vehicular sensor networks,
traffic signal control,
priority vehicles

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DECENTRALIZED CONTROL OF TRAFFIC SIGNALS WITH PRIORITY FOR AMBULANCES

In this paper delays and average travel times of vehicles are analyzed for various decentralized traffic control algorithms that can provide priority for ambulances. Decentralized control strategy is scalable and can be used in road networks where traffic lights are controlled autonomously for multiple intersections of different types. The experiments were performed in a realistic simulation model of complex road network, which is typical for European cities. It was shown that utilization of detailed traffic data from vehicular sensor network significantly improves the performance of signal control algorithms. After proper selection of algorithm parameters, the decentralized control strategy not only provides a quick transition of ambulances, but also has minimal effect on the delay of non-priority vehicles. Research for mesh road network organization has been performed in previous work [16].

1. INTRODUCTION

In most cities around the world, traffic jams still remain a major transportation problem causing delays, increased fuel consumption and monetary losses. Traffic control and management systems with signs, lighting, signals, pavement markings, guardrails, barriers, and crash cushions form an important and inseparable part of road infrastructure affecting safety performance. Significant progress has been made in recent decades to develop vehicle-responsive systems for improved operation of traffic signals. Some of the latest wireless communications and Vehicular Sensor Network (VSN) technologies enable effective collection of detailed data about vehicles traveling in a road network. These technologies significantly supports traffic control functionality [6].

In addition to the data collection methods, it is also important to provide modeling tools for data analysis with use of computer systems. A mathematical model is an abstraction of a real-world system. Under ideal conditions the model should be as simple as possible and maintain the basic properties of the system under consideration. The selection of detail level for the created model is a complex task. On the one hand a complex model provides an accurate description of the systems behavior, but on the other hand a simple model ensures relatively easier representation, computation and analysis. In case of the vehicular traffic numerous models have been proposed in the literature [2], [9], [17], [25].

Current traffic signal control approaches are based on strictly centralized technology. The centralized techniques are not scalable and ineffective. This problem led to the development

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of modern traffic control based on decentralized techniques [10], [12], [22]. The decentralized traffic signals are controlled independently, but from the point of view of their behavior they act as if they exchanged data between themselves. Recent achievements in VSNs enable development of effective decentralized traffic control strategies. In VSN sensor-equipped vehicles can communicate with infrastructure and with other vehicles via wireless multi-hop relaying. The speed and position data of a particular vehicle are collected by road-side units (RSUs), that can be placed at the intersections [7]. This technology could allow the traffic signals to serve ambulances as soon as possible with minimal delays [1], [18]. Minimizing the average delay is important not only from the perspective of the patient, but also when choosing a location for a newly built hospital [3], [8], [27], [28].

This paper is devoted to performance analysis of the decentralized traffic control with priority for ambulances.The analysis is focused on minimizing delays and travel times of ambulances by utilizing traffic information acquired from VSN. The decentralized traffic control system was implemented in a simulation model of complex road network to enable extensive experiments and comparison of various control algorithms.

The paper is organized as follows. Related works are discussed in Section 2. Section 3 describes the proposed method, which introduces priority for ambulances at intersections with traffic signals, controlled according to the decentralized strategy. Results of simulation experiments are presented in Section 4. Finally, conclusions are given in Section 5.

2. RELATED WORKS

In this section a short survey is presented of decentralized signal control strategies that are available in literature. The main advantages of using these methods include the lack of a central controller and no communication between control units that are placed at intersections. Special attention was paid to the systems providing priority for privileged vehicles, e.g., ambulances.

The simplest methods include self-organizing traffic lights (SOTL), which is discussed in detail in [5], [23]. In this approach a preference is given to vehicles that have been waiting longer, and to larger groups of vehicles. The article [24] has shown that even so simple method can increase network capacity compared to Sydney Coordinated Adaptive Traffic System (SCATS) [26].

