# Multi-Path Progression Optimization at an Urban Interchange: A Case Study

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ABSTRACT: Progression optimization is a common approach for coordinating traffic signals along arterial streets as well as arterial networks. This approach has been extended in recent years to provide progression opportunities for major O-D path flows in arterials and in networks as well as at complex interchanges. The program uses a mixed-integer linear programming (MILP) formulation to optimize all relevant signal parameters, including: green times, cycle time, phase sequences and offsets. A special case with added complexity concerns interchanges where multiple origin-destination path flows converge into a limited space, especially when traffic volumes are at or near capacity. In this paper we consider as a case study a major interchange in Tel Aviv, Israel. The objective is to determine optimal progressions that minimize travel times through the interchange and average vehicular delay. Two cases were analyzed: (a.) the existing pattern of flows; (b.) an optimized pattern using the OD-BAND model. This MILP optimization problem is solved by the CPLEX software. The results are then compared by microscopic simulation using the AIMSUN model. The results indicate that by careful selection of the major O-D path flows and using the MILP algorithm one can obtain substantial improvements in system performance.

## 1. INTRODUCTION

Traffic signal coordination plays an important role in the smooth and effective operation of arterial systems. Coordination can be provided with a common cycle length and appropriate offsets such that a platoon of vehicles can travel along the entire arterial without stopping. Compared with uncoordinated traffic signal control plans, an optimal coordinated control plan typically provides a higher level of traffic service that results in more uniform traffic flows, higher average travel speeds, fewer accidents, and less red light violations.

Progression optimization using mathematical programming techniques is a common approach for coordinating traffic signals along arterial streets as well as arterial networks. A number of techniques with varying degrees of refinement have been developed for this purpose (Little et al (1981), Gartner et al. (1990, 1991) Zhang et al. (2015)). In recent years, another layer of sophistication has been added by providing separate bands of progression for major origin-destination path flows crossing in-and-out of the arterial. A typical example is illustrated in Figure. 1 where traffic turning in at intersection A and turning out at intersection C is allocated a separate band that provides it with uninterrupted progression. This occurs concurrently with the two mainstream bands. A program that designs such bands utilizing vehicular traffic origin-destination information is called OD-BAND (Arsava et al. (2014, 2016)).

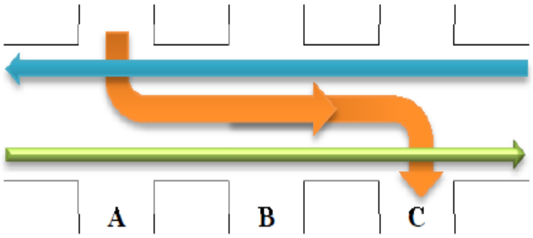

*Figure. 1: Example of concurrent flow patterns used in OD-BAND.*

This approach has been extended to provide progression opportunities for major O-D path flows in both arterials and in networks (Arsava el al. 2016). The program uses a mixed-integer linear programming (MILP) formulation to optimize all relevant signal parameters, including: green times, cycle time, phase sequences and offsets. The integer variables permit discrete choices of signal phase sequences and cycle multiples for the loop constraints of the system. Other authors have applied this approach to arterials and diverging diamond interchanges (CPLEX Optimization Studio, AIMSUN) .

A review of the related literature shows that there are a number of studies on estimating O-D patterns for signalized arterials. Lou and Yin (2010) used detected link counts to develop a decomposition framework for estimating time varying dynamic O-D flows on an arterial. First, they decompose the entire arterial into a set of individual intersections and then they estimate the turning flows with link counts, which in turn serve as the measurements for the arterial O-D estimation. Chang and Tao (1998) incorporated additional constraints from signal timing information in their enhanced model, to estimate time-dependent turning fractions at intersections. The results of extensive simulation experiments indicate that such methods can yield more accurate estimation, compared with the base model of O-D estimation, without considering the impact of signal timings.

In this study we apply the original OD-BAND model described by Arsava et al. (2014), as a special case study at a complex interchange consisting of four closely- spaced intersections with multiple O-D flows, the Hashalom Interchange in Tel Aviv, Israel. Problem Description

## 2. Case study

### 2.1.Description of Case Study

A special case of the O-D progression optimization with added complexity concerns interchanges where multiple origin-destination path flows converge into a limited space, especially when traffic volumes are at or near capacity. We consider as a case study the Hashalom Interchange in Tel Aviv. This interchange consists of four closely-spaced intersections with multiple O-D flows as illustrated in Figure. 2. The interchange is the busiest interchange in Israel, and around 75,000 vehicles pass through it every day. Figure. 3 illustrates the major path flows at the surface level of the interchange: Figure. 3A show the westbound flows, Figure. 3B the eastbound flows. Table (1) present the O-D matrix that have been used for the case study simulation for the main street of the Hashalom Interchange network. The concurrence of multiple streams through the signalized intersections creates extreme demands on the connecting links and requires careful sequencing of the signal phases and the offsets so as to accommodate these demands in an optimal manner.

