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EXPERT INFORMATION PROCESSING SYSTEM FOR TRAFFIC LIGHT SYSTEM DECISION-MAKING WITH ADAPTIVE CONDITIONAL TRAM PRIORITY

The article considers the problem of taking into account the dynamics of a tram with a dedicated right of way as it approaches an intersection to provide conditional traffic signal priority with respect to the private transport flow saturation before the intersection. The expert information processing system for the intersection traffic lights system is developed. Decision-making rules regarding the adaptation of the traffic signal plan time parameters based on the interoperability of the signals and their importance have been proposed. The information processing system is implemented and validated using the SUMO urban mobility simulation tool for moderate and saturated transport demands for an artificial intersection.

1. Introduction

Recently, with the growing prevalence of personal transport in densely populated regions and the need to preserve depletable energy resources, the problem of efficiently moving large amounts of people is becoming more and more urgent. An urban transport network operates in a balance between private (PT) and public transport or mass transit (MT). In the highest demand hours, due to the limited spatial resources in the urban environment, PT is sometimes no longer able to meet the mobility needs of an urban agglomeration due to congestion [1], therefore, the minimization of personal costs (time, monetary, etc.) of moving those involved in economic processes is associated with a decrease in commute time using alternative transport links that do not depend on the conditions of private vehicles traffic. This effect, known as the Downs-Thomson paradox [2], [3], is particularly noticeable in areas with a significant share of public transport with dedicated or separate right of way (ROW) in urban commuting [4].

One of the main differences between MT with dedicated ROW and PT is that higher crowding is not associated with an increase in commute time using MT, on the other hand, it is the attractiveness of this commuting mode that may decrease (the substitutability of the modes varies according to social, geographical, etc. factors [5]). Conversely, reducing commute time, hence increasing the frequency of transport service can contribute to the attractiveness of MT, reducing the share of PT in urban mobility. Among the associated benefits of strengthening the role of MT in the transport network, in particular, via the implementation of transit signal priority, it is worth noting the growth of economic activity, improvement of the quality of the urban environment, reduction of the negative impact on the environmental conditions of an urban agglomeration, etc. [6].

In the case of intersecting traffic flows at a signalized at-grade crossing, a decision-making model for a traffic light system with a priority for public transport, specifically a tram, is intended to reduce its delay at the signals [7]. In addition to passive and active transit signal priority (TSP) [8], for a few years a distinctive real-time or adaptive priority has been considered. It iteratively computes signals sequence and their duration (traffic light plan), relying on both system-wide traffic characteristics such as time losses, halts, etc., and local MT vehicle characteristics [9]. A typical decision-making model in a traffic lights system with adaptive TSP interacts with the following components:

- detectors and interactors for MT vehicles;
- general traffic vehicles detection system;
- priority request servers and generators, control system with adaptive traffic signal plans.

The model itself implements a decision-making algorithm for traffic lights that considers the impact on general traffic and ensures pedestrians' safety. By definition, a TSP-capable traffic light will not adversely affect the coordination of traffic signals [10].

Most modern systems implementing TSP operate in a coordinated way as part of urban traffic control (UTC) systems in real time. Existing control systems with real-time TSP can be viewed as two categories [11]:

- with a constant length of traffic light cycle (rule-based) [12], [13], time parameters are gradually adapted to fluctuations in traffic conditions in real time;
- with a variable cycle length (optimization-based) [14]–[16], adaptive commands continuously optimize the traffic signal plan using the rolling horizon method [17].

Since the traffic flow characteristics definition is naturally associated with uncertainty and some degree of imprecision, and traffic at a particular intersection is controlled according to certain rules, fuzzy control may be the most natural way to solve this problem. In addition, based on expert knowledge rather than modeling a directly controlled process [18], decision-making for a traffic lights system provides control reducing computational costs. Existing studies mainly consider the application of fuzzy computing-based expert systems to adaptive decision-making in a traffic lights system in general, without a detailed focus on the TSP problem [19], [20]. The existing methods explicitly implement TSP-oriented decision-making [21], [22] based on soft computing [23] using a fixed traffic light cycle duration and/or predefined traffic light stages (phases). This inevitably imposes limitations on decision-making adaptiveness. In the papers mentioned above, the MT mainly considered does not have a dedicated ROW, therefore the use of MT vehicle dynamics data is not appropriate in these studies.

