q_{riw} )</td>
<td>Demand flow of movement ( w ) in arm ( i ) at intersection ( r ) (veh/h)</td>
</tr>
<tr>
<td>( Q_{riw}^l )</td>
<td>Adjusted demand flow of movement ( w ) in arm ( i ) at intersection ( r ) considering left turn prohibition (veh/h)</td>
</tr>
<tr>
<td>( a_{riw}^d )</td>
<td>A binary indicator showing if the OD pair ( (o, d) ) makes turning ( w ) on arm ( i ) at intersection ( r ) without considering left turn prohibition (1 - Yes, 0 - No)</td>
</tr>
<tr>
<td>( s_{rik} )</td>
<td>Saturation flow rate of lane ( k ) in arm ( i ) at intersection ( r ) (veh/h)</td>
</tr>
<tr>
<td>( d_{max} )</td>
<td>Maximum acceptable degree of saturation</td>
</tr>
<tr>
<td>( y_{rik} )</td>
<td>Flow ratio of lane ( k ) in arm ( i ) at intersection ( r )</td>
</tr>
<tr>
<td>( C_{min}, C_{max} )</td>
<td>Minimum and maximum cycle length (s)</td>
</tr>
<tr>
<td>( I_{r(iw,l'w')} )</td>
<td>Clearance time for a pair of conflicting traffic movements (s), ( w \in T_i, w' \in T_{i'} )</td>
</tr>
<tr>
<td>( M )</td>
<td>A large positive constant</td>
</tr>
</tbody>
</table>

### Decision variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x_{riwk} )</td>
<td>A binary variable indicating the permission of movement ( w ) on lane ( k ) in arm ( i ) at intersection ( r )</td>
</tr>
<tr>
<td>( n_{r(r+1)} )</td>
<td>Number of reversible lanes used for the direction from intersection ( r ) to intersection ( r + 1 )</td>
</tr>
<tr>
<td>( n_{(r+1)r} )</td>
<td>Number of reversible lanes used for the direction from intersection ( r + 1 ) to intersection ( r )</td>
</tr>
<tr>
<td>( \xi )</td>
<td>Reciprocal of signal cycle length (1/s)</td>
</tr>
<tr>
<td>( g_{riw} )</td>
<td>Start of green for movement ( w ) in arm ( i ) at intersection ( r )</td>
</tr>
<tr>
<td>( \lambda_{riw} )</td>
<td>Green time ratio for movement ( w ) in arm ( i ) at intersection ( r )</td>
</tr>
<tr>
<td>( G_{rik} )</td>
<td>Start of green on lane ( k ) in arm ( i ) at intersection ( r )</td>
</tr>
<tr>
<td>( \Lambda_{rik} )</td>
<td>Green time ratio on lane ( k ) in arm ( i ) at intersection ( r )</td>
</tr>
</tbody>
</table>
3.2 Objective Function

Existing literature has shown that the setting of reversible lanes, dynamic lane assignment, and left turn restrictions can increase the capacity of a target arterial. These may also, however, cause potential driver confusion issues. Traffic management strategies such as lane reversion and turning restriction should not be considered, therefore, until a conventional design can no longer accommodate the traffic demand. Four control objectives, with different priority levels, are considered, therefore, to accommodate different perspectives of authorities and road users. These are: (1) minimizing the number of prohibited movements, (2) minimizing the number of direction adjustments in the segment lanes, (3) maximizing the reserve capacity of the arterial, and (4) maximizing the summation of reserve capacities for all intersections. The first two objectives reflect the perspective of roadway users. The last two are designed to improve the overall system performance set by the responsible agencies. In summary, the overall control objective function is stated as:

$$\text{max } P_1 \sum_{r=1}^{N_r} \sum_{l=1}^{4} \sum_{w=1}^{3} \delta_{r,l,w} - P_2 \sum_{r=1}^{N_r-1} y_{r(r+1)} + P_3\mu + P_4 \sum_{r=1}^{N_r} \mu_r$$

where $P_1, P_2, P_3, P_4$ are priority coefficients for the four control objectives.

3.3 Constraints

Assigned flow constraints

The assigned flows on different lanes, $q_{r,l,w}$, should obey the following set of constraints.