*Figure. 2: The Hashalom Interchange network of signals.*

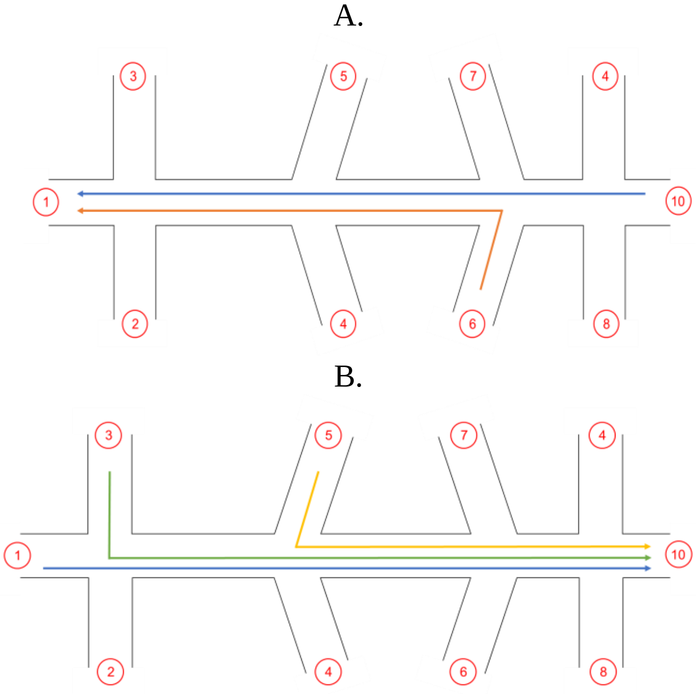

*Figure. 3: Major path flows through the interchange traffic signals.*

*Table 1: O-D Matrix for Case Study Network for the main street*

| Origin | Destination | Demand (veh/hr) |
|---|---|---|
| 10 | 1 | 780 |
| 6 | 1 | 825 |
| 1 | 10 | 680 |
| 3 | 10 | 190 |
| 5 | 10 | 525 |

## 2.2 OD-*BAND MILP Model*

The objective is to determine optimal multi-path progressions that minimize travel time through the interchange, reduce vehicular delays and emissions. The OD-BAND model is particularly suitable for tackling such a complicated case. The objective function of the MILP formulation is illustrated in Figure. 4 (the list of constraints is too long to be included in an abstract). Two cases were analyzed: (a.) the existing timing pattern; (b.) an optimized pattern using the OD-BAND model. This mixed-integer linear programming problem is solved by the CPLEX software [8]. The solution to the optimization problem includes the recommended values for offset times and the arrangement of phases at each traffic signal of the intersection. Objective function of OD-BAND MILP model Arsava et.al (2016)

$$Max \sum_{i=1}^{n-1}(a_i * b) + \left(\bar{a}_i * \bar{b}\right) + \sum_{j=1}^{P}\left[\sum_{i=1}^{N_e-N_s} a_{(o,d)}(i) * y_{N_s,N_e} + \sum_{i=1}^{N_e-N_s} \bar{a}_{(o,d)}(i) * \bar{y}_{N_s,N_e}\right] \quad (1)$$

Where the first part of the function is for the main weighted bandwidths, such as figure 4, and the second part for the O-D weighted bandwidths such as figure 5. Furthermore, the $\sum_{i=1}^{N_e-N_s} a_{(o,d)}(i) * y_{N_s,N_e}$ is for O-D pairs that travel along the outbound direction, and $\sum_{i=1}^{N_e-N_s} \bar{a}_{(o,d)}(i) * \bar{y}_{N_s,N_e}$ is for O-D pairs that travel along the inbound direction.

