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Preemptive Traffic Light Control based on Vehicle Tracking and Queue Lengths

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***Abstract*—Today it is possible to implement adaptive traffic light control as part of intelligent transport systems with the goal to reduce the respond times of emergency services. This allows preemptive traffic light control in an effort to reduce travel times of emergency vehicles in urban areas and negative effects on the total travel times of all vehicles in the traffic network. In this paper, a new algorithm for preemptive traffic light control is proposed. It is based on emergency vehicle location and intersection queue length data. Using these data the algorithm dynamically adapts the signal program of a signalized intersection. Proposed algorithm is tested in four different scenarios using a realistically simulated isolated intersection as a use case. The analysis of the obtained results reveals that travel times of emergency vehicles can be reduced up to 13 %. In the same time, the negative effects on the total travel time of all vehicles in the network can be reduced or even compensated.**

***Keywords*— Intelligent transport systems, Preemptive traffic light control, Microscopic simulation, Urban intersections**

I. Introduction

Traffic in urban areas is primarily controlled with traffic light control systems. Each signalized intersection has a signal controller with an implemented appropriate control logic, i.e. signal program. It changes the traffic lights in a cycle that repeats itself and can be fixed (sequence order of phases and the length of the signal cycle remains the same regarding the traffic situation) and adaptive (according to the current traffic situation the length of phases, their order sequence and cycle length can be modified). According to [1] and [2], 50 % of overall delay in urban areas are caused by incorrect/inadequate signal programs. In order to reduce the overall delay, adaptive traffic control is used. Such adaptive traffic control can be applied for preemptive traffic light control, e.g. for assignment of priority to an emergency vehicle (EV) with the goal to reduce the respond times of emergency services.

Priority assignment strategies on signalized intersections are nowadays being implement as part of intelligent transport systems used for control of urban traffic. According to [3], priority assignment strategies are defined to be active, passive and unconditional priority strategies. Regarding the current traffic situation (queue length, vehicle speed, phase duration, etc.), optimization of signal programs can be achieved, but phase extension must fulfill the constraints of minimum green times for all approaches [4]. A similar approach in [5] was defined for public transport (PT) priority, which can be used for emergency vehicles also. The most common active priority strategy is according to [6] the green extension strategy, with the maximum extension of green time of up to 20 [s].

The reduction of travel times for EVs is essential for improving the response time and one approach is giving priority to EVs on signalized intersections. With active priority strategies, travel times on main approaches for EVs can be reduced overall up to 35 % [7], but the impact on other (secondary) approaches must be considered. In [8], the impact of preemptive priority strategies was measured. It proved that travel times for EVs were significantly reduced, but an increase of delays of other vehicles in average up to 58 % was detected. Therefore, it is necessary to implement rescheduled time recovery so that the traffic situation is normalized in no less than four cycles. In the case of preemptive priority strategies, safety on signalized intersections is decreased also. Therefore, the right recovery strategy must be used.

Most of the preemption systems used today are based on an intersection-to-intersection level, and future work can be focused on the upgrade of signal control through the whole network. But, there are still open problems in optimizing the traffic light control of isolated intersections [9]. In this paper, a new algorithm for preemptive traffic light control for isolated intersections is proposed. It is based on tracking of the EV location and intersection queue length data. The algorithm measures the time rescheduled between the conflicting and non-conflicting phase regarding the route of the EV during priority assignment. After the EV has passed the intersection, the rescheduled time is returned to the conflicting phase according to the ratio of the original durations of the conflicting and non-conflicting phases.

This paper is organized as follows. The second section describes the proposed preemptive control algorithm. Basic features of the implemented simulation framework are presented in the third section. The fourth section presents the simulation setup, obtained results and a short discussion. Conclusion and description of future work end the paper.