1) The sum of the assigned flows on the different lanes should be equal to the increased demand for that movement.

$$\mu_r Q'_{r,l,w} = \sum_{k=1}^{n_{r,l,w}^a+n_{r,l,w}^c} q_{r,l,w}, \quad \forall r \in N; \ i \in A_r; \ w \in T_i$$

2) The reserve capacity of the target arterial should be equal to that of the critical intersection with the lowest reserve capacity. Moreover, since the initial traffic demand must be accommodated, the common flow multiplier should be no smaller than 1.

$$\mu_r \geq \mu \geq 1, \quad \forall r \in N$$

3) Right-of-way constraint: if $x_{r,l,w} = 0$, the movement $w$ in arm $i$ does not have the right-of-way on lane $k$, so the assigned lane flow will be 0.

$$M x_{r,l,w} \geq q_{r,l,w} \geq 0, \quad \forall r \in N; \ i \in A_r; \ w \in T_i; \ k \in \{1, \ldots, n_{r,l,w}^a+n_{r,l,w}^c\}$$

4) Determining the original traffic demand without consideration of left turn prohibition: given the set of demand origins and destinations as an exogenous input, the demand flow $Q_{r,l,w}$ of movement $w$ in arm $i$ intersection $r$ can be obtained according to the following equation.

$$Q_{r,l,w} = \sum_{(o,d)} a_{r,l,w}^{o,d} Q_{o,d}, \quad \forall r \in N; \ i \in A_r; \ w \in T_i$$

5) Determining the adjusted traffic demand considering left turn prohibition: if a left turn from the arterial in arm $i$ intersection $r$ is prohibited, the traffic demand should be transferred to its detour path. It is assumed that all the vehicles of the prohibited movement must first travel through the intersection, then execute a u-turn at the nearest downstream intersection at which a left turn is permitted. Equations (6) and (7) represent the adjusted left turn flow from the arterial arms. Equations (8) and (9) represent the adjusted through movement flow from the arterial arms.
Equations (10) and (11) represent the adjusted right turn flows from the arterial arms. Finally, Equations (12) represents the adjusted flow from cross-street arms.

\[
Q'_{r11} = \delta_{r11} \left( Q_{r11} + \sum_{t=r+1}^{N_r} \prod_{s=r+1}^{t} (1 - \delta_{s11}) Q_{t11} \right), \quad \forall r \in \mathcal{N} \tag{6}
\]

\[
Q'_{r31} = \delta_{r31} \left( Q_{r31} + \sum_{t=1}^{N_r} \prod_{s=t}^{r-1} (1 - \delta_{s31}) Q_{t31} \right), \quad \forall r \in \mathcal{N} \tag{7}
\]

\[
Q'_{r12} = Q_{r12} + \sum_{t=r+1}^{N_r} \prod_{s=r}^{t} (1 - \delta_{s11}) Q_{t11} + \sum_{t=1}^{r-1} \prod_{s=t}^{r} (1 - \delta_{s11}) Q_{t11}, \quad \forall r \in \mathcal{N} \tag{8}
\]

\[
Q'_{r32} = Q_{r32} + \sum_{t=r+1}^{N_r} \prod_{s=r}^{t} (1 - \delta_{s31}) Q_{t31} + \sum_{t=1}^{r-1} \prod_{s=t}^{r} (1 - \delta_{s31}) Q_{t31}, \quad \forall r \in \mathcal{N} \tag{9}
\]

Lane assignment constraints

The assigned direction of the reversible lanes and the permission of movement \( w \) on lane \( k \) in arm \( i \) at intersection \( r \) should obey the following set of constraints.

1) Total number of reversible lanes: the total number of reversible lanes for a segment, which is given as an exogenous input, should be equal to the sum of the number of reversible lanes assigned to the two directions.

\[
n_{r(r+1), (r+1)r} = n_{r(r+1)1} + n_{r(r+1)2}, \quad \forall r \in \mathcal{N} \tag{13}
\]

2) Continuous setting of the assigned direction for the reversible lanes: Constraints (14) and (15) indicate that the assigned direction of the reversible lanes within a segment must be continuous. Constraints (16) to (18) indicate that if the directions of the reversible lanes in two separate segments are changed, the directions of the reversible lanes in the internal segments must also be changed.

\[
n_{r}^{ec} = n_{r+1}^{ec} = n_{r(r+1)r}, \quad \forall r \in \{1, ..., N_r - 1\} \tag{14}
\]

\[
n_{r+1}^{ec} = n_{r}^{ec} = n_{r(r+1)r}, \quad \forall r \in \{1, ..., N_r - 1\} \tag{15}
\]

\[
-M(2 - \gamma_{r(r+1)} - \gamma_{s(s+1)}) \leq (n_{r(r+1)1} - n_{r(r+1)2}) - (n_{t(t+1)} - n_{t(t+1)1}) \leq M(2 - \gamma_{r(r+1)} - \gamma_{s(s+1)}), \quad \forall r, s, t \in \{1, ..., N_r - 1\}; \quad r \leq t \leq s \tag{16}
\]

\[
M\gamma_{r(r+1)} \geq n_{r(r+1)1} - n_{r(r+1)2}, \quad \forall r \in \{1, ..., N_r - 1\} \tag{17}
\]

\[
M\gamma_{r(r+1)} \geq n_{r(r+1)1} - n_{r(r+1)2}, \quad \forall r \in \{1, ..., N_r - 1\} \tag{18}
\]