More complex solution was shown in [22] where cellular automata model was used. In this method the control rules were optimized by evolutionary algorithm. It was shown that by using the evolutionary approach it is possible to adjust the control rules to the prevailing conditions on the road. The fitness function for evolutionary algorithm in that study was evaluated via traffic simulation by using the microscopic cellular automata model.

Dedicated hardware solution that requires data exchange between vehicles and the central controller was shown in [20]. In this simple method distance between the ambulance and the closer junction is calculated in a discrete time steps. If previously mentioned distance is less than specified value, the traffic light change to green for that emergency car. If the RSU loses communication with the vehicle or detected priority car will travel a distance greater than 20 meters then the lights return to their previous state.

Based on WAVE standard, a preemption strategy has been proposed in [19]. In this method traffic signals are adjusted adaptively to get green light at the appropriate time so that the queue at the downstream intersections can be served just in time for the passing ambulance.

More complex decentralized traffic control solution was shown by Lämmer and Helbing [15]. This method takes into account the priorities based on the expected number of vehicles that will pass over a certain time period. The expected numbers of vehicles are determined in this approach by short-term traffic flow prediction based on a macroscopic fluid-dynamic model. Experimental testing of this method showed its superiority in performance from the adaptive approach.

Another control strategy was called Back-pressure [29]. Back-pressure sets the priority on the basis of traffic load differences between the lanes which are connected to the junction. The method assumes that all connections have infinite capacity. This control strategy was originally dedicated to solve in a efficient way the problem of routing (in terms of computer networks). This concept was then adapted to urban road networks for signal control.

A method that uses fuzzy logic was discussed in [4]. According to that method each local controller uses a set of fuzzy decision rules to adjust the standard signal timing parameters (cycle time, phase split, and offset).

Effectiveness of that method was shown through simulation of the traffic flow in a network of controlled intersections. It was shown that implementing this type of control with fuzzy decision rules may enhance the performance of control actions and increase control flexibility.

Another group of methods utilizes the vehicle to infrastructure communication. For such methods it is possible to register many of the incoming vehicles. An example of a solution to this problem is discussed in [11]. Bearing in mind that communication between specified vehicle and the control unit is of a wireless nature, particular attention should be paid to protocol security. In this way we can avoid spoofing type of a vehicle that participates in a road traffic [13], [14].

3. METHODS

This chapter presents details of the approach, which provides priority for ambulances at signalized intersection with decentralized signal control strategy. The main purpose was to serve the ambulances or as soon as possible to minimize their travel time. In addition, the algorithm should be designed to ensure low delays of non-priority vehicles. The analyzed solution uses data obtained from VSN. Important components of the VSN are control units. These elements are used to collect data from passing vehicles. When using this technology, it is possible to read the position and speed of each vehicle equipped with sensors and communication module. The considered control units take control decision about switching traffic signals according to the decentralized traffic control algorithm shown in Algorithm 1.

The input data of this algorithm consists of parameters that describe the traffic streams passing through an intersection. Output of the algorithm is a control decision that determines which traffic lane (or lanes) should get a green signal for a subsequent time interval. During the operation of the algorithm, priority is assigned to specific lanes. Lanes with the highest priority get a green signal for a subsequent time interval. Decision about priority is made at a constant time steps. Priorities are calculated dynamically based on information about current traffic state.

According to this algorithm, the presence of an ambulance on each lane is checked at every step. For this purpose $preemption\_condition$ function is used. Upon detection of an ambulance, two parameters are defined: t_R parameter that was defined as expected time in which the ambulance will reach the traffic signal and t_C parameter which is necessary to clear the queue of vehicles in the considered lane. Dependency between these parameters was defined as follows:

$$t_R \leqslant t_G + t_C, \tag{1}$$

where t_G is required intergreen time between the green period terminating for traffic lanes that are losing right of way and the start of the green period for the lane where ambulance