II. Algorithm for preemptive traffic light control

The primary goal of the proposed algorithm for preemptive traffic light control is to reduce the travel time of EVs passing through an isolated signalised intersection. Because of the analogy of the methods used in PT preemption such as the one described in [10] they can be used for the purpose of EV preemption also. The proposed algorithm can be separated into two parts. In the first part, preemptive traffic light control and assignment of priority are executed. Second part reduces the negative impacts caused by the first part by the periodic return of rescheduled time. Namely, during the first part, the time of the green phase on the route of the EV is prolonged on account of the other conflicting phase. The time associated with the respective green phase is rescheduled from the conflicting phase to the non-conflicting phase on the route of the EV. This rescheduled time is then returned in the second algorithm part to the green light phase shortened during execution of the first algorithm part.

The first part of the proposed algorithm for preemptive traffic light control operates in three distinct stages: (i) vehicle detection and tracking; (ii) reduction of congestion on the EV route based on queue lengths; and (iii) absolute priority. In the first stage, the EV is detected and tracked. The time needed that the EV reaches the controlled isolated intersection is calculated based on its current speed and location in the network similar to the approach shown in [11]. Main difference to [11] is that in this paper the EV arrival time is used to dynamically change the duration of phases instead of changing the offset. When the calculated arrival time is below a predetermined margin, stage two will start. In this paper the margin is obtained by calculating $TAlpha \cdot CycleLength$, where the value of $TAlpha$ was 3 and the value of $CycleLength$ was 90 [s]. Parameter $CycleLength$ denotes the cycle length of the signal program and parameter $TAlpha$ the number of signal program cycles before the EV arrives at the intersection. This stage is implemented in algorithm 1 at the beginning of the while loop with the first two statements. One has to notice that the EV location and arrival time have to be computed during the whole time the preemptive algorithm is active.

When the second stage starts, all queue lengths on the intersection are obtained first. In the case of a light congestion (short queues), the algorithm will dynamically increase the duration of the non-conflicting signal phase on the EV route in order to reduce the queue lengths on the EV route. In cases of a heavier congestion, the duration of the conflicting signal phase will be reduced in addition to the increase of the duration of the non-conflicting phase. Parameters $sAlpha$ and $sBeta$ are used to determine the congestion levels. In this paper parameters $sAlpha$ was set to 10 and $sBeta$ was set to 15. EV arrival time is still being continuously calculated in this stage and when it falls below of $CycleLength/2$, as set by the parameter $TBeta$ (used value 0.5), stage three will start. The second stage is implemented in algorithm 1 with the first if statement group in the while loop.

As soon as stage three begins, the algorithm will adapt the signal program to assign an absolute priority green light to the non-conflicting signal phase regarding the route of the approaching EV. This green light will stay active until the EV has passed the intersection. When the EV passes the controlled intersection, the second part of the algorithm for preemptive traffic light starts. This third stage is implemented in algorithm 1 with the second if statement group in the while loop.

When the EV passes trough the controlled intersection, it is also necessary to return the traffic to the original state in which it was before the occurrence of the EV. Due to the extension of the non-conflicting phase when the preemptive algorithm was active, the traffic related to the conflicting phase can be congested and its queue longer. For this reason, the time rescheduled when the preemptive algorithm was active, has to be returned back to the conflicting phase in order to reduce this congestion. This time rescheduling is done in small amounts in more consecutive signal cycles in order to keep the traffic flow stable, similar to the algorithm presented in [12]. The key difference to [12] is in the approach of calculation of rescheduled time that has to be returned. In this paper, the rescheduled time is calculated taking into account the ratio of the durations of the conflicting and non-conflicting phase. The following equation is used to compute the rescheduled time that has to be returned:

$$T_{resc} = T_{taken} \cdot \frac{t_1}{t_2}, \quad (1)$$

where T_{resc} presents the total rescheduled time that has to be returned, [s]; T_{taken} is the total time taken from the conflicting phase, [s]; t_1 is the original duration the conflicting phase, [s]; and t_2 is the original duration of the non-conflicting phase, [s]. In the approach proposed in this paper the rescheduled time is always returned according to the ratio of the original green phases durations. That means that the longer lasting green phase will receive more returned rescheduled time to alleviate larger increase of congestion and vice versa.

