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DETERMINATION OF OPTIMUM SIGNAL PLAN SEQUENCES IN A TRAFFIC CONTROL SYSTEM: METHOD AND RESULTS

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Abstract: In this paper a method for the determination of optimum signal plan sequences for a network of signalized intersections is described. The method developed for the improvement of a fixed-time traffic control strategy is based on the Dynamic Programming technique. The results of its implementation in the Moscow traffic control system (START) are also presented. Nowadays, the majority of researchers are oriented towards real-time traffic control systems. However, we found it worthwhile to improve fixed-time traffic control strategy performance bearing in mind the following facts: (1) most area traffic control systems use a fixed-time strategy, at least during the first phase of system implementation; (2) this strategy remains in effect as the standby control strategy in case of the failure of traffic detectors (which are necessary for any of the more complex traffic control strategies). This paper presents the method we developed to improve the fixed-time control strategy, based on the Dynamic Programming technique.

Keywords: Traffic control, optimization, dynamic programming.

1. INTRODUCTION

Within the scope of joint research in the traffic control field, performed by Mihajlo Pupin Institute, Belgrade and Mosgortransniiprojekt, Moscow, a method was developed for the determination of optimum signal plan sequences for a network of signalized intersections (OPNIZ [1]), and applied in the Moscow traffic Control System (START).

In a fixed-time traffic control strategy, network signal plans are calculated for a number of characteristic traffic situations and an appropriate signal plan is implemented for a given situation when such a situation arises. This is achieved by applying a timetable. This means that it is assumed that the traffic process under control is stationary in the interval during which a particular traffic situation exists in the network. However, evidence and experience from existing traffic control systems and results gained by simulation have shown that these intervals should not be too short because any change from one signal plan to another causes an extra delay for every vehicle in the network (about 0.5 min per vehicle; Holroyd [2]). Bearing in mind these additional losses, the OPNIZ method was developed for determining optimum sequences in time of signal plans in a network. Optimum signal plans for characteristic situations are calculated using the well-known and widely used TRANSYT program [3], whilst the optimal sequence of plans is determined using dynamic programming. The objective function in determining the optimal sequence of plans is the total delay in the network during a chosen period. The method developed has been in operation in the START system for several years, and has shown good results. This paper presents a description of the method and the results obtained.

2. DESCRIPTION OF THE METHOD

The OPNIZ method determines the optimum sequence of signal plans for a chosen time period (usually one day). The time period is discretized and divided into K equal time intervals. The intervals, indexed from 1 to K, have duration Δ, which is greater than the longest cycle time in the network. It is assumed that the traffic process parameters are known and constant in any interval k, k=1,2,...,K. They are: traffic volumes at all signalized intersection approaches, and free flow speeds between adjacent signalized intersections. The values of traffic parameters are used to calculate the optimum signal plan for each interval. The method for optimum signal plan calculation applied here is TRANSYT. Thus, a set of precalculated signal plans, U, is formed, i.e.:

$$U = \{u_1, u_2, ..., u_k, ..., u_K\} \tag{1}$$

where u_k is the optimum signal plan for traffic parameter values that exist in the k-th interval.

The optimization criterion for determining the best sequence of signal plans is defined as:

$$F(u^1, u^2, ..., u^K) = \sum_{k=1}^{K} \varphi^k(u^k)\Delta + \psi^k(u^k, u^{k+1}) \tag{2}$$

where:

u^k - the signal plan applied in interval k

$\varphi^k(u^k)$ - the losses per unit of time when signal plan u^k is applied

$\psi^k(u^k, u^{k+1})$ - the losses due to signal plan change from plan u^k to u^{k+1}:

$$\psi^k(u^k,u^{k+1}) = \begin{cases} 0, & u^k = u^{k+1} \\ bp^k, & u^k \neq u^{k+1} \end{cases} \quad \text{for } k = 1,\dots,K-1 \tag{3}$$

$$\psi^K(u^K,u^{K+1}) = 0 \quad \text{for } k = K$$

where:

b - the average increase of losses per vehicle in the network due to signal plan change (coefficient of losses)
p^k - the number of vehicles in the network in interval k.