3) Minimum number of permitted movements on traffic lanes: each lane should carry at least one movement, which can be specified as:

\[
\sum_{w=1}^{3} x_{riwk} \geq 1, \quad \forall r \in \mathcal{N}; \quad i \in \mathcal{A}_r; \quad k \in \{1, ..., n_{ri}^{af} + n_{ri}^{ac}\} \tag{19}
\]

4) Minimum number of exit lanes: due to safe and operational considerations, the number of lanes at a movement’s corresponding exit arm should always be at least as many as the total number of lanes assigned to permit such a movement.
\[ n_{r_i}^{af} + n_{r_i}^{ac} \geq \sum_{k=1}^{r_i} x_{r_iwk}, \quad \forall r \in N; \ i \in A_r; \ w \in T_i \] (20)

5) Conflict avoidance within an arm: for any two adjacent traffic lanes, \( k \) (left-hand) and \( k + 1 \) (right-hand) from arm \( i \), if the traffic movement of turn \( w \) is permitted on lane \( k + 1 \), then traffic movements of all the other turns, \( w + 1, ..., 3 \), should be prohibited on lane \( k \) to eliminate potential internal cross-conflicts within the arm.

\[ 1 - x_{r_iwk(k+1)} \geq x_{r_iwk}, \quad \forall r \in N; \ i \in A_r; \ w \in \{1, 2\}; \ w' \in \{w + 1, 3\}; \ k \in \{1, ..., n_{r_i}^{af} + n_{r_i}^{ac} - 1\} \] (21)

6) Number of lanes assigned to prohibited movements should be equal to 0.

\[ \delta_{r_iwk} \geq x_{r_iwk}, \quad \forall r \in N; \ i \in A_r; \ w \in T_i; \ k \in \{1, ..., n_{r_i}^{af} + n_{r_i}^{ac}\} \] (22)

7) **Signal timing constraints**

The signal timing factors including cycle length, phase plan, start of green and green time ratio, should obey the following set of constraints.

1) Cycle length: let the minimum and maximum cycle lengths of the intersection be \( C_{min} \) and \( C_{max} \). Instead of defining the cycle length directly as a control variable, its reciprocal is used to preserve linearity in the mathematical formulation.

\[ \frac{1}{C_{min}} \geq \xi \geq \frac{1}{C_{max}} \] (23)

2) Start of green: since the signal timing at the intersection is cyclical, the start of green can be picked arbitrarily along the time axis as long as it satisfies the other relevant constraints in the formulation. However, for convenience, all of the start of green variables are confined within a signal cycle between 0 and 1.

\[ 1 \geq g_{r_i wk} \geq 0, \quad \forall r \in N; \ i \in A_r; \ w \in T_i \] (24)

3) Green time ratio: the green time ratio of a movement should not be greater than 1. Moreover, if a left turn from the arterial is prohibited, its green time ratio should be equal to 0.

\[ 1 \geq \phi_{r_i wk} \geq 0, \quad \forall r \in N; \ i \in A_r; \ w \in T_i \] (25)

\[ M \delta_{r_i wk} \geq \phi_{r_i wk} \geq -M \delta_{r_i wk}, \quad \forall r \in N; \ i \in A_r; \ w \in T_i \] (26)

4) Lane signal timing: if a lane is shared by more than one movement, these movements must receive identical signal indications to avoid ambiguity. Considering a lane \( k \) from arm \( i \), if a movement \( w \) is permitted on this lane, then the following two constraint sets can be established to fulfill the above condition.

\[ M(1 - x_{r_i wk}) \geq G_{r_i k} - g_{r_i wk} \geq -M(1 - x_{r_i wk}), \]

\[ \forall r \in N; \ i \in A_r; \ w \in T_i; \ k \in \{1, ..., n_{r_i}^{af} + n_{r_i}^{ac}\} \] (27)

\[ M(1 - x_{r_i wk}) \geq \Lambda_{r_i k} - \lambda_{r_i wk} \geq -M(1 - x_{r_i wk}), \]

\[ \forall r \in N; \ i \in A_r; \ w \in T_i; \ k \in \{1, ..., n_{r_i}^{af} + n_{r_i}^{ac}\} \] (28)

5) Phase plan: local practice is an important determinant in the selection of a phase plan and phasing throughout an area should be relatively uniform [31]. In this model, a dual-ring concurrent phasing scheme with assigned movements is adopted. This can be specified as:

\[ g_{r_{11}} = g_{r_{31}} = 0, \quad \forall r \in N \] (29)

\[ g_{r_{32}} = g_{r_{11}} + \lambda_{r_{11}} + I_{r_{11,32}} \delta_{r_{11}}, \quad \forall r \in N \] (30)

\[ g_{r_{12}} = g_{r_{31}} + \lambda_{r_{31}} + I_{r_{31,12}} \delta_{r_{31}}, \quad \forall r \in N \] (31)

\[ g_{r_{32}} + \lambda_{r_{32}} = g_{r_{12}} + \lambda_{r_{12}}, \quad \forall r \in N \] (32)
Flow ratio constraints