Algorithm 1: Preemptive traffic light control

```
while EVinNetwork do
  Get: EVSpeed, EVPosition
  Calculate: IntersectionDistance, ArrivalTime
  if TAlpha · CycleLength > ArrivalTime &&
  ArrivalTime > TBeta · CycleLength then
    Get: QueueLength
    if QueueLength > sAlpha then
      Increase duration of non-conflicting phase
    end if
    if QueueLength > sBeta then
      Reduce duration of conflicting phase
    end if
  end if
  if ArrivalTime < TBeta · CycleLength then
    if CurrentPhase == NonConflicting then
      Hold green on non-conflicting phase
    end if
    if CurrentPhase == Conflicting then
      End phase as soon as possible
    end if
  end if
  if EVPosition == AfterIntersection then
    End of algorithm
  end if
end while
```

Algorithm 2: Return of rescheduled time

Calculate: ReschededTime
while $ReschedduledTime \; != 0$ **do**
  Get: CurrentPhase
  if $CurrentPhaseRescheduled > 0$ **then**
    $CurrentPhaseDuration =$
      $CurrentPhaseDuration + TReturn$
    $ReschedduledTime =$
      $ReschedduledTime - TReturn$
  end if
end while
Return to original signal program

Algorithm 2 presents the logic of how the rescheduled time is returned to the conflicting phase. It consists of a while loop in which the duration of the conflicting phase is increased until all rescheduled time is returned. One has to notice here that the computation of rescheduled time in algorithm 2 is executed only once at the beginning of each process to return the rescheduled time and it uses the default phase durations to compute the adapted durations.

III. VISSIM-MATLAB SIMULATION FRAMEWORK

The microscopic simulator VISSIM [13] was used to simulate the isolated intersection. A microscopic simulation allows the simulation of each traffic entity (vehicle, pedestrian, tramway) individually producing realistic traffic scenarios. VISSIM contains all modes of transport (including pedestrians) and their characteristics in one model. Characteristics of vehicles and vehicle drivers allow individual parameterization. VISSIM can be connected using a COM interface with other software tools. These tools can be used for implementation and execution of different traffic control algorithms. In this paper MATLAB [14] is used for this, i.e. to implement and execute the proposed preemptive traffic light control algorithm.

A. Generating and tracking vehicles in VISSIM

At the beginning of each link on the edges of the modeled traffic network in VISSIM, a traffic source object is located. It generates the traffic using a configuration defined by the user.

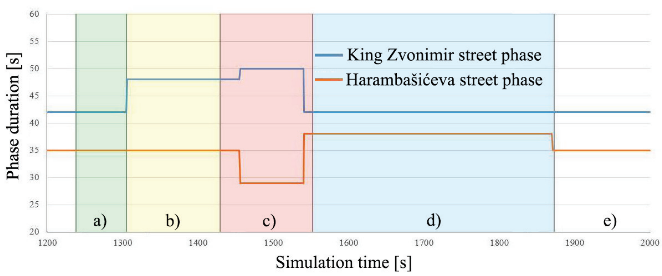

Figure 1. Stages of the preemptive traffic light control algorithm: a) EV detection; b) Congestion reduction; c) Absolute priority; d) Return of rescheduled time; and e) Normal operation.

This configuration includes traffic flow, distribution of vehicle types, driver behavior and distribution of vehicle speeds. To ensure randomness between different simulations, the user can define a different random seed to ensure that the defined amount of vehicles is not always created at the same time.