The paper [24] proposes the expert system for a signalized intersection with an unconditional tram preferential treatment that utilizes the model of a tram dynamics approaching an intersection [25], however under a high transport flow intensity, the application of the unconditional priority may cause secondary delays of MT as a result of a waiting queue length increase and impracticability of its safe discharge interruption later. The study aims to develop an expert information processing system implementing a conditional tram priority on a signalized intersection. To achieve the defined goal, it is necessary to:

- formulate the rules base for fuzzification and decision making in the expert system;
- ensure the adaptation of the system to the diversity of possible intersections, traffic flow intensities, and tram routes configurations;
- implement the conditional minimization of tram passengers' time losses and schedule deviance with respect to traffic light signals controlling the private transport traffic flow;
- ensure the system's resistance to temporary non-standard traffic conditions.

2. Decision-making model for traffic lights system with conditional tram priority

The fuzzy inference-based expert system with a tram priority consists of two levels [24]:

- level of active signals time parameters inference;
- level of the signals activations order inference.

According to the transit signal priority system definition [10], the model's second level must ensure the coordination of traffic signals and not allow simultaneous traffic flows in conflicting directions. This study utilizes a flexible, signal groups-based coordination approach [26], where interoperability of signal groups (SG) is defined by a conflict matrix (Fig. 1), and non-zero values are visually highlighted. The values in this matrix denote the minimum required clearance interval between the pair of signal groups and are identical to those used in [24]. Such an approach allows the real-time generation of permissive signals sets depending on transport demand, minimizing unused signals which may occur during operation under the fixed, pre-defined signals sets (stage-based approach).

Figure 2 describes the information processing framework by the production model of decisions s1..s3(t),

ID	0	1	2	3	4	5	6	7	8	9	10	11	12
0	0	2	1	2	2	0	1	0	2	1	1	0	2
1	5	0	5	2	2	2	2	0	0	2	2	2	3
2	1	2	0	2	2	1	1	0	2	0	1	2	2
3	5	3	5	0	0	5	0	0	3	0	0	2	2
4	5	3	5	0	0	5	0	0	3	0	5	2	0
5	0	2	1	2	2	0	0	0	2	0	1	0	2
6	1	2	1	0	0	0	0	0	2	0	1	2	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0
8	5	0	5	3	3	5	5	0	0	5	5	3	3
9	1	2	0	0	0	0	0	0	2	0	0	2	0
10	1	2	1	2	2	1	1	0	2	0	0	2	2
11	0	3	5	0	2	0	5	0	3	5	5	0	0
12	5	4	5	2	0	5	0	0	4	0	5	0	0

Fig. 1. Conflict matrix (in seconds)

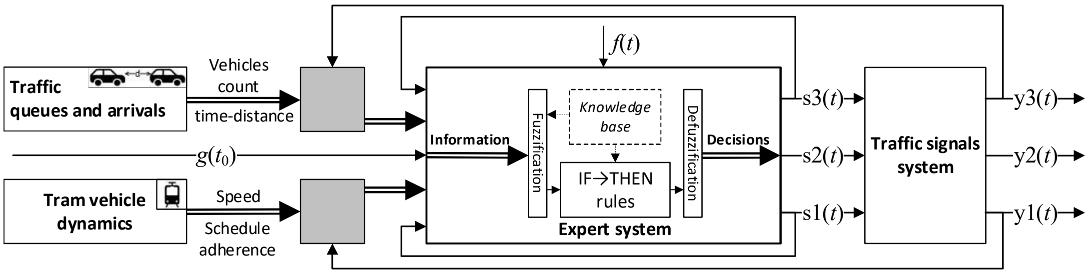

Fig. 2. Information processing framework for the expert system of traffic signal control

then passed to the traffic lights system. The expert system activates the visual signals controlling the dynamics of tram movement, PT, and pedestrian flow with separate type of visual signals provided for each category of road users denoted respectively as y1(t), y3(t), and y2(t) while s1(t), s3(t), and s2(t) are the outputs of the expert system. The initial conditions of the traffic lights system are defined by a parameter $g(t_0)$. In general, the expert decision being received by the traffic lights system is a set $\cup\, s_i$ of SG identifiers, treated as an active stage S_j. The decision-making model considers the PT flow and tram(s) in an active way for each s_i, and passively considers the accidental disturbance $f(t)$ caused by a pedestrian briefly affecting the dynamics of a tram.