The losses per unit of time $\varphi^k(u^k)$, and the number of vehicles, p^k, in each interval $(k = 1,2,\dots,K)$ are obtained by running the TRANSYT program, with the input parameters being the values of volumes, q^k, and speeds, v^k, known for each interval k.

Now, the problem of determining the optimum sequence of signal plans can be stated as follows:

Find the sequence $u^1, u^2, \dots, u^K$, which will minimize

$$F(u^1, u^2, ..., u^K) = \sum_{k=1}^{K} \varphi^k(u^k)\Delta + \psi^k(u^k, u^{k+1}) \tag{4}$$

subject to

$$u^k \in U\ ,\ k = 1,2,\dots,K \tag{5}$$

At first sight, the problem could be solved by direct enumeration of all possible signal plan sequences. But the number of all possible sequences is quite large and equal to the number of variations of K elements. Therefore, the problem is solved using the dynamic programming technique [4]. Since the criterion is additive and the process is Markovian (i.e. the optimum sequence has the property that whatever the initial state and initial signal plan are, the remaining signal plan sequence must constitute an optimal sequence with regard to the state resulting from the first signal plan), the Principle of Optimality can be applied, and the following recurrence relationship can be written:

$$f^{K-i}(u^{K-i}) = \min_{u^{K-i+1}} \{\varphi^{K-i}(u^{K-i})\Delta + \psi^{K-i}(u^{K-i}, u^{K-i+1}) + f^{K-i+1}(u^{K-i+1})\}$$
$$\text{for } i = 1,2,\dots,K-1 \tag{6}$$

$$f^K(u^K) = \varphi^K(u^K)\Delta\ ,$$

and $u^{K-i} \in U$, $u^K \in U$, $i = 1,2,\dots,K-1$.

The solution of the stated problem is obtained using $f^{K-i}(u^{K-i}),\ i = 1,2,\ldots,K-1$ and bearing in mind that

$$\min_{u^1,u^2,\ldots u^K} F(u^1,u^2,\ldots,u^K) = \min_{u^1} f^1(u^1) \tag{7}$$

where $u^1 \in U$.

3. APPLICATION OF THE METHOD IN THE MOSCOW TRAFFIC CONTROL SYSTEM

The first part of the START traffic control system in Moscow is in operation, covering 164 signalized intersections in the central business district. Intensive flows, high saturation degrees, and many points on which traffic conditions are close to congestion characterize this area. On most of the intersections 3- or 4-phase control is applied.

The street network has a radial-ring structure. Residential parts are located on the outskirts of the network, and working areas occupy the central part. Therefore, traffic flows have characteristic changes of direction during a day.

The whole area is divided into six subareas, operating independently one from another. As an example, the subarea 2, comprising 28 signalized intersections, is shown in Fig. 1.