In order to get the location of the EV during simulation, EV position data were simulated in VISSIM by calculation of the EV position on the respective road link. These position data simulate the GPS data which can be used in a real-world implementation as proposed in [15] and [16]. The EV position was calculated as the distance of the EV from the intersection using the lengths of the road links. In order to implement this method of calculating the EV position, it is necessary to customize the start and end of each road link while designing the intersection and the adjacent road network in VISSIM. Each link must start and finish before the intersection. Connection elements are used to tie up these links. The concept of the method for calculating the EV position is shown in Fig. 2. Equation 2 is used to compute the needed distance:

$$L_R = \sum_{i=1}^{k} L_{Li} + L_{LT} - L_V, \qquad (2)$$

where L_R presents the distance of the EV to the intersection, [m]; k is the number of links between the EV and intersection; L_{Li} is the length of i-th link, [m]; L_{LT} is the length of the link in which the EV is currently located, [m]; and L_V is the distance of the EV to the beginning of the link in which the EV is currently located, [m].

B. Changing signal plans from MATLAB

The input parameters for simulation of the proposed algorithm in MATLAB are the original signal program, queue lengths and EV position data. By using these data, the preemptive algorithm can change the original signal program as needed depending on the position of the EV and the current traffic situation (measured queue lengths). After the signal program is changed, MATLAB sends the parameters of the adapted signal program to VISSIM in order to continue the

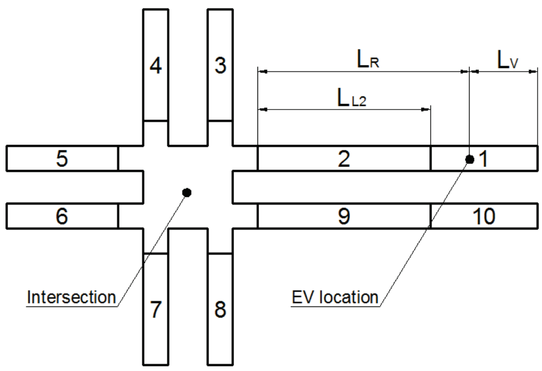

Figure 2. Calculation of the distance of the EV to the simulated isolated intersection

simulation with new simulation parameters or a new signal program. At the end of the simulation, data from VISSIM are used for further in-depth analysis and processing.

The National Electrical Manufacturers Association's (NEMA) standard ring structure was used as a basis for changing the signal program for preemptive control [9]. By using NEMA based traffic controllers and standards it is possible to execute signal programs according to a ring structure with consecutive easy to adapt phase changes. Rings can be defined as a sequence of signal phases that are performed consecutively. The ring structure is expanded in this paper to include data about the protective time interval between phases and the maximally allowed change of the phase durations.

IV. Simulation results and evaluation

In this section, the proposed algorithm will be evaluated using four different scenarios and the simulation framework described above. The influence of the preemptive algorithm was analyzed in different scenarios with respect to evaluation parameters related to EVs, PT and all other vehicles.

A. Simulation model

In order to evaluate the proposed algorithm, a simulation model was created in VISSIM using the data from [17]. The intersection presented in Fig. 3 was chosen because it has: (i) significant difference in traffic demand of primary and secondary traffic flow; (ii) PT (tramways); and (iii) simple fixed time signal program operating in two phases.

The chosen intersection is part of a green wave corridor in the city of Zagreb, Croatia. This corridor is an important horizontal (East-West and vice versa) connection of the City of Zagreb and used by EVs from a nearby hospital. It is also prone to daily reoccurring congestions and therefore important as a use case to test preemptive control on this intersection.

B. Traffic scenarios and traffic data

Algorithm evaluation was done using four different scenarios. In the first and second scenario, the EV travels along the main traffic direction and returns the same way. In the third and fourth scenario EV travels along the main traffic direction and then turns right into a side street at the controlled intersection, and then returns the same way. EV routes for the described scenarios are presented in Fig. 4. Traffic demand for each scenario is shown in Table I. It can be noticed that scenarios one and three have lower, and scenarios two and four have higher traffic demand.

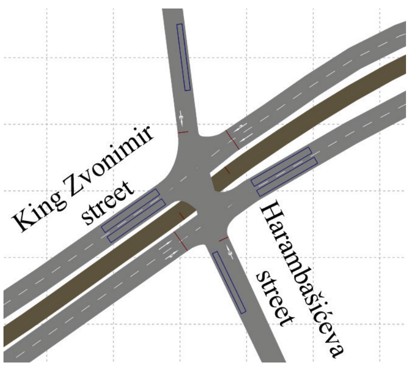

Figure 3. Configuration of the simulated intersection modelled in VISSIM.