The flow ratio of a lane is the ratio of the flow rate to the saturation flow rate that can be calculated by Equation (38).

\[ y_{rik} = \frac{\sum_{w=1}^{3} q_{riwk}}{s_{rik}}, \quad \forall r \in \mathcal{N}; i \in \mathcal{A}_r; w \in \mathcal{T}_i; k \in \{1, ..., n_{ri}^{af} + n_{ri}^{ac}\} \]  

For any approach, it is required that the degrees of saturation must be identical for a pair of adjacent lanes having a common lane marking. Moreover, the signal settings on this pair of adjacent lanes, as set in Constraints (27) and (28), must be equal. Therefore, to ensure identical degrees of saturation, it is necessary that the flow ratios must be identical for a pair of adjacent lanes having a common lane marking.

\[ \begin{align*}
    M\left(2 - \Delta_{riwk} - \Delta_{riw(k+1)}\right) & \geq y_{ri(k+1)} - y_{rik} \geq -M\left(2 - \Delta_{riwk} - \Delta_{riw(k+1)}\right), \\
    & \forall r \in \mathcal{N}; i \in \mathcal{A}_r; w \in \mathcal{T}_i; k \in \{1, ..., n_{ri}^{af} + n_{ri}^{ac} - 1\}
\end{align*} \]  

Degree of saturation constraints

In order to ensure that an intersection performs reasonably well, the degree of saturation of every traffic lane should be no greater than the maximum acceptable limit.

\[ d_{s_{\text{max}}} \Delta_{rik} \geq y_{rik}, \quad \forall r \in \mathcal{N}; i \in \mathcal{A}_r; k \in \{1, ..., n_{ri}^{af} + n_{ri}^{ac}\} \]  

3.4 Solution Algorithm

The integrated optimization model is a multi-objective mixed-integer non-linear programming problem with the objective function of Equation (1) and constraints (2) to (40). Since the four goals are divided into four priority levels, it is a preemptive goal programming problem that can be solved by a streamlined procedure.

This is a mix-integer non-linear programming problem because there are multiplications of multiple 0-1 variables \( \delta_{riw} \) in Constraints (6) to (9). This type of problem can be transformed into a mix-integer linear programming model by introducing a series of new, non-negative variables [32], and then solved using a standard branch-and-bound technique for a global optimum solution.

For Equation (6), the multiplication \( \delta_{r11} \prod_{s=r+1}^{t} (1 - \delta_{s11}) \) could be replaced by the non-negative variable \( u_{1t} \), and the equation could be rewritten as:

\[ Q_{r11} = \delta_{r11} Q_{111} + \sum_{t=r+1}^{N_r} u_{1t} Q_{t11}, \quad \forall r \in \mathcal{N} \]  

\[ \delta_{r11} + \sum_{s=r+1}^{t} (1 - \delta_{s11}) - u_{1t} \leq t - r, \quad \forall r \in \mathcal{N}; t \in \{r + 1, ..., N_r\} \]  

\[ u_{1t} \leq \delta_{r11}, \quad \forall r \in \mathcal{N}; t \in \{r + 1, ..., N_r\} \]  

\[ u_{1t} \leq 1 - \delta_{s11}, \quad \forall r \in \mathcal{N}; t \in \{r + 1, ..., N_r\}; s \in \{r + 1, ..., t\} \]  

\[ u_{1t} \geq 0, \quad \forall r \in \mathcal{N}; t \in \{r + 1, ..., N_r\} \]
For Equation (7), the multiplication $\delta_{r31} \prod_{s=t}^{r-1} (1 - \delta_{s31})$ could be replaced by the non-negative variable $u_{2t}$, and the equation could be rewritten as:

$$Q'_{r31} = \delta_{r31} Q_{r31} + \sum_{t=1}^{r-1} u_{2t} Q_{t31}, \quad \forall r \in \mathcal{N} \quad (46)$$

$$\delta_{r31} + \sum_{t=1}^{r-1} (1 - \delta_{s31}) - u_{2t} \leq r - t, \quad \forall r \in \mathcal{N}; \ t \in \{1,...,r-1\} \quad (47)$$

$$u_{2t} \leq \delta_{r31}, \quad \forall r \in \mathcal{N}; \ t \in \{1,...,r-1\} \quad (48)$$

$$u_{2t} \leq 1 - \delta_{s31}, \quad \forall r \in \mathcal{N}; \ t \in \{1,...,r-1\}; \ s \in \{t,...,r-1\} \quad (49)$$

$$u_{2t} \geq 0, \quad \forall r \in \mathcal{N}; \ t \in \{1,...,r-1\} \quad (50)$$

