Signal Synchronization Optimization for Rapid Transit

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***Abstract*—The paper discusses linear programming strategies for rapid transit optimization by synchronizing traffic signal systems. Synchronizing different paths of enabled signal roads is an NP-hard problem and various combinations can play out together to effectively clear the on-road traffic. Traditional computational methods lack to solve this real-world problem in a systematic procedure bounded by a polynomial function. Our research introduces a linear programming approach to solve this problem efficiently by synchronizing signals along a continuous pathway between intersections, maximizing the traffic movement and ensuring less stoppage time for vehicles. The paper explains a two-intersection model simulation, comparing the duration required to clear on-road traffic in a traditional repetitive cycle of enabled signals and the linear programming approach of synchronization. The results of this test highlight that the proposed model achieves a significantly reduced amount of time to clear the on-road traffic.**

***Index Terms*—component, formatting, style, styling, insert**

I. Motivation

The increase in the number of vehicles in urban settings is causing traffic congestion problems, severely affecting the quality of life and marking an environmental impact. Large vehicle circulation requires traffic optimization, with engineering concepts developing and improving transit flow. The current observed traffic signal system has a cycle of sequential operation of enabled roads, which might not be ideal compared with the observed vehicle growth on roads in today's urban setting. Traffic scenarios during high-traffic days (peak hours) require the vehicles to be cleared quickly to ensure less transit time and reduced vehicle carbon emissions. The proposed method of synchronization of traffic signal systems in real-world scenarios presents a solution to this complex problem using integer linear programming(ILP). ILP is a powerful mathematical optimization technique, ideal for modeling this complex problem with constraints perfectly aligning as the road rules. Variables of an ILP model indicate activated signals, constructing excellent parameters of synchronization along the network of multiple intersection urban settings. Linear programming generates combinations of accurate solutions, achieving maximum traffic clearing and ensuring adjacent roadway synchronization to ensure continuous traffic flow. Such harmonizing can not only ensures rapid transit flow on urban roads but also prioritizes emergency first responder vehicles and public transit.

II. Integer Linear Program Model

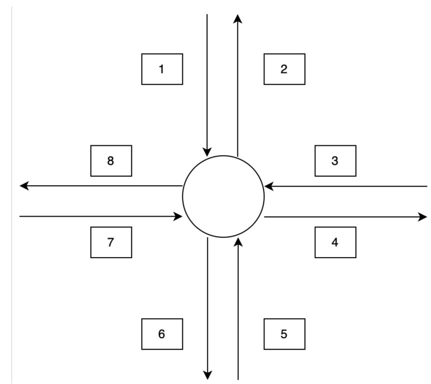

Fig. 1. Roadway intersection represented as a directed graph

Figure 1 is used for establishing an ILP model for a single roadway intersection. All odd-numbered lanes represent that are entering the intersection. These can also be viewed as inflow or inbound edges. Even numbered lanes are exiting an intersection or outflow/outbound edges. ILP model optimization is around these 4 odd variables, indicating the inflow bandwidth of traffic. The solution of the model suggests which signals to be enabled.

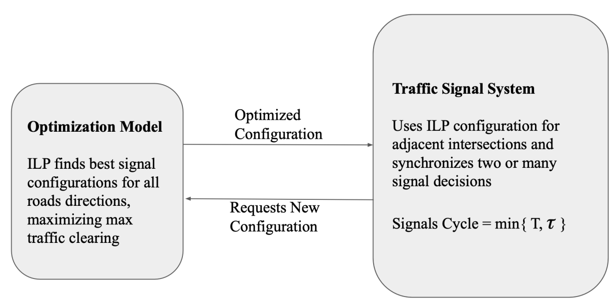

Fig. 2. Traffic synchronization system

Figure 2 provides a high-level overview of the system design. Traffic signal system, after each phase of the signal cycle requests the ILP optimization model for best configuration to clear maximum traffic. Although the minimum phase is

120s as per USA Transportation Research Board, the system activates the new phase as per the desired amount of time.

A. Variables of the model

Variable X are assigned on the inbound directed edges and W are weights of these edges, each indicating the stalled traffic on the lane at the intersection. The model also relies on constant K, which acts as anti stalling priority constant, adjusted by the system to ensure all lanes get equal priority. This constant can also serve as a synchronizing factor by assigning a higher value for subsequent intersections.