Where

$$a_i = \frac{V_i}{S_i}$$

$$\bar{a}_i = \frac{\bar{V}_i}{\bar{S}_i}$$

$$a_{od}(i) = \frac{V_{o,d}}{S_{o,d}}$$

$$\bar{a}_{od}(i) = \frac{\bar{V}_{o,d}}{\bar{S}_{o,d}} \quad (2)$$

Subject to the following Constraints:

$$\frac{1}{c_2} \leq z \geq \frac{1}{c_1} \tag{3}$$

$$(1-k) * \bar{b} \geq (1-k) * k * b \tag{4}$$

$$\begin{aligned}\left(1-k_{od}(j)\right) * y_{N_s,N_e} \\ \geq \left(1-k_{od}(j)\right) * k_{od}(j) * b\end{aligned} \tag{5}$$

$$\begin{aligned}\left(1-\bar{k}_{od}(j)\right) * \bar{y}_{N_s,N_e} \\ \geq \left(1-\bar{k}_{od}(j)\right) * \bar{k}_{od}(j) * \bar{b}\end{aligned} \tag{6}$$

$$\begin{aligned}&w_i + b \leq 1 - r_i \\ &\overline{w_i} + \bar{b} \leq 1 - \overline{r_i} \qquad i = 1, \dots, n \\ &\overline{\grave{w}_i} + \bar{b} \leq 1 - \bar{r}_i\end{aligned} \tag{7}$$

$$\left(\frac{d_i}{f_i}\right) z \leq t_i \geq \left(\frac{d_i}{e_i}\right) z$$

$$\left(\frac{\bar{d}_i}{\overline{f_i}}\right) z \leq \overline{t_i} \geq \left(\frac{\overline{d_i}}{\overline{e_i}}\right) z \qquad i = 1, \dots, n-1 \tag{8}$$

$$\begin{aligned}&\left(\frac{d_i}{h_i}\right) z \leq \left(\frac{d_i}{d_{i+1}}\right) t_{i+1} - t_i \geq \left(\frac{d_i}{g_i}\right) z \\ &\left(\frac{\bar{d}_i}{\overline{h_i}}\right) z \leq \left(\frac{\bar{d}_i}{\bar{d}_{i+1}}\right) \overline{t_{i+1}} - \overline{t_i} \geq \\ &\left(\frac{\overline{d_i}}{\overline{g_i}}\right) z \qquad i = 1, \dots, n-2\end{aligned} \tag{9}$$

$$\begin{aligned}(w_i + \overline{w}_i) - (w_{i+1} + \overline{w}_{i+1}) + (t_i + \bar{t}_i) + \delta_i L_i \\ - \bar{\delta}_i \overline{L}_i - \delta_{i+1} L_{i+1} + \bar{\delta}_{i+1} \overline{L}_{i+1} \\ - m_i = (r_{i+1} - r_i) \\ i = 1, \dots, n-1\end{aligned} \tag{10}$$

$$\overline{\grave{w}_i} + \bar{b} + \overline{w_i} = 1 - \overline{r_i} \qquad i = 1, \dots, n \tag{11}$$

$$\begin{aligned}&\overline{r_i} - \overline{r_{i+1}} + \overline{\grave{w}_i} - \overline{\grave{w}_{i+1}} = w_{i+1} - w_i \\ &i = 1, \dots, n-1\end{aligned} \tag{12}$$

$$X_{N_s,N_e,i} \geq r_i \qquad i = N_s + 1, \dots, N_e \tag{13}$$

$$\bar{X}_{N_s,N_e,i} \geq \overline{r_i} \qquad i = N_s - 1, \dots, N_e \tag{14}$$

$$\begin{aligned}&y_{N_s,N_e} + x_{N_s,N_e,i} \leq r_i \\ &\bar{y}_{N_s,N_e} + \bar{x}_{N_s,N_e,i} \leq \overline{r_i} \qquad i = N_s\end{aligned} \tag{15}$$

$$\begin{aligned}&x_{N_s,N_e,i} - \bar{x}_{N_s,N_e,i+1} = w_i - w_{i+1} - r_{i+1} + r_i \\ &i = N_s, \dots, N_e - 1\end{aligned} \tag{16}$$

$$\begin{aligned}&\bar{x}_{N_s,N_e,i+!} - \bar{x}_{N_s,N_e,i} = \overline{\grave{w}_{i+1}} - \overline{\grave{w}_i} + \overline{r_{i+1}} - \overline{r_i} \\ &i = N_e, \dots, N_s - 1\end{aligned} \tag{17}$$

$$\begin{aligned}&\sum y_{N_s,N_e} + b \leq 1 - r_i \\ &i = \max(N_s) + 1, \dots, \min(N_e)\end{aligned} \tag{18}$$

$$\begin{aligned}&\sum \bar{y}_{N_s,N_e} + \bar{b} \leq 1 - \bar{r}_i \\ &i = \min(N_s) - 1, \dots, \max(N_e)\end{aligned} \tag{19}$$

$$\begin{aligned}&b, \bar{b}, z, w_i, \overline{w}_i, \overline{\grave{w}_i}, t_i, \overline{t_i}, x_{N_s,N_e,i}, \bar{x}_{N_s,N_e,i}, y_{N_s,N_e}, \bar{y}_{N_s,N_e}, \\ &\delta_i, \overline{\delta_i} \geq 0 \qquad i = 1, \dots, n\end{aligned} \tag{20}$$