For Equation (8), the multiplications $\prod_{s=t}^{r} (1 - \delta_{s11})$ and $\prod_{s=t}^{r} (1 - \delta_{s31})$ could be replaced by the non-negative variables $u_{3t}$ and $u_{4t}$, respectively, and the equation could be rewritten as:

$$Q'_{r12} = Q_{r12} + \sum_{t=r}^{N_r} u_{3t} Q_{t11} + \sum_{t=1}^{r-1} u_{4t} Q_{t31}, \quad \forall r \in \mathcal{N} \quad (51)$$

$$\sum_{s=r}^{t} (1 - \delta_{s11}) - u_{3t} \leq t - r, \quad \forall r \in \mathcal{N}; \ t \in \{r,...,N_r\} \quad (52)$$

$$u_{3t} \leq 1 - \delta_{s11}, \quad \forall r \in \mathcal{N}; \ t \in \{r,...,N_r\}; \ s \in \{r,...,t\} \quad (53)$$

$$u_{3t} \geq 0, \quad \forall r \in \mathcal{N}; \ t \in \{r,...,N_r\} \quad (54)$$

$$\sum_{s=t}^{r} (1 - \delta_{s31}) - u_{4t} \leq r - t, \quad \forall r \in \mathcal{N}; \ t \in \{1,...,r-1\} \quad (55)$$

$$u_{4t} \leq 1 - \delta_{s31}, \quad \forall r \in \mathcal{N}; \ t \in \{1,...,r-1\}; \ s \in \{t,...,r\} \quad (56)$$

$$u_{4t} \geq 0, \quad \forall r \in \mathcal{N}; \ t \in \{1,...,r-1\} \quad (57)$$

For Equation (9), the multiplications $\prod_{s=t}^{r} (1 - \delta_{s11})$ and $\prod_{s=t}^{r} (1 - \delta_{s31})$ could be replaced by the non-negative variables $u_{5t}$ and $u_{6t}$, respectively, and the equation could be rewritten as:

$$Q'_{r32} = Q_{r32} + \sum_{t=r+1}^{N_r} u_{5t} Q_{t11} + \sum_{t=1}^{r} u_{6t} Q_{t31}, \quad \forall r \in \mathcal{N} \quad (58)$$

$$\sum_{s=r}^{t} (1 - \delta_{s11}) - u_{5t} \leq t - r, \quad \forall r \in \mathcal{N}; \ t \in \{r+1,...,N_r\} \quad (59)$$

$$u_{5t} \leq 1 - \delta_{s11}, \quad \forall r \in \mathcal{N}; \ t \in \{r+1,...,N_r\}; \ s \in \{r,...,t\} \quad (60)$$

$$u_{5t} \geq 0, \quad \forall r \in \mathcal{N}; \ t \in \{r+1,...,N_r\} \quad (61)$$

$$\sum_{s=t}^{r} (1 - \delta_{s31}) - u_{6t} \leq r - t, \quad \forall r \in \mathcal{N}; \ t \in \{1,...,r\} \quad (62)$$

$$u_{6t} \leq 1 - \delta_{s31}, \quad \forall r \in \mathcal{N}; \ t \in \{1,...,r\}; \ s \in \{t,...,r\} \quad (63)$$

$$u_{6t} \geq 0, \quad \forall r \in \mathcal{N}; \ t \in \{1,...,r\} \quad (64)$$

4. NUMERICAL ANALYSES

In this section, the effectiveness of the proposed model is evaluated by a series of numerical examples. An arterial with three four-arm intersections and two internal segments is studied.
Figure 2 shows the initial layout of the arterial. The medial two lanes within the internal segments are electable reversible lanes. The traffic demands, shown in Table 2, fluctuate during the six different study intervals. Minimum and maximum cycle length is 60 s and 120 s. Clearance time for any pair of mutually incompatible traffic movements is 5.0 s. The saturation flow rate per lane for all movements is 1900 veh/h/ln. The maximum acceptable limit of the degree of saturation is 0.85.