- X_i = 0/1 is variable for directed edges. 1 if edge allowed to travel(green signal), 0 if edge closed to travel(red signal).
- X_i is a vector = [x_l, x_c, x_r] each indicating signal value for left lane, center lane and right lane.
- W_i, weight of directed edge, indicating vehicles lined up to travel left, center and right
- Weight vector [w_l, w_c, w_r], each indicating the aggregated traffic on the road, along the left, center and right lane.
- K matrix is anti stalling priority constant values. K value resets to 1 at each signal period, for the lanes that were active in the last period(light cycle).
- Entries in K are applied via dot product to all weighted lanes in the matrix $W^T X$.

$$\mathrm{X}_{4\times 3} = \begin{bmatrix} x_{1l} & x_{1c} & x_{1r} \\ x_{3l} & x_{3c} & x_{3r} \\ x_{5l} & x_{5c} & x_{5r} \\ x_{7l} & x_{7c} & x_{7r} \end{bmatrix}$$

$$\mathrm{W}_{4\times 3} = \begin{bmatrix} w_{1l} & w_{1c} & w_{1r} \\ w_{3l} & w_{3c} & w_{3r} \\ w_{5l} & w_{5c} & w_{5r} \\ w_{7l} & w_{7c} & w_{7r} \end{bmatrix}$$

$$\mathrm{K}_{4\times 3} = \begin{bmatrix} k_{1l} & k_{1c} & k_{1r} \\ k_{3l} & k_{3c} & k_{3r} \\ k_{5l} & k_{5c} & k_{5r} \\ k_{7l} & k_{7c} & k_{7r} \end{bmatrix}$$

B. Objective of the model

Unlike the traditional method of traffic signal system, the ILP optimization model finds a new combination of signals to enable. This combination is found by maximizing the objective function, which aims to clear maximum road traffic. This maximization ensures rapid transit because clearing the road traffic is proportional to minimizing vehicles wait time on the road and also equivalent to maximizing vehicle average speed.

$$\mathbf{W}^T\mathbf{X} \cdot \mathbf{K} \rightarrow Max$$

C. Constraints of the model

The constraints to achieve maximum objective value would be to have conditions such that enabling signals should avoid collisions. Below are three categories of constraints to avoid any sort of road collisions.

- Having constraints on both center variables can avoid collisions that happen on roads that travel perpendicularly.

$$\mathbf{x}_{\text{2i-1,c}} + \mathbf{x}_{\text{2j-1,c}} \leq 1, \text{ for all i,j} \in [1,4] \text{ and i} \neq \text{j}$$

- Having constraints on center variables and left variables can avoid collisions that happen where one lane travels straight while the other roads travel left.

$$\mathbf{x}_{\text{2i-1,c}} + \mathbf{x}_{\text{2j-1,l}} \leq 1, \text{ for all i,j} \in [1,4] \text{ and i} \neq \text{j}$$

- Having constraints on both left variables can avoid collisions where different roads try to turn left at the same time.

$$\mathbf{x}_{\text{2i-1,l}} + \mathbf{x}_{\text{2j-1,l}} \leq 1, \text{ for all i,j} \in [1,4] \text{ and i} \neq \text{j}$$

III. Problem Statement

Given a directed graph of road network G = (V, E, W) with vertices as signals at intersection, edges as directional paths between vertices, weights as traffic aggregation on directed edge

Find subset of edge activations across different signal vertices to clear maximum possible aggregated traffic

IV. Algorithm

Traffic signal system relies on ILP optimization model for clearing maximum possible traffic at an intersection. Figure 2 shows the high level design of this relation.

- The system requests the ILP optimization model for a signal configuration
- Optimization model maximizes the objective, providing ideal configuration for signal setting
- System takes back this configuration and enables the signals for minimum time between time period of phase of signal cycle T or sufficient amount of time required to clear the traffic.
- The system also observes the outflow edges, whether these are filled up by inflow edge traffic. In such case, the system synchronizes the next intersection to clear this traffic.
- This synchronization is done by manipulating the priority constant, giving preference to the recently filled outflow edge.

V. Analysis

ILP optimization model is implemented using the interior-point method. The time complexity of this algorithm is $O(n^{3L})$ where n is the number of variables used in ILP and L is the number of iterations taken by the algorithm to converge to the solution. The space complexity of the optimization algorithm is $O(n^3)$