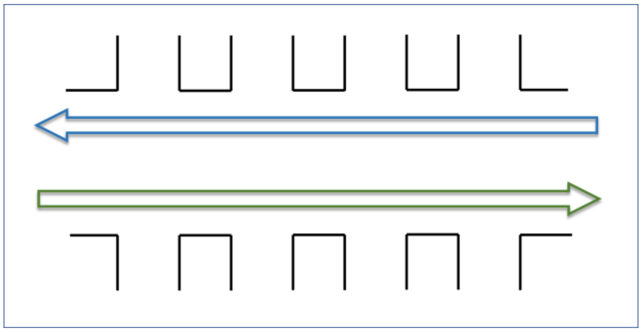

*Figure 4. Main weighted bandwidths*

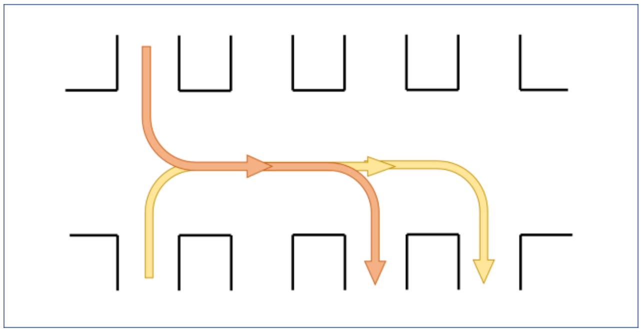

*Figure 5. OD – weighted bandwidths*

The optimization objective is to maximize a weighted sum of the progression bands. For each progression band, its weight is calculated as the sum of the O-D flow to saturation flow ratios of all sections along its path. The objective function is divided into two parts:

1. Maximizes through band9widths
2. Maximizes cross bandwidths

Table (2) present the program input and output from the MILP optimization that we did by CPLEX optimizer (IBM).

*Table 2: Input and Output for the optimization*

| **Program Input** | **Program Output** |
|---|---|
| Traffic volumes | Optimal Cycle time |
| Street geometry | Green splits |
| Desire speeds | Offsets |
| Allowable phase sequences | Travel speeds (on each segment) |
| Lower and upper bounds for cycle time, travel speeds and speed changes | Order of left turn phase sequences |

## 3. RESULTS

MILP Optimization Re-Build signal timing plans as we can see from Figure. (6), maintain the original green time ratio, change the phase sequence, cycle time and offsets.

Figure. (7) and (8) Presents the results of (N4) Begin-Kaplan from the MILP optimization. Figure. 7 shows the signal timing before the optimization results, Figure. 8 presents the signal timing after the optimization, for one of the four closely- spaced intersections.

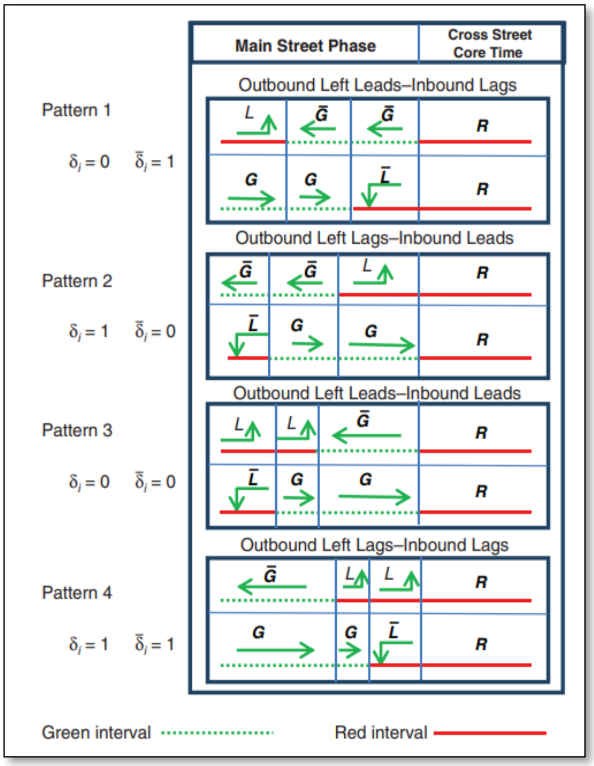

*Figure 6. Possible left-turn patterns ($G(\bar{G})$=green ;time for outbound (inbound) through traffic, R =common(core) red time for through traffic movement along arterial direction) , Arsava et al.2015*

