Bandwidth Maximization Approach for Displaced Left-Turn Crossovers Coordination under Heterogeneous Traffic Conditions

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Abstract: As one of the UAIDs (unconventional alternative intersection designs), DLTs (displaced left-turn crossovers) have been presented to mitigate traffic congestion. Although, qualitatively and quantitatively isolated UAIDs outperform their conventional counterparts, there is no simplified procedure to consider the DLTs coordination. Hence, this research investigates the coordination of consecutive DLTs under heterogeneous traffic conditions. To achieve the optimal coordination and provide an efficient coordination control, a bandwidth maximization progression approach was used. Seeking the optimal offset for each pair of consecutive intersections to guarantee the green bandwidth waves along the coordinated corridor, a mixed-integer linear program was adopted. The optimization problem was formulated and solved based on the standard branch-and-bound technique. As a real-world study case, data of three typical intersections located in an arterial corridor in Cairo, Egypt was used. PTV-VISSIM as a microsimulation platform was employed to simulate and evaluate the different signal timing plans. However, to represent the heterogeneous traffic characteristics as close as possible to the reality, different simulation parameters were tuned and validated carefully. The results emphasized the undoubted improvement of coordinated DLTs by different operational performance indices. The total travel time, average delay, the number of stops per vehicle were obviously improved.

Key words: Displaced left-turn crossovers, signal coordination, bandwidth maximization.

1. Introduction

As demand on the transportation system continues to grow, the corresponding resources to address these demands are becoming scarce. Therefore, in order to alleviate the traffic congestion at signalized intersections, displaced left-turn crossovers that are also known as CFIs (continuous flow intersections), have been presented as an Unconventional Arterial Intersection Design to address the traffic congestion at conventional signalized intersections. Also, DLTs (displaced left-turn crossovers) could facilitate traffic flow by emphasizing a simultaneous proceeding\(^1\) of left-turn traffic and through traffic within the same signal group. Through the DLTs unique design, the left-turn flow is permitted to cross laterally to the edge of the opposing direction a few hundred meters upstream of the main intersection. This design permits displaced left-turn lanes to be allocated in parallel to the assigned through traffic lanes at the intersection as shown in Fig. 1. As a result, the through flow and the left-turn flow could move simultaneously in the same time using only two-phase signal timing plans instead of four phases given for the other conventional signalized intersections. Accordingly, this reduction in the number of signal phases leads to enhancing the intersection operational performance indices. Moreover, reducing the number of the conflict points inside the main intersections results in improving the safety conditions, as in Refs. [1-3].

Despite the wide and prevalent deployment of UAIDs (unconventional alternative intersection designs) as an innovative treatment in some countries, most of the previous research work investigated UAIDs, particularly DLTs, as isolated intersections. Among the 27 previous studies that investigated the
UAIDs operational performance, 24 instances evaluated UAIDs as isolated intersections. Despite the remaining three studies having investigated MUT (median U-turns), SSM (super street median), and USC (upstream signalized crossover) as corridors, DLTs coordination has never been studied, as in Ref. [4].

On the other hand, as mentioned earlier, UAIDs were mainly implemented in the United States or other developed nations where ideal traffic flow is realized, as in Ref. [5]. UAIDs operational performance, however, has not been examined in the developing countries, semi-industrialized and industrializing countries where the complexities due to the dominant heterogeneous traffic arise. These complexities are the result of traffic violation, various dynamic and static properties of vehicles as well as the limited geometric designs, as in Ref. [6]. The previous research distinctly emphasized the obvious impact of traffic heterogeneity on the intersections’ performance, as in Refs. [7-9]. The wide diversity in vehicles’ static and dynamic characteristics, aggressive driving behavior as well as non-lane based phenomena play substantial impacts as salient aspects and unique features of such traffic, as in Ref. [6]. The absence of lane lines and non-segregated lanes by either flow direction or vehicle types, results in non-lane based behaviors where all vehicles can move simultaneously in the same right of way. Therefore, under this traffic condition, drivers tend to change lanes based on the available space without any restrictions. Meanwhile, two-wheeled vehicles experience side-by-side stacking where motorists minimize the lateral distance between travelling vehicles and move through the limited roads cross-sections, as in Ref. [8]. As a result, irrespective of the lane restrictions, drivers tend to overtake in both directions and occupy any position across the roadway, as in Ref. [7].