The SG activation order is defined by their importance (weight) w only, which is inferred on the model's second level [24] using the Mamdani algorithm. Most of the time signal stages are filled up according uniquely to their weights and conflict matrix CM. Each SG can be assigned to one stage only:

$$s_i \in S_j : S_{a=k} \cap \left(\bigcup_{b \neq k} S_b \right) = \varnothing .$$

Only those SG having zero values at the corresponding rows and columns intersection of the conflict matrix are allowed to be added to the same stage:

$$\forall s_x, s_y \in S_j : \mathrm{CM}[x, y] = 0.$$

The next stage is the one with the highest normalized sum of weights of constituent SGs:

$$S_A = \arg\max_i \left(\left\| \sum_{s_i \in S_j} w[s_i] \right\| \right).$$

The model's first level (Fig. 3) also utilizes the Mamdani inference algorithm and decides on the SG time parameters for previously defined stages. The fuzzy production rules for the intermediate Extend or Terminate decision concerning permissive $s3_{i+}$ are defined as in the FUSICO project [27] and they depend on prohibitive SG weights sum, permissive signal duration $t(s3_{i+})$, and time gaps between PT vehicles at the entry and the traffic lane's stop line detectors $dN(s3_{i+})$ and $dT(s3_{i+})$ respectively.

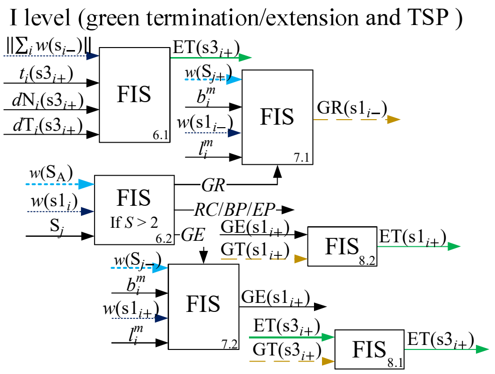

Fig. 3. Diagram of the first level of the model

To minimize tram time losses, the intermediate decision is produced both for prohibitive and permissive SG. If the number of stages exceeds 2, which is always the case except for the simplest intersections, the decision concerning action type is inferred depending on the tram SG weight as well as the current stage weight. The action types are defined as follows: run the Rapid Cycle, keep the Basic Plan, add an Extra Phase to only serve the waiting tram, perform a Green Recall to terminate the conflicting signal group(s), or Extend already running Green signal to allow the tram to proceed without a halt. If the intermediate decision being generated has the value GR or GE, this decision confidence degree is further produced by taking into consideration tram dynamics and SG weights (Fig. 4) [24].

The potential conflicts between priority requests from prohibitive SG $s1_{i-}$ during an active $s1_{i+}$ are resolved according to the rules in Table 1. For the case of a conflict with an active $s3_{i+}$ we propose the corresponding rules (Table 2).

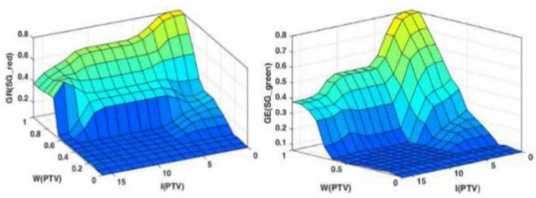

Fig. 4. Reaction functions for SG $s1_{i-}$ and $s1_{i+}$ decision-making (FIS 7.1 and 7.2)

Table 1

$GE(s1_{i+})$	$GT(s1_{i+})$				
	Wait	RatherWait	NotSure	RatherTerminate	Terminate
Wait	Terminate	Terminate	Terminate	Terminate	Terminate
RatherWait	RatherTerminate	RatherTerminate	RatherTerminate	Terminate	Terminate
NotSure	NotSure	NotSure	NotSure	RatherTerminate	Terminate
RatherExtend	RatherExtend	RatherExtend	RatherExtend	RatherExtend	RatherExtend
Extend	Extend	Extend	Extend	Extend	Extend

Table 2

$ET(s3_{i+})$	$GT(s1_{i+})$				
	Wait	RatherWait	NotSure	RatherTerminate	Terminate
Terminate	Terminate	Terminate	Terminate	Terminate	Terminate
RatherTerminate	RatherTerminate	RatherTerminate	RatherTerminate	Terminate	Terminate
NotSure	NotSure	NotSure	NotSure	RatherExtend	Terminate
RatherExtend	RatherExtend	RatherExtend	RatherExtend	NotSure	Terminate
Extend	Extend	Extend	Extend	Extend	RatherExtend

Figure 5 specifies the membership functions for fuzzy decisions regarding the extension or termination of a signal group. The threshold of decision application is defined at 0.5.

3. Modeling results analysis

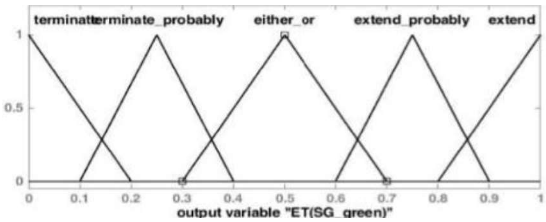

Fig. 5. Membership functions of fuzzy decision on s_{i+}.