Algorithm 1 Decentralized traffic signal control with priority for ambulances

```
for each time step do
    if not setup time then
        preemption = false
        for each lane do
            if preemption_condition(lane) = true then
                preemption = true
                priority[lane] = preemption_priority(lane)
            else
                priority[lane] = 0
            end if
        end for
        if preemption = false then
            for each line do
                priority[lane] = regular_priority(lane)
            end for
        end if
        provide green signal for lane with the highest priority
    end if
end for
```

is detected. The intergreen time has to be introduced to ensure traffic safety. Signal reaching time is calculated as:

$$t_R = d/v_F, \tag{2}$$

where d denotes distance of the ambulance to traffic signal and v_F is desired speed of the ambulance, which is observed in low traffic (free flow) conditions and in the absence of traffic signals. The vehicle node calculates the desired speed based on collected historical sensor readings and reports it to the control unit. Queue clearance time is estimated by using the formula:

$$t_C = n/s + t_0, \tag{3}$$

where n denotes number of vehicles in a queue ahead of the ambulance, s is saturation flow rate, i.e. the maximum number of vehicles that can pass through the intersection during a time unit, when the traffic signal is green, t_0 is the time lost at the beginning of green light, when vehicles are accelerating. If an ambulance is detected, priority will be calculated on the basis of $preemption\_priority$. This feature takes into account the situation where more than one vehicle is approaching in more than one conflicting traffic lanes. Conflict resolution was implemented in the following way.

$$preemption\_priority = \frac{m}{t_G^{start} + t_S + t_G^{end}}, \tag{4}$$

where m is number of ambulances in the given lane, t_G^{start} is intergreen time, which has to be introduced before giving green signal for the considered lane ($t_G^{start} = 0$ if the considered lane already has the green signal), t_S is the green time necessary for the m ambulances to leave the intersection, and t_G^{end} denotes intergreen time after green signal for the considered lane. The above preemption priority has been proposed in [15].

In situations where no ambulances are detected then for the calculation of priority the algorithm uses $regular\_priority$. This function calculates the priority of each lane based on selected state-of-the-art traffic control method. Function $regular\_priority$ takes care if each of the lanes at the intersection received the green signal at least once in a predefined time period. The research uses a different approaches to $regular\_priority$ and is described in the next chapter. These definitions depends on the specific self-organizing traffic control methods described in the literature.

4. EXPERIMENTS

In this study the state-of-art decentralized traffic signal control methods are extended to reduce travel time of ambulances and effectively utilize data received from VSN. During simulation experiments different decentralized traffic control methods with priority for ambulances are compared. The analysis of experimental results presented in this section focuses on travel time, delay and average speed. These parameters were evaluated for complex road network model with different types of intersections.

4.1. SIMULATION SETUP

SUMO traffic simulator was used for the experimental evaluation of decentralized traffic control algorithms. SUMO (Simulation of Urban MObility) is an open-source software, which includes road traffic simulator as well as supporting tools that make it possible to transfer data directly from different environments, such as MATLAB, that can be used for implementation of the control algorithms. This simulator provides a fair approximation of real world traffic. Topology of the simulated network is a collection of intersecting roads of different lengths. The proposed road network model includes 18 signalized intersections and roundabout. Schema of the simulated road network and examples of intersections are presented in Figure 1. During single run of simulation, the traffic intensity was changed from 0.02 to 0.14 vehicles per second. The vehicles were generated with the same intensity at each entrance of the road network. One simulation run corresponds to one hour. Percentage of the ambulances was changed between 0% and 3.5%. This percentage was determined for each one-hour simulation test. Four classes of vehicle were considered. Two of them are priority type (slow and fast ambulances) and the remaining ones are non-priority vehicles (car and bus). Slow ambulance move with maximum speed of 72km/h and fast with the maximum speed of 90 km/h. Maximum speed of the non-priority vehicles was equal to 72 km/h for car and 60km/h for bus. Results of the simulation include travel time, delay and average speeds of the vehicles. The results were collected for five intersections in the simulated road network.

All traffic signals at the simulated intersections were controlled by using decentralized self-organizing algorithms. Six different signal control algorithms were implemented in the simulation environment (Tab. 1). These algorithms use three control strategies (LH, SOTL and BP) to compute the regular priorities for traffic lanes.