Because of the unique design features of the unconventional intersections, a number of studies have reported that commercial signal timing packages have not been able to be utilized to develop the DLTs optimal signal timings, as in Refs. [3, 10]. The previous research’s main findings revealed that modeling the displaced left-turn movement was not
possible based on SYNCHRO or TRANSYT-7F. It was summarized that the calculation of optimal signal timing and offsets was not possible for a given DLT intersection geometric configuration, as in Ref. [3]. Therefore, this research aims to develop a signal coordination model for three DLT intersections in a corridor based on the bandwidth maximization approach.

The proposed model highlighted the heterogeneous traffic conditions as a dominant condition in developing countries. On the solid foundation of the optimization principles, a bandwidth maximization approach was proposed in order to achieve this study objective. The objective function was formulated as a mixed-integer linear program. The Morgan and Little green bandwidth maximization model (1964), was utilized to determine the optimal offsets’ values of the coordinated corridor, as in Ref. [4]. Additionally, the branch-and-bound optimization algorithm was employed to provide an efficient coordination control under MATLAB environment. This study context methodology enhancement could be achieved by examining and evaluating the proposed model through a microsimulation platform. Therefore, PTV-VISSIM, a high-performance microsimulation program, was adopted to test the proposed strategy. Here, it is essential to modify the simulation settings in order to represent the traffic heterogeneity requirements. Based on the simulation outputs, the proposed model effectiveness will be analyzed and discussed.

2. Literature Review

Although there has been considerable attention paid to the UAIDs implementation technologies, DLTs have never been estimated as a coordinated corridor, as in Ref. [4]. Indeed, a great deal of literatures have demonstrated the qualitative and quantitative benefits of DLTs design over other conventional signalized intersections, however, little research focused on methodologies dealing with the synchronization of DLTs in a corridor. The previous studies highlighted the operational performance analysis as well as the geometric design aspects, as in Refs. [1, 3, 11-14]. The research outcomes revealed the observed superior performance of DLTs over both other several UAIDs and conventional intersections. Also, they outperformed USC and conventional signalized intersections under various traffic volumes, as in Ref. [11]. Moreover, the results referred that DLT performed significantly better that PFI (parallel flow intersection) in terms of average delay and intersection throughput, as in Refs. [14, 15]. Seeking an optimal operation of DLTs, a lane-based optimization model was proposed as a systematic approach. As a multi-objective optimization problem, the proposed model combined type of intersection selection, the length of the displaced left-turn lane, signal timing and lane markings. The optimization problem was formulated as a series of mixed-integer non-linear models and solved by the standard branch-and-bound technique. The extensive numerical and simulation analyses revealed that the optimal designs and the performance improvement could vary under different traffic demand types and different geometric configurations, as in Ref. [16]. As mentioned earlier, although a number of studies focused on investigating the operational performance of different unconventional intersection designs, the methodologies to obtain the optimal signal timings for them were not discussed coherently. Therefore, two optimization approaches namely, the Monte Carlo method and the bandwidth maximization method were used to obtain the optimal signal timings of DLTs for two different traffic demand scenarios.

The main findings referred to the flexibility of Monte Carlo method to provide intersection-tailored solutions with intersection specific design parameters. Also, it was emphasized that the two optimization approaches may result in different optimal solutions, while the Monte Carlo simulation could provide near optimum parameter selection ranges for the given traffic demands, as in Ref. [10]. Instead of utilizing
the commercial signal timing packages, another optimization model was developed using the operational research solver WINQSB. The DLT intersection was broken into a group of hypothetical intersections to optimize the signal timings and offsets of three different design configurations. Consistently, the DLT intersection outperformed the conventional one for the cases modeled even at low traffic volumes. Tremendous vehicular delay savings as well as a considerable increase in capacity could be clearly emphasized as a result of the reduction in number of phases on approaches with DLT geometries of the intersection. The results stated that cycle length was the most dominating factor that influenced signal timing plans for all modeled cases, as in Ref. [3].