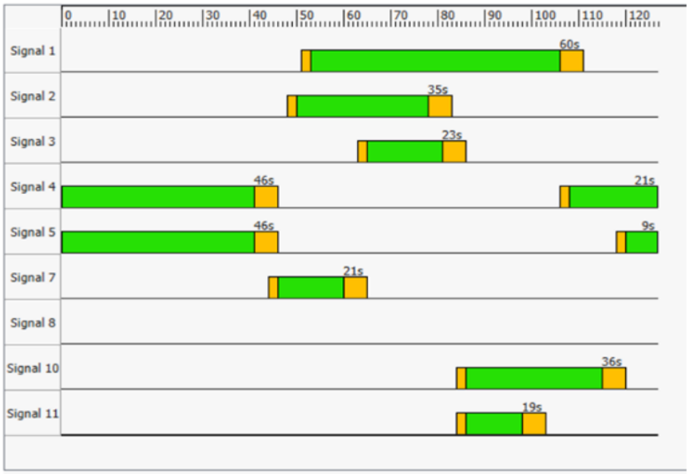

*Figure 7. (N4) bejen-kaplan before*

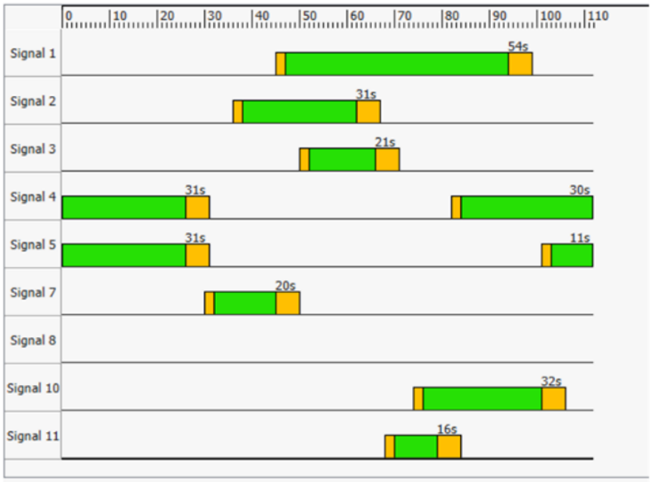

*Figure 8. (N4) bejen-kaplan after*

To evaluate the traffic situation at the interchange, we used the AIMSUN microscopic simulation software. The road network, traffic flow data, and the current traffic signal plans were coded into the model. In addition, the flow characteristics and behavior of the vehicles in the model were calibrated to match reality in the field after a series of observations and assimilation of the driving behavior definitions of the simulation model. Five performance measures were evaluated for the two cases that were analyzed and are listed in Table 1.

As we can see from the result in Table 3, there are positive consequences of applying the new traffic management system at the interchange. Average delay and travel time rates decrease by approximately 10%. Average speed increases from 19.2 (km/h) to 21.44 (km/h), (increase by approximately 12%). And the CO2 emissions decrease by approximately 4% at the interchange.

*Table 3: Comparison of alternatives through microscopic simulation*

| Variable | Existing | OD-band results | Diff (%) |
|---|---|---|---|
| Avg. Delay (sec/veh) | 269.35 | 242.64 | -9.9% |
| Avg. Speed (km/h) | 19.2 | 21.44 | %11.7 |
| Travel Time Rate (sec/km) | 324.61 | 297.85 | -8.2% |
| Fuel Consumption (l/veh) | 740.1 | 0.163 | -6.6% |
| $CO_2$ emissions (gram/veh) | 656.51 | 631.23 | -3.9% |

## 4. CONCLUSIONS

This paper presented the OD-BAND MILP models, as a special case study at an interchange consisting of four closely- spaced intersections with multiple O-D flows, the Hashalom Interchange in Tel Aviv. The modified OD-BAND model was formulated as a mixed-integer linear program and was solved by the CPLEX Optimization Studio, with all relevant signal parameters, including: green times, cycle times, phase sequences and offsets. The integer variables permit discrete choices of signal phase sequences and cycle multiples for the loop constraints of the system. On the basis of Aimsun simulation results of this case study, some of the important conclusions that can be drawn are:

Multi-path progression optimization can lead to substantial improvements in traffic flows at complicated interchanges.

Mathematical programming models can be a powerful tool for intelligent transportation system applications.

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