![Figure 2 Layout of the numerical example.](image)

### Table 2 Traffic demand of all intervals

<table>
<thead>
<tr>
<th>Origin Arm</th>
<th>Destination Arm</th>
<th>Interval 1</th>
<th>Interval 2</th>
<th>Traffic demand (pcu/h) Interval 3</th>
<th>Interval 4</th>
<th>Traffic demand (pcu/h) Interval 5</th>
<th>Interval 6</th>
</tr>
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<tbody>
<tr>
<td>(1,2)</td>
<td>(1,3)</td>
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<td>200</td>
<td>200</td>
<td>240</td>
<td>240</td>
<td>320</td>
</tr>
<tr>
<td>(1,2)</td>
<td>(1,4)</td>
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<td>150</td>
<td>150</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>(1,2)</td>
<td>(2,2)</td>
<td>15</td>
<td>20</td>
<td>20</td>
<td>24</td>
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<td>32</td>
</tr>
<tr>
<td>(1,2)</td>
<td>(2,4)</td>
<td>15</td>
<td>20</td>
<td>20</td>
<td>24</td>
<td>72</td>
<td>32</td>
</tr>
<tr>
<td>(1,2)</td>
<td>(3,1)</td>
<td>96</td>
<td>128</td>
<td>128</td>
<td>153</td>
<td>115</td>
<td>204</td>
</tr>
<tr>
<td>(1,2)</td>
<td>(3,2)</td>
<td>12</td>
<td>16</td>
<td>16</td>
<td>19</td>
<td>14</td>
<td>26</td>
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<tr>
<td>(1,2)</td>
<td>(3,4)</td>
<td>12</td>
<td>16</td>
<td>16</td>
<td>20</td>
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<td>26</td>
</tr>
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<td>(1,2)</td>
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<td>100</td>
<td>50</td>
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<td>60</td>
<td>80</td>
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<tr>
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<td>(1,4)</td>
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<td>100</td>
<td>50</td>
<td>60</td>
<td>60</td>
<td>80</td>
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<td>160</td>
<td>160</td>
<td>192</td>
<td>192</td>
<td>256</td>
</tr>
<tr>
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<td>(2,4)</td>
<td>120</td>
<td>160</td>
<td>160</td>
<td>192</td>
<td>572</td>
<td>256</td>
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<td>1024</td>
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<td>128</td>
<td>128</td>
<td>153</td>
<td>115</td>
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<td>(1,3)</td>
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<td>128</td>
<td>128</td>
<td>153</td>
<td>115</td>
<td>204</td>
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<tr>
<td>(1,4)</td>
<td>(1,2)</td>
<td>300</td>
<td>150</td>
<td>150</td>
<td>30</td>
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<tr>
<td>(1,4)</td>
<td>(1,3)</td>
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<td>200</td>
<td>200</td>
<td>240</td>
<td>240</td>
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<td>128</td>
<td>128</td>
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<td>115</td>
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</tr>
<tr>
<td>(1,4)</td>
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<td>16</td>
<td>16</td>
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<td>(3,4)</td>
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<td>16</td>
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<td>26</td>
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<td>(1,2)</td>
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<td>10</td>
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<td>6</td>
<td>6</td>
<td>8</td>
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<td>80</td>
<td>40</td>
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<td>48</td>
<td>64</td>
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<td>15</td>
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<td>8</td>
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<tr>
<td>(2,2)</td>
<td>(2,1)</td>
<td>750</td>
<td>600</td>
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<td>480</td>
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<td>240</td>
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<td>160</td>
<td>160</td>
<td>192</td>
<td>576</td>
<td>256</td>
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<td>(2,2)</td>
<td>(3,2)</td>
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<td>20</td>
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<td>32</td>
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<td>32</td>
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<tr>
<td>(2,4)</td>
<td>(1,2)</td>
<td>15</td>
<td>10</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>8</td>
</tr>
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</table>
In order to fully identify the potential benefits of the proposed model, three additional constraint general practical designs are used for comparison:

Case 1: Proposed model (integrated optimization of reversible lanes, dynamic lane assignment, left-turn restrictions, and signal timings).

Case 2: Signal timing optimization with fixed lane markings (no reversible lanes, no left-turn restrictions, and no dynamic lane assignment).

Case 3: Reversible lanes + dynamic lane assignment strategy (no left-turn restriction).

Case 4: Reversible lanes + left turn restriction strategy (no dynamic lane assignment).

The optimization results are shown in Figure 3, Table 3, and Table 4. Figure 3 shows the optimal lane configurations for all the intersections and reversible lanes generated from the optimization model. This information is particularly useful when designing and operating an arterial with many intersections where each of them has multiple approach lanes and the optimal lane channelization plan is not straightforward to figure out through engineering judgment.

Table 3 summarizes the optimization results from the proposed model including the maximized common flow multipliers and the adopted optimization strategies. Table 4 further illustrates the performance comparison between the proposed model and the other three design methods. The following observations can be made from Tables 3 and 4.

1) The principal objective of the proposed model is to automatically optimize the reversible lane strategy, the left turn restriction strategy, the lane assignments, and the signal timings for an arterial in a unified optimization framework. It could change the arterial geometry
when the traffic demand varies pronouncedly and adjust the signal settings for a small volume
situation. It has, therefore, a high level of maneuverability. Compared to the other design
methods, the proposed model could maintain the permitted degree of saturation for every
intersection at a minimum cost.