Generally, the extensive research investigated various signal coordination problems. The proposed models were built on two main approaches; bandwidth-based models and performance-based models. The bandwidth maximization concept aims to maximize the two-way green bandwidths of a given arterial; therefore, vehicles may have larger chances to travel without stops. However, the performance-based models attempt to optimize the signal settings to improve the performance indices such as delay, stop and queue length directly, as in Ref. [17]. A phase sequence optimization model was proposed based on NEMA phase for coordination control. Based on the developed computer program, it was concluded that leading and lagging left turn phasing were more likely to be involved in progression bandwidth solution of signal systems with randomly distributed spacing, as in Ref. [18]. The genetic algorithm as an artificial intelligence technique was also used to provide a signal timing strategy that produces the smoothest traffic flow. The results revealed that the genetic algorithm could find balanced conditions of green phase times and a reasonable cycle length as a function of traffic demand, as in Ref. [19]. Based on a novel two-way bandwidth maximization model, a coordination methodology was proposed considering the queuing process. A queuing model was developed to estimate and calculate the queue clearance time. Not only the phases that provide the right of way to coordinated directions but also the phases that provide the right of way to uncoordinated directions were considered during the optimization of phase sequences. Compared with the Maxband model and the Multiband model, the simulation results have demonstrated the effectiveness of the proposed model under different demands scenarios, as in Ref. [20].

Another two models were built based on Little’s bandwidth maximization model, namely MaxBandLA and MaxBandGN as small-sized mixed-integer linear programs. The MaxBandLA model was proposed to optimize the arterial partition plan as well as the signal coordination plans. While the MaxBandGN was developed to handle the offsets optimization for all the signals in a grid network without cycle constraints. The numerical tests of the two proposed models emphasized the potential capability to produce coordination plans compared with optimized signal plans by SYNCHRO, as in Ref. [17]. A genetic algorithm-based signal optimization program was presented to handle oversaturated signalized intersections. The presented program was tested under three different demand volume levels; low, medium and high demand. The outputs stated the superior capability of the proposed program under the low and high demand volume cases. It could produce statistically better signal timing plans than TRANSYT-7F in terms of queue time. However, for the medium-demand volume level, the proposed program provided a signal timing plan with statically equivalent queueing time compared with TRANSYT-7F software, as in Ref. [21]. A stochastic traffic signal optimization method was presented to consider stochastic variability in drivers’ behavior and vehicular inter-arrival times, vehicle mix. The developed stochastic optimization method consisted of the stochastic simulation model in addition to three widely-used optimization methods (i.e., genetic
algorithm, simulated annealing and OptQuest engine) as an external optimizer. Compared with the existing optimization programs included in TRANSYT-7F and SYNCHRO, the results indicated the outperformance of the proposed method. Also, the results emphasized that the additional controller and detector settings could improve the coordinated actuated signal control operation systems, as in Ref. [22].

Although the reviewed literature clearly showed the extensive results regarding the arterial coordination, little research has turned attention to the DLTs coordination. Furthermore, even though most of the previous works indicated the considerable impacts of the traffic heterogeneity particularly, on the intersections’ performance, little research investigated the signalized intersection coordination under heterogeneous conditions. Hence, this research investigates the coordination of consecutive DLTs considering the heterogeneous traffic conditions featuring real cases in Cairo, Egypt.

3. Methodology

This context is a part of an ongoing research project designed to estimate the applicability of DLTs under the heterogeneous traffic conditions. In the previously conducted work, the operational performance of DLTs was evaluated as isolated intersections by Shokry et al. [29]. This article describes the bandwidth maximization progression approach to coordinate traffic signals for improving the overall traffic flow propagation along the studied corridor.

The driving force of this study is to provide a simplified procedure to tackle the DLTs coordination under the heterogeneous traffic conditions. The green bandwidth maximization model by Morgan and Little model (1965) was employed to obtain the optimal offset values to fulfill the maximum bandwidth in both directions of major approach. The offset optimization problem was solved as a mixed-integer linear program [23]. MATLAB as a multi-paradigm numerical computing environment was employed to solve branch-and-bound algorithm in order to provide an efficient solution of the mixed-integer linear program.