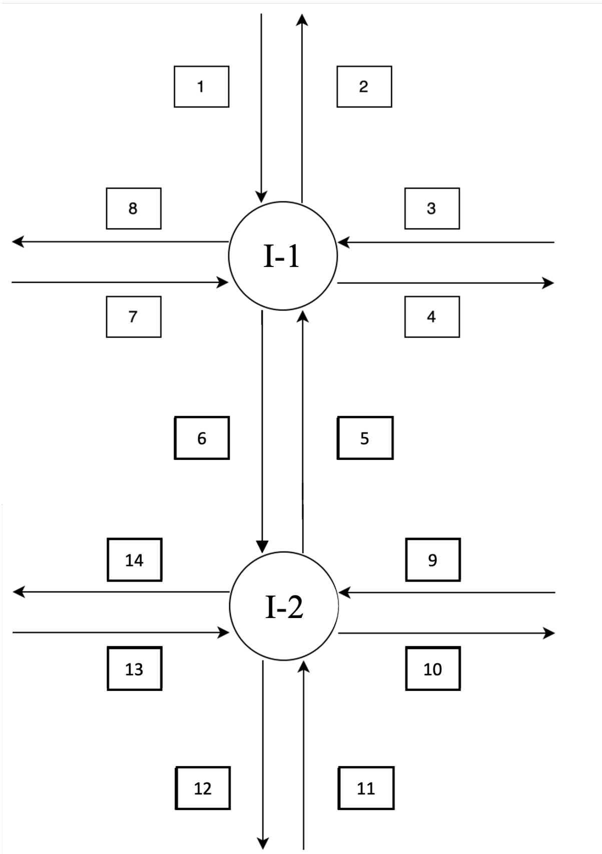

Fig. 3. 2 Intersection road network graph

VI. SIMULATION

We have simulated the traffic signal system in 2 modes

- Conventional repetitive cycle traffic signal system
- ILP optimized synchronized traffic signal system

Both these modes have assigned weights along all inbound edges of the intersections I-1 and I-2. All vehicles travel with the speed of road speed limit and the distance required for vehicles to clear the intersection is assumed to be 0.01 miles. These parameters are used to calculate the time required for vehicles to clear the intersection. Another assumption under this simulation is that new weights don't get added to the road edges and the optimization model only tries to clear current on road traffic.

A. Conventional traffic signal system

Figure 3 Two intersection model is simulated with a conventional traffic signal system. This signal cycle has 120s for all phases/combinations, each phase running green signals for a duration of 30s per phase. We have simulated the signal that happens with these 2 combinations shown in Figure 4 and computed the time required to clear all the traffic at both intersections. This 2-intersection model at I-2 also handles the outflow of the I-1 intersection and produces a possible range of when signal at intersection I-2 will clear this traffic of I-1. Additionally, we also configured the phase times to be equal to the time required instead of 30s per phase, to perform a comparative analysis between the synchronized model discussed below.

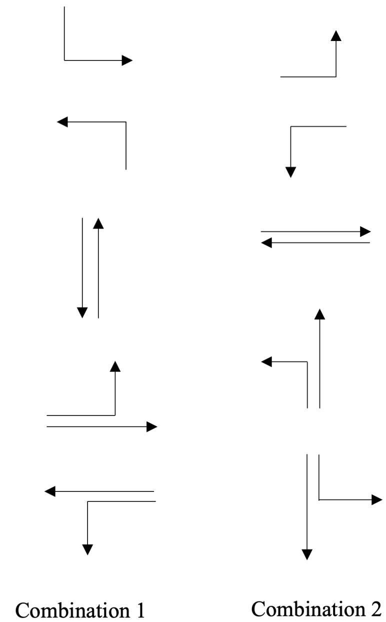

Fig. 4. Combinations of conventional traffic signal system

B. ILP Synchronized traffic signal system

This model doesn't require following any combination, but the ILP optimization model produces this combination based on the constraints or no collision. And the model produces a combination that clears maximum traffic at an intersection. Both intersection I-1 and I-2 have the same phase in the synchronization model and whenever the outflow of common edges is filled up, the ILP optimizes the solution such that the paths between I-1 and I-2 are synchronized. The phase times of the signals between these two intersections are the time required for certain combinations produced by the ILP model to clear the intersection.

VII. RESULTS

We have found out that the synchronization ILP model requires significantly less time to clear the traffic at both the intersection I-1 and I-2, compared with the 30s phase cycle of the conventional traffic signal system. Such a significant difference is observed because both traffic signal systems work in a synchronous fashion with common phases and there is no wasted wait time that keeps the signal enabled when it's unnecessary. Moreover, if the conventional traffic signal system uses the minimum time required to clear road traffic, instead of a 30s phase cycle, the synchronized system performed better compared with the modified version of a conventional system. These times are shown in Table 1 and Table 2.

TABLE I
RESULTS OF CONVENTIONAL TRAFFIC SIGNAL SYSTEM

Phase Times	Time to clear traffic	
	Combination 1	***Combination 2***
30s	I-1 = 240s	I-1 = 240s
30s	I-2 range [240s - 480s]	I-2 range [240s - 480s]
min time	I-1 = 98s	I-2 = 98s
min time	I-2 range [167s - 287s]	I-2 range [152s - 272s]

TABLE II
RESULTS OF SYNCHRONIZED TRAFFIC SIGNAL SYSTEM

Phase	Time to clear traffic
min time	I-1 and I-2 = 60s

VIII. CONCLUSION AND FUTURE SCOPE

The results show that the synchronization model works and can produce efficient times to clear traffic in large-scale road network systems. Our future work will further be on simulating the synchronization ILP model on bigger road networks and evaluating the results with real-time data. Moreover, the simulation only worked on clearing the traffic present on the road, with the assumption of new traffic doesn't flow in, which would be another key area of improvement for the future scope of this research

REFERENCES

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