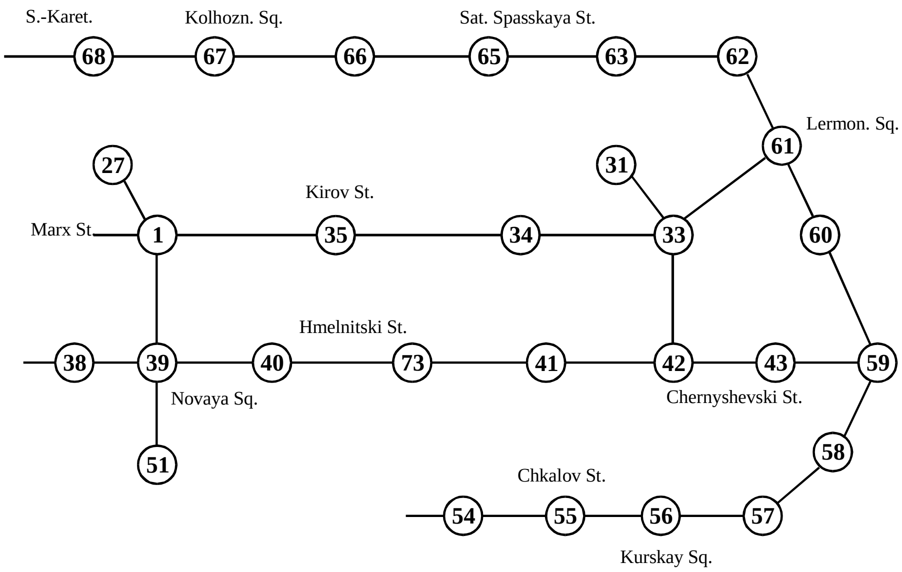

Figure 1: Schematic representation of subarea 2 in the Moscow START system

In each subarea a library of signal plans exists, such that each plan is most appropriate for a given interval during a day. In accordance with the diagrams of traffic flows, eight intervals during a day were distinguished during which the traffic process could be considered stationary, and the set of optimum signal plans was calculated using the TRANSYT program. This means that the following sets of signal plans were calculated: $U_j = \{u_{j1}, u_{j2}, ..., u_{jk}, ..., u_{jK}\}$, $j = 1,2,\ldots,6$, where j stands for subarea index, and K=8 is the number of intervals. Then the OPNIZ method was used to determine the daily sequences of signal plans. The results of OPNIZ application in subarea 2 are presented in Table 1.

Application of the OPNIZ method has proved to be efficient. It reduced vehicle total time loss in the network during a day, and reduced the number of signal plans necessary to be calculated (and updated, periodically).

Table 1: OPNIZ results

Traffic situations during a day	The optimum plan calculated for the interval, subarea 2	The optimum sequence of signal plans to be applied in subarea 2
1	u_{21}	u_{21}
2	u_{22}	u_{22}
3	u_{23}	u_{22}
4	u_{24}	u_{24}
5	u_{25}	u_{23}
6	u_{26}	u_{24}
7	u_{27}	u_{27}
8	u_{28}	u_{26}

Assessment of the decrease in time loss was performed in the following way. Firstly, losses without applying the OPNIZ method were estimated. In this way, the losses in each interval were minimized separately, but during signal plan changes significant losses arose, proportional to the number of vehicles in the network. The coefficient of losses was assumed to be 0.5 min/veh. Application of the OPNIZ method showed that only 4 or 5 signal plans were necessary for daily control, although 8 had been calculated. The losses in some intervals did increase by a small amount, but the additional losses due to signal plan changes were reduced since the number of signal plan changes decreased.

A summary of the obtained results is presented in Table 2. It presents the difference between the performance measure values obtained with the OPNIZ method, and the values obtained with "independent" optimum signal plans implemented in each of the 8 intervals. The range of differences shows that the effects were different in the subareas considered.

Table 2: Comparison between the OPNIZ sequence and the sequence of "independent" optimum plans

Performance measure	Diff.
Decrease in time losses (%)	6-9
Decrease in fuel consumption (%)	15
Decrease in CO emission in air pollutants from vehicles during a day (t)	3
Decrease in the number of signal plans used for control (%)	25-50

4. CONCLUSIONS

The results of the OPNIZ application in Moscow's Centralized Traffic Control System START have shown that this method has practical and concrete value, and can be used for network traffic control in modern automatic traffic control systems. For example, in the first phase of developing any traffic control system, when traffic data detectors are not calibrated and the traffic control strategy of a traffic-responsive type is still not operational, this method ensures good results of the fixed-time traffic control strategy. Also, it has practical value in cases when the detectors used for signal plan selection are out of order, and during periods with small traffic volume, during weekends, etc.

The results of the OPNIZ application in the START system show that better results can be achieved using this method than using classical fixed-time control. Thus, the OPNIZ method enables low-cost improvement of control even before traffic-responsive strategies are introduced in a traffic control system.

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