Also, PTV-VISSIM, a powerful simulation-based assessment approach was used to evaluate the effectiveness of the proposed model. On the bases of psychophysical car-following model as well as the lane-by-lane development road network facility provided by PTV-VISSIM, the operational performance of DLTs could be represented exactly like they would appear as in the real world, as in Refs. [4, 24]. The previous studies recommended the choice of PTV-VISSIM because of the provided versatility of the software that allows unconventional movements to be modeled in congruence with field operations, as in Ref. [3]. However, essential modifications were taken carefully into consideration to represent the heterogeneous traffic flow complexities.

Later, given the results, a before-and-after comprehensive analysis was carried out. The analysis highlighted the quantitative indices of the operational performance between the existing conventional intersections, DLTs under isolated control and DLTs under the proposed coordinated control.

3.1 The Branch-and-Bound Algorithm

As a recommended technique for solving mixed-integer linear programming optimization problems, the branch-and-bound algorithm was utilized in this research. By systematic enumeration, a set of candidate solutions is formed as a rooted tree as Fig. 2 illustrates. This algorithm, basically, depends on splitting the original problem into branches of sub-problems. Each node in the rooted tree is considered as a new integer linear programming optimization problem. Also, a bounding function is used to limit the search space. Based upon the upper and lower estimated bounds of the optimal solution, each branch is checked. The branch will be discarded in case of not producing a better solution than that found by the algorithm in the previous step, as in Ref. [25].
3.2 The Basic Model Concept

The entire control algorithm of the proposed model was built based on the common cycle calculation and offset optimization. Employing Webster’s (1958) method, the optimal total cycle length of each studied intersection was calculated as shown in Eq. (1), while the split green time was calculated as shown in Eq. (2). However, in order to ensure the fundamental coordination along the whole corridor, the longest cycle length was assigned for the three intersections, then the split time was reassigned based on each phase flow ratios as shown in Eq. (2). Each intersection requires six signal groups to control the main intersections as well as the upstream crossovers for the major and the minor approach as Fig. 3 depicts. According to Webster’s delay minimization method, the overall delay inside the intersection is minimized by optimizing the green time based on the flow ratio of each phase, as in Ref. [26].

\[
C = \frac{(1.5 \times LT + 5)}{(1 - \sum FR)} \quad (1)
\]

\[
\text{gi} = \frac{(C - LT) \times \text{Max.FR}}{\left( \sum \text{Max.FR} \right)} \quad (2)
\]

where,
- \(C\): optimal signal cycle time (s);
- \(LT\): total lost time per cycle (s);
- \(\text{FR}\): critical flow ratio for each phase (max. traffic volume of the phase /saturation flow rate);
- \(\text{Max.FR}\): Max. value of critical flow ratio value among the signal group for the same phase in the approaches being discharged during a signal phase;
- \(\text{gi}\): effective green time for phase (i) in seconds.

3.3 The Objective Function

The objective function was formulated as a linear mixed-integer problem to obtain the optimal offset value which maximizes the green bandwidth of the major approach for both directions. By giving different weights of each direction bandwidth, one objective function was used to consider the bandwidth of two directions as shown in Eq. (3). However, for this study context eastbound bandwidth and westbound bandwidth has the same weight.

Maximize: \(w_{\text{east}} \times b + w_{\text{west}} \times b\) \quad (3)

where,
- \(w_{\text{east}}\) and \(w_{\text{west}}\) are the weight for eastbound bandwidth and westbound bandwidth respectively.

In this context, the objective function is subjected to six sets of constraints as follow:
- \(b = b\);
- \(w_i + b \leq 1 - r_i\);
\[ \bar{w}_i + b \leq 1 - r_i; \]
\[ (w_i + \bar{w}_i) - (w_1 + \bar{w}_1) - m_i - (r_i - r_1) - (t_i + \bar{t}_i); \]
\[ m_i = \text{integer}; \]
\[ b, \bar{b}, w_i, \bar{w}_i > 0. \]

where,
\[ b, \bar{b}: \text{the bandwidth of west and eastbound respectively in seconds;} \]
\[ w_i, \bar{w}_i: \text{the total lost time per cycle in seconds;} \]
\[ r_i, r_1: \text{red time of (S_i) DLT and (S_1) DLT respectively in cycles;} \]
\[ t_i, \bar{t}_i: \text{travel time from/to (S_i) DLT and (S_1) DLT respectively (cycles) as shown in Fig. 4.} \]