The SOTL (Self-Organizing Traffic Lights) approach [15] decides about switching the traffic lights by taking into account the numbers of vehicles approaching the intersection. Each traffic light has a counter. When signal turns to red the counter is set to zero. Counter is incremented when vehicles are approaching the signal. If the counter is equal to a specified value then the traffic lane gets the highest priority. In addition, a minimum green time constraint has been introduced to counteract frequent switching of the signals. This algorithm allows vehicle groups (platoons) to pass the intersection without stopping. However, large platoons of vehicles are divided, otherwise they would excessively block the traffic flow of intersecting streets. Details of this algorithm have been presented in [5].

Another method was introduced by Lämmer and Helbing. This approach is based on two control rules: optimization rule and stabilization rule. Stabilization rule introduce the cost, which is associated with providing green signal for a particular lane. The cost is defined as a total increase of vehicle delay. The traffic lane with minimum cost gets the highest priority. Main goal of stabilization rule is to provide green signal for all traffic lanes at least once in a specified maximum time period. This rule is important in situation where one of the lanes has a small load. Without this rule the vehicle could wait an infinite amount of time. More information about this method can be found in [21].

Back Pressure (BP) method was originally proposed for routing algorithms in wireless networks. This strategy uses priorities that are proportional to the difference of queue lengths in traffic lanes leading into the intersection and those leading out. Pseudo-code of the BP strategy can be found in [29].

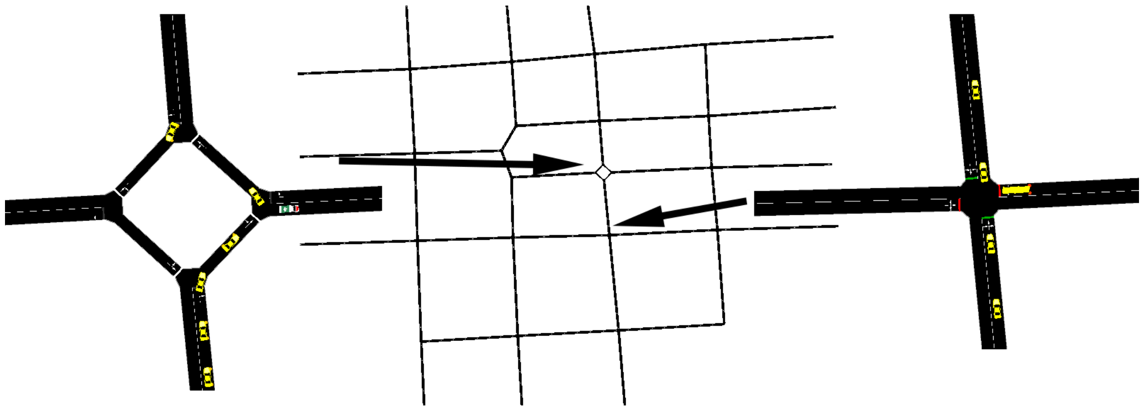

Fig. 1. Simulated road network.

Table 1. Compared algorithms

Algorithm	SOTL1	LH1	BP1	SOTL2	LH2	BP2
Source of information about non-priority vehicles	RSD	VSN	Road-side detectors (RSD)		VSN	RSD
Source of information about priority vehicles	RSD or V2I communication			VSN		
Preemption condition	Distance to signal			Time to reach signal		
Preemption priority	Order of requests			Minimum delay		

Main features of the algorithms considered in this study are presented in Tab. 1. The algorithms have been categorized into two groups with different preemption method. According to the first method, a preemption request is triggered when the distance of ambulance to junction is less than specified threshold. In case when many request are registered, the highest priority is assigned to the first registered request. This method has been implemented to SOTL1, LH1 and BP1 algorithms. Application of data from the VSN gives the opportunity to create a second set of algorithms (SOTL2, LH2 and BP2). These algorithms include the preemption condition and the preemption priority functions that have been described in Sect. 3.