For the applicability study, the decision-making system providing unconditional adaptive preferential tram treatment proposed in [24] is used as a baseline. The modeling was performed for the same intersection using the SUMO tool [28] and the demand parameters remain unchanged. More details on the experiment itself and its conditions are provided in [24].

Comparing tram time loss distributions, the application of conditional priority significantly increases the delay experienced by tram vehicles during off-peak periods (Fig. 6). However, the difference between passenger delays is not so significant (using a non-parametric test yields a p-value of 0.12). The following Table 3 generalizes the characteristics of tram traffic in non-peak conditions.

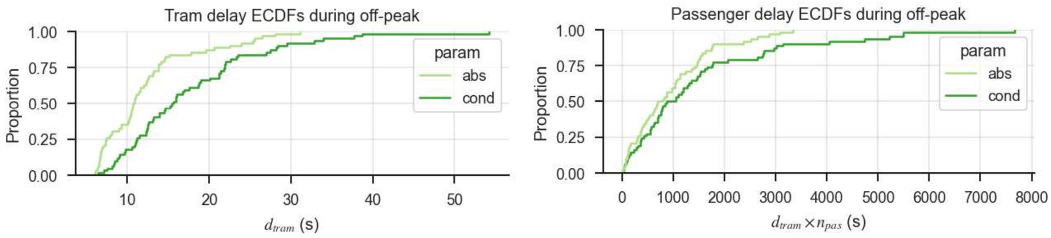

Fig. 6. Comparison of non-peak trams and passengers time losses under different priority types

The switch to conditional priority is associated with approximately a 50 % tram time loss increase, while the time loss experienced by all passengers in it increased only by 35 %. The number of complete halts is higher by 1.5 times and the crossing speed is dropped by 15 %.

Table 3

line	TramTimeLoss (s)		PasTimeLoss (s)		HaltsPerTram		Speed (kph)		priority
	median	std	median	std	mean	std	mean	std	
T1	15.89	8.71	1496.79	1764.84	0.54	0.58	18.21	4.01	cond
T2	13.16	11.43	558.78	683.54	0.47	0.51	20.28	5.01	cond
T3	14.62	6.72	1058.0	1686.0	0.63	0.5	20.37	4.2	cond
T1	11.58	4.6	1070.16	868.34	0.19	0.4	21.21	2.83	abs
T2	10.09	7.95	382.08	478.16	0.24	0.44	22.85	5.49	abs
T3	7.4	5.3	821.06	812.94	0.21	0.42	24.91	3.67	abs

The characteristics of private transport flow are compared as a difference between the vehicle queue size under unconditional (abs) and conditional priority types. To reduce minor fluctuations and have a clearer view of the general trend, the data was downsampled to 3 minutes (Fig. 7). In both cases under the off-peak demand, the difference in queue size is negligible and the mean value is around 0.

The following Table 4 is a summary of the queue length on the busiest lanes of the intersection in non-peak conditions. The conditional priority has al most no effect on the queue lengths for off-peak demand.

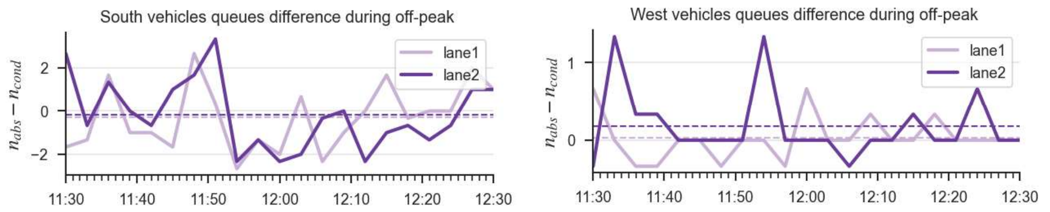

Fig. 7. General traffic time characteristics difference between different priority types under off-peak conditions

Table 4

origin	lane	nVehWithin		priority	nVehWithin		priority
		mean	std		mean	std	
S	1	2.1	1.47	cond	1.75	1.57	abs
S	2	3.08	2.56	cond	2.87	2.35	abs
W	1	0.49	0.72	cond	0.52	0.85	abs
W	2	0.34	0.66	cond	0.52	0.81	abs

Compared to the off-peak conditions, the distribution of tram delay during the peak demand under the conditional priority remains almost the same (Fig. 8), while passenger delay ECDFs follow each other very closely and the difference is still not significant with a p-value close to 0.10.