4. Study Area

Actual realistic data of three consecutive signalized intersections located in an arterial corridor in Cairo, Egypt was selected to assess the coordination of DLTs as a real case of study as shown in Fig. 5. The three intersections are namely AT (Al Tayran), AA (Abbass Al-Akkad) and ME (Makram Ebid). The geometric layout of the intersection is depicted in Fig. 6. As it’s shown, the southbound through and left-turn as well as westbound left-turn are not permitted at the intersection. Therefore, these movements must use the provided U-turns located at the downstream of each intersection. As an efficient and recommended technique for data collection, video observation was used to observe the different traffic flow elements, accurate and classified counts of vehicles’ performances as well as heterogeneous operations’ performance. The peak-hour volumes were used in this study. The obtained volumes were recorded as 8,364 veh/h for AT intersection, while it was recorded as 8,795 veh/h and 7,448 veh/h for AA and ME intersection respectively. The total traffic volume and the directional flow ratio of each approach for each intersection are illustrated in Fig. 7.

Despite the existence of an exclusive bus lane along the studied corridor, only the public buses could use it. It is prohibited for other shuttle buses, private or school buses to use. As a result, these buses have to share the right of way with the other vehicles’ types as a mixed traffic phenomenon. Moreover, the captured videos emphasized the unique characteristics of heterogeneous traffic flow performance. The continuous stimulus of the two-wheeled vehicles to sneak and occupy
Fig. 4  Time-space diagram shows the coordination structure.

Fig. 5  A Google map of the studied arterial.
the front queues through the interspace between the other bigger vehicles was observed. Also, the side-by-side stacking of vehicles across the road width as a result of lane line absence as well as poor lane discipline was clearly detected based on the recorded videos.

5. Traffic Simulation Models

In order to represent the studied intersections as indisputable to reality, the simulation process was built based on Wiedemann 74 car following model. However, considering the credibility of the simulated
models, it’s essential to tune and reset the several default behavioral parameters to represent the heterogeneity conditions in this study. Therefore, VISSIM versatility such as vehicles static and dynamic properties, as well as the driving behavior parameters such as min. lateral distances, lane change behavior and maneuverability was tuned to represent the model as close as possible to reality. Resetting and giving appropriate values, the aggressive driving behavior that is the most common and unique feature of the heterogeneous traffic could be represented. These values were tuned on the foundation of the considerable previous works, and guide manuals, as in Refs. [8, 24].

For an accurate modelling of the continuous stimulus sneaking attitude of the two-wheeled vehicles as well as stop line violation, two signal heads were installed for each lane to represent this maneuverability. The first signal head was assigned to control two-wheeled vehicles, with 2.0 m ahead of the second, which was designated to the other vehicles types. The diamond shaped queuing feature, which allows for staggered queues (e.g. for cyclists) according to the realistic shape of vehicles, was also selected to represent the stop line violation phenomenon [24]. On the other hand, lateral driving behavior was readjusted for each corresponding speed of each vehicle category in order to replicate the non-lane based movements of the mixed traffic flow where no restrictions to change lanes exist as shown in Table 1. Therefore, both (left and right) sides—overtaking were maintained and permitted to simulate this driving behavior. For free lane changing, the lane change behavior was selected as uncooperative lane change and the desired decision at free flow was checked to any position. Other simulation parameters such as emergency stopping distance, the number of observed preceding vehicles, Min. headways and average standstill distance were also tuned to fulfill the aggressive driving behavior as a common and unique feature of the heterogeneous traffic as shown in Table 2.

The model validation process is required to assure the representation of the simulated model as indisputable to reality. For this purpose and in order to evaluate the model accuracy, a comparison between the observed and the corresponding simulation outputs was conducted. GEH empirical static test as a recommended method to validate the traffic volumes as well as the travel times comparison along the studied arterial was used. As a modified Chi-square static test, GEH test was designed to compare the observed with simulated hourly traffic flow as shown in Eq. (4).

\[
GEH = \sqrt{\frac{(M - O)^2}{0.5 \times (M + O)}}
\]

where:

M: The observed flow on a link in (veh/h);
O: The simulated flow for the same link in (veh/h).