2) For interval 1, all the optimized common flow multipliers for the control area are
larger than 1. This means that all the control methods can satisfy the traffic demand under the
given maximum permitted degree of saturation (0.85). In this case, which is the result optimized
by the proposed model, there is no need to use any special management strategies, and the signal
timings alone can accommodate the traffic demand.

3) For interval 2, 65 percent of the traffic moves in one direction on the internal segments.
In this case, all the control methods can still satisfy the traffic demand since the imbalance
between the traffic volumes in the two directions is small enough to be accommodated by
optimizing signal timings alone. The result optimized by the proposed model supports the
conventional design, and no special management strategies are required.

4) For interval 3, there is a significant imbalance between the traffic volumes in the two
directions (the ratio of the traffic demand on the major direction to that on the minor direction is
4:1). The conventional design can keep the control area under the given maximum permitted
degree of saturation because the total volume on the internal segment is low. Therefore, no
special management strategies are needed.

5) For interval 4, the traffic demand increases about 20% over scenario 3. The
optimization result of case 2 shows that the traffic demand imbalance exceeds the signal timing
adjustment effect. Therefore, to balance the degree of saturation of the two travel directions, the
'reversible lanes + dynamic lane' assignment strategy is selected as the optimization result of the
proposed model. The reversible lanes operation is justified for the situation where the traffic flow
is relatively high and the difference of the volume between the major and minor traffic directions
is significant. Since the number of approach and exit lanes is changed, the lane markings at the
intersection have been adjusted accordingly.

6) For interval 5, using the traffic demand in scenario 4 as a benchmark, the left turn
proportion in arm (2, 3) is raised from 10% to 30%. The proposed model can accommodate this
kind of traffic demand variation well using the dynamic lane assignment strategy. It can be seen
that the combined management strategy of reversible lanes and dynamic lane assignment has a
high level of maneuverability. This can accommodate the traffic demand variations of both the
imbalance of the two directions and the turning proportion.

7) For interval 6, the total volume is too high to be accommodated by control strategies
other than the 'reversible lanes + left-turn restriction' strategy. Therefore, it should be selected as
the optimization result that is the same as the proposed model. It can be seen, however, that the
application of this management strategy has many limitations, including forcing the left turn
traffic to make a detour. This, in turn, may cause extra driving and increase the total vehicle-
miles traveled in the network as well as shift the critical intersection. The nearby intersections,
therefore, must have low saturation to accommodate the additional traffic flow.
Figure 3 Optimization results layout for the example.
### Table 3 Optimized common flow multiplier for the example

<table>
<thead>
<tr>
<th>Interval</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total volume on each internal segment (veh/h)</td>
<td>3000</td>
<td>3000</td>
<td>2500</td>
<td>3000</td>
<td>3000</td>
<td>4000</td>
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<tr>
<td>Ratio of a major to minor traffic count on the internal segment</td>
<td>1:1</td>
<td>2:1</td>
<td>4:1</td>
<td>4:1</td>
<td>4:1</td>
<td>4:1</td>
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<tr>
<td>Left-turn proportion in arm (1,1)</td>
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<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>Left-turn proportion in arm (2,3)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.3</td>
<td>0.1</td>
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<tr>
<td>Left-turn proportion in arm (2,2)</td>
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<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Left-turn proportion in arm (3,3)</td>
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<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
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<td>Adoption of the signal timing optimization</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
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<td>Adoption of the reversible lanes</td>
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<td>no</td>
<td>yes</td>
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<td>yes</td>
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<tr>
<td>Adoption of the dynamic lane assignment</td>
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<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>Adoption of the left-turn restriction</td>
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<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
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<td>Maximum degree of saturation</td>
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<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
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<tr>
<td>Maximum μ</td>
<td>1.122</td>
<td>1.035</td>
<td>1.077</td>
<td>1.122</td>
<td>1.087</td>
<td>1.023</td>
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</table>