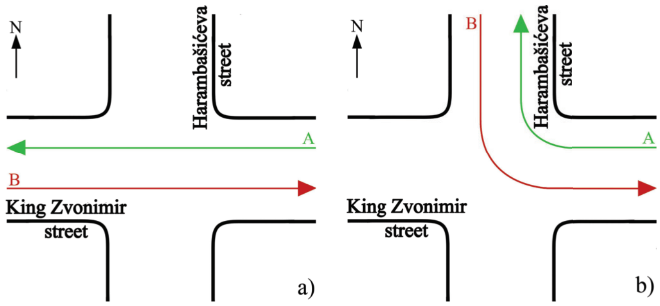

Figure 4. EV route for scenarios: a) one and two; b) three and four.

TABLE I
Traffic demand for each scenario

Scenario	Traffic demand [veh/h]			
	Harambašićeva Street		King Zvonimir Street	
	North	South	East	West
1	220	150	1100	720
2	350	210	1540	1008
3	220	150	1100	720
4	350	210	1540	1008

The simulation of each scenario lasted $1\ h$ with an 15 min warm-up period. The 15 min warm-up period was used to fill the simulated traffic network with vehicles. This warm-up period is excluded from the evaluation of the proposed algorithm. One EV was generated around the 20th simulation minute to perform the entry route and another around the 40th simulation minute to perform the return route. These time points for EV generation were defined to alleviate the detection and tracking of the generated EV.

C. Obtained traffic parameters

Each traffic scenario was simulated 10 times without the use of the preemptive algorithm, with the preemptive algorithm without the return of rescheduled time, and with the preemptive algorithm including the return of rescheduled time. Obtained averaged simulation results are presented in detail in Tables II and III. The following measure of effectiveness (MoE) or traffic parameters that describe the level of service related to EVs, PT (tramways) and all other vehicles were obtained for each scenario: TT_{EV} as the travel time of EVs; NS_{EV} as the number of stops of the EV; LT_{EV} as the lost time of the EV; ST_{EV} as the stop time of the EV; TTT as the total travel time of all vehicles; and TTT_{PT} as the total travel time of PT vehicles.

TABLE II
AVERAGE VALUES OF OBTAINED RESULTS FOR SCENARIOS 1 AND 2

MoE	Scenario 1					Scenario 2				
	No preemption	With preemption		Preemption and return		No preemption	With preemption		Preemption and return	
		Value	Change [%]	Value	Change [%]		Value	Change [%]	Value	Change [%]
TT_{EV} $[s]$	454	407	-10.27	409	-9.78	524	467	-10.83	451	-13.83
NS_{EV}	2	0	-100.00	0	-100.00	3	1	-66.67	0	-100.00
LT_{EV} $[s]$	120	74	-38.33	76	-36.67	190	134	-29.47	118	-37.89
ST_{EV} $[s]$	32	0	-100.00	0	-100.00	52	9	-82.91	2	-95.54
TTT $[h]$	93.5	93.3	-0.23	93.4	-0.04	139.5	138.3	-0.84	138.3	-0.82
TTT_{PT} $[s]$	$2,895$	$2,876$	-0.66	$2,879$	-0.56	$2,895$	$2,868$	-0.92	$2,873$	-0.76

TABLE III
AVERAGE VALUES OF OBTAINED RESULTS FOR SCENARIOS 3 AND 4

MoE	Scenario 3					Scenario 4				
	No preemption	With preemption		Preemption and return		No preemption	With preemption		Preemption and return	
		Value	Change [%]	Value	Change [%]		Value	Change [%]	Value	Change [%]
TT_{EV} $[s]$	456	416	-8.88	411	-10.00	487	452	-7.32	447	-8.35
NS_{EV}	2	0	-100.00	0	-100.00	2	1	-50.00	0	-100.00
LT_{EV} $[s]$	118	78	-33.90	72	-38.98	149	114	-23.49	109	-26.85
ST_{EV} $[s]$	34	6	-82.76	3	-90.06	39	5	-87.48	2	-95.16
TTT $[h]$	93.5	93.4	-0.07	93.6	0.13	138.4	138.5	0.07	137.9	-0.28
TTT_{PT} $[s]$	$2,895$	$2,886$	-0.29	$2,897$	0.07	$2,895$	$2,895$	0.01	$2,885$	-0.32