According to the DMRB (design manual for roads and bridges), the simulated model could be accepted when 85% of the volumes in a traffic model with GEH values are less than 5.0, as in Refs. [27, 28]. The GEH calculated values emphasized the acceptance criterion of the simulated models as shown in Table 3.

On the other hand, the travel time comparison indicated the simulated model effectiveness. The estimated differential ratios between the observed and

<table>
<thead>
<tr>
<th>Vehicle category</th>
<th>Desired speed (Km/h)</th>
<th>Acceleration (m/s²)</th>
<th>Deceleration (m/s²)</th>
<th>Min. lateral distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Max.</td>
<td>Desired</td>
<td>Max.</td>
</tr>
<tr>
<td>Two-wheels vehicle</td>
<td>40</td>
<td>2.5</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Normal vehicle</td>
<td>50</td>
<td>1.5</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Microbus</td>
<td>50</td>
<td>1.9</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Shuttle bus</td>
<td>30</td>
<td>2.0</td>
<td>0.7</td>
<td>1.2</td>
</tr>
<tr>
<td>Bus</td>
<td>30</td>
<td>2.5</td>
<td>0.8</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Table 2  Micro-simulation model tuned parameters.

<table>
<thead>
<tr>
<th>Simulation parameters</th>
<th>Given values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. standstill distance</td>
<td>0.5 m</td>
</tr>
<tr>
<td>No. of observed vehicles</td>
<td>2 veh</td>
</tr>
<tr>
<td>Look back distance</td>
<td>Min. 30.0 m Max. 150.0 m</td>
</tr>
<tr>
<td>Look ahead distance</td>
<td>Min. 5.0 m Max. 100.0 m</td>
</tr>
</tbody>
</table>

Table 3  GEH empirical test outputs.

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Direction</th>
<th>Observed flow (veh/h)</th>
<th>Simulated flow (veh/h)</th>
<th>GEH value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME</td>
<td>Westbound</td>
<td>2,245</td>
<td>2,442</td>
<td>4.07</td>
</tr>
<tr>
<td></td>
<td>Eastbound</td>
<td>2,574</td>
<td>2,407</td>
<td>3.35</td>
</tr>
<tr>
<td></td>
<td>Southbound</td>
<td>1,385</td>
<td>1,321</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td>Northbound</td>
<td>1,244</td>
<td>1,266</td>
<td>0.62</td>
</tr>
<tr>
<td>AA</td>
<td>Westbound</td>
<td>1,905</td>
<td>1,978</td>
<td>1.66</td>
</tr>
<tr>
<td></td>
<td>Eastbound</td>
<td>3,578</td>
<td>3,294</td>
<td>4.84</td>
</tr>
<tr>
<td></td>
<td>Southbound</td>
<td>1,596</td>
<td>1,462</td>
<td>3.43</td>
</tr>
<tr>
<td></td>
<td>Northbound</td>
<td>1,716</td>
<td>1,699</td>
<td>0.41</td>
</tr>
<tr>
<td>AT</td>
<td>Westbound</td>
<td>2,270</td>
<td>2,447</td>
<td>3.64</td>
</tr>
<tr>
<td></td>
<td>Eastbound</td>
<td>3,040</td>
<td>2,982</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>Southbound</td>
<td>1,640</td>
<td>1,673</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>Northbound</td>
<td>1,434</td>
<td>1,394</td>
<td>1.06</td>
</tr>
</tbody>
</table>

Table 4  The travel time validation.

<table>
<thead>
<tr>
<th>Average travel time (s)</th>
<th>% Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>From AT to AA</td>
<td>0.9</td>
</tr>
<tr>
<td>From AA to ME</td>
<td>12.07</td>
</tr>
<tr>
<td>From ME to AA</td>
<td>1.98</td>
</tr>
<tr>
<td>From AA to AT</td>
<td>1.18</td>
</tr>
</tbody>
</table>

simulated travel times were 0.9% and 1.98%. However, as a result of the absence of the priority rules among travelling vehicles, especially at the U-turns on the arterial corridor, the differential ratios recorded 12.07% for the travel time from AA to ME as shown in Table 4.