4.2. EXPERIMENTAL RESULTS

The signal preemption strategy should allow for rapid transition of ambulances with minimal negative impact on non-priority vehicles. The traffic simulations were conducted to evaluate average speed, travel time and stop delay of vehicles for the compared algorithms. Travel time is measured from the moment when the vehicle is detected by VSN sensors, to the moment it exits the intersection. In this section the simulation results are analyzed to determine the impact of signal preemption on ambulances and non-priority vehicles. At the beginning the signal preemption procedure was calibrated by adjusting its parameters in a series of simulations for Lämmer's and Helbing's algorithm. Simulations have been made for fixed number of ambulances at approximately 5% rate. Impact of the algorithm parameters on travel time of ambulances and standard vehicles was shown in Figure 2.

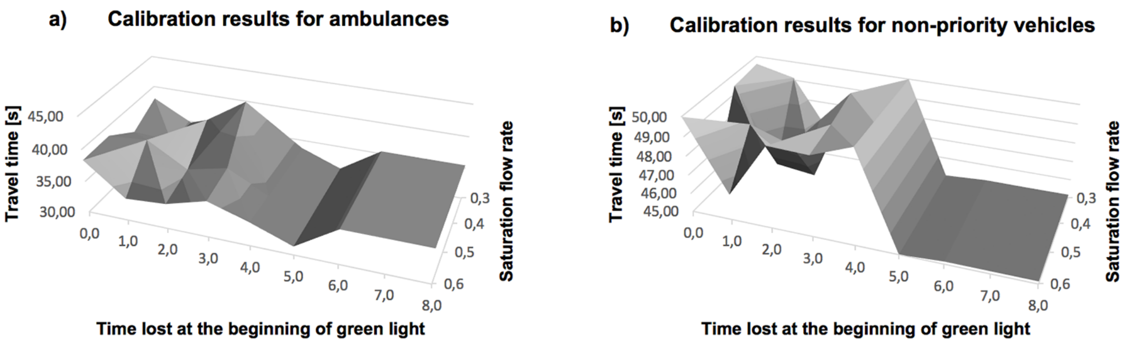

Fig. 2. Calibration results for ambulances and non-priority vehicles

Average travel time of ambulances and standard vehicles for the considered algorithms are compared in Figure 3. The lowest travel time was observed for the the LH algorithm, which utilizes the detailed data delivered from VSN. The algorithms, which use road-side-detectors (SOTL and BP) give worse results. When analysing the travel time of ambulance for the algorithms that use preemption strategy based on VSN (LH2, SOTL2 and BP2), it can be observed that the considered approach works with maximum level of performance for the LH strategy. The introduced preemption has decreased the average travel time by 10% for LH algorithm. In case of SOTL solution, the travel time remains almost at the same level.

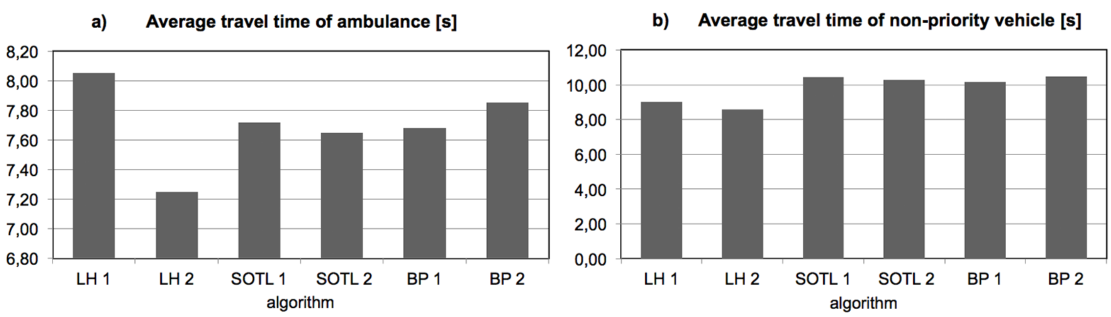

Fig. 3. Average travel time of ambulances and non-priority vehicles for the compared algorithms.