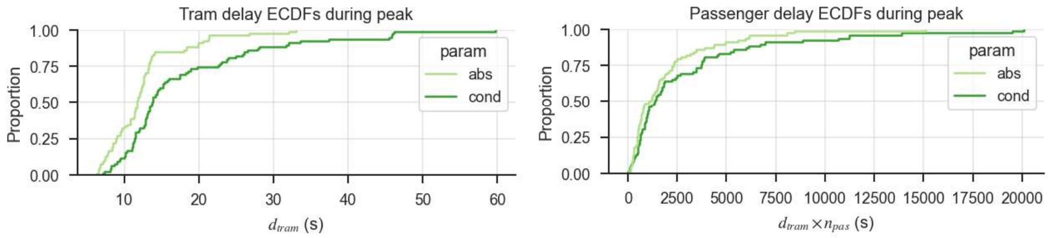

Fig. 8. Comparison of peak trams and passengers time losses under different priority types

Table 5

line	TramTimeLoss (s)		PasTimeLoss (s)		HaltsPerTram		Speed (kph)		priority
	median	std	median	std	mean	std	median	std	
T1	14.06	12.19	1748.84	5394.21	0.38	T1	14.06	12.19	cond
T2	13.83	10.92	1450.8	2979.62	0.52	T2	13.83	10.92	cond
T3	11.48	6.54	1079.5	1252.35	0.48	T3	11.48	6.54	cond
T1	13.02	5.79	1785.32	3274.74	0.28	T1	13.02	5.79	abs
T2	10.87	4.2	820.88	1244.44	0.14	T2	10.87	4.2	abs
T3	9.0	3.39	698.03	956.78	0.08	T3	9.0	3.39	abs

Table 5 contains a summary of the tram traffic characteristics during the peak demand. Unlike unconditional priority, the conditional way manages to decrease the delay of trams compared to the off-peak conditions. The average increase of tram delays after switching to the conditional priority is less than 20%, and respective passenger time loss is increased by 43%. Compared to unconditional priority, the reduction in the speed at which trams run through the intersection decreases by 12%. Even with a slight increase in time losses relative to unconditional priority, the difference with non-adaptive reference methods presented in [24] is still considerable, e.g., compared to vehicle-actuated decision-making decrease of median tram losses is expected to be 40% and time losses of tram passengers decrease by 25%.

As for the private vehicle traffic, under the peak demand, for the busiest southern lanes, the conditional priority has a clear advantage as it reduces queue length significantly (Fig. 9). This can be seen as the average difference being above zero and in the middle of the simulation thus in the highest traffic the difference rises above 3 vehicles. For the western lanes, the difference is more centered around zero for the whole simulation.

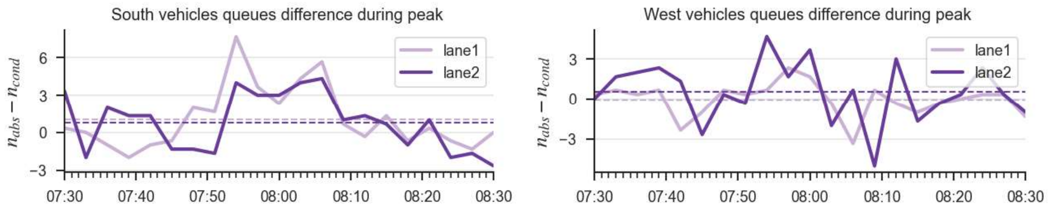

Fig. 9. General traffic time characteristics difference between different priority types under peak conditions

As shown above, the only significant decrease in average queue length and its spread is observed for the southern lanes (Table 6), which makes the application of suggested conditional priority only reasonable in very busy traffic, so that the negative impact on it is less than under the unconditional priority with comparable tram and passengers time losses.

Table 6

origin	lane	nVehWithin		priority	nVehWithin		priority
		mean	std		mean	std	
S	1	3.0	2.28	cond	4.21	3.61	abs
S	2	3.53	2.7	cond	4.49	3.47	abs
W	1	1.11	1.72	cond	1.08	1.69	abs
W	2	2.59	2.35	cond	3.0	2.55	abs

Conclusions

The application of the proposed expert information processing system for a traffic light system decision-making with an adaptive conditional priority of the tram as MT with dedicated ROW is appropriate for saturated traffic conditions and allows the reduction of PT vehicles queues at traffic lights with a slight increase in tram passengers time losses, which, however, are lower than in the case of the non-adaptive decision-making.

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