6. Results and Discussion

The optimal offset values could produce the desirable green waves which would improve the overall traffic flow propagation along the studied corridor. Related to this research work, the conventional intersections in the same arterial have been represented, analyzed and evaluated in the previous publications. Also, the DLTs were proposed as isolated intersections to alleviate the traffic congestion at the same studied intersections. The results indicated that DLTs prevailed over other studied conventional intersections, as in Ref. [29]. For this article, the proposed model was adopted to calculate the optimal offset for each pair of consecutive intersections. The calculated cycle length of AA intersection was 71 seconds as the longest cycle and it was set up for all the intersections to ensure the coordination through the studied corridor. Although the cycle length was reduced by -38% compared to the existing cycle length of the studied intersections, the intersections throughputs were enhanced for all the intersections along the corridor as shown in Fig. 8.

According to the simulation results, the average delay of the coordinated corridor was reduced by -81.15% as shown in Table 5. The average number of stops for the whole corridor was decreased by -88.23%. The results indicated the smooth travel through the coordinated intersections. The simulation
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![Traffic Throughput](image)

Fig. 8  Intersections throughputs comparison.

Table 5  Corridor operational performance indices.

<table>
<thead>
<tr>
<th>Performance index</th>
<th>Conventional intersections</th>
<th>Non-coordinated DLTs</th>
<th>Coordinated DLTs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total travel time (h)</td>
<td>2,544.14</td>
<td>1,335.38</td>
<td>1,306.38</td>
</tr>
<tr>
<td>Avg. delay/veh. (s)</td>
<td>409.11</td>
<td>200.518</td>
<td>192.17</td>
</tr>
<tr>
<td>Avg. speed (km/h)</td>
<td>12.98</td>
<td>19.21</td>
<td>22.415</td>
</tr>
<tr>
<td>Avg. No. of stops/veh.</td>
<td>20.66</td>
<td>2.88</td>
<td>2.43</td>
</tr>
<tr>
<td>Avg. delay/veh. (s)</td>
<td>166.30</td>
<td>36.44</td>
<td>30.72</td>
</tr>
</tbody>
</table>

![TRAVEL TIME FOR THE WHOLE CORRIDOR](image)

Fig. 9  The total travel times along the studied corridor.
outputs highlighted the superiority of the coordinated DLTs over the existing intersections. All performance indices such as the total travel time, overall delay, and so on showed improvements as shown in Table 5. The results revealed the obvious enhancement of the travel time for both coordinated directions (west and eastbound) in the studied corridor as shown in Fig. 9.

The westbound average travel time was reduced by -72.36%, while the eastbound travel time was reduced by -48.61%. Although the average travel time has fluctuated along the corridor, the coordination of DLTs along the corridor could provide a stable travel time as a result of the green bandwidth maximization. Furthermore, considerable savings in overall delays in all the intersections were observed. The reduction percentage of overall delay is -53.02%, while the increase percentage in average speed along the corridor is 72.65%.

7. Conclusion

This research work has outlined the coordination of a series of DLTs in a corridor. The heterogeneous traffic conditions as dominant in developing, semi-industrialized and industrializing countries were considered in this study. In this paper, the green bandwidth maximization technique was used for the signal coordination. The offset optimization problem was formulated as a mixed-integer linear program. A multi-paradigm numerical computing environment, MATLAB, was employed to solve branch-and-bound algorithm in order to provide an efficient solution of the mixed-integer linear program. To assess the efficiency of the proposed model, a comprehensive before-and-after analysis for the studied corridor among the coordinated, non-coordinated DLTs and the existing conventional intersections in Cairo, Egypt was carried out. An extensive evaluation was carried out based on VISSIM simulation results. The simulation outputs emphasized the outperformance of the coordinated DLTs over the existing conventional counterparts as well as the non-coordinated DLTs. The intersection capacity, the overall delay time, total travel time, the average speed, the queue length and the average stopped delay per vehicle were improved obviously.

8. Future Work

In order to fulfill the heterogeneous traffic conditions needs, it’s required to develop a real-time demand-responsive signal control system utilizing the dynamic optimization principles that solve the intertemporal optimization problems, calculate the optimal offsets values and change signal parameters iteratively for each time interval. The system should also consider the platoon dispersion as natural stochastic variations of heterogeneous traffic conditions. Also, by considering the individual vehicle arrival rates, the system may minimize the total delay for consecutive DLTs traffic signals instead of the bandwidth maximization technique.

References

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