The charts in Figure 4 and Figure 5 compare average speed and delay of priority and standard vehicles. These results show how important is the calibration process. The best results were obtained for LH algorithm, which was previously calibrated by changing the parameters s and t_0 that are explained in Section 3. The introduced preemption decreases the average delay of ambulances by 85% for LH algorithm and increases the average speed by 8% for LH algorithm with positive influence to standard vehicles. In case of the remaining algorithms: the SOTL results have been gently improved, but BP proved to be useless for this type of road network, where junctions without traffic lights are present (e.g., roundabouts).

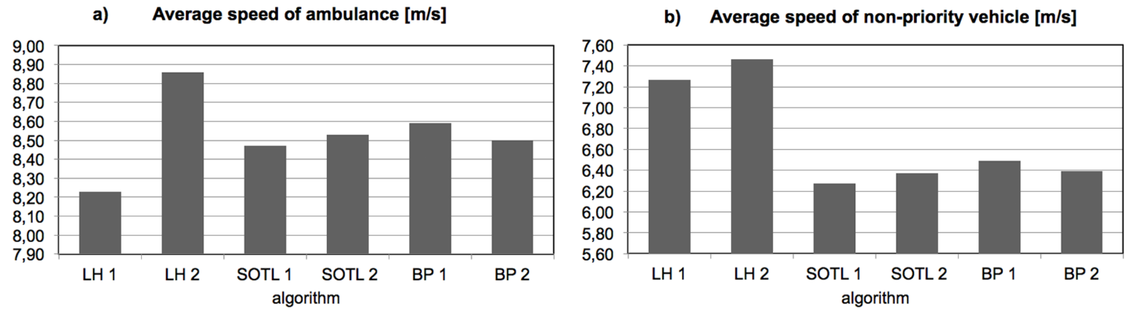

Fig. 4. Speed of ambulances and non-priority vehicles for the compared algorithms.

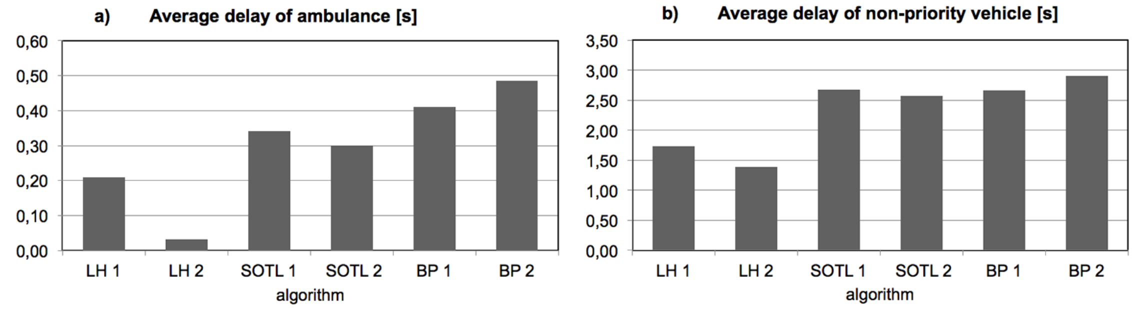

Fig. 5. Delay of ambulances and non-priority vehicles for the compared algorithms.

5. CONCLUSION

In this paper a self-organizing traffic lights control method is presented, which considerably reduces travel time and delays of ambulances. It was shown that this method is suitable for complex scenarios with multiple-way intersections. The research was carried out not only for standard intersections but also for roundabout. Utilization of the data collected from VSN, which describe positions and velocities of particular vehicles gives possibility to achieve the efficient distributed traffic signal control. In addition, the algorithm reduces the impact of the ambulances on the travel time for the rest of vehicles. The results show that using the VSN and V2I technologies, it is possible to increase the control efficiency for the currently proposed solutions that. When using a decentralized strategy, the algorithm is scalable and can be used in complex road networks, where traffic lights are controlled independently for a large number of intersections. An important insight is that the cost of data collection in VSN can be kept at a low level because data for the considered algorithm have to be collected locally at intersections and are not transmitted to one central point.

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