D. Discussion

Reduction of the travel time of the EV (TT_{EV}) has been obtained in each scenario with the implementation of the proposed preemptive algorithm. Additionally, small improvements can be seen in all scenarios except scenario one when the algorithm for the return of rescheduled time is used also. Best result has been obtained in scenario two where the EV travel time was reduced by 10.83 % with the preemption algorithm, and 13.83 % with preemption and return of rescheduled time. This can be explained by the fact that the EV travels only on the primary traffic flow and the prolonged green phase for the non-conflicting phase clears the route of the EV for its return also.

The total number of stops of the EV is shown in Tables II and III as NS_{EV}. From Tables II and III it is apparent that using both preemptive algorithms completely eliminates the number of stops in some scenarios. Without the preemptive algorithm, the EV stops in average two times during the simulation. By using the preemptive algorithm and algorithm for returning of rescheduled time, the EV passes on average through the simulated transport network without stopping.

In the case of the lost time of EV (LT_{EV}), an analogy with the travel time of EV (TT_{EV}) is observed. This confirms that the reduction of the travel time of the EV is caused by the reduction of the lost time of the EV. Without the preemptive algorithm, the EV was stopped on average for 32 s. By implementing the algorithm for preemptive control and the algorithm for returning of rescheduled time, EV was on average stopped for 0 s because the EV did not stop in any simulated scenario.

Total travel time of all vehicles (TTT) is slightly reduced with the use of the preemptive algorithm in all scenarios except scenario four. This result is credited to the large difference of traffic demand of the primary and secondary traffic flow. The EV spends most of its travel time on the primary traffic flow and with the use of preemptive algorithm TTT is reduced because the prolonged green phase is assigned to a larger number of vehicles. With the use of the algorithm for the return of the rescheduled time, there are no significant changes in TTT except in scenario four where an improvement of 0.28 % was observed.

The PT total travel time (given in Tables II and III with TTT_{PT}) shows a similar result as the total travel time of all vehicles. It was reduced in all scenarios except in scenario three in which the algorithm for the return of rescheduled time was used.

V. CONCLUSION AND FUTURE WORK

In this paper, an algorithm for preemptive traffic light control of an isolated intersection based on vehicle tracking and queue lengths is proposed. The algorithm assigns the priority to EVs in order to reduce the travel time of such vehicles. This is done by rescheduling of the green phase time from the conflicting to the non-conflicting phase. After the EV passes the intersection, the rescheduled time is returned to the conflicting phase in order to minimize the influence of preemptive traffic light control on the surrounding urban traffic network. For the return of rescheduled time, the algorithm takes into account the ratio of the original conflicting and non-conflicting green phase durations.

To analyze the impact of preemptive traffic light control, an isolated intersection on one of the green wave corridors of city of Zagreb, Croatia was simulated using a VISSIM-MATLAB framework and realistic traffic data. Obtained MoEs reveal that the proposed algorithm can reduce the travel time of EVs for about up to 13 % and in some cases eliminate the number of stops of the EV. The influence on other vehicles is up to 1 % related to changes in travel time what is small compared to the decreased response time of emergency services.

Future work on this topic will include augmentation of the proposed algorithm to enable preemptive traffic light control on the whole route of the EV. Ability to cope with more complex intersections containing signal programs with more phases and PT interfering from both horizontal and vertical traffic directions will be added and evaluated also. That means preemptive traffic light control on several consecutive intersections placed close to each other in a realistic urban traffic network.

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