### Table 4 Comparison between different control strategies

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<th>3</th>
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<th>5</th>
<th>6</th>
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<td>Case 1: Proposed model</td>
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<td></td>
<td></td>
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<tr>
<td>Degree of saturation of intersection 1</td>
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<td>0.588</td>
<td>0.570</td>
<td>0.659</td>
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<td>0.850</td>
<td>0.850</td>
<td>0.850</td>
<td>0.850</td>
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<td>0.700</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Number of direction reversed lanes</td>
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<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Maximum μ</td>
<td>1.122</td>
<td>1.035</td>
<td>1.077</td>
<td>1.122</td>
<td>1.087</td>
<td>1.023</td>
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<tr>
<td>Case 2: Signal timing optimization alone</td>
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<td>0.570</td>
<td>0.573</td>
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<td>0.850</td>
<td>0.850</td>
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<td>0.707</td>
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<td>Number of prohibited movements</td>
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<td>0</td>
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<td>0</td>
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<tr>
<td>Number of direction reversed lanes</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<td>Case 3: Reversible lanes + dynamic lane assignment</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degree of saturation of intersection 1</td>
<td>0.691</td>
<td>0.588</td>
<td>0.570</td>
<td>0.659</td>
<td>0.638</td>
<td>0.750</td>
</tr>
<tr>
<td>Degree of saturation of intersection 2</td>
<td>0.850</td>
<td>0.850</td>
<td>0.850</td>
<td>0.850</td>
<td>0.850</td>
<td>0.850</td>
</tr>
<tr>
<td>Degree of saturation of intersection 3</td>
<td>0.595</td>
<td>0.680</td>
<td>0.707</td>
<td>0.723</td>
<td>0.700</td>
<td>0.777</td>
</tr>
<tr>
<td>Number of prohibited movements</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Number of direction reversed lanes</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Maximum μ</td>
<td>1.122</td>
<td>1.035</td>
<td>1.077</td>
<td>1.122</td>
<td>1.087</td>
<td>0.961</td>
</tr>
<tr>
<td>Case 4: Reversible lanes + left-turn restriction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degree of saturation of intersection 1</td>
<td>0.850</td>
<td>0.793</td>
<td>0.712</td>
<td>0.809</td>
<td>0.585</td>
<td>0.850</td>
</tr>
<tr>
<td>Degree of saturation of intersection 2</td>
<td>0.810</td>
<td>0.850</td>
<td>0.850</td>
<td>0.850</td>
<td>0.621</td>
<td>0.773</td>
</tr>
<tr>
<td>Degree of saturation of intersection 3</td>
<td>0.831</td>
<td>0.825</td>
<td>0.834</td>
<td>0.834</td>
<td>0.850</td>
<td>0.827</td>
</tr>
<tr>
<td>Number of prohibited movements</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Number of direction reversed lanes</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Maximum μ</td>
<td>1.329</td>
<td>1.256</td>
<td>1.270</td>
<td>1.294</td>
<td>0.937</td>
<td>1.023</td>
</tr>
</tbody>
</table>

In addition to the deterministic capacity analysis mentioned above, the simulation package, VISSIM, was used as an unbiased evaluator to capture the stochastic variation of the traffic flow and evaluate the performance of the optimization results. Two performance indices,
the total throughput and the average vehicular delay, were selected. Simulation and comparison results are shown in Figure 4.

It can be seen that in intervals 1, 2, and 3, the control plans were all comparable in terms of total throughput. Though case 4 outperformed the other designs in average delay, the advantage was insignificant since signal timing optimization could have also ensured that the intersection would perform reasonably well. In intervals 4 and 5, the signal timing optimization (case 2) could not accommodate the traffic demand. In this case, the proposed model selected case 3, the optimization design scheme, which clearly outperformed case 2 with significantly lower average delays (20.8% and 41.7% reduction for intervals 4 and 5 respectively). In interval 6, neither case 2 nor 3 designs could accommodate the traffic demand. The proposed model, therefore, selected case 4, the optimization design scheme, which clearly outperformed case 2 and 3 with significantly lower average delays (46.8% and 23.6% reduction respectively).

The simulation analysis also indicated that the effectiveness of special traffic management strategies such as lane reversion and turning restriction is very limited when the intersection can perform reasonably well. Therefore, it is not recommended to consider special traffic management strategies when the conventional design can accommodate the traffic demand.

![Figure 4 Simulation analysis results.](image-url)
5. CONCLUSION

This paper presented a lane-based optimization model for the integrated design of an arterial. It was formulated using a multi-objective mix-integer non-linear programming problem to simultaneously optimize the reversible lanes, left turn restriction, lane assignments, and signal timing. The problem was transformed into a single-objective integer linear programming model using a streamlined procedure and introducing a series of new non-negative variables. This was then solved by a standard branch-and-bound technique.

Extensive numerical analysis was conducted to evaluate the performance of the proposed design under different traffic demand intervals, from which the following conclusions could be drawn.

1. The optimization design scheme obtained by the proposed model could automatically select the best control strategies according to the traffic demand and the layout situation.
2. In low-demand or little imbalanced flow distribution between two directions scenarios, there is no need to use any special management strategies, and signal timing could accommodate these small volume fluctuations quite well.
3. The combined management strategy of reversible lanes and dynamic lane assignment has a high level of maneuverability that can accommodate the traffic demand variations of both the imbalance of the two directions and the turning proportion.
4. The application of the combined management strategy of reversible lanes and left-turn restriction has many limitations. This option must be carefully considered to prevent new traffic congestion that may be caused by the additional detour traffic.

It is assumed that the segment of the arterial, in this paper, is sufficiently long. In a real application, overflowing queue problems should also be considered.

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